

# Radar Rainfall Analysis

## September 2016 Summary Report



*Improving our region's water quality*

Prepared for 3 Rivers Wet Weather

October 20, 2016



301 David L. Boren Blvd., Suite 3050  
Norman, Oklahoma 73072  
[www.vieuxinc.com](http://www.vieuxinc.com)

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## Glossary

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**Average Difference (AD)** – Average of the absolute percentage differences between the rain gauge data and uncalibrated radar data sampled over the gauges.

**Bias Correction Factor** – Bias is a systematic error that can be corrected through calibration. The correction factor is the sum of the gauges divided by the sum of the sampled radar values over the gauges.

**Calibrated Average Difference (CAD)** – Average of the absolute percentage differences between the rain gauges and local bias calibrated radar data sampled over the gauges.

**Cumulative Distribution Plot (CDP)** – A graph depicting the accumulation of a rain gauge and the unadjusted/adjusted radar over that gauge.

**Decibels of Reflectance (dBZ)** – The logarithmic scale for measuring radar reflectivity factor or a measure of reflectivity of a radar signal off a remote object.

**Gauge Adjusted Radar Rainfall (GARR)** – Bias corrected radar rainfall through comparison with rain gauges.

**KCCX** – Federal Communications Commission (FCC) call sign for the NEXRAD near State College, PA.

**KPBZ** – Federal Communications Commission (FCC) call sign for the NEXRAD near Pittsburgh, PA.

**Level II** – The Level II radar products are the highest resolution, and consist of the base data that includes reflectivity measured in decibels of reflectance (dBZ) among Doppler velocity and spectrum width.

**Level III** – The Level III radar products are derivative products from Level II, and consist of horizontal and vertical reflectivity among other products.

**Local Bias (LB)** – An approach to adjusting radar rainfall that uses the ratio of gauge to radar accumulations from surrounding gauges, with the closest gauge having the most weight.

**Minimum Storm Total Threshold (MSTT)** – A check used to remove radar/gauge pairs whose cumulative radar and/or gauge values for a given event period were below 0.05 inches.

**Next Generation RADAR (NEXRAD)** – A network of S-band (10.5-cm wavelength) radars operated by the National Weather Service.

**Radio Detection and Ranging (RADAR)** – An electronic instrument used for the detection and ranging of distant objects of such composition that they scatter or reflect radio energy.

**Radar-Gauge (RG)** – A pair of rainfall accumulations measured by the rain gauge and the radar rainfall accumulation sampled above the gauge.

**Z-R relationship** – An empirical relationship between radar reflectivity factor  $Z$  ( $\text{mm}^6 \text{ m}^{-3}$ ) and rain rate  $R$  ( $\text{mm hr}^{-1}$ ). Radar reflectivity factor is dependent on the rain drop size distribution. [ $Z = aR^b$ , where  $a$  and  $b$  are empirically derived constants]

- **Convective** – generally used for convective (i.e. thunderstorms) rainfall [ $Z = 300R^{1.4}$ ]
- **Eastern U.S. Cool Stratiform** – generally used for cool season, non-convective rainfall that occurs east of the Continental Divide [ $Z = 130R^{2.0}$ ]

## Overview

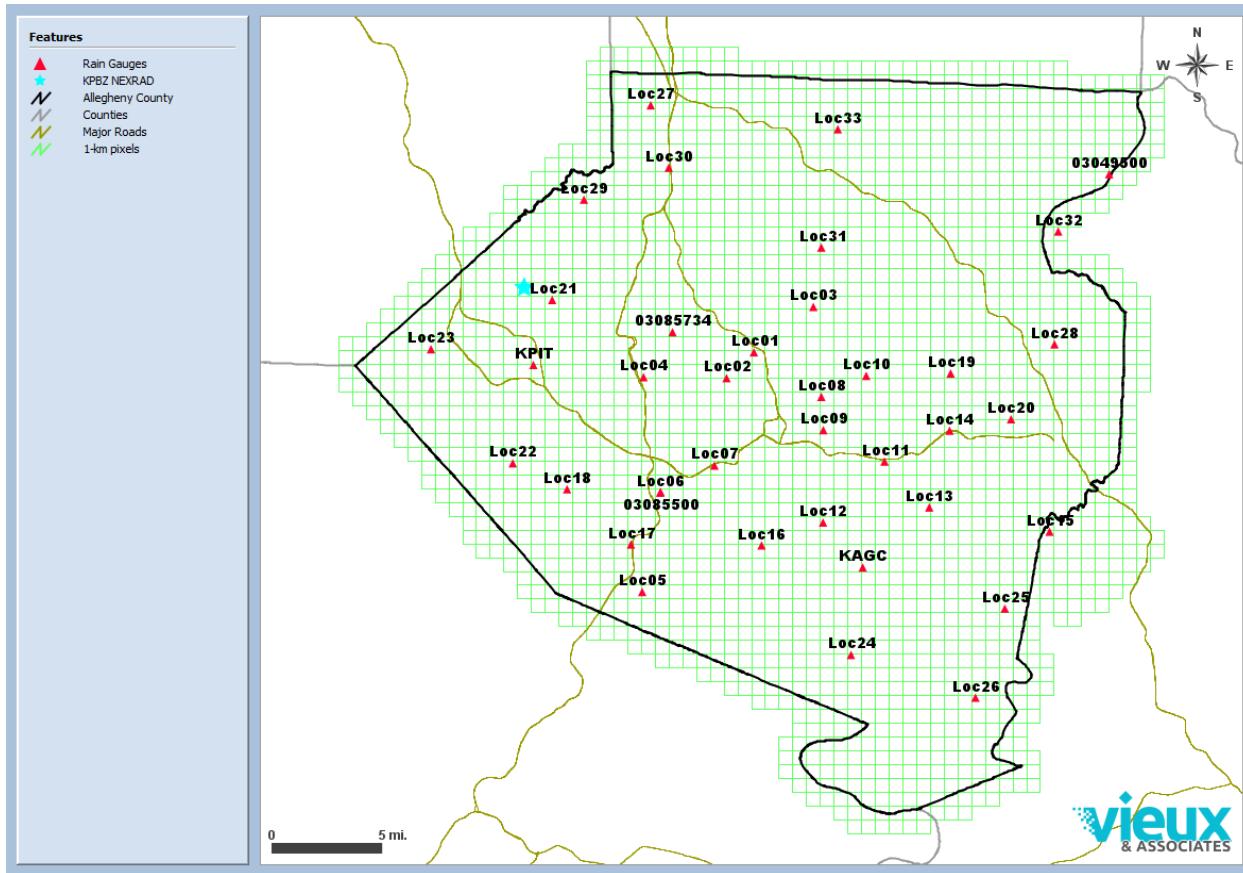
Vieux & Associates, Inc. (Vieux) processes radar and rain gauge data for 3 Rivers Wet Weather (3RWW). During each month, radar and rain gauge data are quality controlled (QC). To produce QC gauge-adjusted radar rainfall (GARR), both radar and rain gauge data are reviewed manually to remove inconsistent data. Only rainfall events that qualified for gauge-adjustment of the radar are included in this report.

Radar data used in production of GARR is produced by the National Weather Service (NWS) Next Generation Radar (NEXRAD) system. NEXRAD Level II radar data are often referred to as Base Data and contain the full spatial/temporal/data resolution data from the radar. Level II radar data measures reflectivity in decibels of reflectance (dBZ), and at a spatial resolution of 0.5-degree by 0.25-km every 4 – 10 minutes with a data resolution of 0.5 dBZ amounting to 256 data levels of data. Level III Q1 radar data have the same data and temporal resolution, but a reduced spatial resolution of 1-degree by 1-km.

The primary radar data source used to process this period was Level II NEXRAD data from KPBZ located near Pittsburgh, PA. The succession of data used gives priority to Level II followed by Level III products. If KPBZ Level II NEXRAD data are unavailable, then KPBZ Level III Q1 is substituted. If no radar data are available from KPBZ, then Level II NEXRAD data from KCCX (State College, PA) are used. In the event that all radar sources are unavailable or if the radar provides insufficient rainfall information, then a gauge-only product that spatially distributes point rainfall estimates is used. All radar data were processed into fifteen-minute increments.

Because the radar measures reflectivity in polar coordinates centered on the radar installation, the 1-degree azimuth increases in width as range increases from the radar. Range resolution of the Level II radar data is 1-km and is measured out to 230 km from the radar. Due to the proximity of KPBZ to the study area, the polar coordinates defining horizontal resolution over Allegheny County range from 0.1 – 0.9 km, whereas KCCX ranges from 2.5 – 3.6 km. The radar data represented in these polar coordinates are sampled through spatial averaging into a Cartesian grid of uniform resolution, i.e. 1x1 km. An advantage of the Cartesian grid is that one radar can be substituted for the other without changing the grid resolution, as would be necessary if polar coordinates were used for output of rainfall information at 1x1 km spatial resolution. The Cartesian grid used was defined by a 1-km<sup>2</sup> grid domain shapefile containing 2313 1-km<sup>2</sup> pixels covering the study area.

Rain gauge data from as many as 38 gauges were used to adjust the radar. 3RWW provided rain data in 15-minute increments for 33 stations. In addition, rain gauge data were obtained from three United States Geological Survey (USGS) stations and two NWS Automated Surface Observing System (ASOS) stations. Figure 1 depicts the spatial distribution of the rain gauge network, KPBZ NEXRAD and 1-km<sup>2</sup> pixels. For the gauges shown in Figure 1, the ID, name and source of each gauge is listed in Table 1. Radar data review, preparation and sampling the radar over the gauges and 1-km<sup>2</sup> pixels were achieved using software developed at Vieux.



**Figure 1. Spatial Distribution of the Rain Gauge Network, KPBZ NEXRAD and 1-km<sup>2</sup> Pixels**

**Table 1. Rain Gauge ID, Name and Source**

| Gauge ID | Gauge Name            | Source |
|----------|-----------------------|--------|
| Loc01    | PWSA-Montana St.      | 3RWW   |
| Loc02    | ALCOSAN WWTP Lab      | 3RWW   |
| Loc03    | Shaler Munic Bldg     | 3RWW   |
| Loc04    | Kennedy Twp PS        | 3RWW   |
| Loc05    | Upper St. Clair       | 3RWW   |
| Loc06    | Carnegie Transit Time | 3RWW   |
| Loc07    | Greentree Munic Bldg  | 3RWW   |
| Loc08    | AC Health Dept Bldg   | 3RWW   |
| Loc09    | Univ of Pittsburgh    | 3RWW   |
| Loc10    | PWSA-Highland Park    | 3RWW   |
| Loc11    | M-46 Access Shaft     | 3RWW   |
| Loc12    | Baldwin               | 3RWW   |
| Loc13    | M-59 Access Shaft     | 3RWW   |
| Loc14    | Churchill Munic Bldg  | 3RWW   |

| Gauge ID | Gauge Name  | Source     |
|----------|---|------------|
| Loc15    | Trafford Maint Bldg                               | 3RWW       |
| Loc16    | Castle Shannon                                    | 3RWW       |
| Loc17    | Chartiers Pump Station                            | 3RWW       |
| Loc18    | Oakdale Pump Station                              | 3RWW       |
| Loc19    | Sandy Creek Eq Facility                           | 3RWW       |
| Loc20    | Gascola Eq Facility                               | 3RWW       |
| Loc21    | Moon TWP  | 3RWW       |
| Loc22    | North Fayette TWP                                 | 3RWW       |
| Loc23    | Clinton Munic Bldg                                | 3RWW       |
| Loc24    | Jefferson Hills                                   | 3RWW       |
| Loc25    | White Oak Public Works Bldg                       | 3RWW       |
| Loc26    | Elizabeth TWP Municipal Bldg                      | 3RWW       |
| Loc27    | Marshall TWP                                      | 3RWW       |
| Loc28    | Plum Municipal Bldg                               | 3RWW       |
| Loc29    | Bell Acres Munic Bldg                             | 3RWW       |
| Loc30    | McCandless Twn Hall                               | 3RWW       |
| Loc31    | Hampton Municipal Bldg                            | 3RWW       |
| Loc32    | Arnold  | 3RWW       |
| Loc33    | Richland TWP                                      | 3RWW       |
| KAGC     | Pittsburgh Allegheny Cty                          | NWS - ASOS |
| KPIT     | Greater Pittsburgh Int'l                          | NWS - ASOS |
| 03049500 | Allegheny River at Natrona                        | USGS       |
| 03085500 | Chartiers Creek at Carnegie                       | USGS       |
| 03085734 | Ohio River at Emsworth Dam Lower Pool at Emsworth | USGS       |

The 38 rain gauges and the two NWS NEXRAD radars are used to produce gauge-adjusted radar rainfall (GARR). The methodology used in production of the GARR and the dataset metadata are described in the following sections.

## Methodology

Statistical control of the data makes radar rainfall measurements more accurate. By statistical comparison between the radar and rain gauge accumulations during a calibration interval, statistical outliers may be identified. Radar data is enhanced by correcting it for systematic errors called bias, which helps improve the accuracy of the rainfall product. The bias correction factors are multiplicative factors applied to the radar that enhances the accuracy of the radar rainfall for any accumulation period. By adjusting the radar data with rain gauge data, better maps of rainfall are produced than either sensor system could produce alone. Qualified rainfall events are defined based on a storm event definition where, for any given hour, at least 50% of all working 3RWW gauges have an accumulation of 0.05 inches.

In the production of GARR, radar rainfall is bias corrected through comparison with rain gauge accumulations. To the extent possible, individual gauges are combined to cover the target area for use in bias adjustment. The method of adjustment depends on the hydrologic application and the spatial extent of the area of interest. The local bias (LB) approach to adjusting the radar rainfall uses the ratio of gauge to radar accumulations from surrounding gauges with the closest gauge having the most weight. The LB approach distributes the variation of bias over the region, and is computed and applied within each event period.

The LB uses the ratio between the sum of each gauge divided by the sum of the sampled radar values over each gauge. Gauge and radar accumulations were computed for each event period. A minimum storm total threshold (MSTT) check was used to remove radar/gauge (RG) pairs whose R or G cumulative values for a given event period were below a chosen threshold (i.e. 0.05 inches for this study). The remaining RG pairs were then checked for statistical outliers. Those RG pairs with individual bias ( $G/R$ ) or average difference ( $(G-R)/G$ ) values greater than three standard deviations from the mean were then excluded from being used to adjust the radar.

After RG pairs have been removed on an event basis by either the MSTT or outlier check, the individual biases of the remaining RG pairs are then distributed spatially over the analysis area using the LB weighted distance method. The resulting LB value over each radar bin is the multiplicative factor that adjusts the radar. For example, a bias of 1.5 can be interpreted as a 33% underestimation by the radar. The statistical measures reported are 1) average difference (AD) and 2) calibrated average difference (CAD). Both of these statistical measures are expressed as an absolute percentage about the mean of  $G/R$  accumulations for each event period. The 1-km<sup>2</sup> pixels are then filtered spatially from the final adjusted radar bins using an area-averaged technique.

After bias correction, though generally small, differences between rain gauge and radar rainfall accumulations still exist due to sampling differences or local meteorological conditions among other reasons. A major reason for departures is that radar collects data by averaging reflectivity over a 1-degree by 1-km sample volume, while rain gauges measure at a point. Another source of difference is that radar measures above the ground, while rain gauges measure close to the ground. Further, updrafts and downdrafts during storms can decrease or increase rain rates, respectively. However, radar cannot detect local wind effects, while rain gauges can be affected. Differences between the radar data and the rain gauge data are also affected by precipitation processes associated with the type of storm, which also are affected by the season of the year.

## Metadata

Data accompanying this document provides a continuous rainfall record of all 2313 1-km<sup>2</sup> pixels for all events. The data is provided in CSV format. The data file documentation follows:

### CSV metadata:

- Single CSV file for each 1-km<sup>2</sup> pixel in 15-minute intervals.
- Comma-delimited text file, first five columns represent the month, day, year, hour and minute, respectively.
- The sixth and last column represents the rainfall depth in inches.
- Data values represent 15-min accumulation (inches) at end of interval.
- Time zone is in Eastern local time (e.g. EST/EDT).
- The 1-km<sup>2</sup> pixel ID is contained in the filename.

## Gauge-Adjusted Radar Rainfall (GARR)

GARR was processed continuously at fifteen-minute increments for each qualified rainfall event. Five rainfall events were identified as having met the storm definition during September 2016. The GARR statistics for each event are listed in Table 2. Five of the events were split into multiple sub-event periods to improve gauge-adjustment of the radar, resulting in a total of thirteen event and sub-event periods. The events that were split into multiple periods are shown in the **Event#** column with the letter "a", "b", "c", etc. appended to the event number (e.g., E1a, E1b, E1c). The **Source** column shows what rainfall source was used to produce GARR for each event or sub-event period. The listed **Event Date** shown in Table 2 corresponds to the day or portion of the day when most of the rainfall occurred for that GARR event period. All five rainfall events are discussed in more detail in the following Events section.

The **Bias** value shown in Table 2 is the sum of the gauges divided by the sum of the sampled radar values over the gauges. Those rain events with the lowest CAD values shown in Table 2 represent the best agreement between GARR and gauge values for all radar/gauge pairs used to adjust the radar. On average, lower values of CAD imply higher statistical confidence in the reliability of the dataset. Typically, stratiform rainfall events (i.e., low spatial variability) have lower CAD values than convective rainfall events (i.e., high spatial variability). Based on all thirteen event and sub-event periods, the event CAD averaged 4.7%, indicating that the mean GARR agrees with the mean gauge accumulation to within  $\pm 2.4\%$ .

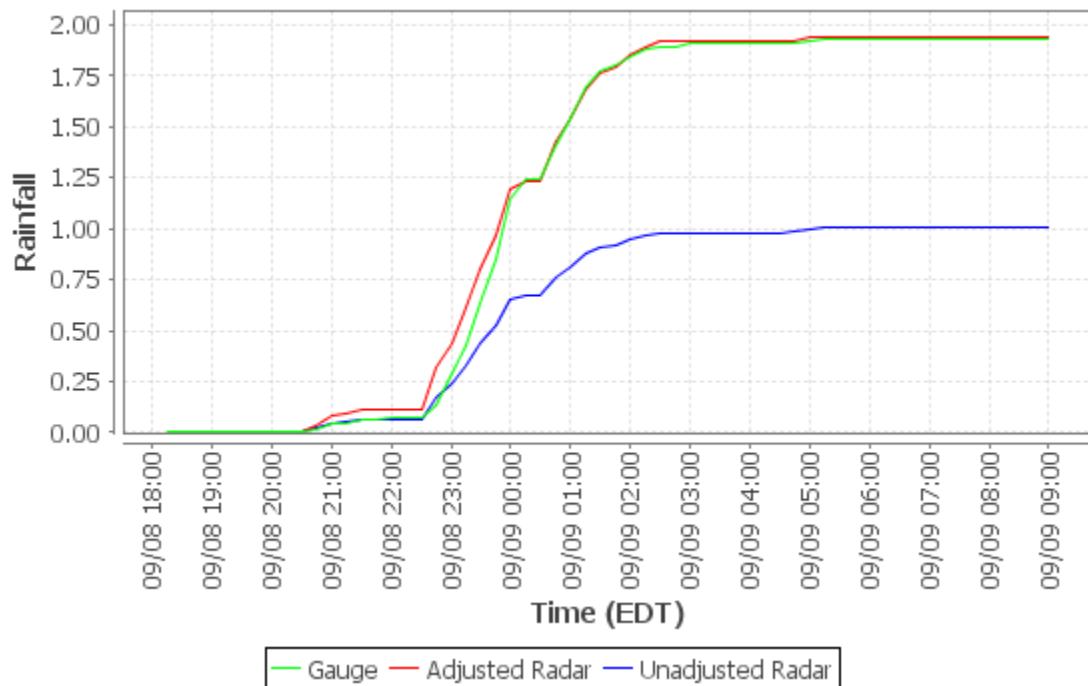
**Table 2. Storm Events and GARR Statistics**

| Event # | Source   | Event Date    | Gauges Used (38) | Avg. Depth (in) | Bias  | AD (%) | CAD (%) |
|---------|----------|---------------|------------------|-----------------|-------|--------|---------|
| E1a     | KPBZ LII | 2016-09-09    | 7                | 0.249           | 1.909 | 46.1   | 0.9     |
| E1b     | KPBZ LII | 2016-09-09    | 34               | 0.457           | 2.246 | 53.4   | 2.6     |
| E1c     | KPBZ LII | 2016-09-09    | 13               | 0.052           | 1.115 | 16.9   | 4.9     |
| E2a     | KPBZ LII | 2016-09-18    | 21               | 0.165           | 2.983 | 65.4   | 7.4     |
| E2b     | KPBZ LII | 2016-09-18    | 19               | 0.213           | 1.838 | 44.4   | 2.9     |
| E3a     | KPBZ LII | 2016-09-29 AM | 18               | 0.160           | 1.329 | 32.6   | 7.5     |
| E3b     | KPBZ LII | 2016-09-29 AM | 33               | 0.202           | 2.017 | 48.3   | 4.5     |
| E3c     | KPBZ LII | 2016-09-29 AM | 30               | 0.088           | 1.201 | 20.8   | 8.6     |
| E4a     | KPBZ LII | 2016-09-29 PM | 36               | 0.514           | 1.673 | 37.9   | 3.1     |
| E4b     | KPBZ LII | 2016-09-29 PM | 30               | 0.202           | 1.963 | 48.1   | 5.4     |
| E4c     | KPBZ LII | 2016-09-29 PM | 28               | 0.275           | 2.494 | 61.2   | 3.2     |
| E5a     | KPBZ LII | 2016-09-30    | 31               | 0.222           | 1.600 | 35.5   | 5.9     |
| E5b     | KPBZ LII | 2016-09-30    | 25               | 0.094           | 0.976 | 13.3   | 4.2     |

Statistical review of the data can provide an indication of data quality. Depending on the quality of the radar and gauge data, CAD values for individual events less than 10% are considered excellent, 10 - 20% are considered good, and 20 - 30% are considered fair. However, CAD may not serve as a reliable indicator of data quality when abrupt changes in bias occur within the analysis period, particularly when compensating over- and under-estimation results due to using

an assumed Z-R relationship throughout the period while atmospheric conditions merit different Z-R coefficients. The effects from abrupt changes in Z-R are mitigated by splitting the event periods.

Rain gauges were analyzed to identify those that were not consistent with the radar or surrounding gauges. Cumulative Distribution Plots (CDPs) at each gauge location showing gauge, unadjusted radar and GARR values were produced for each rainfall event and are presented in Appendices B - F. CDPs are useful for visualizing rain gauge performance. Figure 2 shows the rainfall accumulation at the Marshall TWP (Loc27) gauge during the 2016-09-09 event as measured by the gauge (green), unadjusted radar (blue), and gauge-adjusted radar (red). Rain gauges that are not performing consistently with the radar or surrounding gauges have characteristics such as clogs, synchronization or other mechanical/transmission malfunctions that can be visually identified in the CDP graph.



**Figure 2. CDP Showing Rain Gauge Versus Unadjusted Radar Versus GARR**

Reasons for not using gauges in rainfall analysis include clogs, significant under- or over-reporting of rainfall, gauges that stop reporting during rainfall, or a combination of these reasons. A list of possible reasons for not using a gauge based on CDP analysis is shown in Table 3. Those gauges that were excluded from analysis are shown in [Appendix A](#). Additional gauges were not used to adjust the radar for a given event or sub-event period if they did not meet the statistical criteria outlined in the Methodology section.

**Table 3. List of Possible Reasons for Exclusion of Rain Gauges**

| <b>Reason</b>     | <b>Explanation</b>   |
|-------------------|--|
| Clog (C)          | Gauge appeared to be clogged   |
| Zero (Z)          | Gauge did not report any rainfall while radar rainfall estimates reported significant rainfall   |
| Stop (S)          | Gauge appeared to stop reporting rainfall while radar rainfall estimates reported significant rainfall   |
| Over (O)          | Gauge appeared to significantly over-report rainfall as compared to radar rainfall estimates and surrounding gauges (e.g. anomalously high rainfall values caused by field calibration, data transmission error, or switch malfunctions) |
| Under (U)         | Gauge appeared to significantly under-report as compared to radar rainfall estimates and surrounding Gauges (e.g. half-tipper)   |
| Sync (SY)         | Gauge appeared to be reporting out-of-sync with the radar rainfall estimates   |
| Frozen/Melt (F/M) | Gauge not reporting properly due to frozen or melting precipitation  |
| Other (T)         | Combination of multiple reasons  |
| No Data (ND)      | Gauge reported "no data" for a significant amount of time  |

A synopsis for each event is described below in terms of the specific processing protocol applied to each event period as well as specific GARR information.

## Events

### Event 1: 2016-09-09

The analysis period was from 2016-09-08 18:00 EDT to 2016-09-09 09:00 EDT. The event was then split into three sub-event periods at 2016-09-09 00:30 EDT and 2016-09-09 03:15 EDT to improve gauge adjustment of the radar.

The gauges listed in [Appendix A](#) were not used to adjust the radar due to inconsistencies between the gauge and the radar or surrounding gauges, or they did not have data available for this event. Gauges Loc01, Loc02, Loc03, Loc04, Loc05, Loc06, Loc07, Loc08, Loc09, Loc10, Loc11, Loc12, Loc13, Loc14, Loc15, Loc16, Loc17, Loc18, Loc19, Loc20, Loc22, Loc23, Loc24, Loc25, Loc26, Loc28, KAGC, KPIT and 03085734 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 1a. Gauges Loc01, Loc02, Loc03, Loc04, Loc10, Loc12, Loc13, Loc15, Loc16, Loc21, Loc22, Loc23, Loc27, Loc28, Loc29, Loc30, Loc31, Loc32, Loc33, KAGC, KPIT, 03049500 and 03085734 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 1c.

A convective Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 4 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 5 - 7 summarize the results for each RG pair used for final radar adjustment, where  $G_i$  is the gauge estimate,  $R_i$  is the non-adjusted radar estimate,  $R_i^*$  is the GARR estimate, and  $Diff^*$

(%) is the percent difference between the gauge and GARR estimate. Figures 3 - 5 show the scatter plots of the gauge-adjusted RG pairs. Figure 6 depicts the GARR storm total over the 1-km<sup>2</sup> pixels. The GARR amounts for the 2313 1-km<sup>2</sup> pixels range from 0.2 - 3.2 inches with a mean of 0.8 inches. Table 8 shows the Depth Duration Frequency (DDF) maximum values for the 1-km<sup>2</sup> pixels.

**Table 4. GARR Statistics for Event 1**

| Event # | Radar    | Event Date | Gauges Used (38) | Avg. Depth (in) | Bias  | AD (%) | CAD (%) |
|---------|----------|------------|------------------|-----------------|-------|--------|---------|
| E1a     | KPBZ LII | 2016-09-09 | 7                | 0.249           | 1.909 | 46.1   | 0.9     |
| E1b     | KPBZ LII | 2016-09-09 | 34               | 0.457           | 2.246 | 53.4   | 2.6     |
| E1c     | KPBZ LII | 2016-09-09 | 13               | 0.052           | 1.115 | 16.9   | 4.9     |

**Table 5. Summary of Individual RG Pairs for Event 1a**

| Gauge ID              | Name                   | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|-----------------------|------------------------|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc30</a> | McCandless Twn Hall    | 0.47                | 0.26                | 0.48                  | -0.01      | -2.1      |
| <a href="#">Loc21</a> | Moon TWP               | 0.10                | 0.05                | 0.10                  | 0.00       | 0.0       |
| <a href="#">Loc27</a> | Marshall TWP           | 1.24                | 0.67                | 1.24                  | 0.00       | 0.0       |
| <a href="#">Loc29</a> | Bell Acres Munic Bldg  | 0.31                | 0.17                | 0.31                  | 0.00       | 0.0       |
| <a href="#">Loc31</a> | Hampton Municipal Bldg | 0.17                | 0.11                | 0.17                  | 0.00       | 0.0       |
| <a href="#">Loc32</a> | Arnold                 | 0.25                | 0.12                | 0.25                  | 0.00       | 0.0       |
| <a href="#">Loc33</a> | Richland TWP           | 1.25                | 0.59                | 1.25                  | 0.00       | 0.0       |

**Table 6. Summary of Individual RG Pairs for Event 1b**

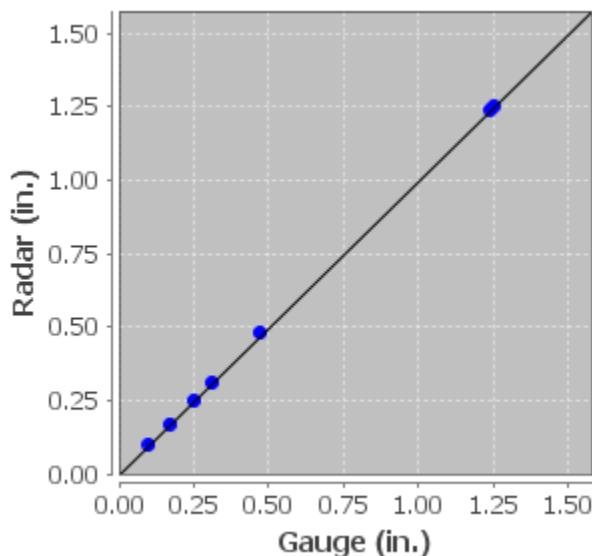
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc13</a>    | M-59 Access Shaft                                 | 0.17                | 0.11                | 0.20                  | -0.03      | -17.6     |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.12                | 0.07                | 0.13                  | -0.01      | -8.3      |
| <a href="#">Loc11</a>    | M-46 Access Shaft                                 | 0.32                | 0.16                | 0.34                  | -0.02      | -6.3      |
| <a href="#">Loc12</a>    | Baldwin   | 0.20                | 0.10                | 0.21                  | -0.01      | -5.0      |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.47                | 0.20                | 0.49                  | -0.02      | -4.3      |
| <a href="#">Loc03</a>    | Shaler Munic Bldg                                 | 0.61                | 0.28                | 0.63                  | -0.02      | -3.3      |
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.36                | 0.18                | 0.37                  | -0.01      | -2.8      |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.46                | 0.22                | 0.47                  | -0.01      | -2.2      |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.47                | 0.22                | 0.48                  | -0.01      | -2.1      |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.57                | 0.26                | 0.58                  | -0.01      | -1.8      |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.67                | 0.31                | 0.68                  | -0.01      | -1.5      |

| Gauge ID              | Name                         | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|-----------------------|------------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">KAGC</a>  | Pittsburgh Allegheny Cty     | 0.22       | 0.11       | 0.22         | 0.00       | 0.0       |
| <a href="#">KPIT</a>  | Greater Pittsburgh Int'l     | 0.65       | 0.26       | 0.65         | 0.00       | 0.0       |
| <a href="#">Loc06</a> | Carnegie Transit Time        | 0.32       | 0.15       | 0.32         | 0.00       | 0.0       |
| <a href="#">Loc15</a> | Trafford Maint Bldg          | 0.23       | 0.10       | 0.23         | 0.00       | 0.0       |
| <a href="#">Loc17</a> | Chartiers Pump Station       | 0.23       | 0.12       | 0.23         | 0.00       | 0.0       |
| <a href="#">Loc18</a> | Oakdale Pump Station         | 0.33       | 0.15       | 0.33         | 0.00       | 0.0       |
| <a href="#">Loc19</a> | Sandy Creek Eq Facility      | 0.46       | 0.20       | 0.46         | 0.00       | 0.0       |
| <a href="#">Loc20</a> | Gascola Eq Facility          | 0.44       | 0.20       | 0.44         | 0.00       | 0.0       |
| <a href="#">Loc22</a> | North Fayette TWP            | 0.43       | 0.18       | 0.43         | 0.00       | 0.0       |
| <a href="#">Loc23</a> | Clinton Munic Bldg           | 0.75       | 0.30       | 0.75         | 0.00       | 0.0       |
| <a href="#">Loc24</a> | Jefferson Hills              | 0.17       | 0.09       | 0.17         | 0.00       | 0.0       |
| <a href="#">Loc26</a> | Elizabeth TWP Municipal Bldg | 0.15       | 0.09       | 0.15         | 0.00       | 0.0       |
| <a href="#">Loc29</a> | Bell Acres Munic Bldg        | 0.59       | 0.24       | 0.59         | 0.00       | 0.0       |
| <a href="#">Loc32</a> | Arnold                       | 0.64       | 0.26       | 0.64         | 0.00       | 0.0       |
| <a href="#">Loc33</a> | Richland TWP                 | 0.71       | 0.32       | 0.71         | 0.00       | 0.0       |
| <a href="#">Loc21</a> | Moon TWP                     | 0.65       | 0.25       | 0.64         | 0.01       | 1.5       |
| <a href="#">Loc30</a> | McCandless Twn Hall          | 0.64       | 0.27       | 0.63         | 0.01       | 1.6       |
| <a href="#">Loc31</a> | Hampton Municipal Bldg       | 0.61       | 0.27       | 0.60         | 0.01       | 1.6       |
| <a href="#">Loc14</a> | Churchill Munic Bldg         | 0.44       | 0.19       | 0.43         | 0.01       | 2.3       |
| <a href="#">Loc16</a> | Castle Shannon               | 0.22       | 0.10       | 0.21         | 0.01       | 4.5       |
| <a href="#">Loc10</a> | PWSA-Highland Park           | 0.55       | 0.21       | 0.52         | 0.03       | 5.5       |
| <a href="#">Loc09</a> | Univ of Pittsburgh           | 0.54       | 0.21       | 0.51         | 0.03       | 5.6       |
| <a href="#">Loc02</a> | ALCOSAN WWTP Lab             | 0.52       | 0.21       | 0.49         | 0.03       | 5.8       |

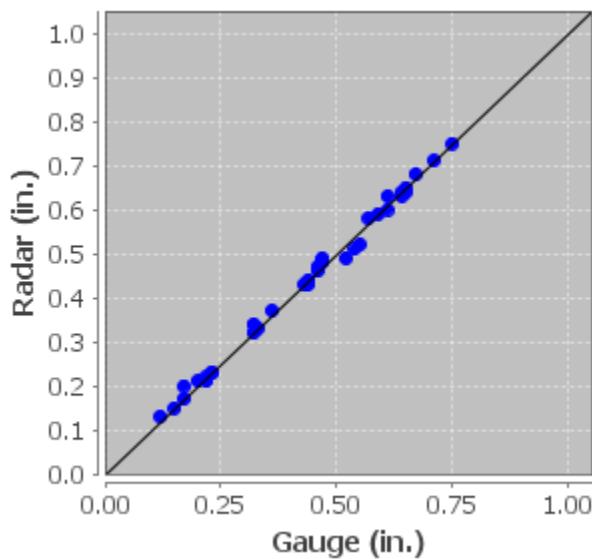
**Table 7. Summary of Individual RG Pairs for Event 1c**

| Gauge ID              | Name                    | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|-----------------------|-------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">Loc09</a> | Univ of Pittsburgh      | 0.07       | 0.08       | 0.08         | -0.01      | -14.3     |
| <a href="#">Loc17</a> | Chartiers Pump Station  | 0.09       | 0.09       | 0.10         | -0.01      | -11.1     |
| <a href="#">Loc06</a> | Carnegie Transit Time   | 0.10       | 0.08       | 0.10         | 0.00       | 0.0       |
| <a href="#">Loc07</a> | Greentree Munic Bldg    | 0.10       | 0.09       | 0.10         | 0.00       | 0.0       |
| <a href="#">Loc11</a> | M-46 Access Shaft       | 0.07       | 0.07       | 0.07         | 0.00       | 0.0       |
| <a href="#">Loc14</a> | Churchill Munic Bldg    | 0.07       | 0.08       | 0.07         | 0.00       | 0.0       |
| <a href="#">Loc19</a> | Sandy Creek Eq Facility | 0.05       | 0.06       | 0.05         | 0.00       | 0.0       |
| <a href="#">Loc20</a> | Gascola Eq Facility     | 0.06       | 0.07       | 0.06         | 0.00       | 0.0       |
| <a href="#">Loc24</a> | Jefferson Hills         | 0.09       | 0.08       | 0.09         | 0.00       | 0.0       |

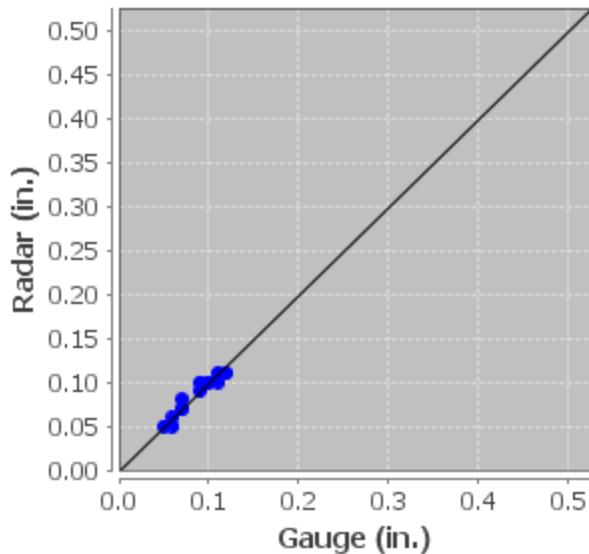
| Gauge ID              | Name                         | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|-----------------------|------------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">Loc26</a> | Elizabeth TWP Municipal Bldg | 0.11       | 0.08       | 0.11         | 0.00       | 0.0       |
| <a href="#">Loc18</a> | Oakdale Pump Station         | 0.12       | 0.08       | 0.11         | 0.01       | 8.3       |
| <a href="#">Loc05</a> | Upper St. Clair              | 0.11       | 0.08       | 0.10         | 0.01       | 9.1       |
| <a href="#">Loc08</a> | AC Health Dept Bldg          | 0.06       | 0.06       | 0.05         | 0.01       | 16.7      |



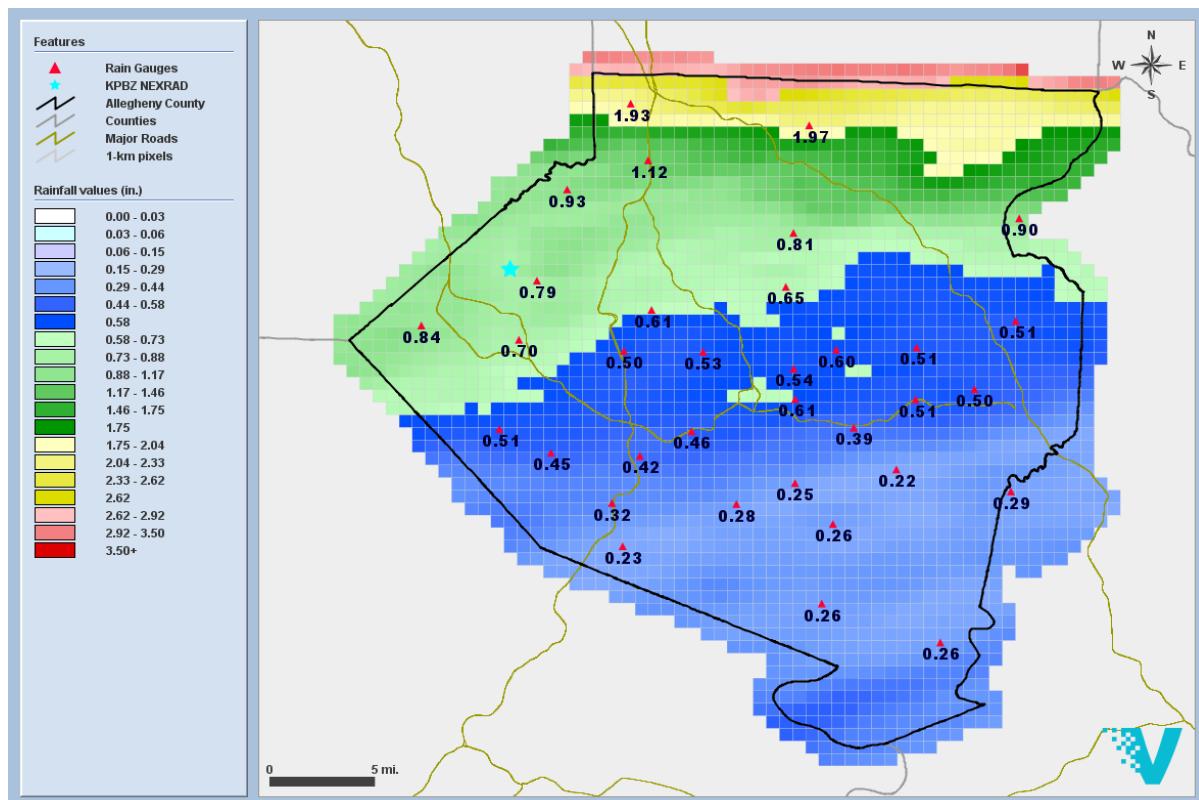
**Figure 3. Scatter Plot of Gauge-Adjusted RG Pairs for Event 1a**



**Figure 4. Scatter Plot of Gauge-Adjusted RG Pairs for Event 1b**



**Figure 5. Scatter Plot of Gauge-Adjusted RG Pairs for Event 1c**



**Figure 6. GARR Storm Total for Event 1**

**Table 8. Depth Duration Frequency Analyses for Event 1**

| <b>Duration</b> | <b>Depth (in)</b> | <b>Pixel</b> | <b>Time (EDT)</b> | <b>Frequency</b> |
|-----------------|-------------------|--------------|-------------------|------------------|
| 15 minutes      | 0.526             | 134111       | 2016-09-08 22:45  | <1 yr.           |
| 30 minutes      | 0.813             | 135111       | 2016-09-08 23:00  | 1 yr.            |
| 1 hour          | 1.361             | 134111       | 2016-09-08 23:30  | 2 yr.            |
| 2 hour          | 2.033             | 134111       | 2016-09-09 00:30  | 5 yr.            |
| 3 hour          | 2.560             | 135111       | 2016-09-09 01:30  | 10 yr.           |
| 6 hour          | 2.936             | 134111       | 2016-09-09 02:15  | 10 yr.           |
| 12 hour         | 3.182             | 167112       | 2016-09-09 06:00  | 5 yr.            |

## Event 2: 2016-09-18

The analysis period was from 2016-09-18 07:00 EDT to 2016-09-18 21:00 EDT. The event was then split into two sub-event periods at 2016-09-18 14:30 EDT to improve gauge adjustment of the radar.

The gauges listed in [Appendix A](#) were not used to adjust the radar due to inconsistencies between the gauge and the radar or surrounding gauges, or they did not have data available for this event. Gauges Loc01, Loc02, Loc04, Loc18, Loc21, Loc22, Loc23, Loc26, Loc27, Loc29, Loc30, Loc31, Loc33, KPIT and 03085734 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 2a. Gauges Loc01, Loc02, Loc03, Loc04, Loc06, Loc13, Loc18, Loc21, Loc22, Loc24, Loc29, Loc30, Loc31, Loc33, KAGC, KPIT and 03085734 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 2b.

A convective Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 9 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 10 - 11 summarize the results for each RG pair used for final radar adjustment, where  $G_i$  is the gauge estimate,  $R_i$  is the non-adjusted radar estimate,  $R_i^*$  is the GARR estimate, and Diff\* (%) is the percent difference between the gauge and GARR estimate. Figures 7 - 8 show the scatter plots of the gauge-adjusted RG pairs. Figure 9 depicts the GARR storm total over the 1-km<sup>2</sup> pixels. The GARR amounts for the 2313 1-km<sup>2</sup> pixels range from 0.0 - 1.5 inches with a mean of 0.4 inches. Table 12 shows the Depth Duration Frequency (DDF) maximum values for the 1-km<sup>2</sup> pixels.

**Table 9. GARR Statistics for Event 2**

| <b>Event #</b> | <b>Radar</b> | <b>Event Date</b> | <b>Gauges Used (38)</b> | <b>Avg. Depth (in)</b> | <b>Bias</b> | <b>AD (%)</b> | <b>CAD (%)</b> |
|----------------|--------------|-------------------|-------------------------|------------------------|-------------|---------------|----------------|
| E2a            | KPBZ LII     | 2016-09-18        | 21                      | 0.165                  | 2.983       | 65.4          | 7.4            |
| E2b            | KPBZ LII     | 2016-09-18        | 19                      | 0.213                  | 1.838       | 44.4          | 2.9            |

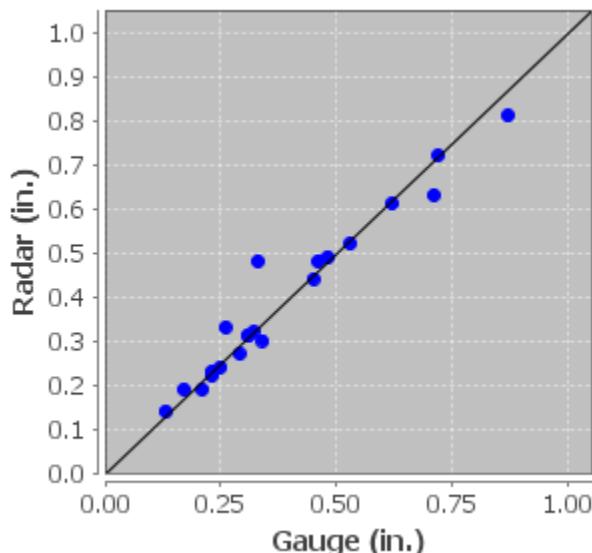
**Table 10. Summary of Individual RG Pairs for Event 2a**

| Gauge ID                 | Name                       | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|----------------------------|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc09</a>    | Univ of Pittsburgh         | 0.33                | 0.18                | 0.48                  | -0.15      | -45.5     |
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility    | 0.26                | 0.13                | 0.33                  | -0.07      | -26.9     |
| <a href="#">Loc05</a>    | Upper St. Clair            | 0.17                | 0.06                | 0.19                  | -0.02      | -11.8     |
| <a href="#">03049500</a> | Allegheny River at Natrona | 0.13                | 0.05                | 0.14                  | -0.01      | -7.7      |
| <a href="#">KAGC</a>     | Pittsburgh Allegheny Cty   | 0.46                | 0.18                | 0.48                  | -0.02      | -4.3      |
| <a href="#">Loc07</a>    | Greentree Munic Bldg       | 0.48                | 0.16                | 0.49                  | -0.01      | -2.1      |
| <a href="#">Loc13</a>    | M-59 Access Shaft          | 0.31                | 0.10                | 0.31                  | 0.00       | 0.0       |
| <a href="#">Loc15</a>    | Trafford Maint Bldg        | 0.72                | 0.21                | 0.72                  | 0.00       | 0.0       |
| <a href="#">Loc16</a>    | Castle Shannon             | 0.23                | 0.08                | 0.23                  | 0.00       | 0.0       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg        | 0.31                | 0.11                | 0.31                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold                     | 0.32                | 0.11                | 0.32                  | 0.00       | 0.0       |
| <a href="#">Loc17</a>    | Chartiers Pump Station     | 0.62                | 0.18                | 0.61                  | 0.01       | 1.6       |
| <a href="#">Loc06</a>    | Carnegie Transit Time      | 0.53                | 0.16                | 0.52                  | 0.01       | 1.9       |
| <a href="#">Loc24</a>    | Jefferson Hills            | 0.45                | 0.14                | 0.44                  | 0.01       | 2.2       |
| <a href="#">Loc12</a>    | Baldwin                    | 0.25                | 0.09                | 0.24                  | 0.01       | 4.0       |
| <a href="#">Loc03</a>    | Shaler Munic Bldg          | 0.23                | 0.07                | 0.22                  | 0.01       | 4.3       |
| <a href="#">Loc10</a>    | PWSA-Highland Park         | 0.87                | 0.27                | 0.81                  | 0.06       | 6.9       |
| <a href="#">Loc14</a>    | Churchill Munic Bldg       | 0.29                | 0.09                | 0.27                  | 0.02       | 6.9       |
| <a href="#">Loc20</a>    | Gascola Eq Facility        | 0.21                | 0.07                | 0.19                  | 0.02       | 9.5       |
| <a href="#">Loc08</a>    | AC Health Dept Bldg        | 0.71                | 0.22                | 0.63                  | 0.08       | 11.3      |
| <a href="#">Loc11</a>    | M-46 Access Shaft          | 0.34                | 0.10                | 0.30                  | 0.04       | 11.8      |

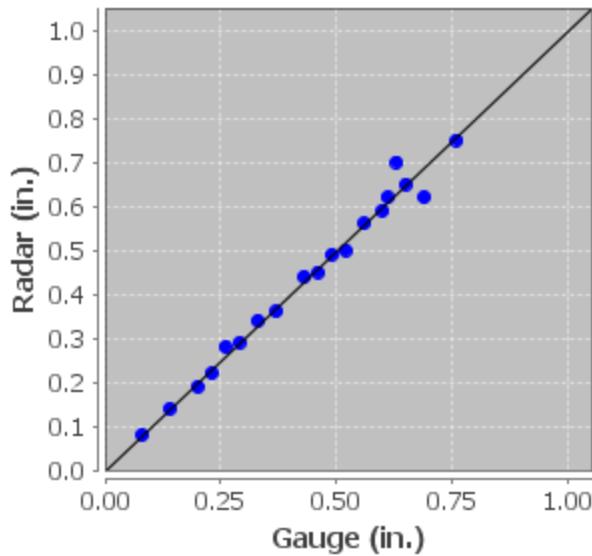
**Table 11. Summary of Individual RG Pairs for Event 2b**

| Gauge ID              | Name                         | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|-----------------------|------------------------------|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc11</a> | M-46 Access Shaft            | 0.63                | 0.45                | 0.70                  | -0.07      | -11.1     |
| <a href="#">Loc12</a> | Baldwin                      | 0.26                | 0.17                | 0.28                  | -0.02      | -7.7      |
| <a href="#">Loc05</a> | Upper St. Clair              | 0.33                | 0.18                | 0.34                  | -0.01      | -3.0      |
| <a href="#">Loc20</a> | Gascola Eq Facility          | 0.43                | 0.27                | 0.44                  | -0.01      | -2.3      |
| <a href="#">Loc32</a> | Arnold                       | 0.61                | 0.28                | 0.62                  | -0.01      | -1.6      |
| <a href="#">Loc08</a> | AC Health Dept Bldg          | 0.29                | 0.15                | 0.29                  | 0.00       | 0.0       |
| <a href="#">Loc14</a> | Churchill Munic Bldg         | 0.65                | 0.40                | 0.65                  | 0.00       | 0.0       |
| <a href="#">Loc15</a> | Trafford Maint Bldg          | 0.14                | 0.08                | 0.14                  | 0.00       | 0.0       |
| <a href="#">Loc23</a> | Clinton Munic Bldg           | 0.08                | 0.07                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc26</a> | Elizabeth TWP Municipal Bldg | 0.56                | 0.37                | 0.56                  | 0.00       | 0.0       |
| <a href="#">Loc27</a> | Marshall TWP                 | 0.49                | 0.23                | 0.49                  | 0.00       | 0.0       |

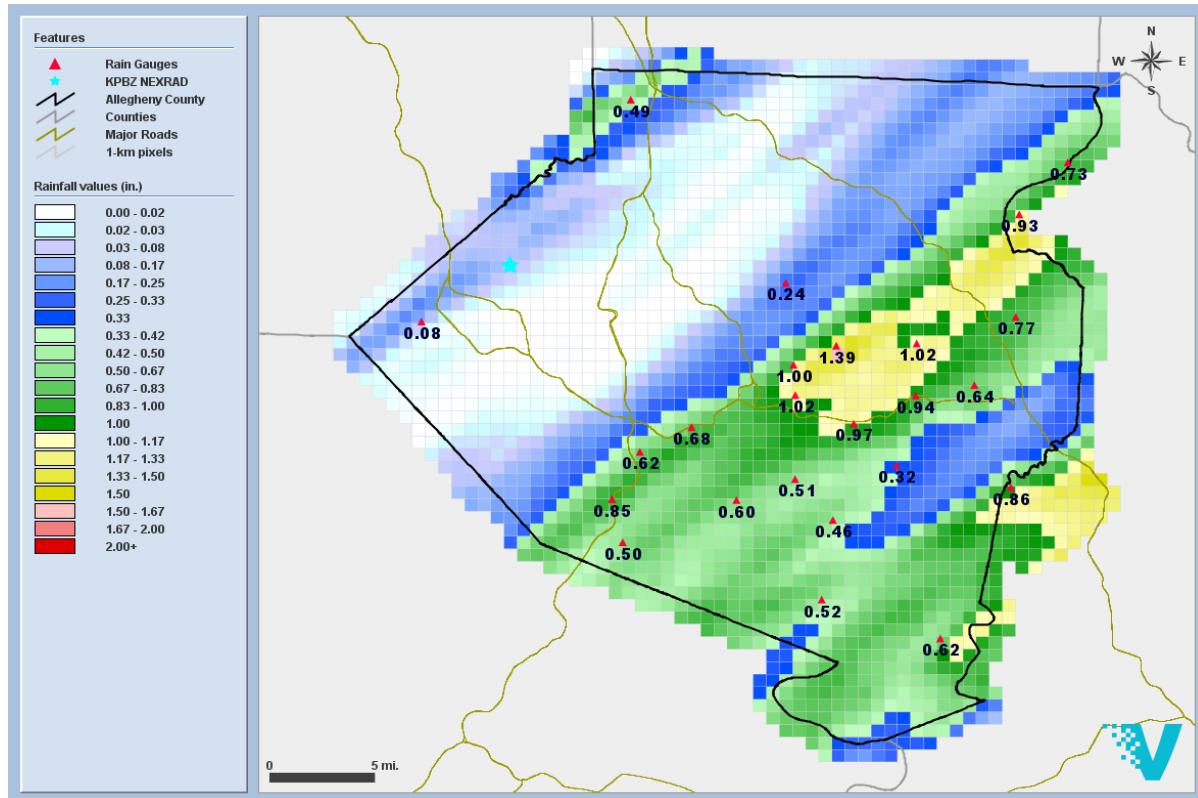
| Gauge ID                 | Name                       | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|--------------------------|----------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility    | 0.76       | 0.43       | 0.75         | 0.01       | 1.3       |
| <a href="#">03049500</a> | Allegheny River at Natrona | 0.60       | 0.24       | 0.59         | 0.01       | 1.7       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg        | 0.46       | 0.24       | 0.45         | 0.01       | 2.2       |
| <a href="#">Loc16</a>    | Castle Shannon             | 0.37       | 0.19       | 0.36         | 0.01       | 2.7       |
| <a href="#">Loc10</a>    | PWSA-Highland Park         | 0.52       | 0.26       | 0.50         | 0.02       | 3.8       |
| <a href="#">Loc17</a>    | Chartiers Pump Station     | 0.23       | 0.11       | 0.22         | 0.01       | 4.3       |
| <a href="#">Loc07</a>    | Greentree Munic Bldg       | 0.20       | 0.09       | 0.19         | 0.01       | 5.0       |
| <a href="#">Loc09</a>    | Univ of Pittsburgh         | 0.69       | 0.32       | 0.62         | 0.07       | 10.1      |



**Figure 7. Scatter Plot of Gauge-Adjusted RG Pairs for Event 2a**



**Figure 8. Scatter Plot of Gauge-Adjusted RG Pairs for Event 2b**



**Figure 9. GARR Storm Total for Event 2**

**Table 12. Depth Duration Frequency Analyses for Event 2**

| <b>Duration</b> | <b>Depth (in)</b> | <b>Pixel</b> | <b>Time (EDT)</b> | <b>Frequency</b> |
|-----------------|-------------------|--------------|-------------------|------------------|
| 15 minutes      | 0.588             | 138114       | 2016-09-18 15:45  | <1 yr.           |
| 30 minutes      | 0.844             | 173147       | 2016-09-18 17:00  | 1 yr.            |
| 1 hour          | 1.146             | 170151       | 2016-09-18 17:00  | 1 yr.            |
| 2 hour          | 1.193             | 170151       | 2016-09-18 17:15  | <1 yr.           |
| 3 hour          | 1.193             | 170151       | 2016-09-18 17:15  | <1 yr.           |
| 6 hour          | 1.507             | 153135       | 2016-09-18 17:45  | <1 yr.           |
| 12 hour         | 1.507             | 153135       | 2016-09-18 19:00  | <1 yr.           |

### Event 3: 2016-09-29 AM

The analysis period was from 2016-09-29 00:00 EDT to 2016-09-29 16:00 EDT. The event was then split into three sub-event periods at 2016-09-29 03:30 EDT and 2016-09-29 09:00 EDT to improve gauge adjustment of the radar.

The gauges listed in [Appendix A](#) were not used to adjust the radar due to inconsistencies between the gauge and the radar or surrounding gauges, or they did not have data available for this event. Gauges Loc01, Loc02, Loc05, Loc06, Loc07, Loc16, Loc17, Loc18, Loc21, Loc22, Loc23, Loc27, Loc29, Loc32, Loc33, KPIT and 03049500 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 3a. Gauges Loc15 and Loc26 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 3b. Gauges Loc03, Loc14, Loc19, Loc25, Loc26, Loc31 and Loc33 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 3c.

A convective Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 13 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 14 - 16 summarize the results for each RG pair used for final radar adjustment, where  $G_i$  is the gauge estimate,  $R_i$  is the non-adjusted radar estimate,  $R_i^*$  is the GARR estimate, and Diff\* (%) is the percent difference between the gauge and GARR estimate. Figures 10 - 12 show the scatter plots of the gauge-adjusted RG pairs. Figure 13 depicts the GARR storm total over the 1-km<sup>2</sup> pixels. The GARR amounts for the 2313 1-km<sup>2</sup> pixels range from 0.2 - 1.8 inches with a mean of 0.4 inches. Table 17 shows the Depth Duration Frequency (DDF) maximum values for the 1-km<sup>2</sup> pixels.

**Table 13. GARR Statistics for Event 3**

| <b>Event #</b> | <b>Radar</b> | <b>Event Date</b> | <b>Gauges Used (38)</b> | <b>Avg. Depth (in)</b> | <b>Bias</b> | <b>AD (%)</b> | <b>CAD (%)</b> |
|----------------|--------------|-------------------|-------------------------|------------------------|-------------|---------------|----------------|
| E3a            | KPBZ LII     | 2016-09-29 AM     | 18                      | 0.160                  | 1.329       | 32.6          | 7.5            |
| E3b            | KPBZ LII     | 2016-09-29 AM     | 33                      | 0.202                  | 2.017       | 48.3          | 4.5            |
| E3c            | KPBZ LII     | 2016-09-29 AM     | 30                      | 0.088                  | 1.201       | 20.8          | 8.6            |

**Table 14. Summary of Individual RG Pairs for Event 3a**

| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc12</a>    | Baldwin   | 0.16                | 0.27                | 0.21                  | -0.05      | -31.2     |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.05                | 0.05                | 0.06                  | -0.01      | -20.0     |
| <a href="#">Loc15</a>    | Trafford Maint Bldg                               | 0.07                | 0.11                | 0.08                  | -0.01      | -14.3     |
| <a href="#">Loc10</a>    | PWSA-Highland Park                                | 0.22                | 0.18                | 0.25                  | -0.03      | -13.6     |
| <a href="#">Loc31</a>    | Hampton Municipal Bldg                            | 0.13                | 0.11                | 0.14                  | -0.01      | -7.7      |
| <a href="#">Loc14</a>    | Churchill Munic Bldg                              | 0.35                | 0.26                | 0.37                  | -0.02      | -5.7      |
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility                           | 0.29                | 0.23                | 0.30                  | -0.01      | -3.4      |
| <a href="#">Loc13</a>    | M-59 Access Shaft                                 | 0.39                | 0.27                | 0.40                  | -0.01      | -2.6      |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.11                | 0.07                | 0.11                  | 0.00       | 0.0       |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.08                | 0.05                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc09</a>    | Univ of Pittsburgh                                | 0.30                | 0.21                | 0.30                  | 0.00       | 0.0       |
| <a href="#">Loc24</a>    | Jefferson Hills                                   | 0.21                | 0.18                | 0.21                  | 0.00       | 0.0       |
| <a href="#">Loc26</a>    | Elizabeth TWP Municipal Bldg                      | 0.99                | 0.73                | 0.99                  | 0.00       | 0.0       |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.13                | 0.07                | 0.13                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.32                | 0.22                | 0.31                  | 0.01       | 3.1       |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.30                | 0.20                | 0.29                  | 0.01       | 3.3       |
| <a href="#">Loc03</a>    | Shaler Munic Bldg                                 | 0.29                | 0.18                | 0.27                  | 0.02       | 6.9       |
| <a href="#">Loc11</a>    | M-46 Access Shaft                                 | 0.41                | 0.21                | 0.34                  | 0.07       | 17.1      |

**Table 15. Summary of Individual RG Pairs for Event 3b**

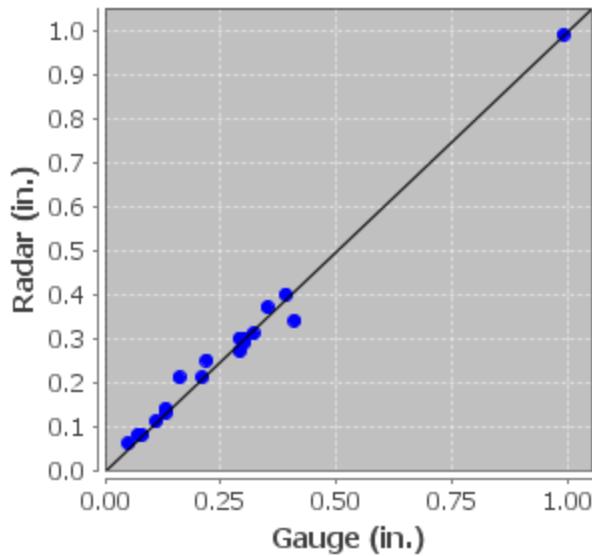
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.33                | 0.20                | 0.37                  | -0.04      | -12.1     |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.10                | 0.07                | 0.11                  | -0.01      | -10.0     |
| <a href="#">Loc09</a>    | Univ of Pittsburgh                                | 0.21                | 0.13                | 0.23                  | -0.02      | -9.5      |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.22                | 0.13                | 0.24                  | -0.02      | -9.1      |
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility                           | 0.14                | 0.09                | 0.15                  | -0.01      | -7.1      |
| <a href="#">Loc11</a>    | M-46 Access Shaft                                 | 0.20                | 0.12                | 0.21                  | -0.01      | -5.0      |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.43                | 0.24                | 0.45                  | -0.02      | -4.7      |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.25                | 0.14                | 0.26                  | -0.01      | -4.0      |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.28                | 0.13                | 0.29                  | -0.01      | -3.6      |
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.29                | 0.14                | 0.30                  | -0.01      | -3.4      |

| Gauge ID              | Name                        | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|-----------------------|-----------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">Loc16</a> | Castle Shannon              | 0.30       | 0.14       | 0.31         | -0.01      | -3.3      |
| <a href="#">Loc08</a> | AC Health Dept Bldg         | 0.17       | 0.10       | 0.17         | 0.00       | 0.0       |
| <a href="#">Loc13</a> | M-59 Access Shaft           | 0.25       | 0.14       | 0.25         | 0.00       | 0.0       |
| <a href="#">Loc17</a> | Chartiers Pump Station      | 0.46       | 0.23       | 0.46         | 0.00       | 0.0       |
| <a href="#">Loc22</a> | North Fayette TWP           | 0.37       | 0.16       | 0.37         | 0.00       | 0.0       |
| <a href="#">Loc23</a> | Clinton Munic Bldg          | 0.41       | 0.16       | 0.41         | 0.00       | 0.0       |
| <a href="#">Loc24</a> | Jefferson Hills             | 0.22       | 0.11       | 0.22         | 0.00       | 0.0       |
| <a href="#">Loc25</a> | White Oak Public Works Bldg | 0.11       | 0.06       | 0.11         | 0.00       | 0.0       |
| <a href="#">Loc27</a> | Marshall TWP                | 0.22       | 0.11       | 0.22         | 0.00       | 0.0       |
| <a href="#">Loc28</a> | Plum Municipal Bldg         | 0.08       | 0.06       | 0.08         | 0.00       | 0.0       |
| <a href="#">Loc31</a> | Hampton Municipal Bldg      | 0.13       | 0.07       | 0.13         | 0.00       | 0.0       |
| <a href="#">Loc32</a> | Arnold                      | 0.18       | 0.11       | 0.18         | 0.00       | 0.0       |
| <a href="#">Loc33</a> | Richland TWP                | 0.15       | 0.08       | 0.15         | 0.00       | 0.0       |
| <a href="#">KPIT</a>  | Greater Pittsburgh Int'l    | 0.38       | 0.14       | 0.37         | 0.01       | 2.6       |
| <a href="#">Loc29</a> | Bell Acres Munic Bldg       | 0.25       | 0.10       | 0.24         | 0.01       | 4.0       |
| <a href="#">Loc12</a> | Baldwin                     | 0.40       | 0.17       | 0.38         | 0.02       | 5.0       |
| <a href="#">Loc14</a> | Churchill Munic Bldg        | 0.19       | 0.10       | 0.18         | 0.01       | 5.3       |
| <a href="#">Loc21</a> | Moon TWP                    | 0.19       | 0.07       | 0.18         | 0.01       | 5.3       |
| <a href="#">Loc02</a> | ALCOSAN WWTP Lab            | 0.33       | 0.16       | 0.31         | 0.02       | 6.1       |
| <a href="#">Loc03</a> | Shaler Munic Bldg           | 0.13       | 0.06       | 0.12         | 0.01       | 7.7       |
| <a href="#">Loc06</a> | Carnegie Transit Time       | 0.31       | 0.13       | 0.28         | 0.03       | 9.7       |
| <a href="#">Loc04</a> | Kennedy Twp PS              | 0.33       | 0.14       | 0.29         | 0.04       | 12.1      |
| <a href="#">Loc10</a> | PWSA-Highland Park          | 0.22       | 0.10       | 0.19         | 0.03       | 13.6      |

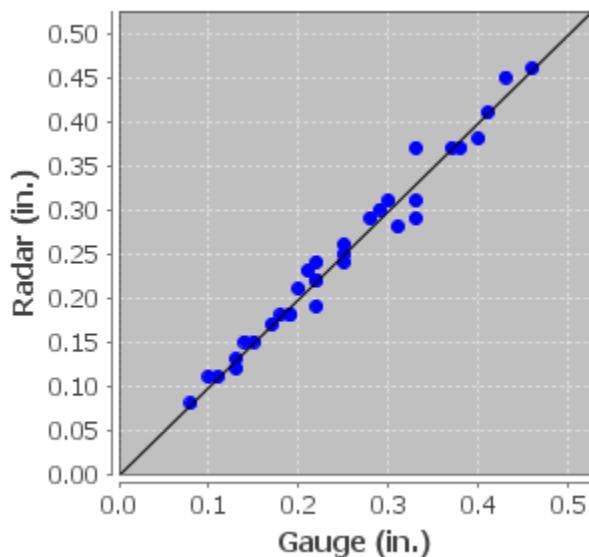
**Table 16. Summary of Individual RG Pairs for Event 3c**

| Gauge ID                 | Name                       | $G_i$ (in) | $R_i$ (in) | $R_i^*$ (in) | Diff* (in) | Diff* (%) |
|--------------------------|----------------------------|------------|------------|--------------|------------|-----------|
| <a href="#">Loc09</a>    | Univ of Pittsburgh         | 0.05       | 0.07       | 0.08         | -0.03      | -60.0     |
| <a href="#">Loc17</a>    | Chartiers Pump Station     | 0.09       | 0.10       | 0.11         | -0.02      | -22.2     |
| <a href="#">Loc22</a>    | North Fayette TWP          | 0.06       | 0.08       | 0.07         | -0.01      | -16.7     |
| <a href="#">KAGC</a>     | Pittsburgh Allegheny Cty   | 0.08       | 0.08       | 0.09         | -0.01      | -12.5     |
| <a href="#">Loc02</a>    | ALCOSAN WWTP Lab           | 0.08       | 0.08       | 0.09         | -0.01      | -12.5     |
| <a href="#">Loc07</a>    | Greentree Munic Bldg       | 0.12       | 0.11       | 0.13         | -0.01      | -8.3      |
| <a href="#">Loc16</a>    | Castle Shannon             | 0.14       | 0.14       | 0.15         | -0.01      | -7.1      |
| <a href="#">03049500</a> | Allegheny River at Natrona | 0.12       | 0.09       | 0.12         | 0.00       | 0.0       |

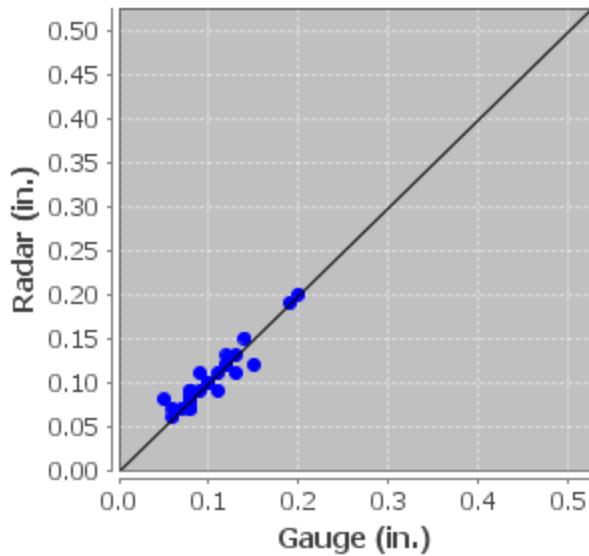
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">KPIT</a>     | Greater Pittsburgh Int'l                          | 0.12                | 0.10                | 0.12                  | 0.00       | 0.0       |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.13                | 0.11                | 0.13                  | 0.00       | 0.0       |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.10                | 0.10                | 0.10                  | 0.00       | 0.0       |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.08                | 0.07                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc11</a>    | M-46 Access Shaft                                 | 0.10                | 0.08                | 0.10                  | 0.00       | 0.0       |
| <a href="#">Loc13</a>    | M-59 Access Shaft                                 | 0.09                | 0.06                | 0.09                  | 0.00       | 0.0       |
| <a href="#">Loc15</a>    | Trafford Maint Bldg                               | 0.08                | 0.06                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.11                | 0.10                | 0.11                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.08                | 0.06                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc21</a>    | Moon TWP  | 0.08                | 0.08                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc23</a>    | Clinton Munic Bldg                                | 0.08                | 0.05                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc24</a>    | Jefferson Hills                                   | 0.07                | 0.06                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.08                | 0.06                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.19                | 0.14                | 0.19                  | 0.00       | 0.0       |
| <a href="#">Loc29</a>    | Bell Acres Munic Bldg                             | 0.06                | 0.05                | 0.06                  | 0.00       | 0.0       |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.08                | 0.06                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold  | 0.20                | 0.16                | 0.20                  | 0.00       | 0.0       |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.08                | 0.06                | 0.07                  | 0.01       | 12.5      |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.08                | 0.05                | 0.07                  | 0.01       | 12.5      |
| <a href="#">Loc12</a>    | Baldwin   | 0.13                | 0.08                | 0.11                  | 0.02       | 15.4      |
| <a href="#">Loc10</a>    | PWSA-Highland Park                                | 0.11                | 0.07                | 0.09                  | 0.02       | 18.2      |
| <a href="#">Loc06</a>    | Carnegie Transit Time                             | 0.15                | 0.09                | 0.12                  | 0.03       | 20.0      |



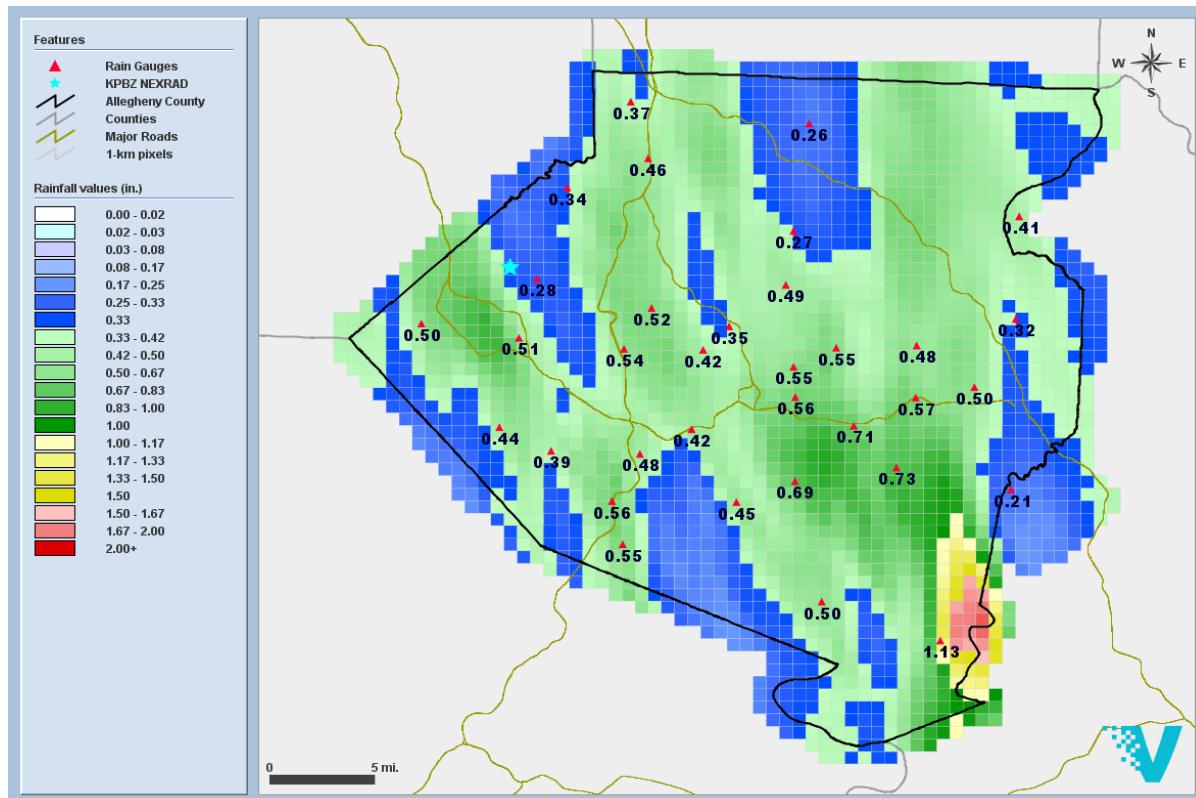
**Figure 10. Scatter Plot of Gauge-Adjusted RG Pairs for Event 3a**



**Figure 11. Scatter Plot of Gauge-Adjusted RG Pairs for Event 3b**



**Figure 12. Scatter Plot of Gauge-Adjusted RG Pairs for Event 3c**



**Figure 13. GARR Storm Total for Event 3**

**Table 17. Depth Duration Frequency Analyses for Event 3**

| <b>Duration</b> | <b>Depth (in)</b> | <b>Pixel</b> | <b>Time (EDT)</b> | <b>Frequency</b> |
|-----------------|-------------------|--------------|-------------------|------------------|
| 15 minutes      | 0.783             | 164156       | 2016-09-29 03:00  | 2 yr.            |
| 30 minutes      | 1.218             | 162157       | 2016-09-29 03:15  | 5 yr.            |
| 1 hour          | 1.606             | 164156       | 2016-09-29 03:15  | 5 yr.            |
| 2 hour          | 1.704             | 164156       | 2016-09-29 04:00  | 2 yr.            |
| 3 hour          | 1.710             | 164156       | 2016-09-29 04:45  | 2 yr.            |
| 6 hour          | 1.710             | 164156       | 2016-09-29 06:00  | 1 yr.            |
| 12 hour         | 1.785             | 164156       | 2016-09-29 12:00  | <1 yr.           |

## Event 4: 2016-09-29 PM

The analysis period was from 2016-09-29 16:00 EDT to 2016-09-30 13:00 EDT. The event was then split into three sub-event periods at 2016-09-29 22:00 EDT and 2016-09-30 00:00 EDT to improve gauge adjustment of the radar.

The gauges listed in [Appendix A](#) were not used to adjust the radar due to inconsistencies between the gauge and the radar or surrounding gauges, or they did not have data available for this event. Gauges Loc11, Loc13, Loc15, Loc24, Loc25, Loc26 and 03049500 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 4b. Gauges Loc11, Loc13, Loc14, Loc15, Loc25, Loc26 and KAGC did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 4c.

A convective Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 18 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 19 - 21 summarize the results for each RG pair used for final radar adjustment, where  $G_i$  is the gauge estimate,  $R_i$  is the non-adjusted radar estimate,  $R_i^*$  is the GARR estimate, and Diff\* (%) is the percent difference between the gauge and GARR estimate. Figures 14 - 16 show the scatter plots of the gauge-adjusted RG pairs. Figure 17 depicts the GARR storm total over the 1-km<sup>2</sup> pixels. The GARR amounts for the 2313 1-km<sup>2</sup> pixels range from 0.6 - 1.9 inches with a mean of 1.0 inches. Table 22 shows the Depth Duration Frequency (DDF) maximum values for the 1-km<sup>2</sup> pixels.

**Table 18. GARR Statistics for Event 4**

| <b>Event #</b> | <b>Radar</b> | <b>Event Date</b> | <b>Gauges Used (38)</b> | <b>Avg. Depth (in)</b> | <b>Bias</b> | <b>AD (%)</b> | <b>CAD (%)</b> |
|----------------|--------------|-------------------|-------------------------|------------------------|-------------|---------------|----------------|
| E4a            | KPBZ LII     | 2016-09-29 PM     | 36                      | 0.514                  | 1.673       | 37.9          | 3.1            |
| E4b            | KPBZ LII     | 2016-09-29 PM     | 30                      | 0.202                  | 1.963       | 48.1          | 5.4            |
| E4c            | KPBZ LII     | 2016-09-29 PM     | 28                      | 0.275                  | 2.494       | 61.2          | 3.2            |

**Table 19. Summary of Individual RG Pairs for Event 4a**

| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc16</a>    | Castle Shannon                                    | 0.33                | 0.27                | 0.37                  | -0.04      | -12.1     |
| <a href="#">Loc02</a>    | ALCOSAN WWTP Lab                                  | 0.28                | 0.19                | 0.31                  | -0.03      | -10.7     |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.24                | 0.20                | 0.26                  | -0.02      | -8.3      |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.61                | 0.37                | 0.66                  | -0.05      | -8.2      |
| <a href="#">Loc31</a>    | Hampton Municipal Bldg                            | 0.64                | 0.39                | 0.67                  | -0.03      | -4.7      |
| <a href="#">Loc11</a>    | M-46 Access Shaft                                 | 0.66                | 0.40                | 0.69                  | -0.03      | -4.5      |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.25                | 0.18                | 0.26                  | -0.01      | -4.0      |
| <a href="#">Loc22</a>    | North Fayette TWP                                 | 0.26                | 0.20                | 0.27                  | -0.01      | -3.8      |
| <a href="#">Loc13</a>    | M-59 Access Shaft                                 | 0.57                | 0.36                | 0.59                  | -0.02      | -3.5      |
| <a href="#">Loc21</a>    | Moon TWP  | 0.29                | 0.21                | 0.30                  | -0.01      | -3.4      |
| <a href="#">Loc17</a>    | Chartiers Pump Station                            | 0.36                | 0.24                | 0.37                  | -0.01      | -2.8      |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.46                | 0.31                | 0.47                  | -0.01      | -2.2      |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.45                | 0.28                | 0.46                  | -0.01      | -2.2      |
| <a href="#">03049500</a> | Allegheny River at Natrona                        | 0.52                | 0.29                | 0.52                  | 0.00       | 0.0       |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.38                | 0.25                | 0.38                  | 0.00       | 0.0       |
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.35                | 0.23                | 0.35                  | 0.00       | 0.0       |
| <a href="#">Loc10</a>    | PWSA-Highland Park                                | 0.74                | 0.42                | 0.74                  | 0.00       | 0.0       |
| <a href="#">Loc15</a>    | Trafford Maint Bldg                               | 0.71                | 0.37                | 0.71                  | 0.00       | 0.0       |
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility                           | 0.63                | 0.37                | 0.63                  | 0.00       | 0.0       |
| <a href="#">Loc23</a>    | Clinton Munic Bldg                                | 0.42                | 0.28                | 0.42                  | 0.00       | 0.0       |
| <a href="#">Loc24</a>    | Jefferson Hills                                   | 0.48                | 0.29                | 0.48                  | 0.00       | 0.0       |
| <a href="#">Loc26</a>    | Elizabeth TWP Municipal Bldg                      | 0.61                | 0.33                | 0.61                  | 0.00       | 0.0       |
| <a href="#">Loc29</a>    | Bell Acres Munic Bldg                             | 0.32                | 0.20                | 0.32                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold  | 0.49                | 0.28                | 0.49                  | 0.00       | 0.0       |
| <a href="#">Loc33</a>    | Richland TWP                                      | 0.91                | 0.45                | 0.91                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.76                | 0.43                | 0.75                  | 0.01       | 1.3       |
| <a href="#">Loc14</a>    | Churchill Munic Bldg                              | 0.57                | 0.32                | 0.56                  | 0.01       | 1.8       |
| <a href="#">Loc12</a>    | Baldwin   | 0.49                | 0.28                | 0.48                  | 0.01       | 2.0       |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.49                | 0.27                | 0.48                  | 0.01       | 2.0       |
| <a href="#">Loc06</a>    | Carnegie Transit Time                             | 0.44                | 0.28                | 0.43                  | 0.01       | 2.3       |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.36                | 0.24                | 0.35                  | 0.01       | 2.8       |
| <a href="#">KAGC</a>     | Pittsburgh Allegheny Cty                          | 0.57                | 0.32                | 0.55                  | 0.02       | 3.5       |
| <a href="#">Loc03</a>    | Shaler Munic Bldg                                 | 0.83                | 0.44                | 0.80                  | 0.03       | 3.6       |
| <a href="#">KPIT</a>     | Greater Pittsburgh Int'l                          | 0.26                | 0.17                | 0.25                  | 0.01       | 3.8       |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.55                | 0.29                | 0.51                  | 0.04       | 7.3       |

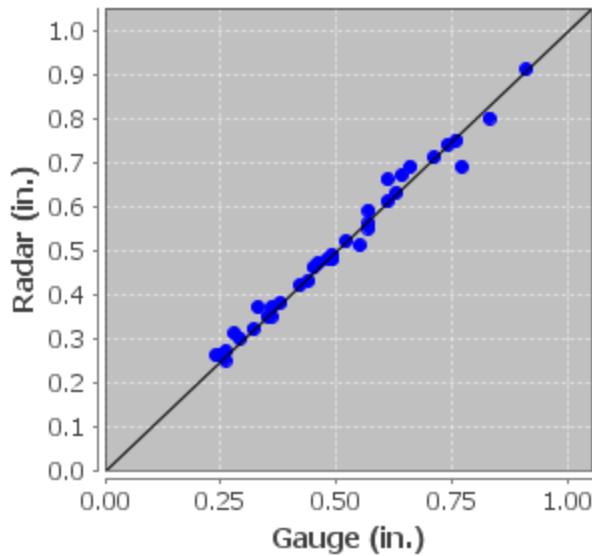
| Gauge ID              | Name               | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|-----------------------|--------------------|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc09</a> | Univ of Pittsburgh | 0.77                | 0.38                | 0.69                  | 0.08       | 10.4      |

**Table 20. Summary of Individual RG Pairs for Event 4b**

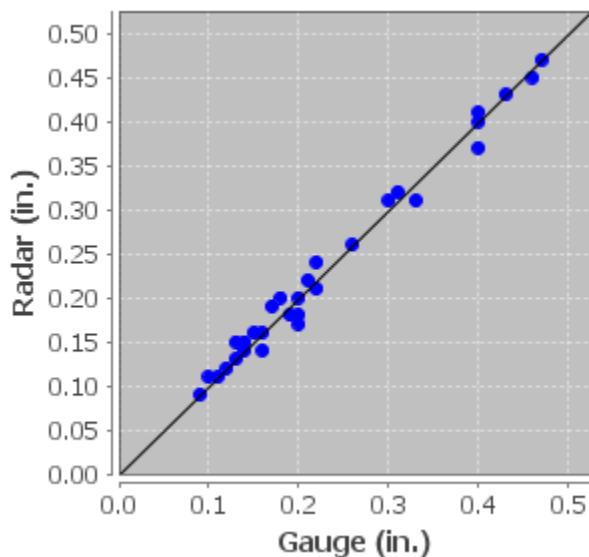
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc16</a>    | Castle Shannon                                    | 0.13                | 0.10                | 0.15                  | -0.02      | -15.4     |
| <a href="#">Loc31</a>    | Hampton Municipal Bldg                            | 0.17                | 0.12                | 0.19                  | -0.02      | -11.8     |
| <a href="#">Loc02</a>    | ALCOSAN WWTP Lab                                  | 0.18                | 0.10                | 0.20                  | -0.02      | -11.1     |
| <a href="#">Loc14</a>    | Churchill Munic Bldg                              | 0.10                | 0.06                | 0.11                  | -0.01      | -10.0     |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.22                | 0.13                | 0.24                  | -0.02      | -9.1      |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.14                | 0.07                | 0.15                  | -0.01      | -7.1      |
| <a href="#">KAGC</a>     | Pittsburgh Allegheny Cty                          | 0.15                | 0.09                | 0.16                  | -0.01      | -6.7      |
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.21                | 0.12                | 0.22                  | -0.01      | -4.8      |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.30                | 0.15                | 0.31                  | -0.01      | -3.3      |
| <a href="#">Loc21</a>    | Moon TWP  | 0.31                | 0.18                | 0.32                  | -0.01      | -3.2      |
| <a href="#">Loc06</a>    | Carnegie Transit Time                             | 0.40                | 0.20                | 0.41                  | -0.01      | -2.5      |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.12                | 0.05                | 0.12                  | 0.00       | 0.0       |
| <a href="#">Loc09</a>    | Univ of Pittsburgh                                | 0.14                | 0.07                | 0.14                  | 0.00       | 0.0       |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.40                | 0.21                | 0.40                  | 0.00       | 0.0       |
| <a href="#">Loc19</a>    | Sandy Creek Eq Facility                           | 0.13                | 0.08                | 0.13                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.09                | 0.05                | 0.09                  | 0.00       | 0.0       |
| <a href="#">Loc22</a>    | North Fayette TWP                                 | 0.43                | 0.23                | 0.43                  | 0.00       | 0.0       |
| <a href="#">Loc23</a>    | Clinton Munic Bldg                                | 0.47                | 0.23                | 0.47                  | 0.00       | 0.0       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.11                | 0.05                | 0.11                  | 0.00       | 0.0       |
| <a href="#">Loc29</a>    | Bell Acres Munic Bldg                             | 0.26                | 0.12                | 0.26                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold  | 0.16                | 0.08                | 0.16                  | 0.00       | 0.0       |
| <a href="#">Loc33</a>    | Richland TWP                                      | 0.20                | 0.08                | 0.20                  | 0.00       | 0.0       |
| <a href="#">KPIT</a>     | Greater Pittsburgh Int'l                          | 0.46                | 0.24                | 0.45                  | 0.01       | 2.2       |
| <a href="#">Loc10</a>    | PWSA-Highland Park                                | 0.22                | 0.10                | 0.21                  | 0.01       | 4.5       |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.19                | 0.08                | 0.18                  | 0.01       | 5.3       |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.33                | 0.15                | 0.31                  | 0.02       | 6.1       |
| <a href="#">Loc17</a>    | Chartiers Pump Station                            | 0.40                | 0.17                | 0.37                  | 0.03       | 7.5       |
| <a href="#">Loc12</a>    | Baldwin   | 0.20                | 0.10                | 0.18                  | 0.02       | 10.0      |
| <a href="#">Loc03</a>    | Shaler Munic Bldg                                 | 0.16                | 0.07                | 0.14                  | 0.02       | 12.5      |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.20                | 0.08                | 0.17                  | 0.03       | 15.0      |

**Table 21. Summary of Individual RG Pairs for Event 4c**

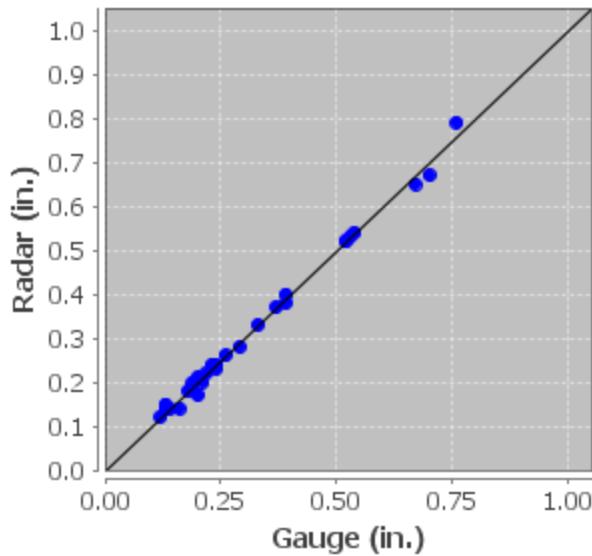
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc09</a>    | Univ of Pittsburgh                                | 0.13                | 0.06                | 0.15                  | -0.02      | -15.4     |
| <a href="#">Loc02</a>    | ALCOSAN WWTP Lab                                  | 0.13                | 0.05                | 0.14                  | -0.01      | -7.7      |
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.19                | 0.10                | 0.20                  | -0.01      | -5.3      |
| <a href="#">Loc08</a>    | AC Health Dept Bldg                               | 0.20                | 0.07                | 0.21                  | -0.01      | -5.0      |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.23                | 0.08                | 0.24                  | -0.01      | -4.3      |
| <a href="#">Loc17</a>    | Chartiers Pump Station                            | 0.76                | 0.39                | 0.79                  | -0.03      | -3.9      |
| <a href="#">KPIT</a>     | Greater Pittsburgh Int'l                          | 0.39                | 0.19                | 0.40                  | -0.01      | -2.6      |
| <a href="#">03049500</a> | Allegheny River at Natrona                        | 0.26                | 0.07                | 0.26                  | 0.00       | 0.0       |
| <a href="#">Loc03</a>    | Shaler Munic Bldg                                 | 0.22                | 0.07                | 0.22                  | 0.00       | 0.0       |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.37                | 0.14                | 0.37                  | 0.00       | 0.0       |
| <a href="#">Loc12</a>    | Baldwin   | 0.12                | 0.05                | 0.12                  | 0.00       | 0.0       |
| <a href="#">Loc16</a>    | Castle Shannon                                    | 0.18                | 0.09                | 0.18                  | 0.00       | 0.0       |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.52                | 0.25                | 0.52                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.19                | 0.06                | 0.19                  | 0.00       | 0.0       |
| <a href="#">Loc21</a>    | Moon TWP  | 0.52                | 0.23                | 0.52                  | 0.00       | 0.0       |
| <a href="#">Loc23</a>    | Clinton Munic Bldg                                | 0.33                | 0.15                | 0.33                  | 0.00       | 0.0       |
| <a href="#">Loc24</a>    | Jefferson Hills                                   | 0.14                | 0.07                | 0.14                  | 0.00       | 0.0       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.53                | 0.17                | 0.53                  | 0.00       | 0.0       |
| <a href="#">Loc31</a>    | Hampton Municipal Bldg                            | 0.24                | 0.07                | 0.24                  | 0.00       | 0.0       |
| <a href="#">Loc33</a>    | Richland TWP                                      | 0.54                | 0.17                | 0.54                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold  | 0.39                | 0.10                | 0.38                  | 0.01       | 2.6       |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.67                | 0.32                | 0.65                  | 0.02       | 3.0       |
| <a href="#">Loc29</a>    | Bell Acres Munic Bldg                             | 0.29                | 0.09                | 0.28                  | 0.01       | 3.4       |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.24                | 0.07                | 0.23                  | 0.01       | 4.2       |
| <a href="#">Loc06</a>    | Carnegie Transit Time                             | 0.70                | 0.32                | 0.67                  | 0.03       | 4.3       |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.21                | 0.08                | 0.20                  | 0.01       | 4.8       |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.16                | 0.05                | 0.14                  | 0.02       | 12.5      |
| <a href="#">Loc10</a>    | PWSA-Highland Park                                | 0.20                | 0.06                | 0.17                  | 0.03       | 15.0      |



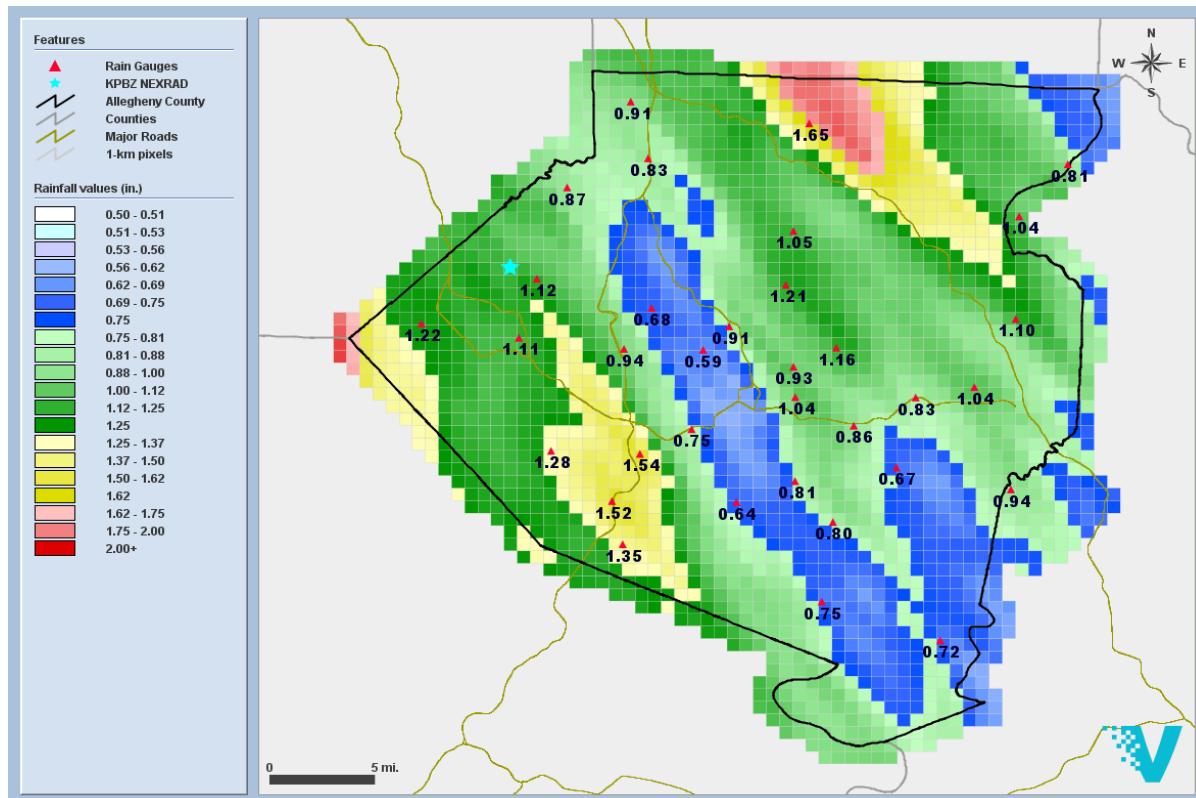
**Figure 14. Scatter Plot of Gauge-Adjusted RG Pairs for Event 4a**



**Figure 15. Scatter Plot of Gauge-Adjusted RG Pairs for Event 4b**



**Figure 16. Scatter Plot of Gauge-Adjusted RG Pairs for Event 4c**



**Figure 17. GARR Storm Total for Event 4**

**Table 22. Depth Duration Frequency Analyses for Event 4**

| <b>Duration</b> | <b>Depth (in)</b> | <b>Pixel</b> | <b>Time (EDT)</b> | <b>Frequency</b> |
|-----------------|-------------------|--------------|-------------------|------------------|
| 15 minutes      | 0.388             | 155119       | 2016-09-29 21:15  | <1 yr.           |
| 30 minutes      | 0.586             | 155119       | 2016-09-29 21:30  | <1 yr.           |
| 1 hour          | 0.919             | 155119       | 2016-09-29 21:30  | <1 yr.           |
| 2 hour          | 1.134             | 155119       | 2016-09-29 22:15  | <1 yr.           |
| 3 hour          | 1.192             | 155119       | 2016-09-29 22:30  | <1 yr.           |
| 6 hour          | 1.825             | 153117       | 2016-09-30 02:00  | 1 yr.            |
| 12 hour         | 1.842             | 153117       | 2016-09-30 04:00  | 1 yr.            |

## Event 5: 2016-09-30

The analysis period was from 2016-09-30 13:00 EDT to 2016-10-01 02:00 EDT. The event was then split into two sub-event periods at 2016-09-30 20:30 EDT to improve gauge adjustment of the radar.

The gauges listed in [Appendix A](#) were not used to adjust the radar due to inconsistencies between the gauge and the radar or surrounding gauges, or they did not have data available for this event. Gauges Loc02, Loc27, Loc30, Loc32, 03049500 and 03085734 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 5a. Gauges Loc03, Loc08, Loc09, Loc10, Loc11, Loc14, Loc19, Loc24, Loc25, Loc31 and Loc33 did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar during Event 5b.

A convective Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 23 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 24 - 25 summarize the results for each RG pair used for final radar adjustment, where  $G_i$  is the gauge estimate,  $R_i$  is the non-adjusted radar estimate,  $R_i^*$  is the GARR estimate, and Diff\* (%) is the percent difference between the gauge and GARR estimate. Figures 18 - 19 show the scatter plots of the gauge-adjusted RG pairs. Figure 20 depicts the GARR storm total over the 1-km<sup>2</sup> pixels. The GARR amounts for the 2313 1-km<sup>2</sup> pixels range from 0.1 - 0.7 inches with a mean of 0.3 inches. Table 26 shows the Depth Duration Frequency (DDF) maximum values for the 1-km<sup>2</sup> pixels.

**Table 23. GARR Statistics for Event 5**

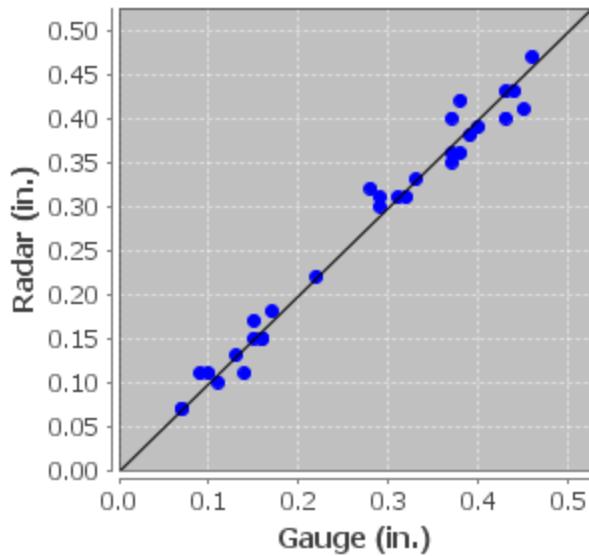
| <b>Event #</b> | <b>Radar</b> | <b>Event Date</b> | <b>Gauges Used (38)</b> | <b>Avg. Depth (in)</b> | <b>Bias</b> | <b>AD (%)</b> | <b>CAD (%)</b> |
|----------------|--------------|-------------------|-------------------------|------------------------|-------------|---------------|----------------|
| E5a            | KPBZ LII     | 2016-09-30        | 31                      | 0.222                  | 1.600       | 35.5          | 5.9            |
| E5b            | KPBZ LII     | 2016-09-30        | 25                      | 0.094                  | 0.976       | 13.3          | 4.2            |

**Table 24. Summary of Individual RG Pairs for Event 5a**

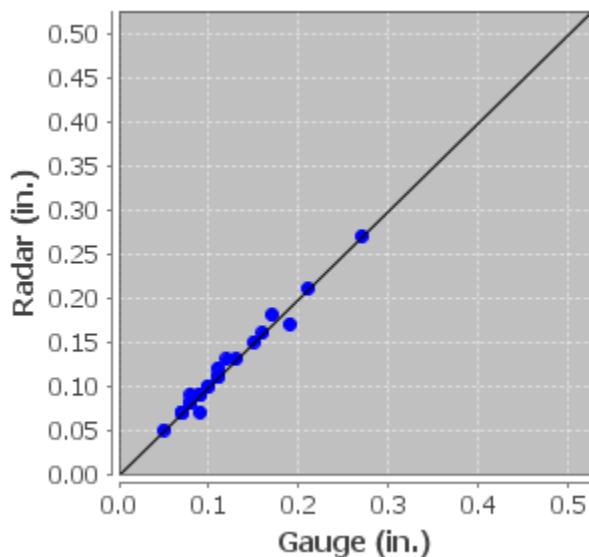
| Gauge ID              | Name                         | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|-----------------------|------------------------------|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc28</a> | Plum Municipal Bldg          | 0.09                | 0.11                | 0.11                  | -0.02      | -22.2     |
| <a href="#">Loc19</a> | Sandy Creek Eq Facility      | 0.28                | 0.23                | 0.32                  | -0.04      | -14.3     |
| <a href="#">Loc17</a> | Chartiers Pump Station       | 0.15                | 0.13                | 0.17                  | -0.02      | -13.3     |
| <a href="#">Loc11</a> | M-46 Access Shaft            | 0.38                | 0.26                | 0.42                  | -0.04      | -10.5     |
| <a href="#">Loc07</a> | Greentree Munic Bldg         | 0.10                | 0.06                | 0.11                  | -0.01      | -10.0     |
| <a href="#">KAGC</a>  | Pittsburgh Allegheny Cty     | 0.37                | 0.26                | 0.40                  | -0.03      | -8.1      |
| <a href="#">Loc31</a> | Hampton Municipal Bldg       | 0.29                | 0.23                | 0.31                  | -0.02      | -6.9      |
| <a href="#">Loc21</a> | Moon TWP                     | 0.17                | 0.12                | 0.18                  | -0.01      | -5.9      |
| <a href="#">Loc25</a> | White Oak Public Works Bldg  | 0.29                | 0.17                | 0.30                  | -0.01      | -3.4      |
| <a href="#">Loc10</a> | PWSA-Highland Park           | 0.46                | 0.29                | 0.47                  | -0.01      | -2.2      |
| <a href="#">Loc04</a> | Kennedy Twp PS               | 0.07                | 0.06                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc05</a> | Upper St. Clair              | 0.22                | 0.17                | 0.22                  | 0.00       | 0.0       |
| <a href="#">Loc15</a> | Trafford Maint Bldg          | 0.33                | 0.19                | 0.33                  | 0.00       | 0.0       |
| <a href="#">Loc18</a> | Oakdale Pump Station         | 0.13                | 0.09                | 0.13                  | 0.00       | 0.0       |
| <a href="#">Loc22</a> | North Fayette TWP            | 0.15                | 0.09                | 0.15                  | 0.00       | 0.0       |
| <a href="#">Loc23</a> | Clinton Munic Bldg           | 0.31                | 0.18                | 0.31                  | 0.00       | 0.0       |
| <a href="#">Loc29</a> | Bell Acres Munic Bldg        | 0.07                | 0.06                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc33</a> | Richland TWP                 | 0.43                | 0.28                | 0.43                  | 0.00       | 0.0       |
| <a href="#">Loc26</a> | Elizabeth TWP Municipal Bldg | 0.44                | 0.20                | 0.43                  | 0.01       | 2.3       |
| <a href="#">Loc03</a> | Shaler Munic Bldg            | 0.40                | 0.25                | 0.39                  | 0.01       | 2.5       |
| <a href="#">Loc24</a> | Jefferson Hills              | 0.39                | 0.22                | 0.38                  | 0.01       | 2.6       |
| <a href="#">Loc14</a> | Churchill Munic Bldg         | 0.37                | 0.23                | 0.36                  | 0.01       | 2.7       |
| <a href="#">Loc12</a> | Baldwin                      | 0.32                | 0.19                | 0.31                  | 0.01       | 3.1       |
| <a href="#">Loc09</a> | Univ of Pittsburgh           | 0.38                | 0.21                | 0.36                  | 0.02       | 5.3       |
| <a href="#">Loc08</a> | AC Health Dept Bldg          | 0.37                | 0.20                | 0.35                  | 0.02       | 5.4       |
| <a href="#">KPIT</a>  | Greater Pittsburgh Int'l     | 0.16                | 0.10                | 0.15                  | 0.01       | 6.3       |
| <a href="#">Loc16</a> | Castle Shannon               | 0.16                | 0.08                | 0.15                  | 0.01       | 6.3       |
| <a href="#">Loc20</a> | Gascola Eq Facility          | 0.43                | 0.25                | 0.40                  | 0.03       | 7.0       |
| <a href="#">Loc13</a> | M-59 Access Shaft            | 0.45                | 0.24                | 0.41                  | 0.04       | 8.9       |
| <a href="#">Loc01</a> | PWSA-Montana St.             | 0.11                | 0.06                | 0.10                  | 0.01       | 9.1       |
| <a href="#">Loc06</a> | Carnegie Transit Time        | 0.14                | 0.07                | 0.11                  | 0.03       | 21.4      |

**Table 25. Summary of Individual RG Pairs for Event 5b**

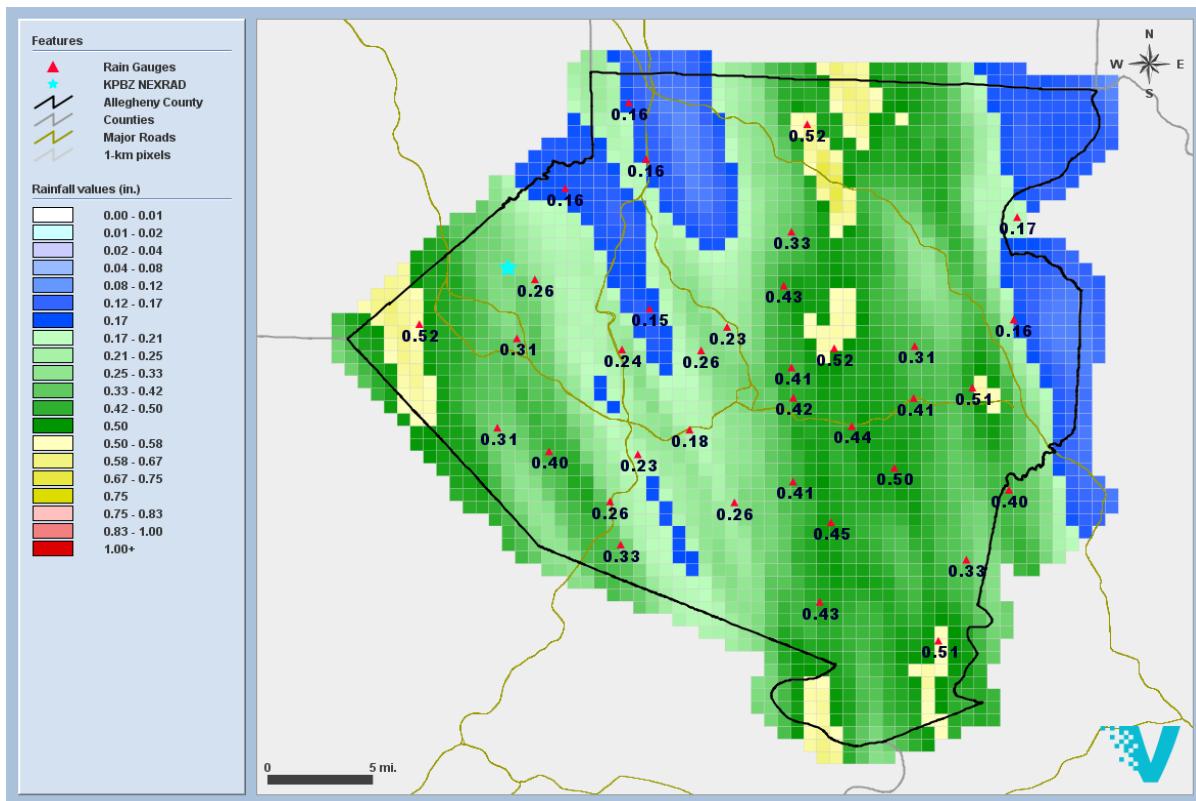
| Gauge ID                 | Name  | G <sub>i</sub> (in) | R <sub>i</sub> (in) | R <sub>i</sub> * (in) | Diff* (in) | Diff* (%) |
|--------------------------|---|---------------------|---------------------|-----------------------|------------|-----------|
| <a href="#">Loc07</a>    | Greentree Munic Bldg                              | 0.08                | 0.09                | 0.09                  | -0.01      | -12.5     |
| <a href="#">Loc05</a>    | Upper St. Clair                                   | 0.11                | 0.14                | 0.12                  | -0.01      | -9.1      |
| <a href="#">Loc01</a>    | PWSA-Montana St.                                  | 0.12                | 0.10                | 0.13                  | -0.01      | -8.3      |
| <a href="#">Loc04</a>    | Kennedy Twp PS                                    | 0.17                | 0.16                | 0.18                  | -0.01      | -5.9      |
| <a href="#">03085734</a> | Ohio River at Emsworth Dam Lower Pool at Emsworth | 0.11                | 0.09                | 0.11                  | 0.00       | 0.0       |
| <a href="#">KAGC</a>     | Pittsburgh Allegheny Cty                          | 0.08                | 0.08                | 0.08                  | 0.00       | 0.0       |
| <a href="#">KPIT</a>     | Greater Pittsburgh Int'l                          | 0.15                | 0.16                | 0.15                  | 0.00       | 0.0       |
| <a href="#">Loc12</a>    | Baldwin   | 0.09                | 0.09                | 0.09                  | 0.00       | 0.0       |
| <a href="#">Loc13</a>    | M-59 Access Shaft                                 | 0.05                | 0.06                | 0.05                  | 0.00       | 0.0       |
| <a href="#">Loc15</a>    | Trafford Maint Bldg                               | 0.07                | 0.08                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc16</a>    | Castle Shannon                                    | 0.10                | 0.09                | 0.10                  | 0.00       | 0.0       |
| <a href="#">Loc17</a>    | Chartiers Pump Station                            | 0.11                | 0.12                | 0.11                  | 0.00       | 0.0       |
| <a href="#">Loc18</a>    | Oakdale Pump Station                              | 0.27                | 0.31                | 0.27                  | 0.00       | 0.0       |
| <a href="#">Loc20</a>    | Gascola Eq Facility                               | 0.08                | 0.06                | 0.08                  | 0.00       | 0.0       |
| <a href="#">Loc21</a>    | Moon TWP  | 0.09                | 0.09                | 0.09                  | 0.00       | 0.0       |
| <a href="#">Loc22</a>    | North Fayette TWP                                 | 0.16                | 0.19                | 0.16                  | 0.00       | 0.0       |
| <a href="#">Loc23</a>    | Clinton Munic Bldg                                | 0.21                | 0.23                | 0.21                  | 0.00       | 0.0       |
| <a href="#">Loc26</a>    | Elizabeth TWP Municipal Bldg                      | 0.07                | 0.08                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc27</a>    | Marshall TWP                                      | 0.11                | 0.13                | 0.11                  | 0.00       | 0.0       |
| <a href="#">Loc28</a>    | Plum Municipal Bldg                               | 0.07                | 0.08                | 0.07                  | 0.00       | 0.0       |
| <a href="#">Loc29</a>    | Bell Acres Munic Bldg                             | 0.09                | 0.09                | 0.09                  | 0.00       | 0.0       |
| <a href="#">Loc30</a>    | McCandless Twn Hall                               | 0.10                | 0.14                | 0.10                  | 0.00       | 0.0       |
| <a href="#">Loc32</a>    | Arnold  | 0.13                | 0.11                | 0.13                  | 0.00       | 0.0       |
| <a href="#">Loc02</a>    | ALCOSAN WWTP Lab                                  | 0.19                | 0.13                | 0.17                  | 0.02       | 10.5      |
| <a href="#">Loc06</a>    | Carnegie Transit Time                             | 0.09                | 0.07                | 0.07                  | 0.02       | 22.2      |



**Figure 18. Scatter Plot of Gauge-Adjusted RG Pairs for Event 5a**



**Figure 19. Scatter Plot of Gauge-Adjusted RG Pairs for Event 5b**



**Figure 20. GARR Storm Total for Event 5**

**Table 26. Depth Duration Frequency Analyses for Event 5**

| Duration   | Depth (in) | Pixel  | Time (EDT)       | Frequency |
|------------|------------|--------|------------------|-----------|
| 15 minutes | 0.328      | 153167 | 2016-09-30 16:45 | <1 yr.    |
| 30 minutes | 0.427      | 153112 | 2016-09-30 17:45 | <1 yr.    |
| 1 hour     | 0.519      | 153112 | 2016-09-30 18:15 | <1 yr.    |
| 2 hour     | 0.521      | 153112 | 2016-09-30 18:30 | <1 yr.    |
| 3 hour     | 0.521      | 153112 | 2016-09-30 18:30 | <1 yr.    |
| 6 hour     | 0.644      | 152120 | 2016-09-30 23:00 | <1 yr.    |
| 12 hour    | 0.669      | 152120 | 2016-10-01 01:00 | <1 yr.    |

## **Appendices**

- [Appendix A](#) - Gauge Summary Table
- [Appendix B](#) - Event 1 (2016-09-09) CDPs
- [Appendix C](#) - Event 2 (2016-09-18) CDPs
- [Appendix D](#) - Event 3 (2016-09-29 AM) CDPs
- [Appendix E](#) - Event 4 (2016-09-29 PM) CDPs
- [Appendix F](#) - Event 5 (2016-09-30) CDPs

## Appendix A - Gauge Summary Table

| <b>Reason</b>     | <b>Explanation</b>   |
|-------------------|--|
| Clog (C)          | Gauge appeared to be clogged   |
| Zero (Z)          | Gauge did not report any rainfall while radar rainfall estimates reported significant rainfall   |
| Stop (S)          | Gauge appeared to stop reporting rainfall while radar rainfall estimates reported significant rainfall   |
| Over (O)          | Gauge appeared to significantly over-report rainfall as compared to radar rainfall estimates and surrounding gauges (e.g. anomalously high rainfall values caused by field calibration, data transmission error, or switch malfunctions) |
| Under (U)         | Gauge appeared to significantly under-report as compared to radar rainfall estimates and surrounding Gauges (e.g. half-tipper)   |
| Sync (SY)         | Gauge appeared to be reporting out-of-sync with the radar rainfall estimates   |
| Frozen/Melt (F/M) | Gauge not reporting properly due to frozen or melting precipitation  |
| Other (T)         | Combination of multiple reasons  |
| No Data (ND)      | Gauge reported "no data" for a significant amount of time  |

|       | <u>E1a</u> | <u>E1b</u> | <u>E1c</u> | <u>E2a</u> | <u>E2b</u> | <u>E3a</u>    |
|-------|------------|------------|------------|------------|------------|---------------|
| Gauge | 2016-09-09 | 2016-09-09 | 2016-09-09 | 2016-09-18 | 2016-09-18 | 2016-09-29 AM |
| Loc01 |            | U          |            |            |            |               |
| Loc02 |            |            |            |            |            |               |
| Loc03 |            |            |            |            |            |               |
| Loc04 |            |            |            |            |            |               |
| Loc05 |            |            |            |            |            |               |
| Loc06 |            |            |            |            |            |               |
| Loc07 |            |            |            |            |            |               |
| Loc08 |            |            |            |            |            |               |
| Loc09 |            |            |            |            |            |               |
| Loc10 |            |            |            |            |            |               |
| Loc11 |            |            |            |            |            |               |
| Loc12 |            |            |            |            |            |               |
| Loc13 |            |            |            |            |            |               |
| Loc14 |            |            |            |            |            |               |
| Loc15 |            |            |            |            |            |               |
| Loc16 |            |            |            |            |            |               |
| Loc17 |            |            |            |            |            |               |
| Loc18 |            |            |            |            |            |               |
| Loc19 |            |            |            |            |            |               |
| Loc20 |            |            |            |            |            |               |
| Loc21 |            |            |            |            |            |               |
| Loc22 |            |            |            |            |            |               |
| Loc23 |            |            |            |            |            |               |
| Loc24 |            |            |            |            |            |               |
| Loc25 |            | S          | Z          | S          | Z          | U             |
| Loc26 |            |            |            |            |            |               |
| Loc27 |            |            |            |            |            |               |
| Loc28 |            |            |            |            |            |               |

|          | <u>E1a</u> | <u>E1b</u> | <u>E1c</u> | <u>E2a</u> | <u>E2b</u> | <u>E3a</u>    |
|----------|------------|------------|------------|------------|------------|---------------|
| Gauge    | 2016-09-09 | 2016-09-09 | 2016-09-09 | 2016-09-18 | 2016-09-18 | 2016-09-29 AM |
| Loc29    |            |            |            |            |            |               |
| Loc30    |            |            |            |            |            |               |
| Loc31    |            |            |            |            |            |               |
| Loc32    |            |            |            |            |            |               |
| Loc33    |            |            |            |            |            |               |
| KAGC     |            |            |            |            |            | O             |
| KPIT     |            |            |            |            |            |               |
| 03049500 | U          | U          |            |            |            |               |
| 03085500 | ND         | ND         | ND         | ND         | ND         | ND            |
| 03085734 |            |            |            |            |            |               |

|       | <u>E3b</u>       | <u>E3c</u>       | <u>E4a</u>       | <u>E4b</u>       | <u>E4c</u>       | <u>E5a</u> |
|-------|------------------|------------------|------------------|------------------|------------------|------------|
| Gauge | 2016-09-29<br>AM | 2016-09-29<br>AM | 2016-09-29<br>PM | 2016-09-29<br>PM | 2016-09-29<br>PM | 2016-09-30 |
| Loc01 |                  |                  |                  |                  |                  |            |
| Loc02 |                  |                  |                  |                  |                  |            |
| Loc03 |                  |                  |                  |                  |                  |            |
| Loc04 |                  |                  |                  |                  |                  |            |
| Loc05 |                  |                  |                  |                  |                  |            |
| Loc06 |                  |                  |                  |                  |                  |            |
| Loc07 |                  |                  |                  |                  |                  |            |
| Loc08 |                  |                  |                  |                  |                  |            |
| Loc09 |                  |                  |                  |                  |                  |            |
| Loc10 |                  |                  |                  |                  |                  |            |
| Loc11 |                  |                  |                  |                  |                  |            |
| Loc12 |                  |                  |                  |                  |                  |            |
| Loc13 |                  |                  |                  |                  |                  |            |
| Loc14 |                  |                  |                  |                  |                  |            |
| Loc15 |                  |                  |                  |                  |                  |            |
| Loc16 |                  |                  |                  |                  |                  |            |
| Loc17 |                  |                  |                  |                  |                  |            |
| Loc18 |                  |                  |                  |                  |                  |            |
| Loc19 |                  |                  |                  |                  | Z                |            |
| Loc20 |                  |                  |                  |                  |                  |            |
| Loc21 |                  |                  |                  |                  |                  |            |
| Loc22 |                  |                  |                  |                  | U                |            |
| Loc23 |                  |                  |                  |                  |                  |            |
| Loc24 |                  |                  |                  |                  |                  |            |
| Loc25 |                  |                  | S                |                  |                  |            |

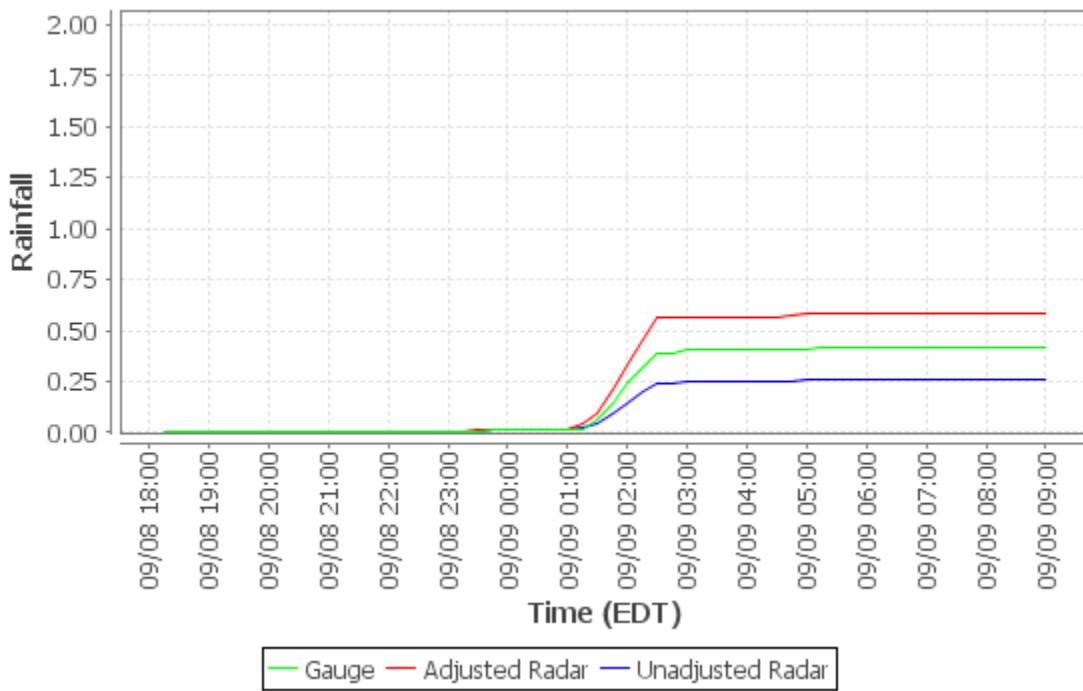
|          | <u>E3b</u>       | <u>E3c</u>       | <u>E4a</u>       | <u>E4b</u>       | <u>E4c</u>       | <u>E5a</u> |
|----------|------------------|------------------|------------------|------------------|------------------|------------|
| Gauge    | 2016-09-29<br>AM | 2016-09-29<br>AM | 2016-09-29<br>PM | 2016-09-29<br>PM | 2016-09-29<br>PM | 2016-09-30 |
| Loc26    |                  |                  |                  |                  |                  |            |
| Loc27    |                  |                  |                  |                  |                  |            |
| Loc28    |                  |                  |                  |                  |                  |            |
| Loc29    |                  |                  |                  |                  |                  |            |
| Loc30    |                  |                  |                  |                  |                  |            |
| Loc31    |                  |                  |                  |                  |                  |            |
| Loc32    |                  |                  |                  |                  |                  |            |
| Loc33    |                  |                  |                  |                  |                  |            |
| KAGC     | U                |                  |                  |                  |                  |            |
| KPIT     |                  |                  |                  |                  |                  |            |
| 03049500 | U                |                  |                  |                  |                  |            |
| 03085500 | ND               | ND               | ND               | ND               | ND               | ND         |
| 03085734 |                  |                  |                  |                  |                  |            |

|              |                   |
|--------------|-------------------|
|              | <b><u>E5b</u></b> |
| <b>Gauge</b> | <b>2016-09-30</b> |
| Loc01        |                   |
| Loc02        |                   |
| Loc03        |                   |
| Loc04        |                   |
| Loc05        |                   |
| Loc06        |                   |
| Loc07        |                   |
| Loc08        |                   |
| Loc09        |                   |
| Loc10        |                   |
| Loc11        |                   |
| Loc12        |                   |
| Loc13        |                   |
| Loc14        |                   |
| Loc15        |                   |
| Loc16        |                   |
| Loc17        |                   |
| Loc18        |                   |
| Loc19        |                   |
| Loc20        |                   |
| Loc21        |                   |
| Loc22        |                   |
| Loc23        |                   |
| Loc24        |                   |
| Loc25        |                   |
| Loc26        |                   |

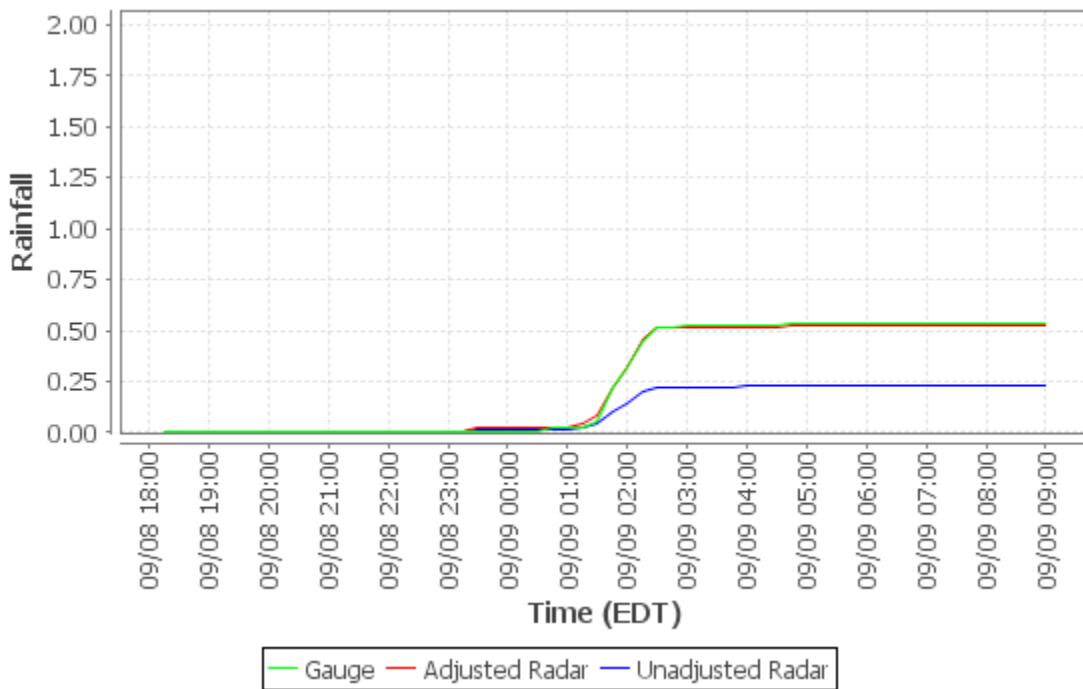
|          |            |
|----------|------------|
|          | <u>E5b</u> |
| Gauge    | 2016-09-30 |
| Loc27    |            |
| Loc28    |            |
| Loc29    |            |
| Loc30    |            |
| Loc31    |            |
| Loc32    |            |
| Loc33    |            |
| KAGC     |            |
| KPIT     |            |
| 03049500 | U          |
| 03085500 | ND         |
| 03085734 |            |

## **Appendix B - Event 1 (2016-09-09) CDPs**

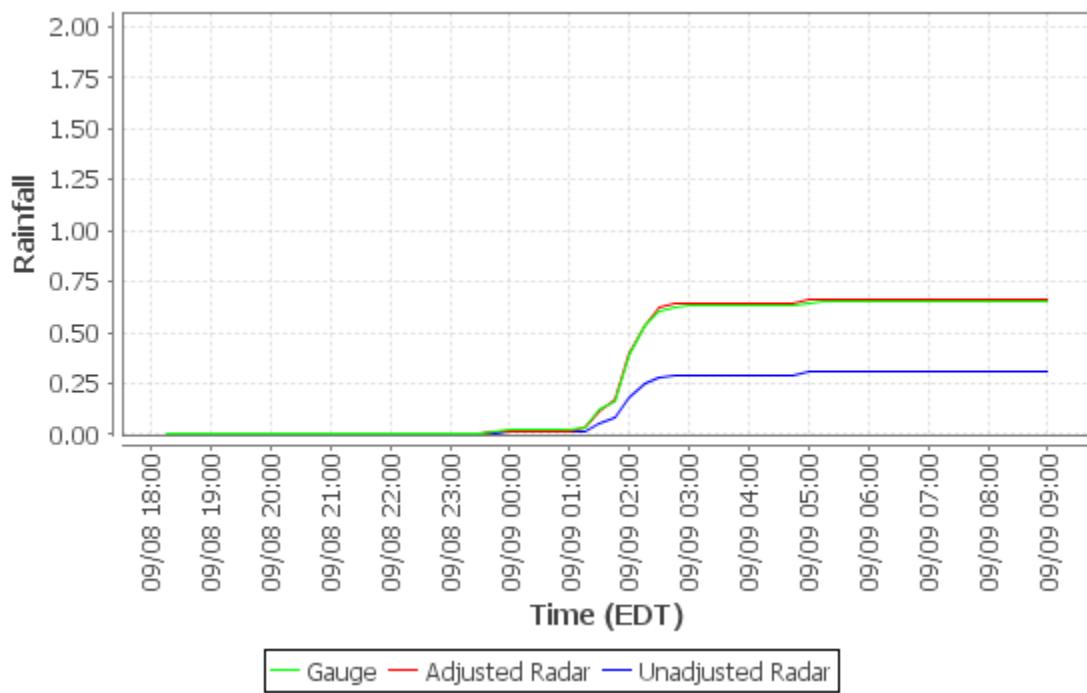
### Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



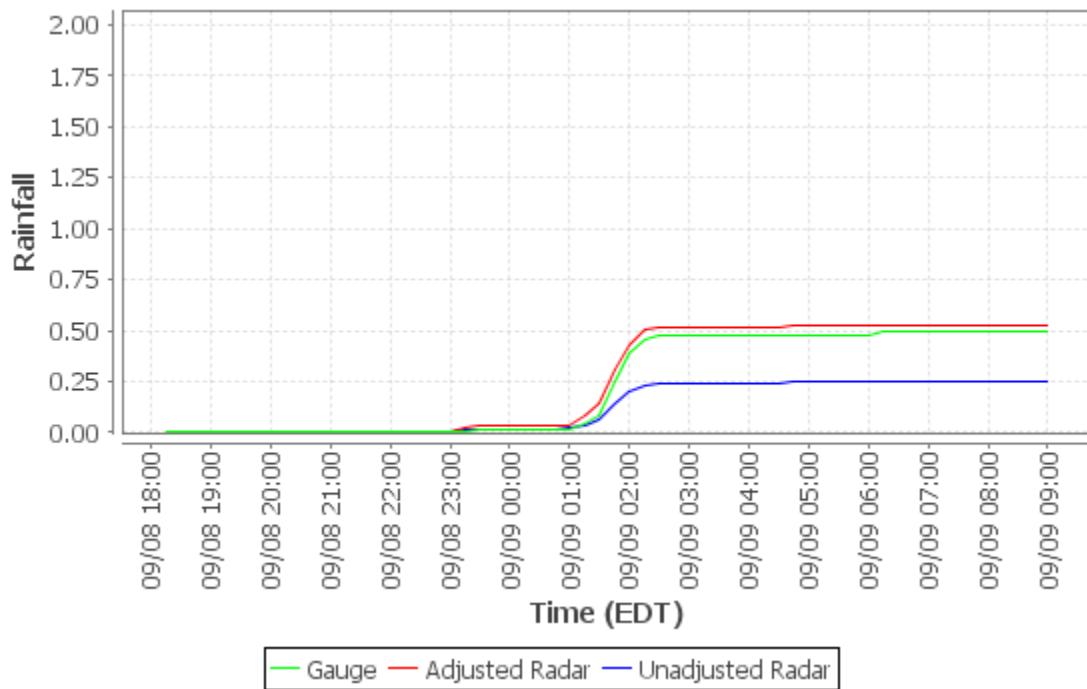
### Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



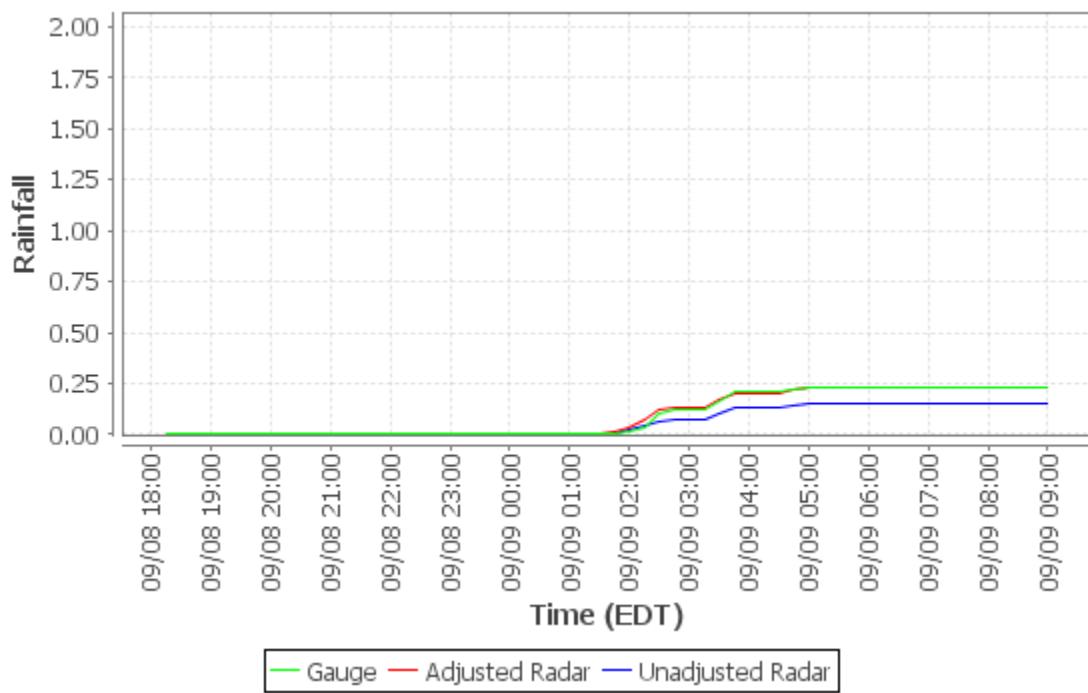
### Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



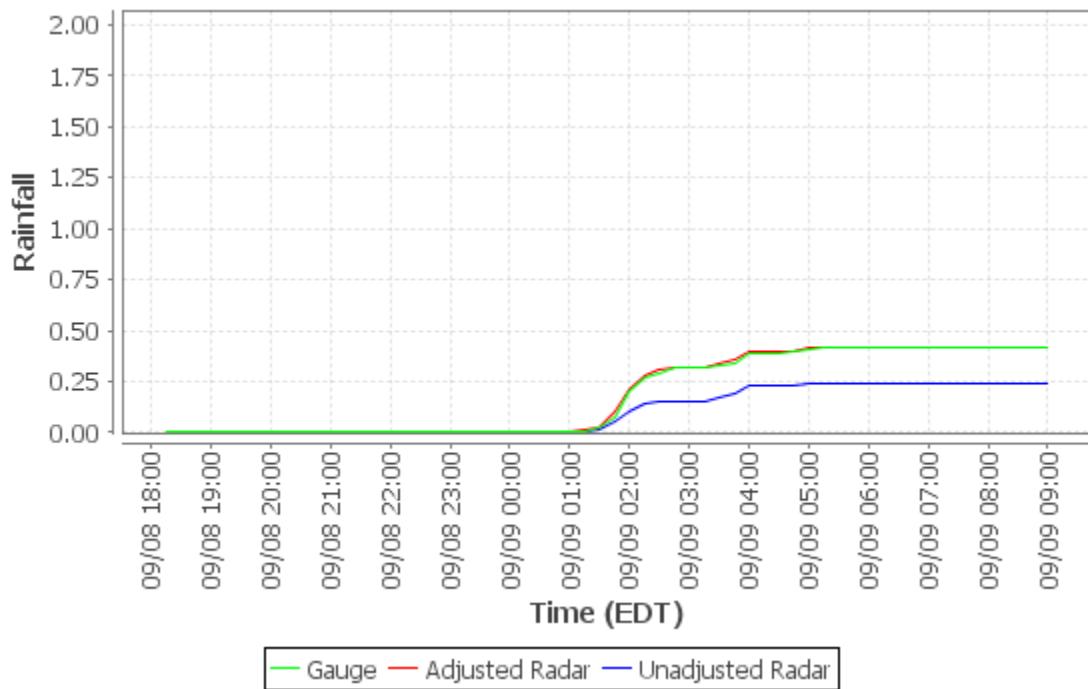
### Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



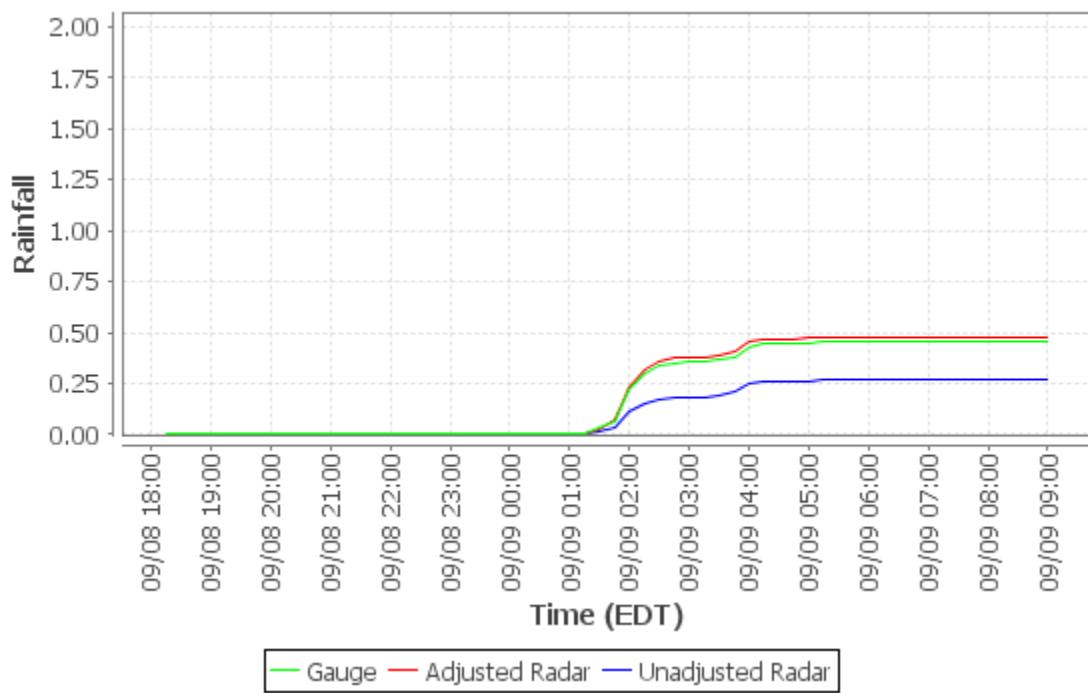
### Cumulative Distribution Plot - Upper St. Clair (Loc05)



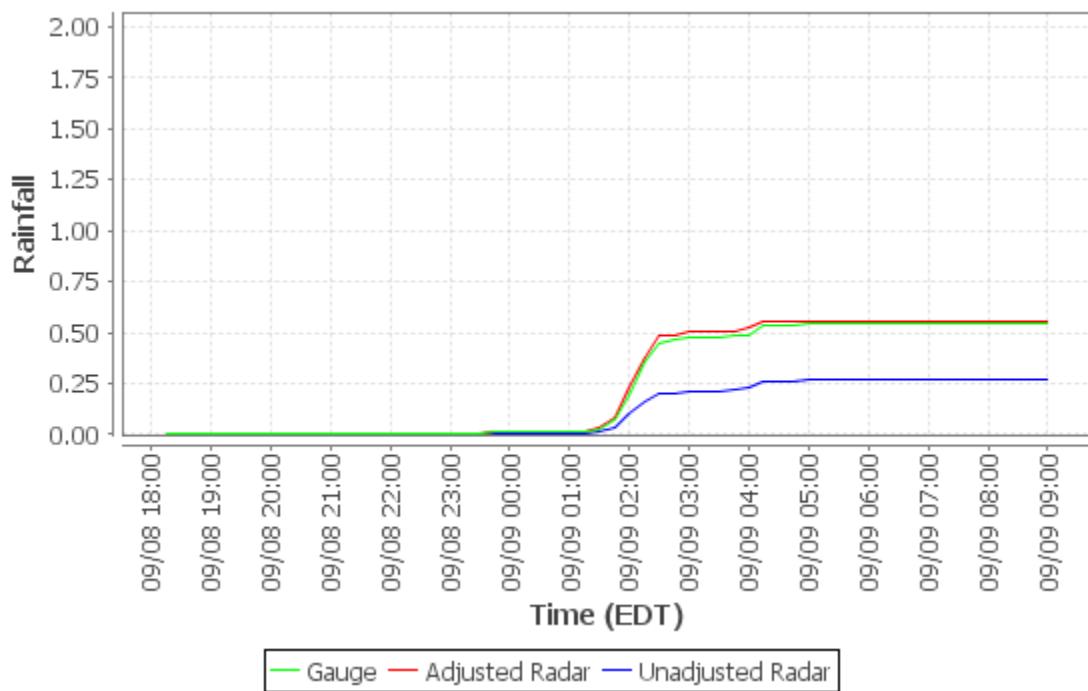
### Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



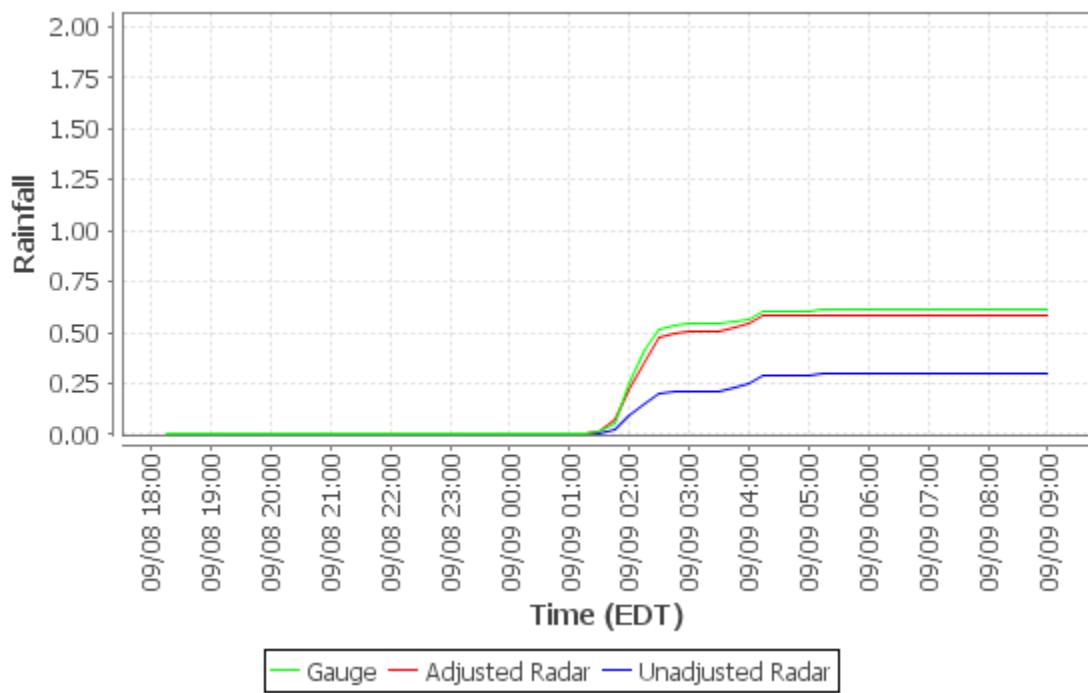
### Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



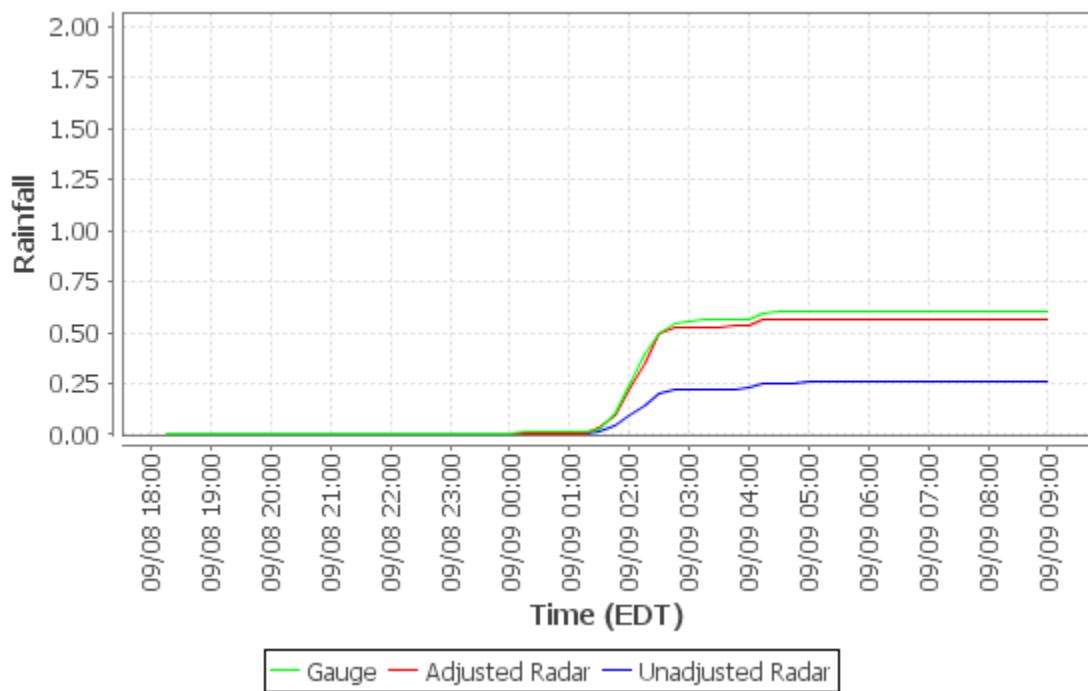
### Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



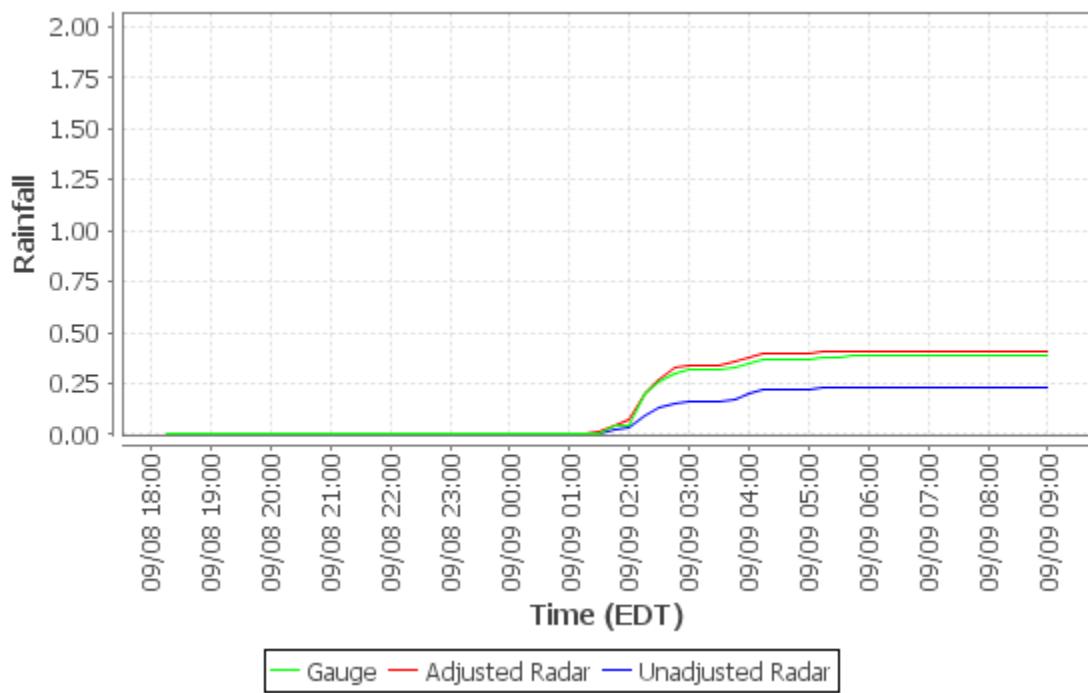
### Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



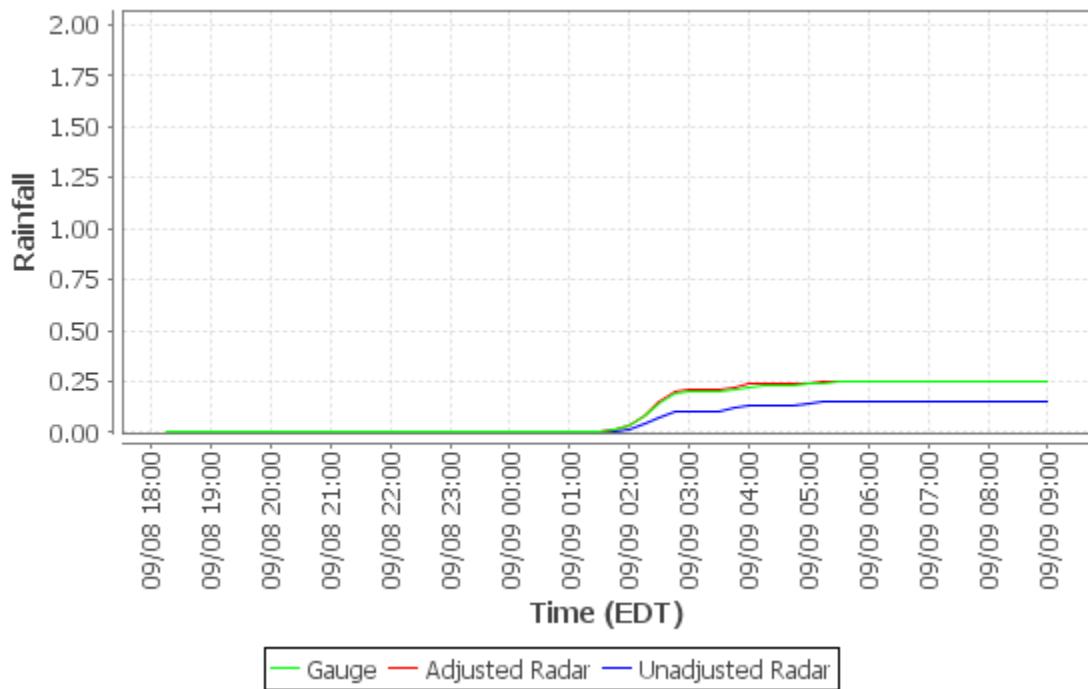
### Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



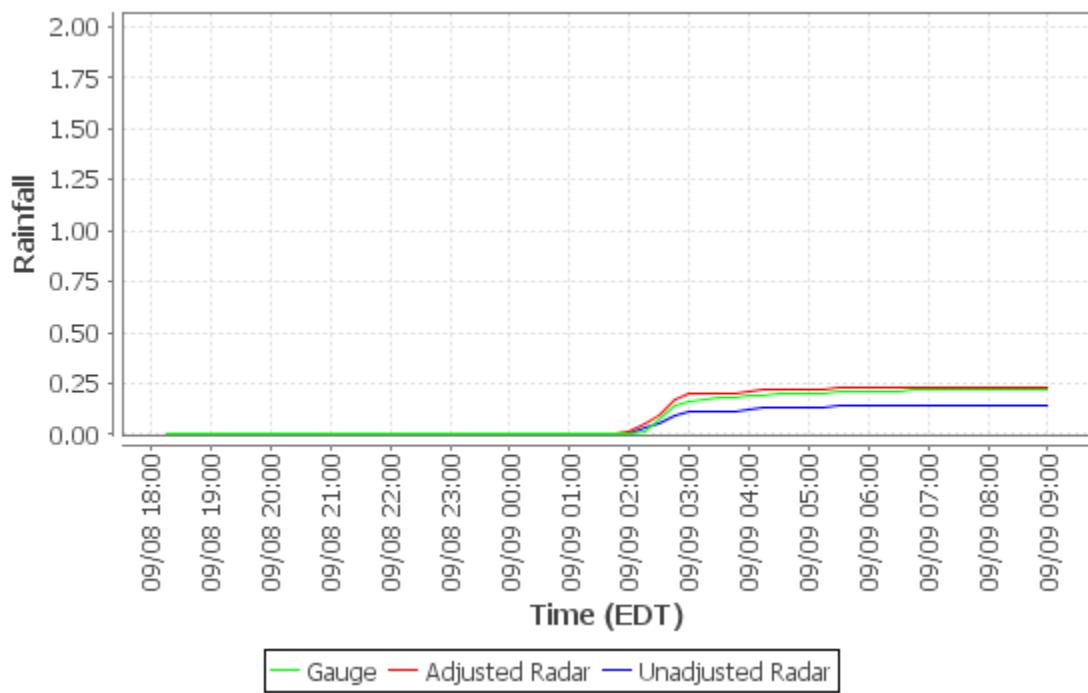
### Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



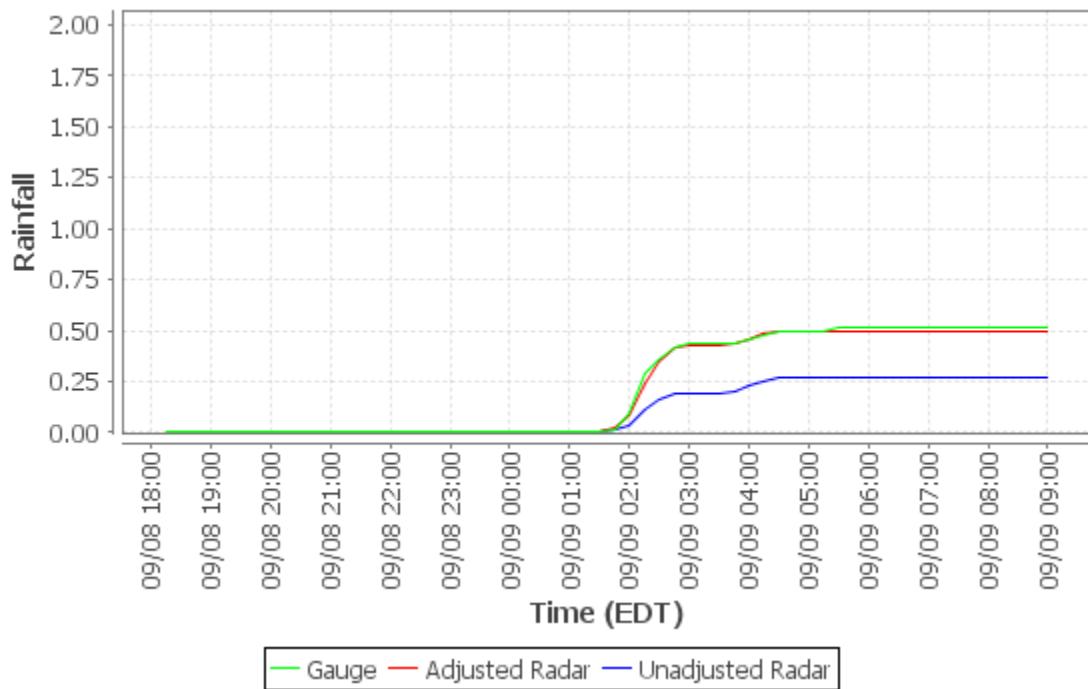
### Cumulative Distribution Plot - Baldwin (Loc12)



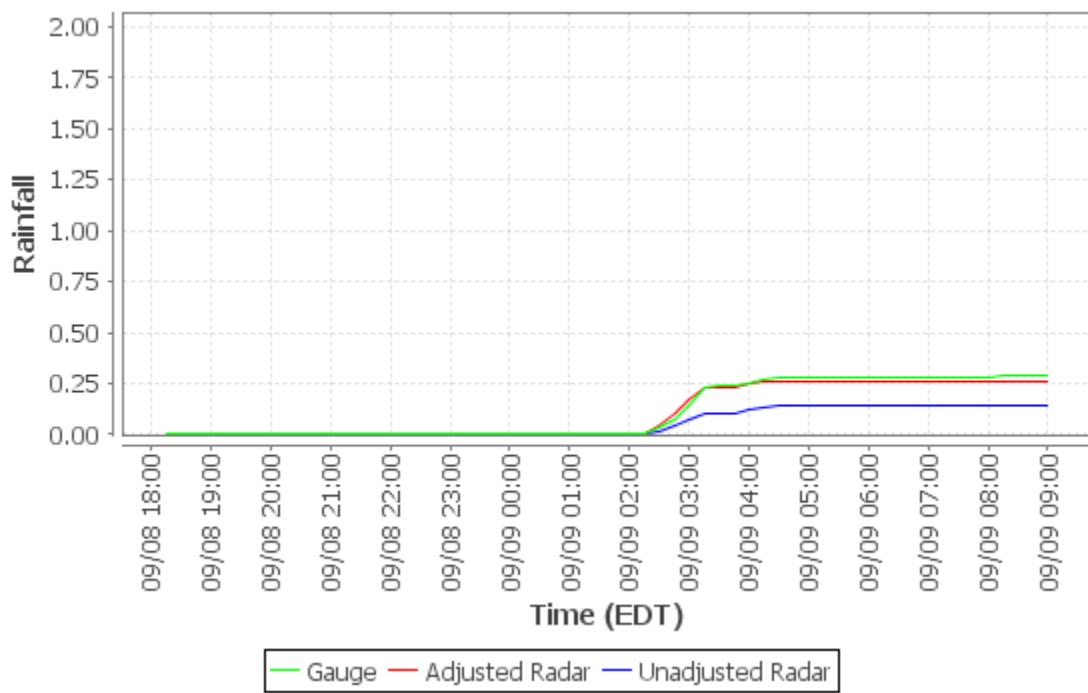
### Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



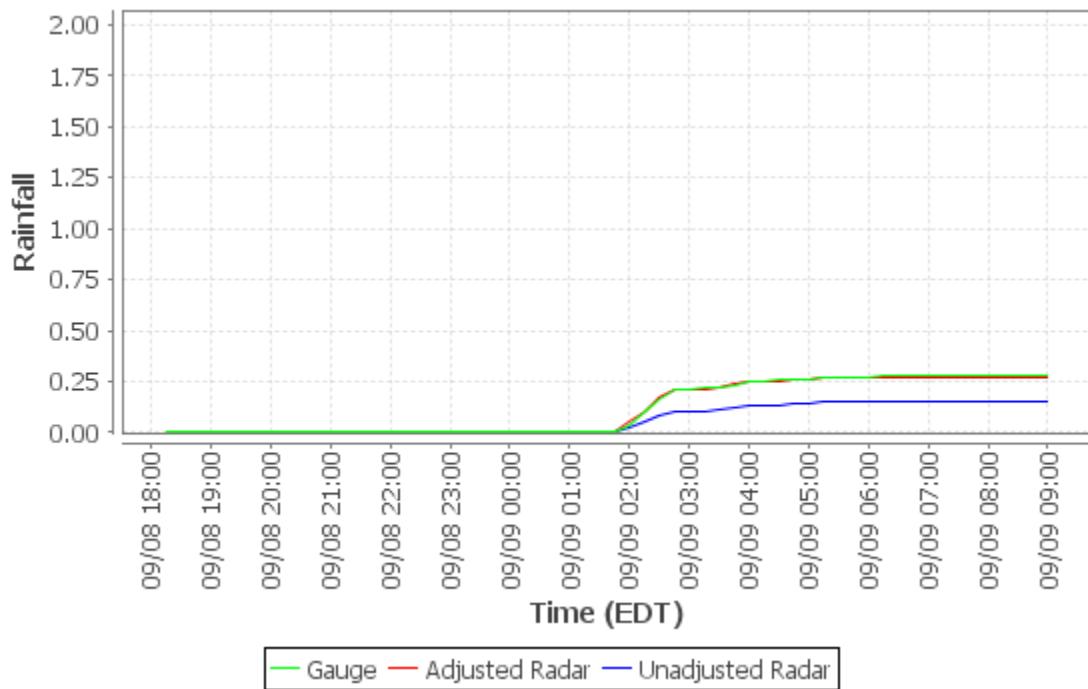
### Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



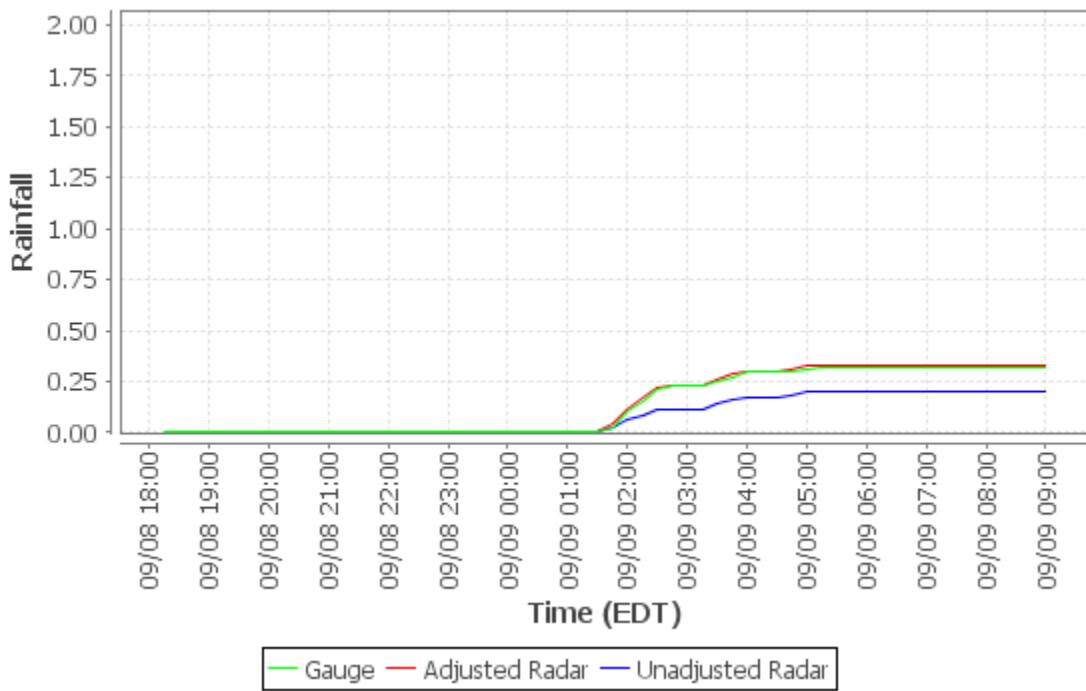
### Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



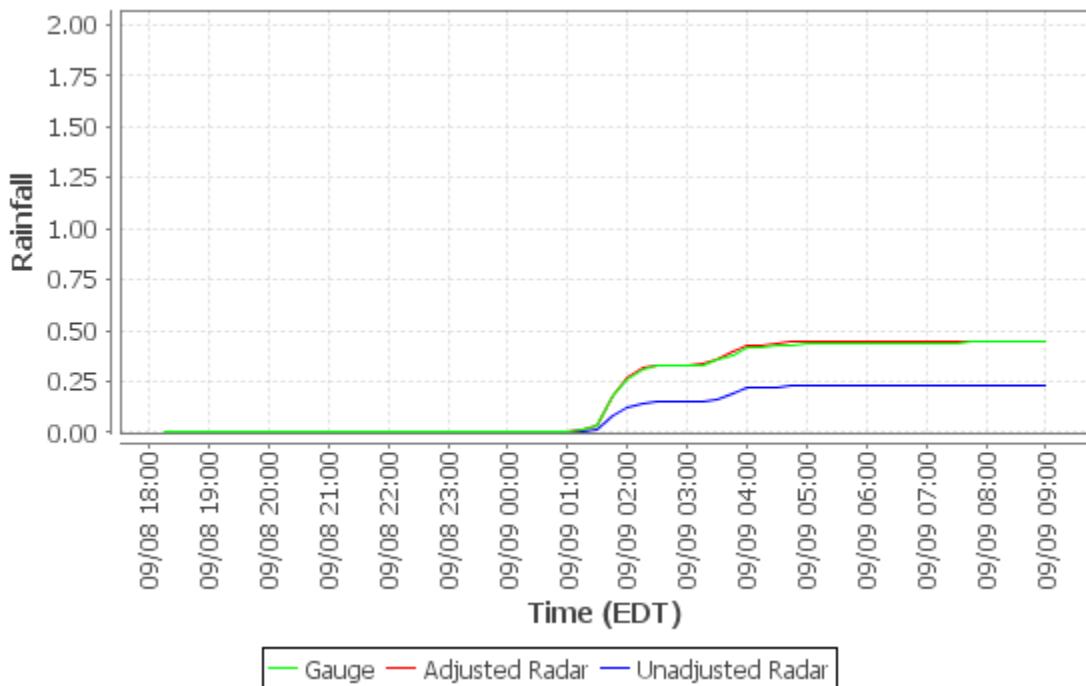
### Cumulative Distribution Plot - Castle Shannon (Loc16)



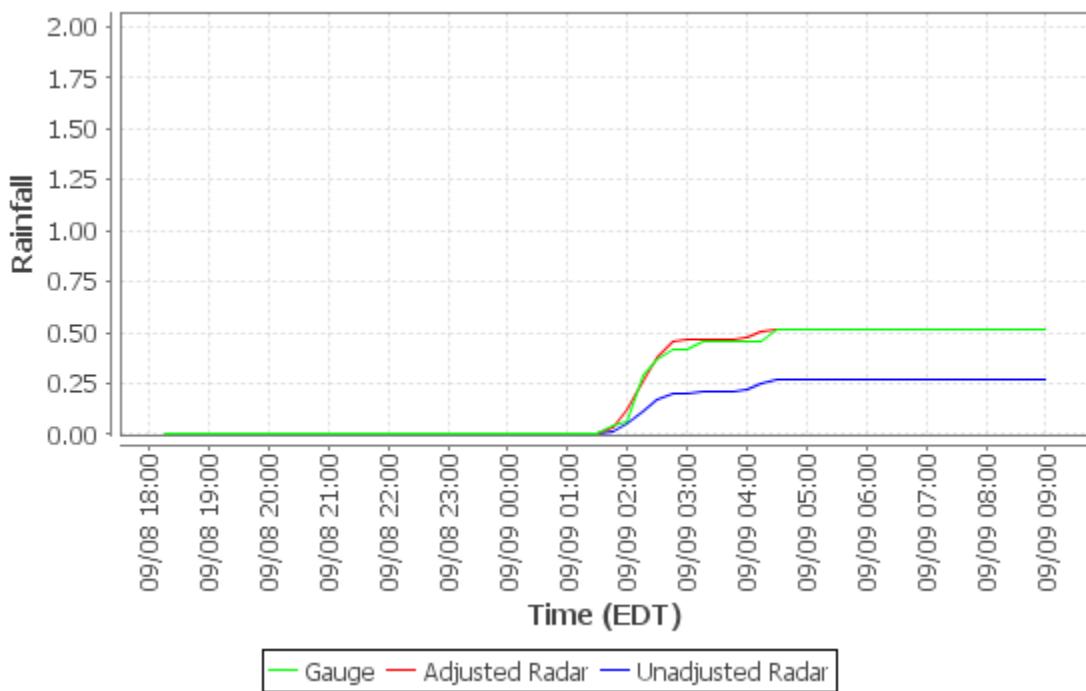
### Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



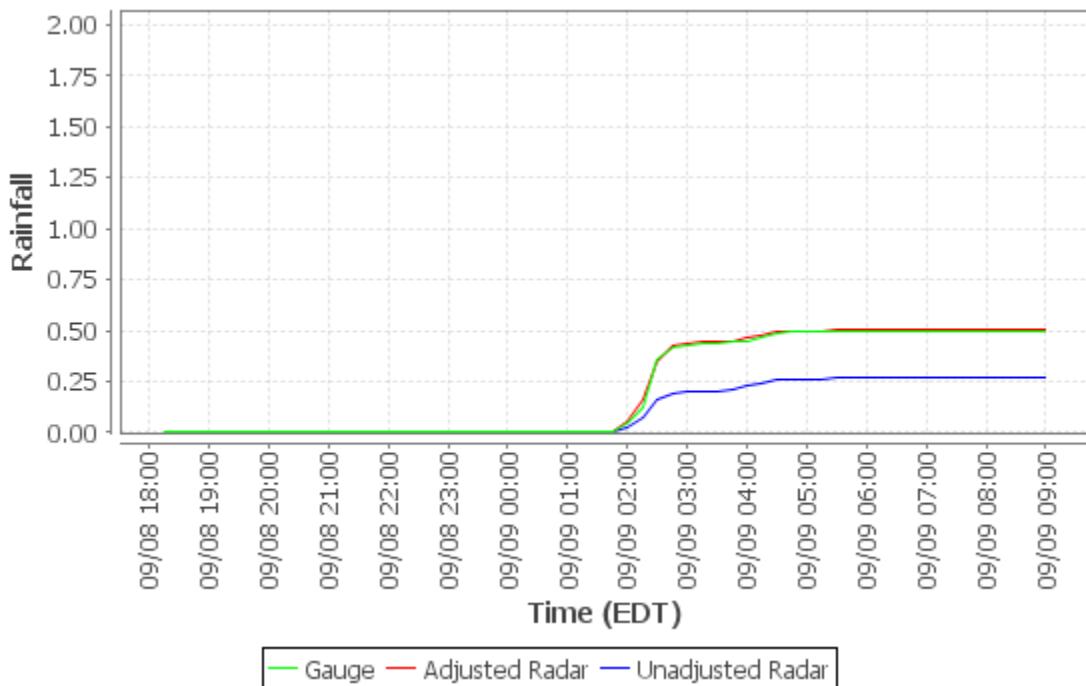
### Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



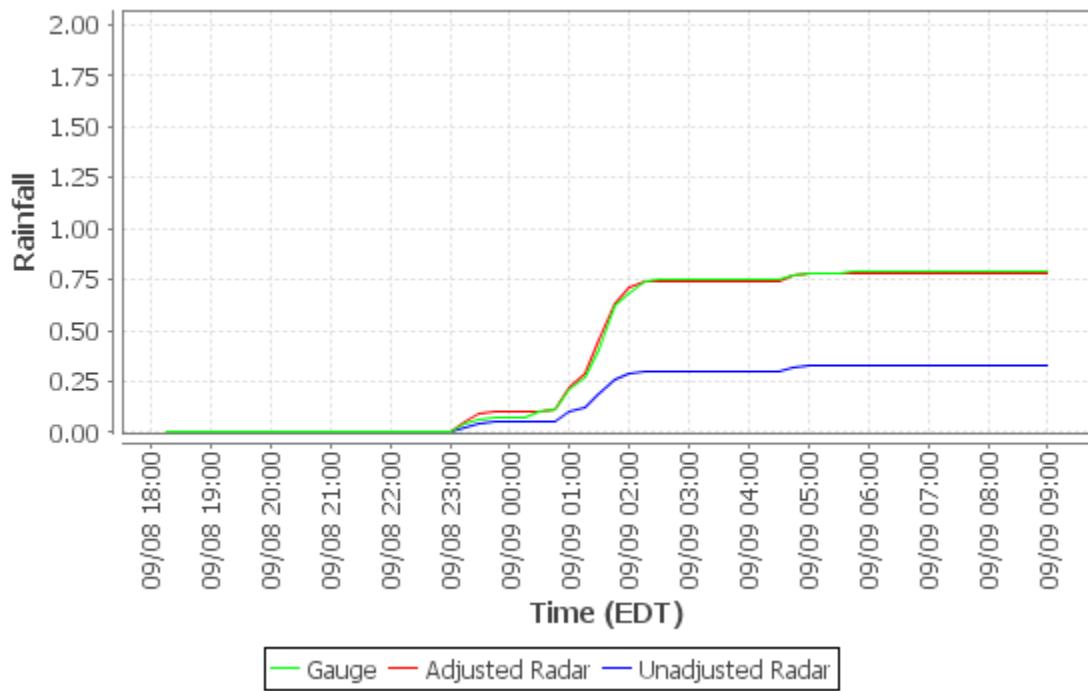
### Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



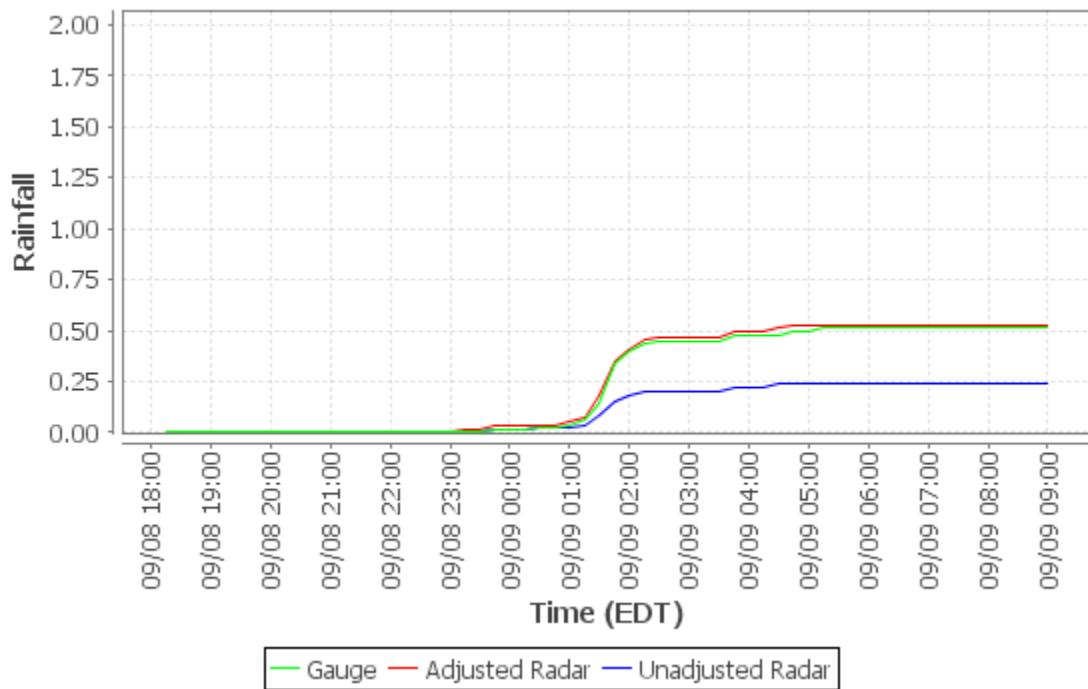
### Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



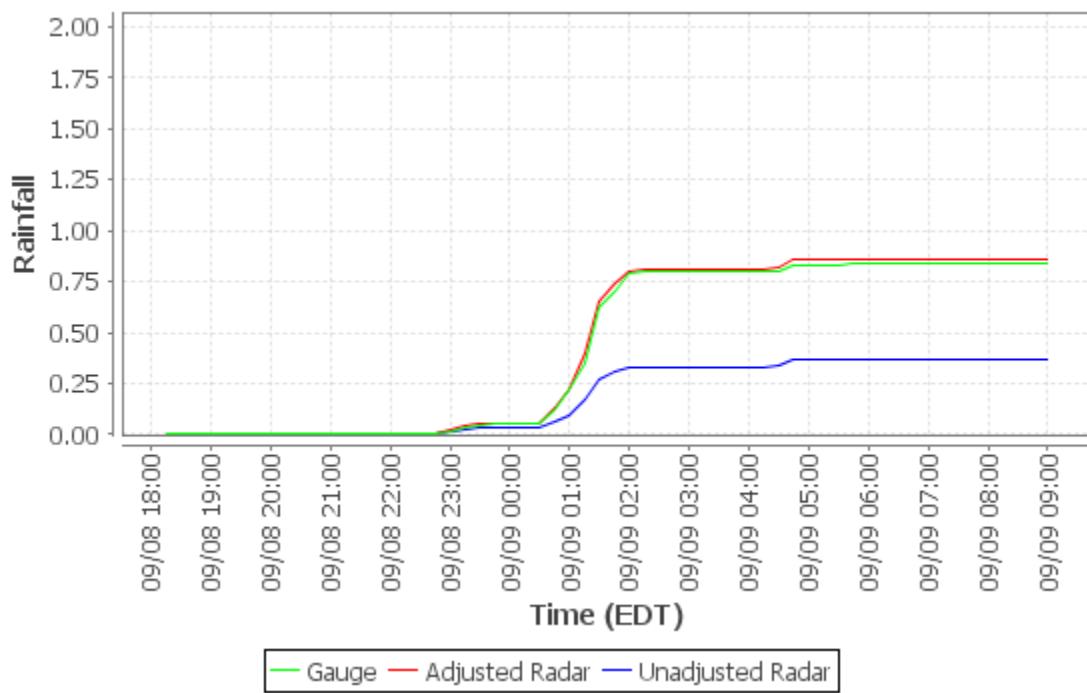
### Cumulative Distribution Plot - Moon TWP (Loc21)



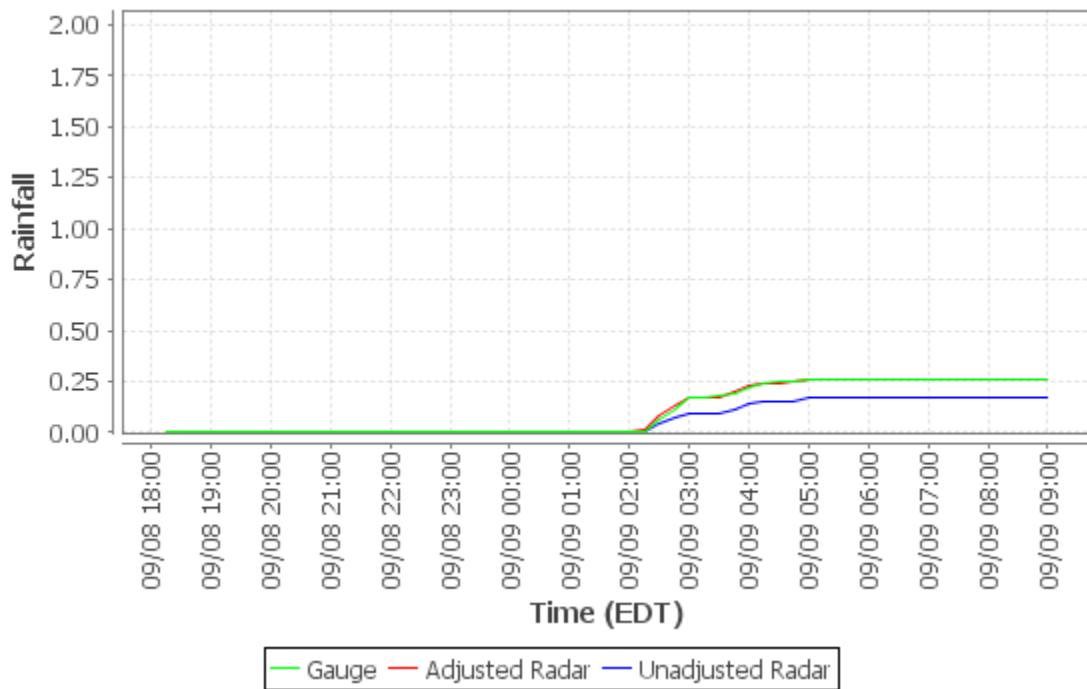
### Cumulative Distribution Plot - North Fayette TWP (Loc22)



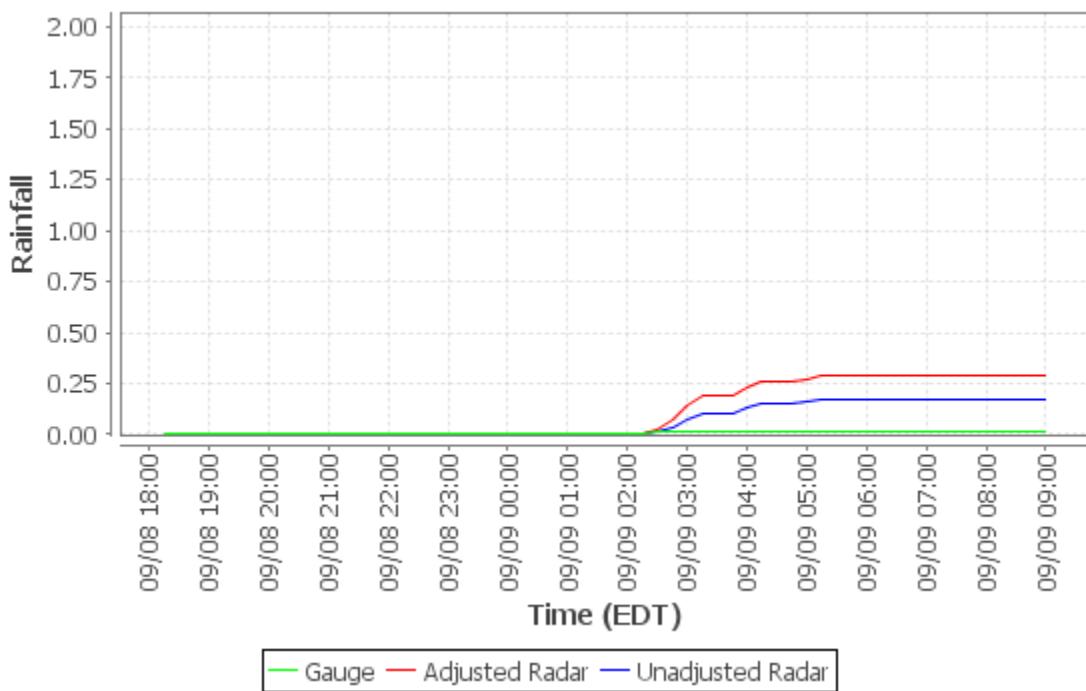
### Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



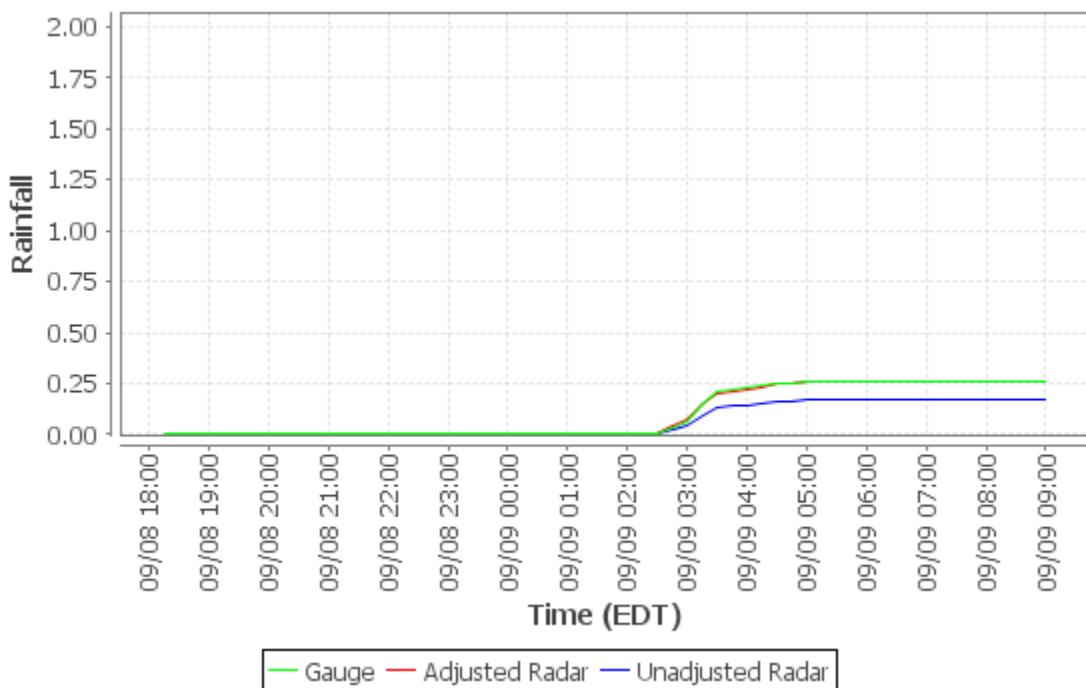
### Cumulative Distribution Plot - Jefferson Hills (Loc24)



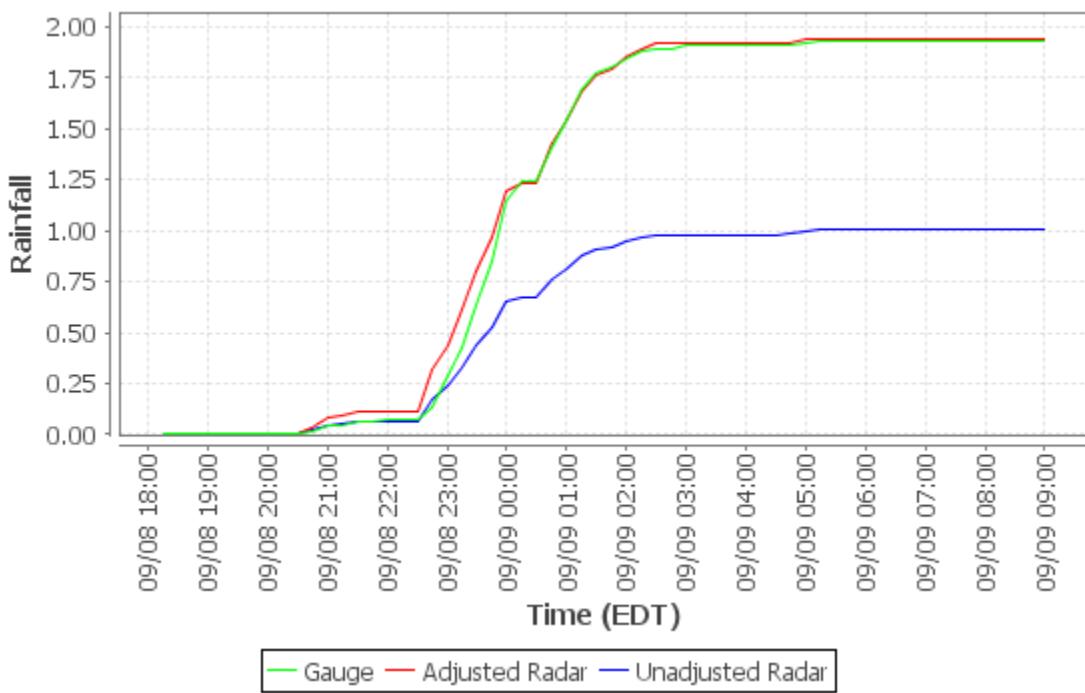
### Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



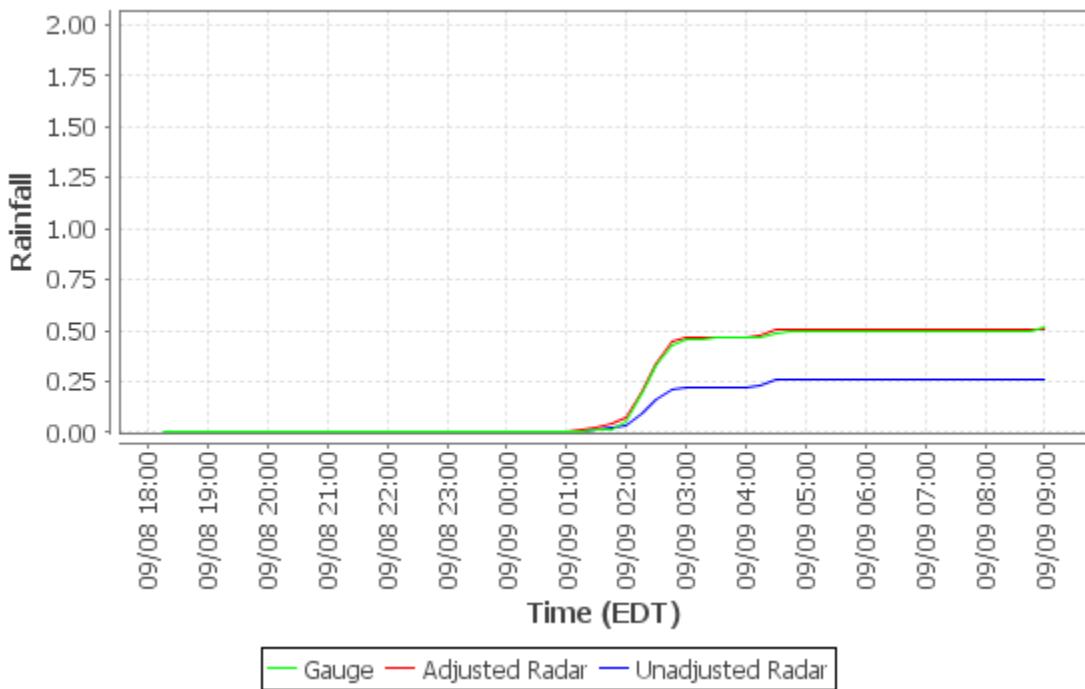
### Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



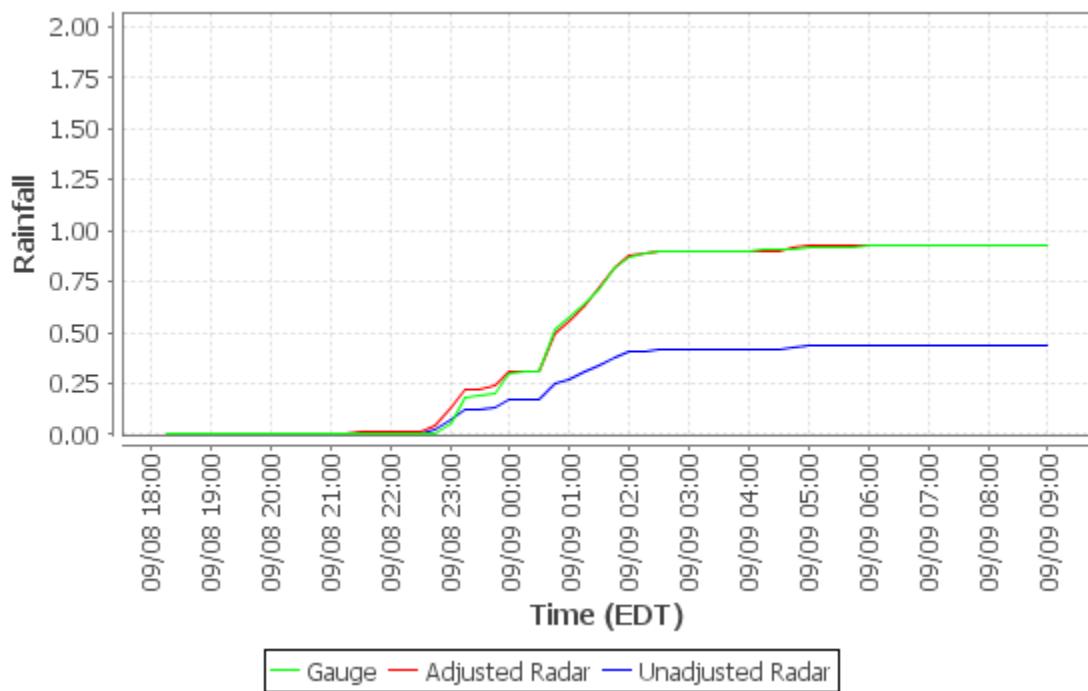
### Cumulative Distribution Plot - Marshall TWP (Loc27)



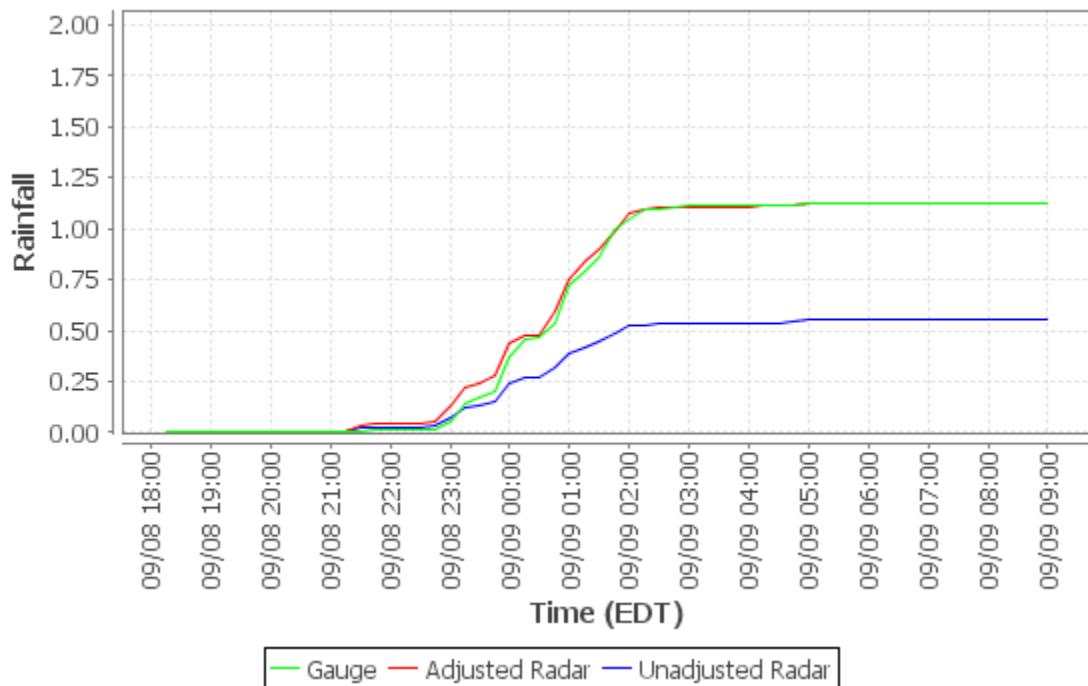
### Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



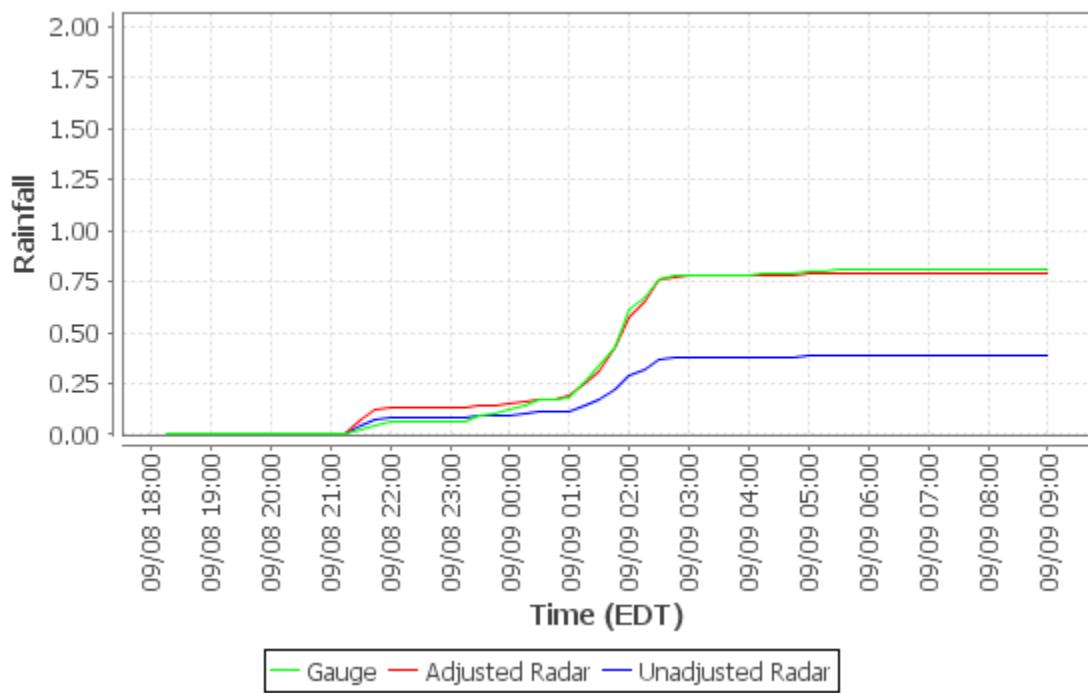
### Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



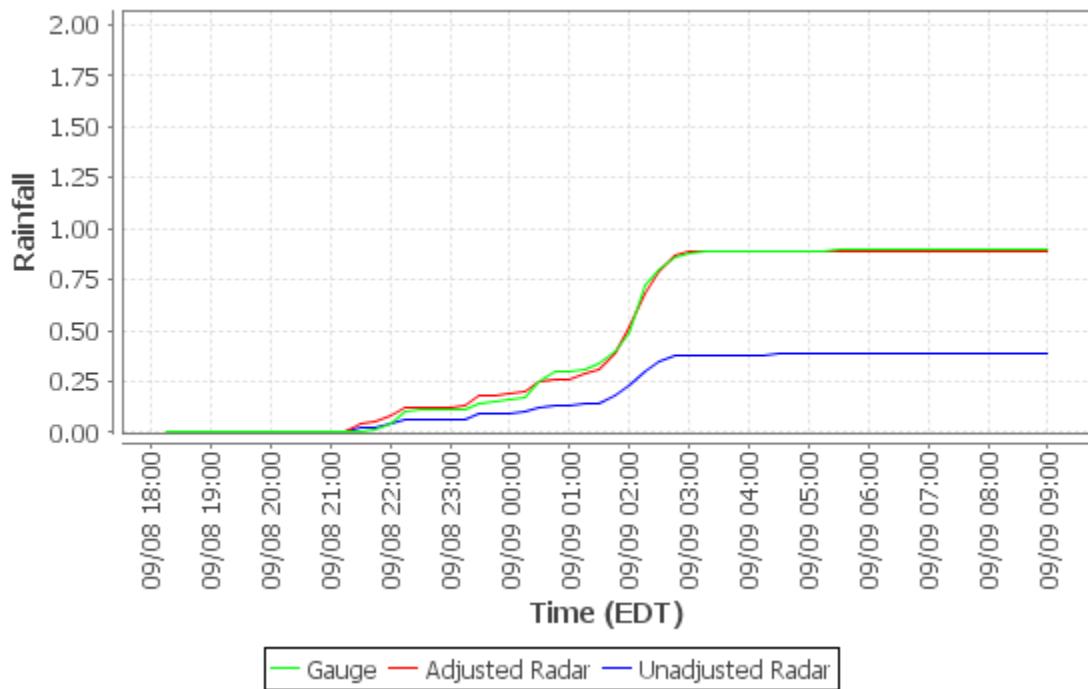
### Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



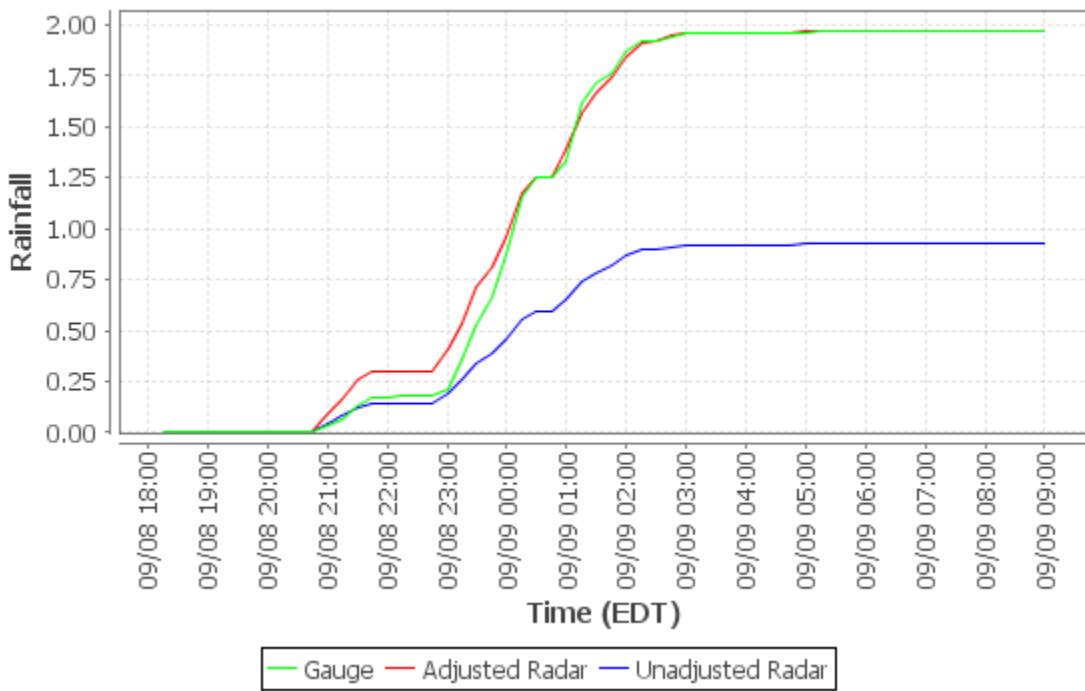
### Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



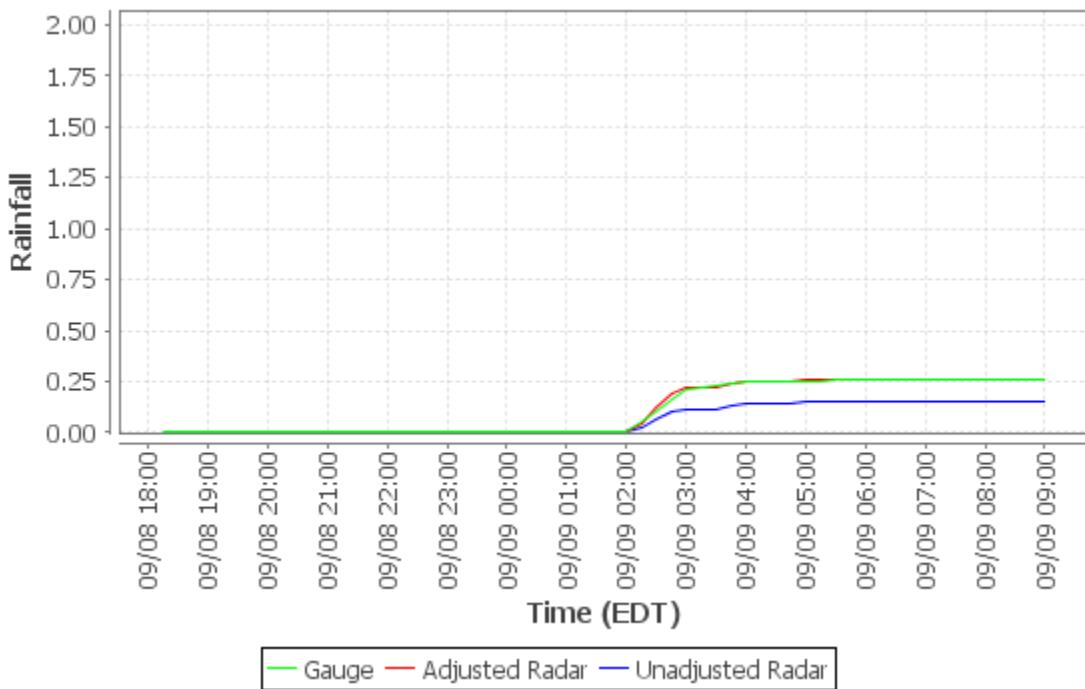
### Cumulative Distribution Plot - Arnold (Loc32)



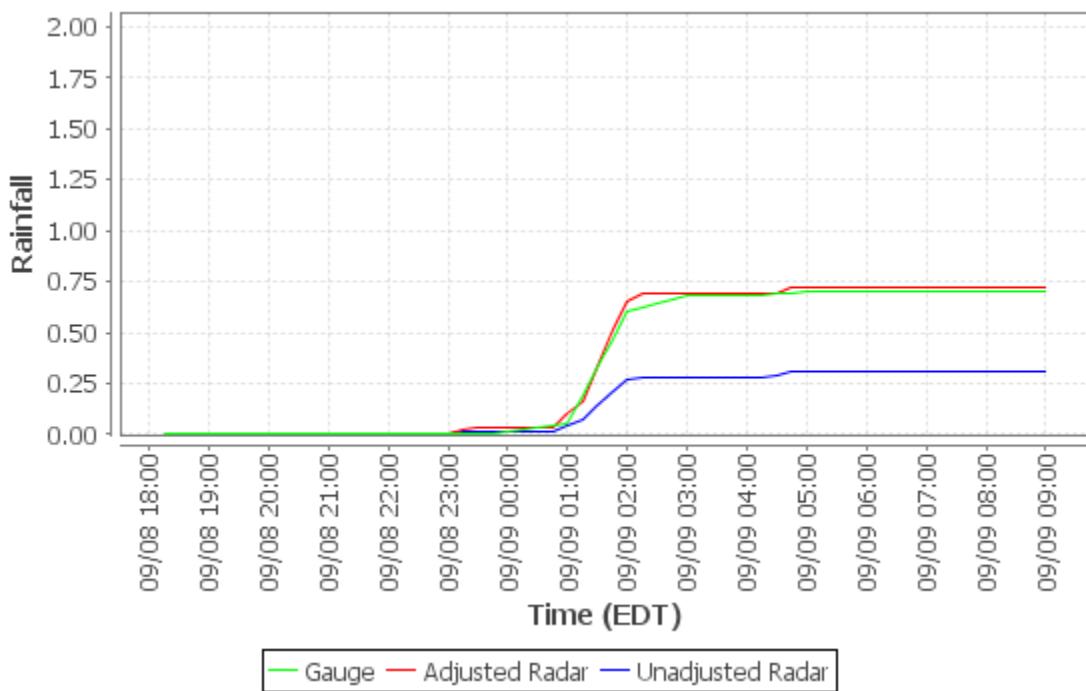
### Cumulative Distribution Plot - Richland TWP (Loc33)



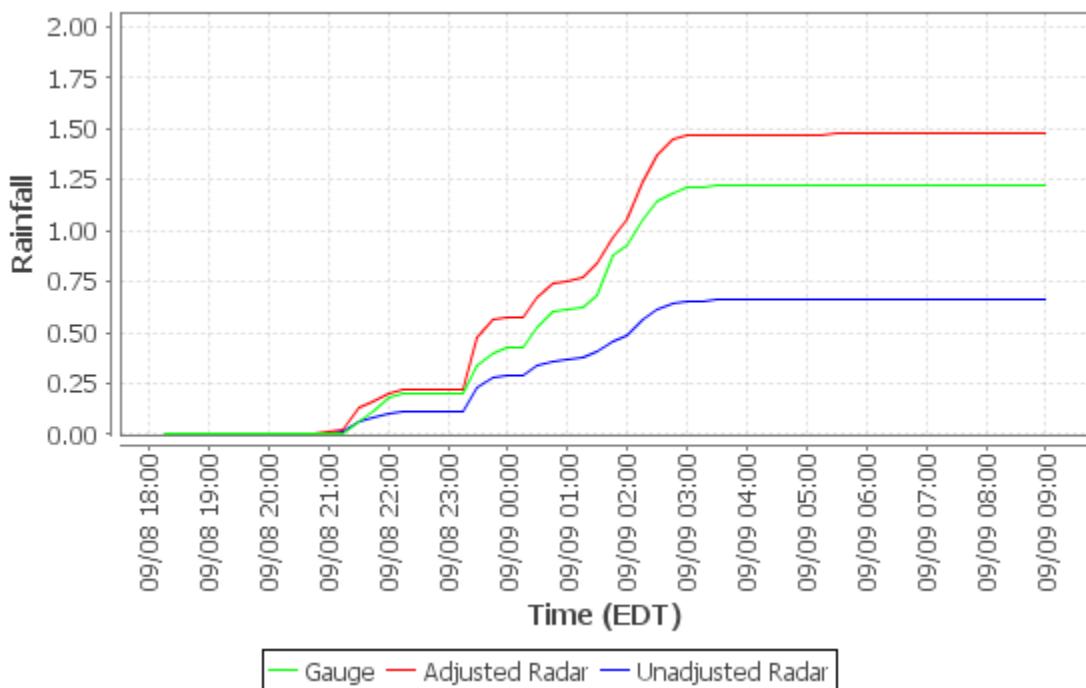
### Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



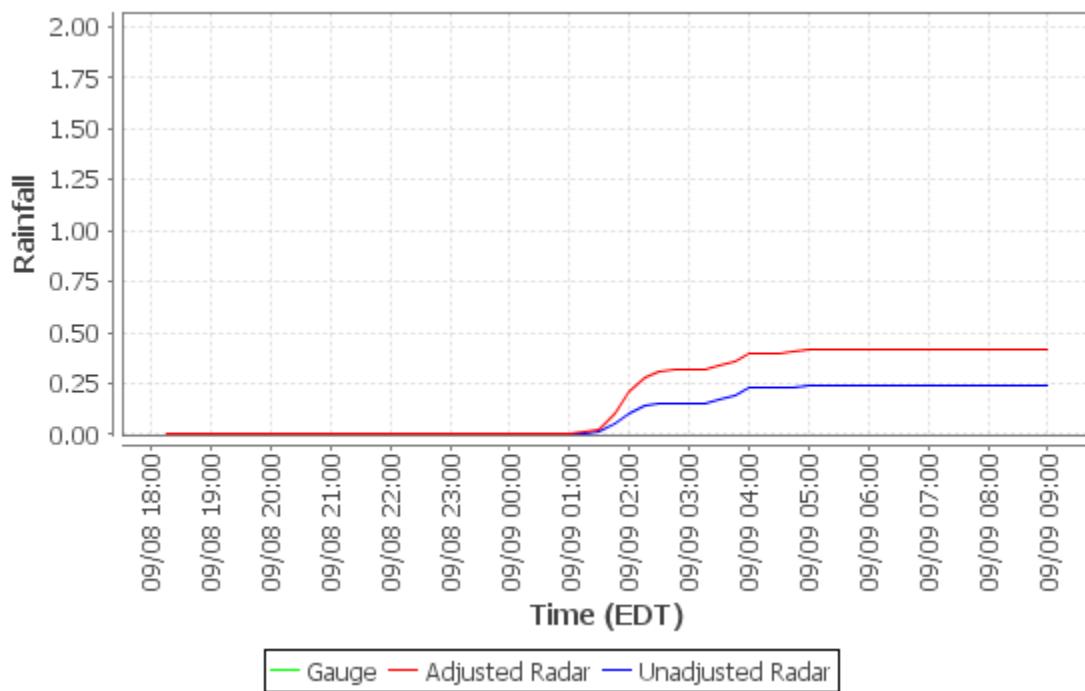
### Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



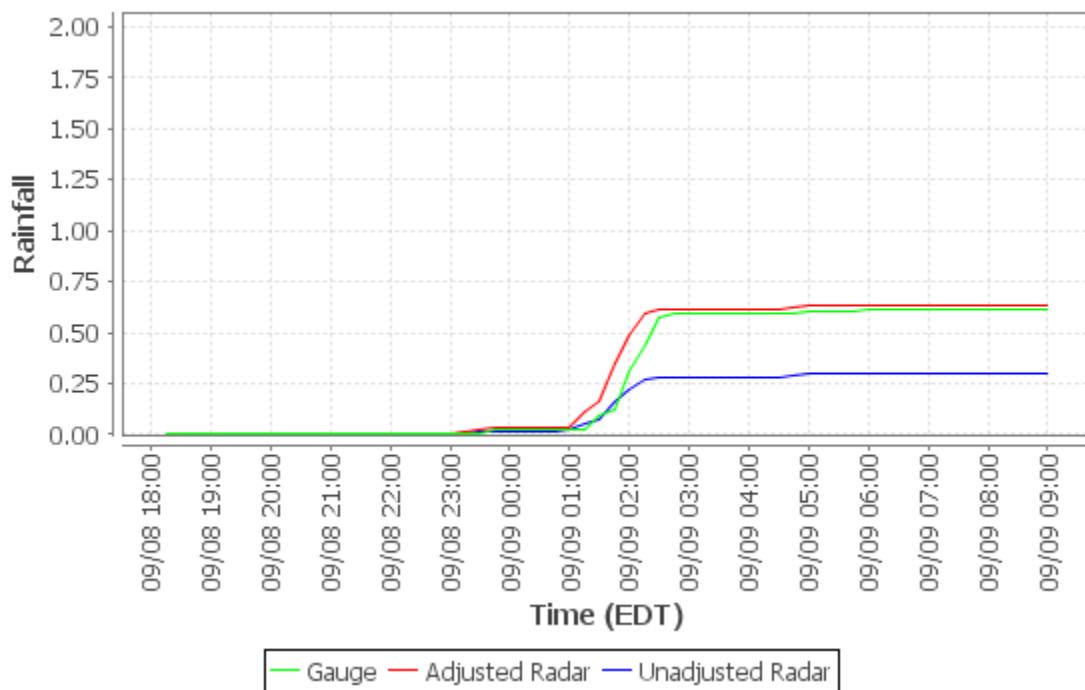
### Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



### Cumulative Distribution Plot - Chartiers Creek at Carnegie (03085500)

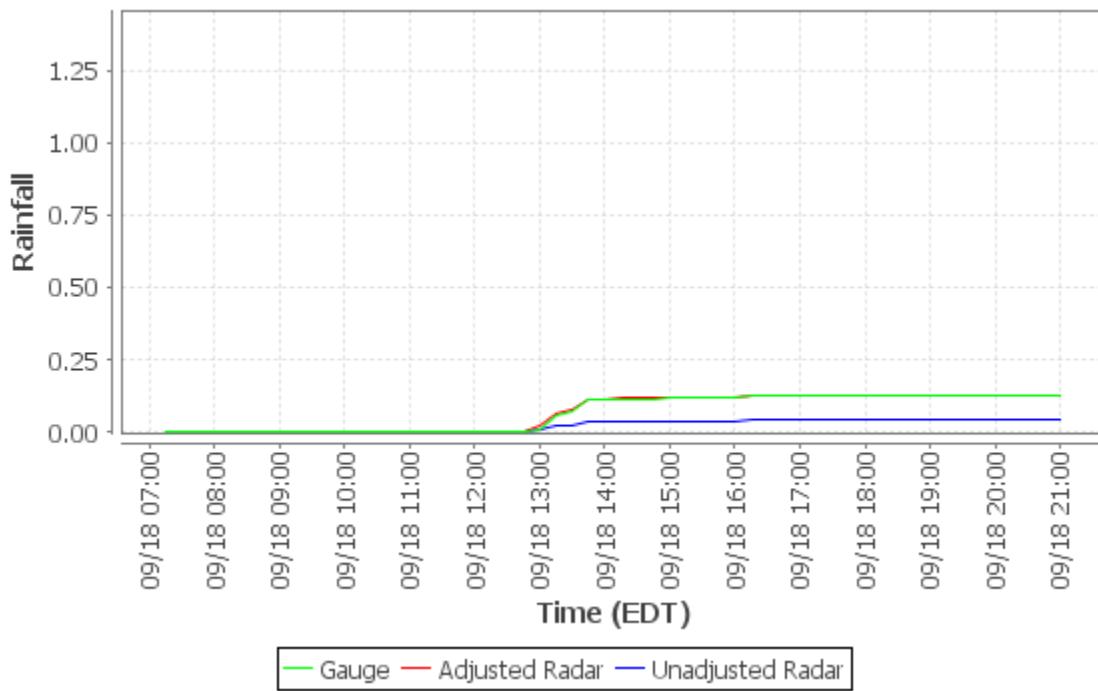


### Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

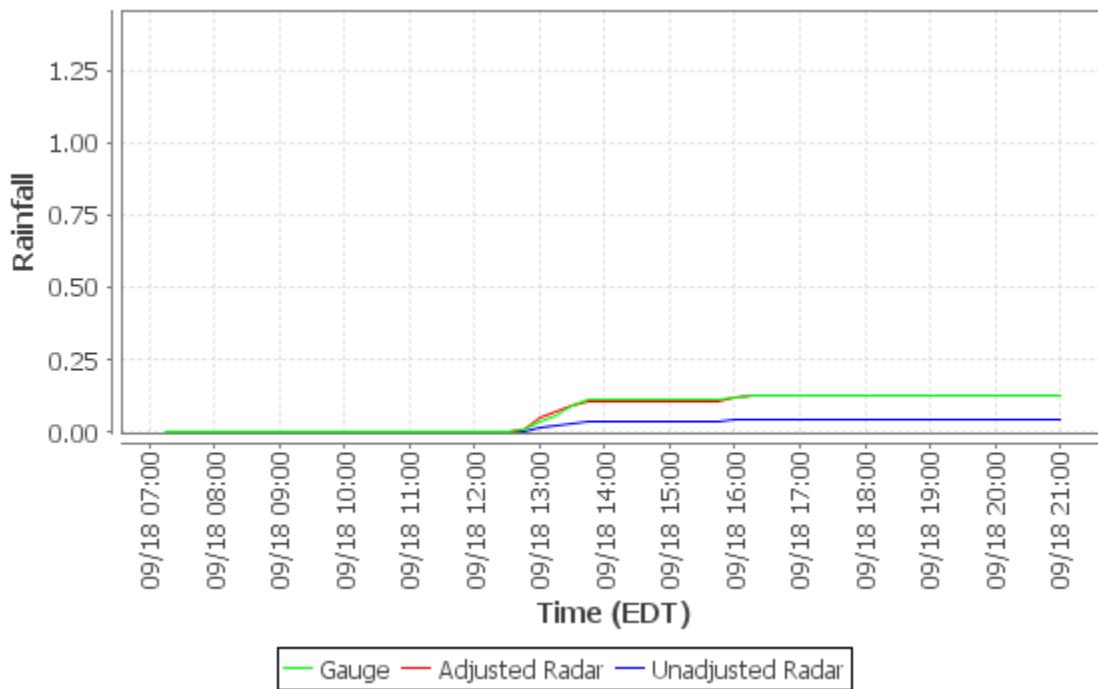


## **Appendix C - Event 2 (2016-09-18) CDPs**

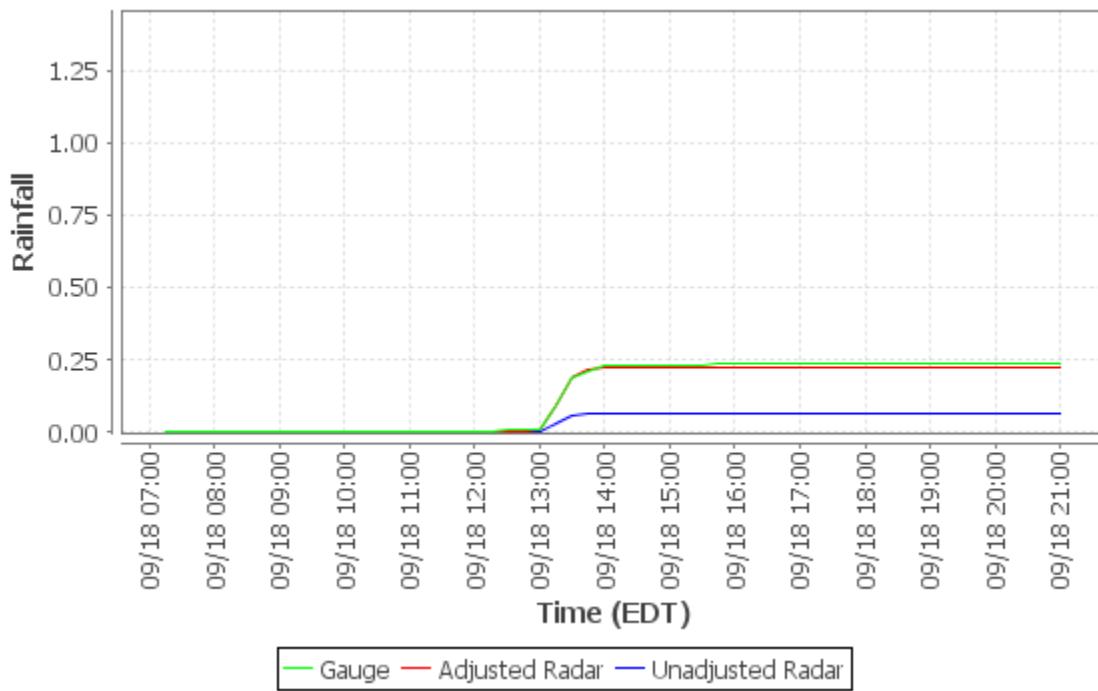
### Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



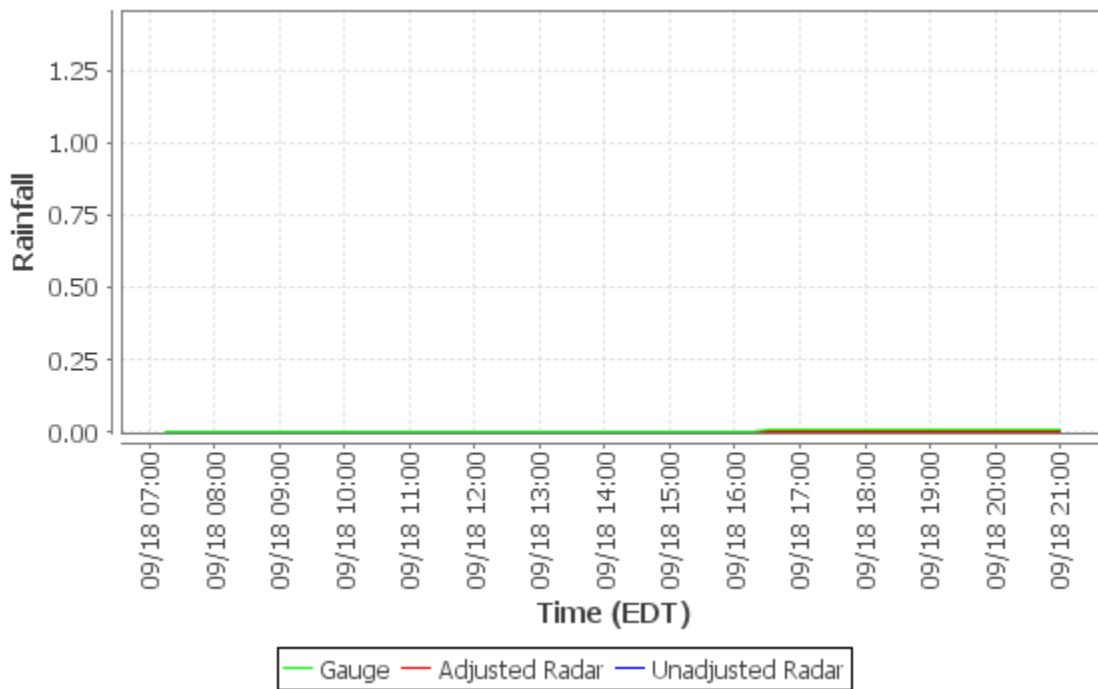
### Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



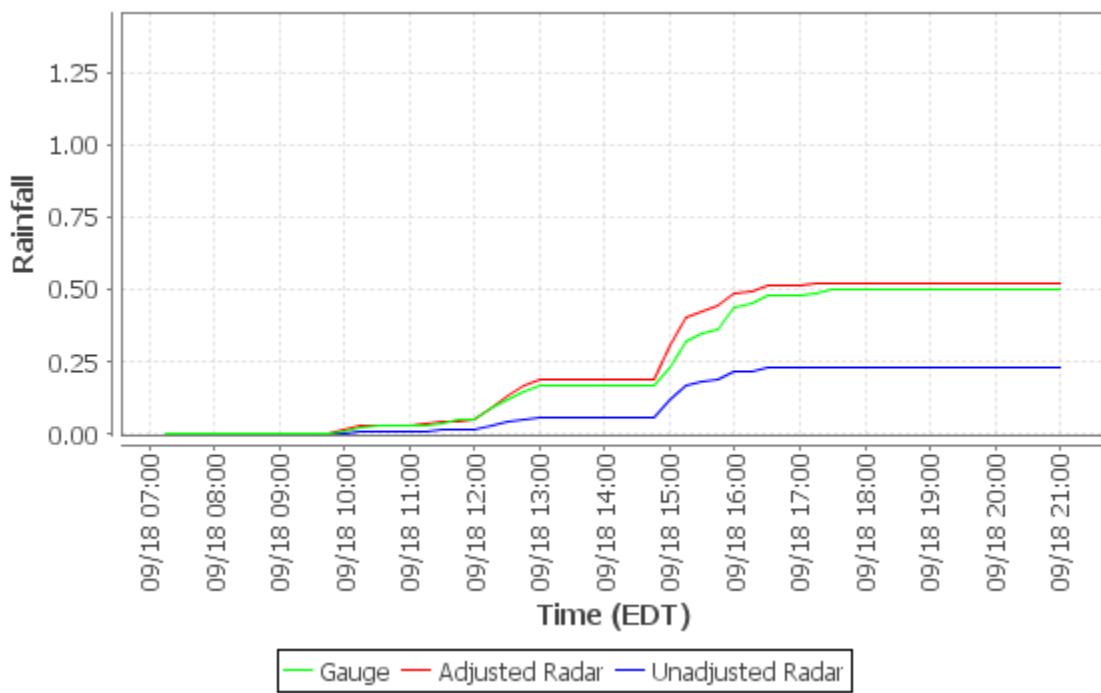
**Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)**



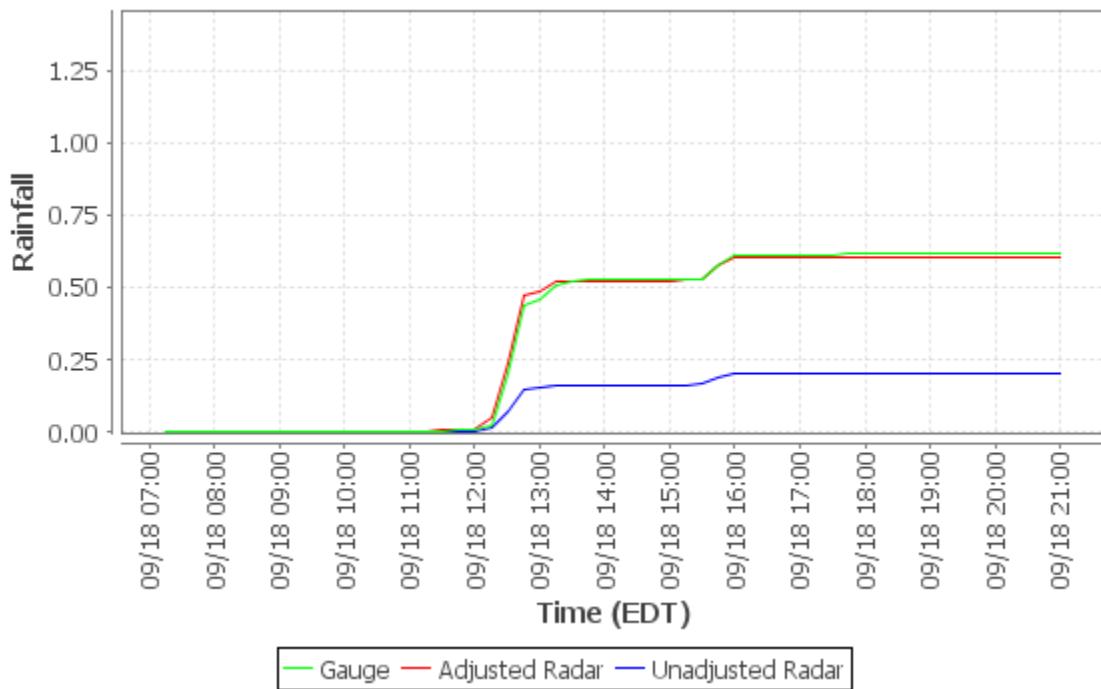
**Cumulative Distribution Plot - Kennedy Twp PS (Loc04)**



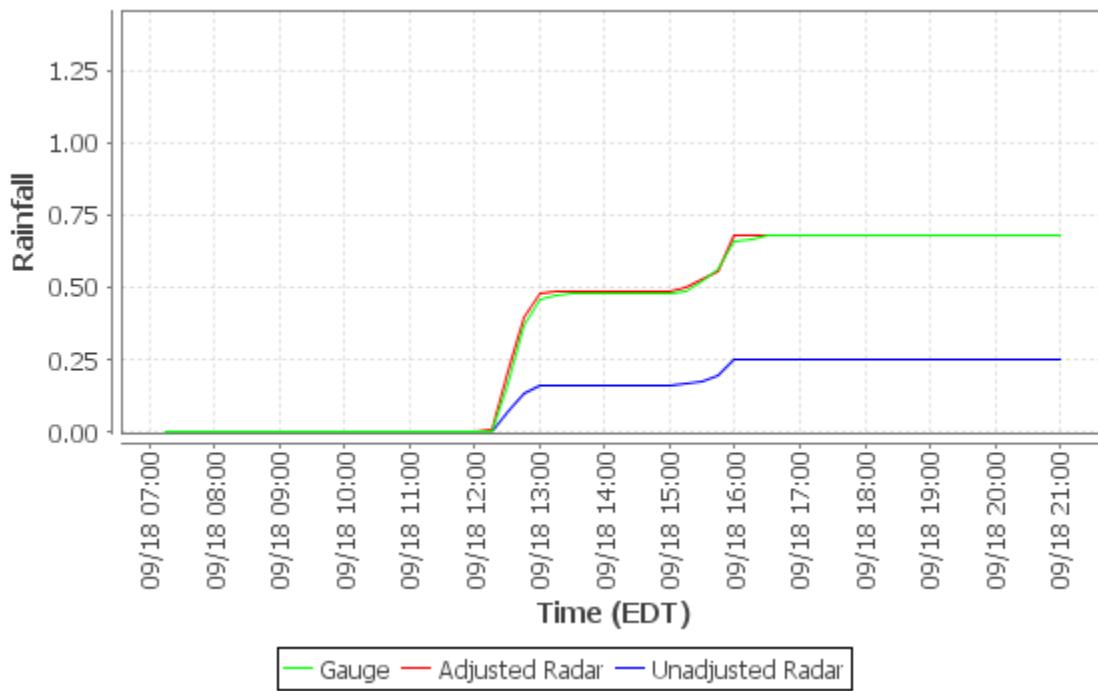
### Cumulative Distribution Plot - Upper St. Clair (Loc05)



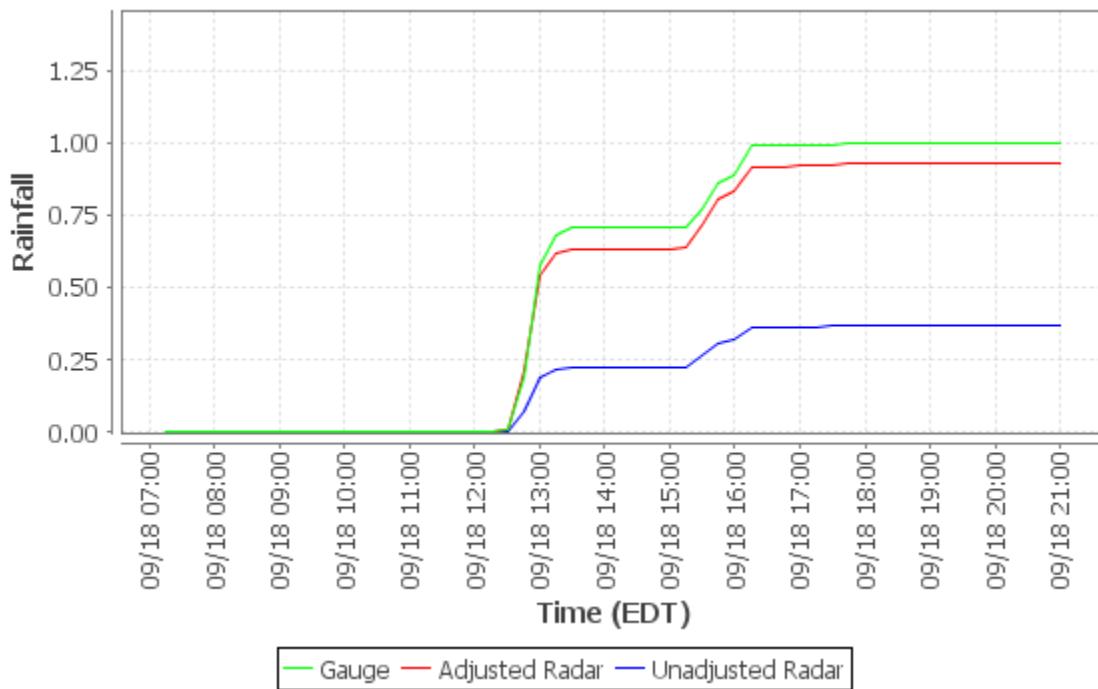
### Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



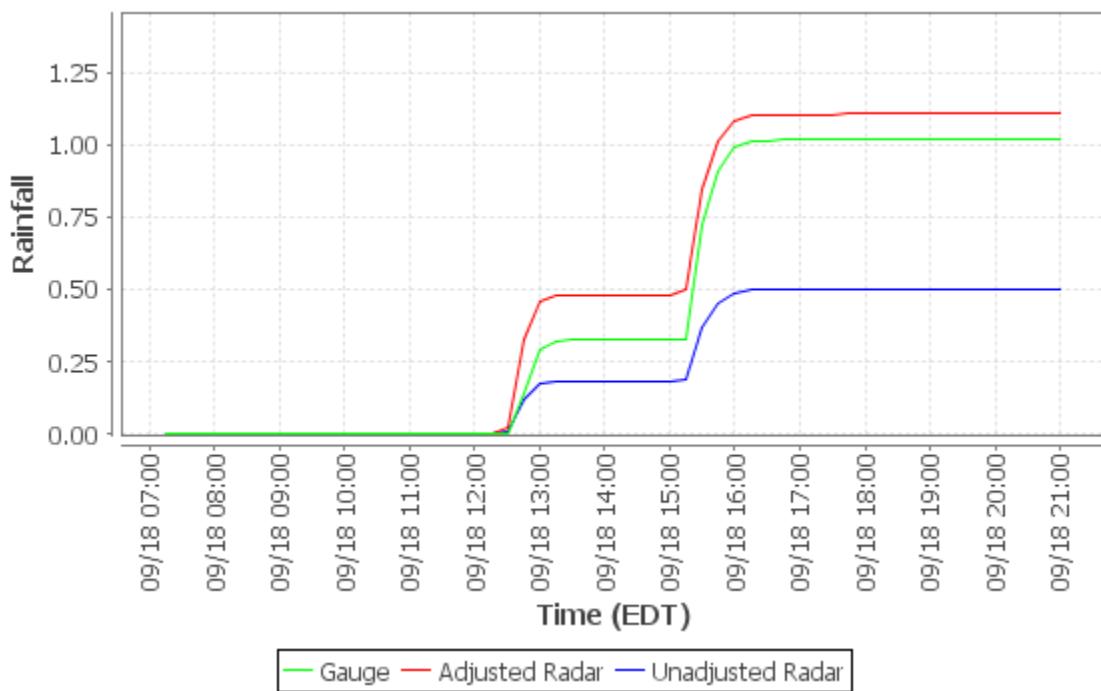
### Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



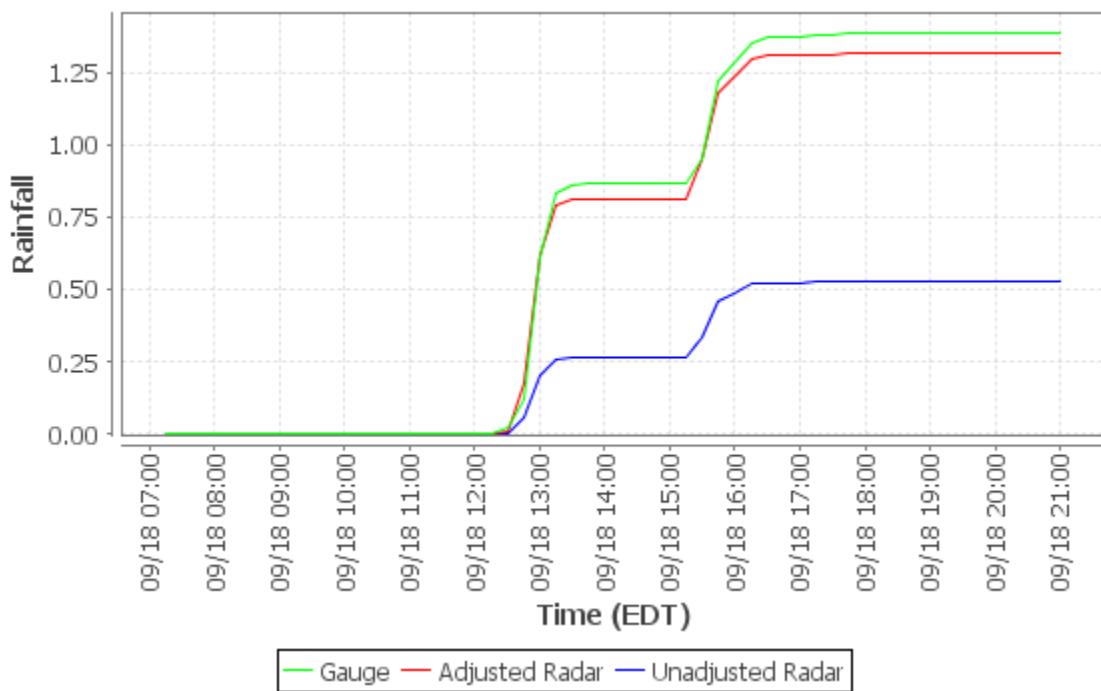
### Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



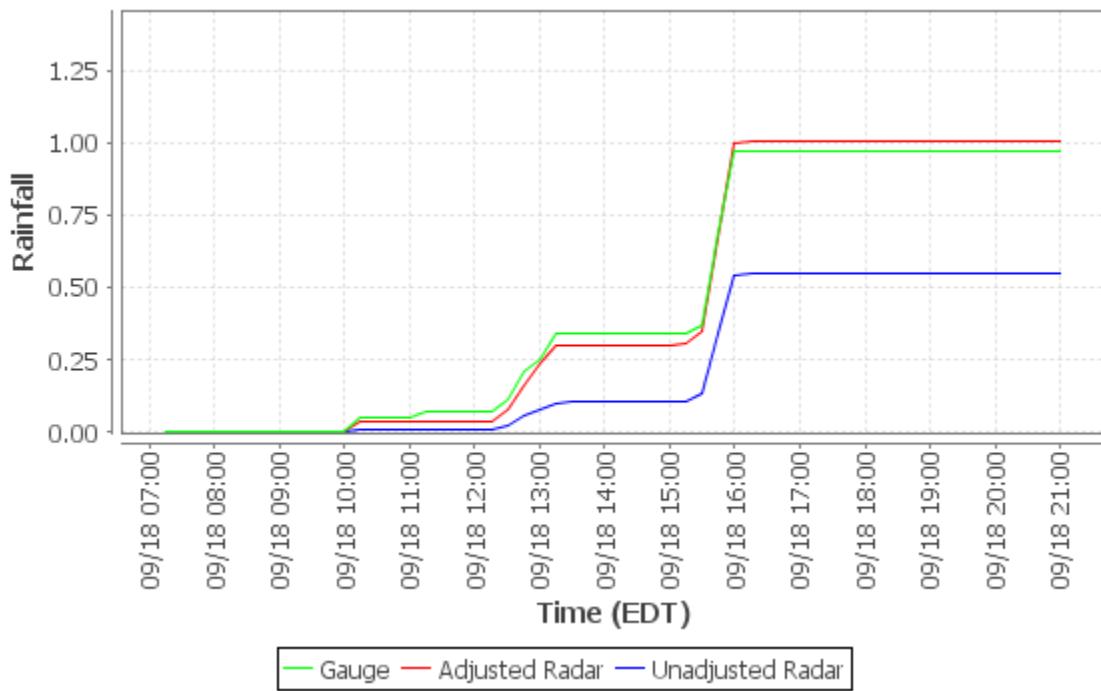
### Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



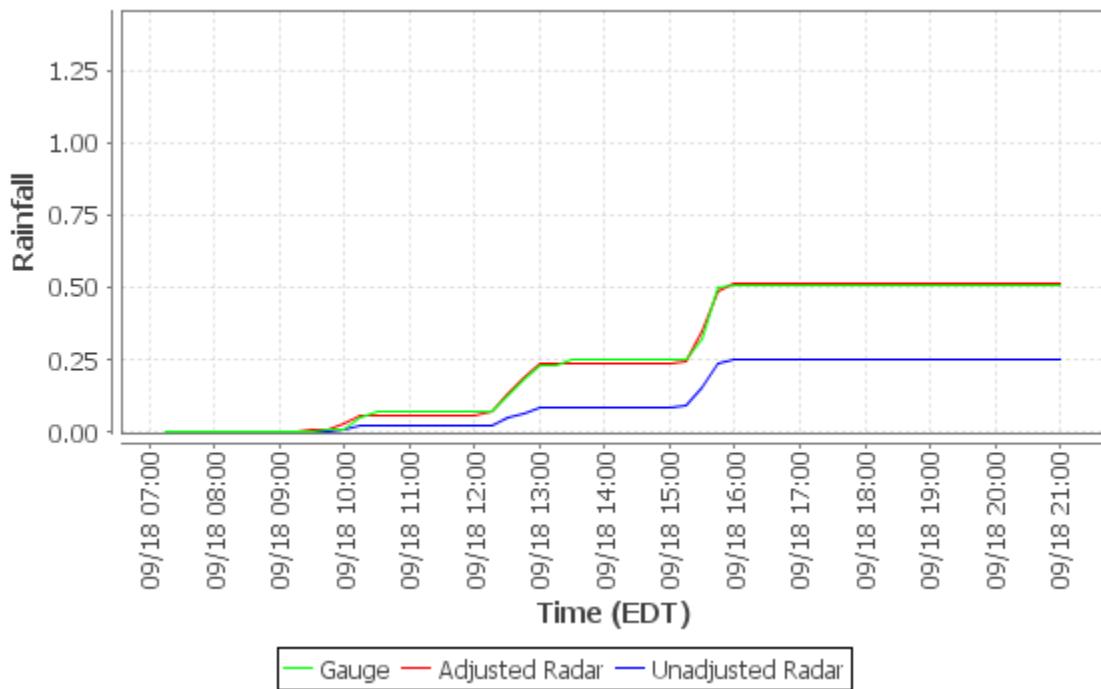
### Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



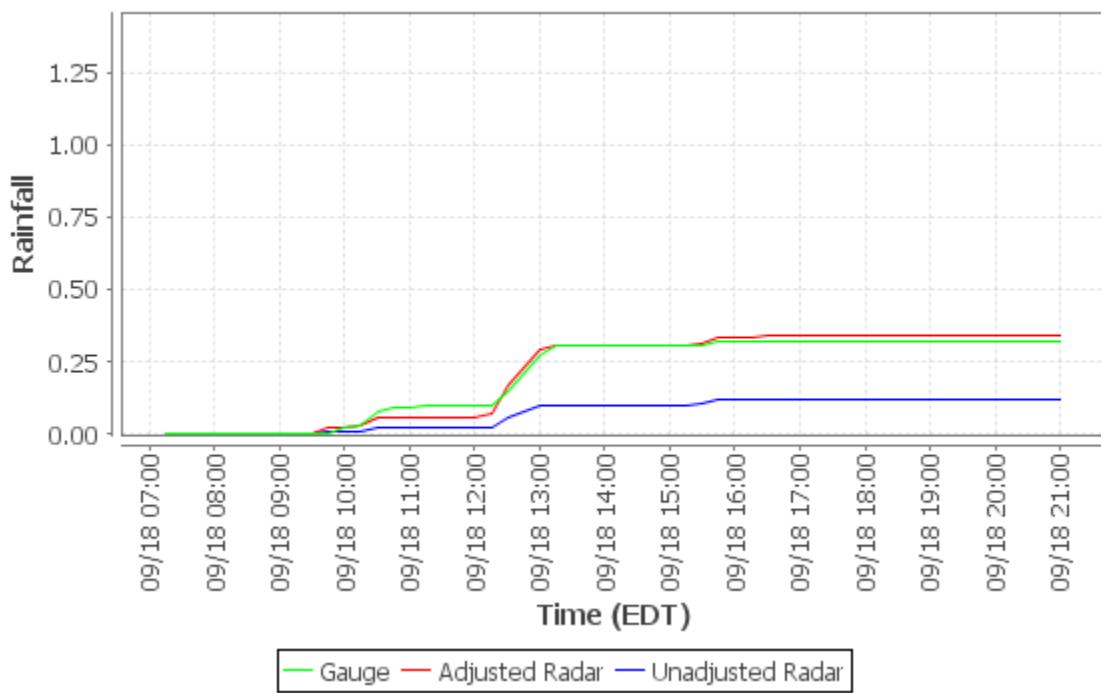
### Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



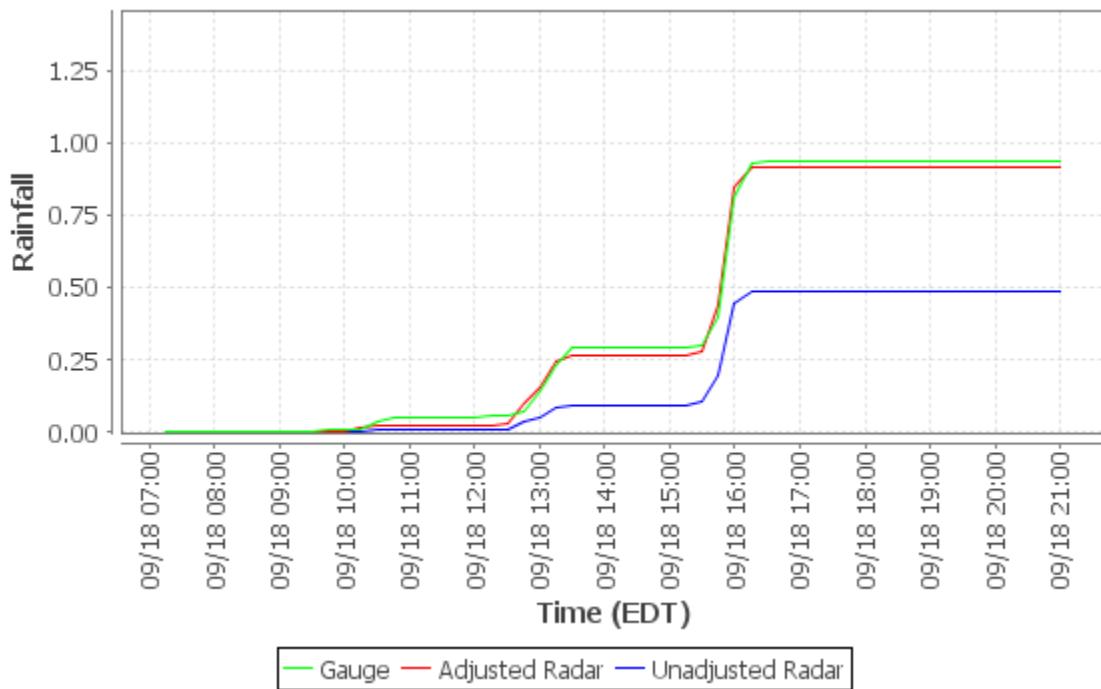
### Cumulative Distribution Plot - Baldwin (Loc12)



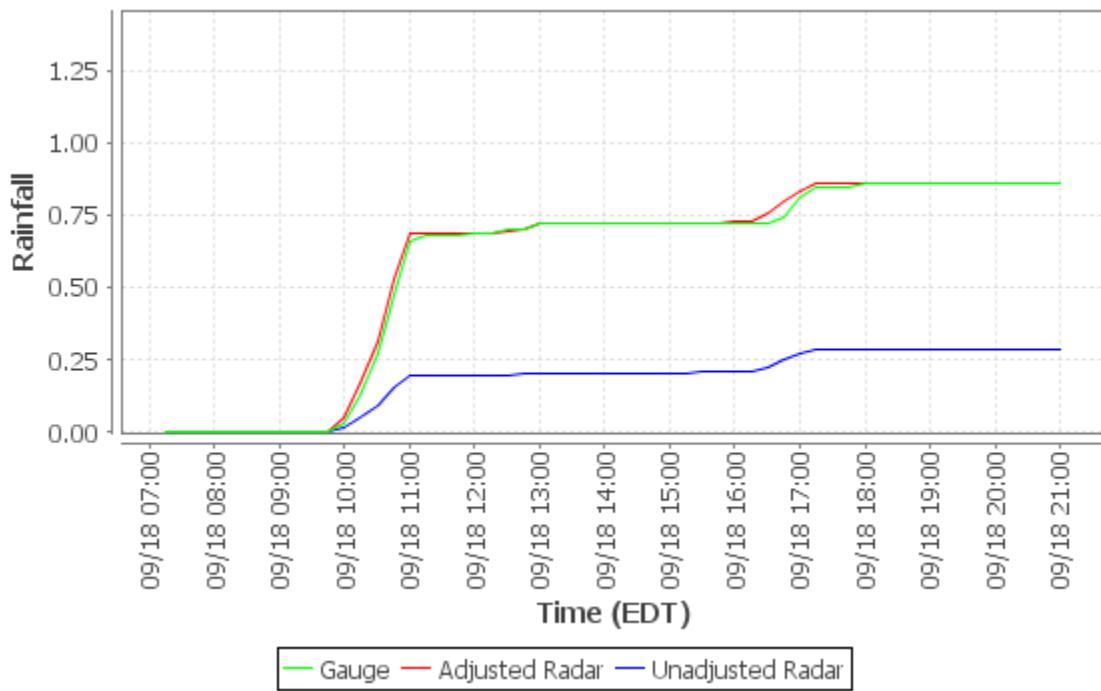
### Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



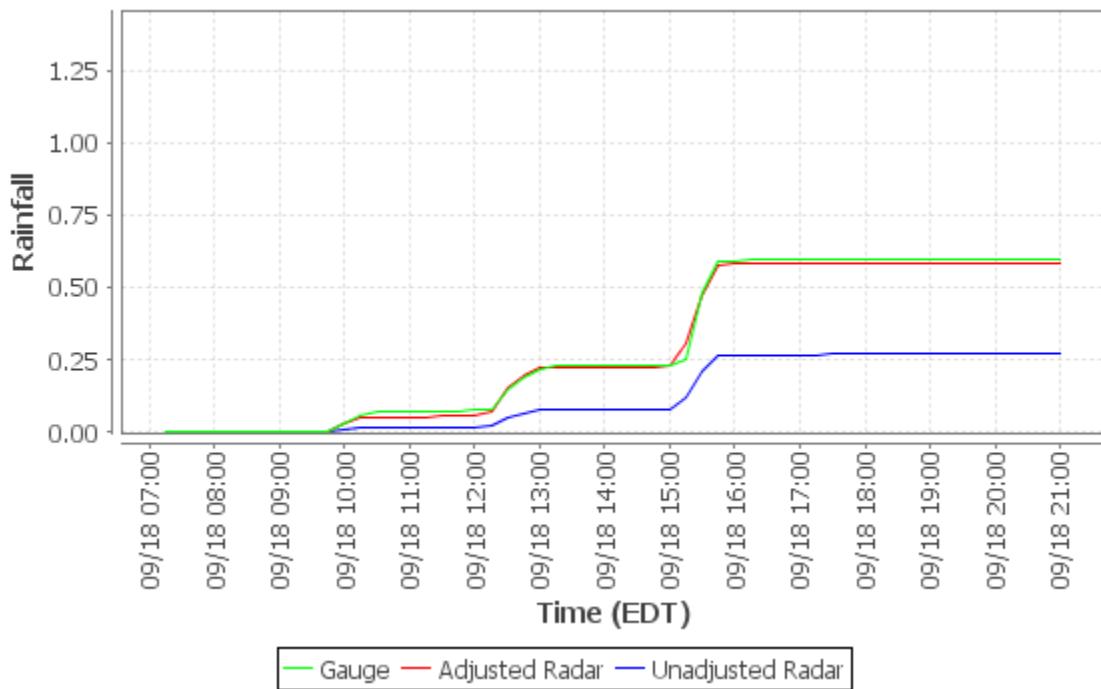
### Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



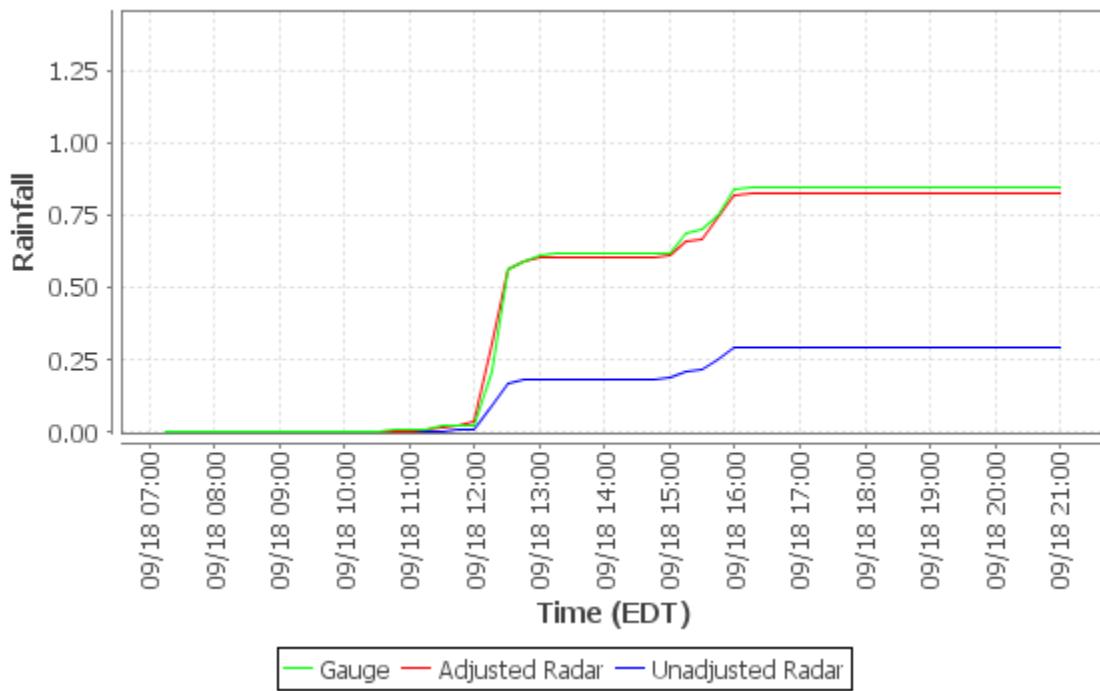
**Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)**



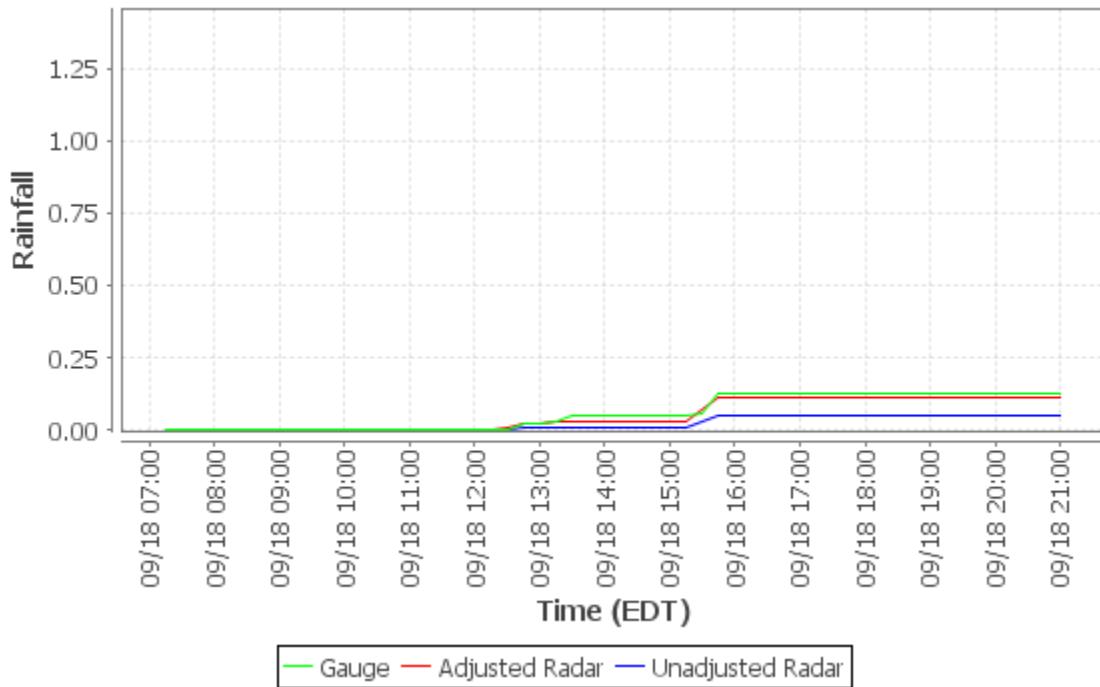
**Cumulative Distribution Plot - Castle Shannon (Loc16)**



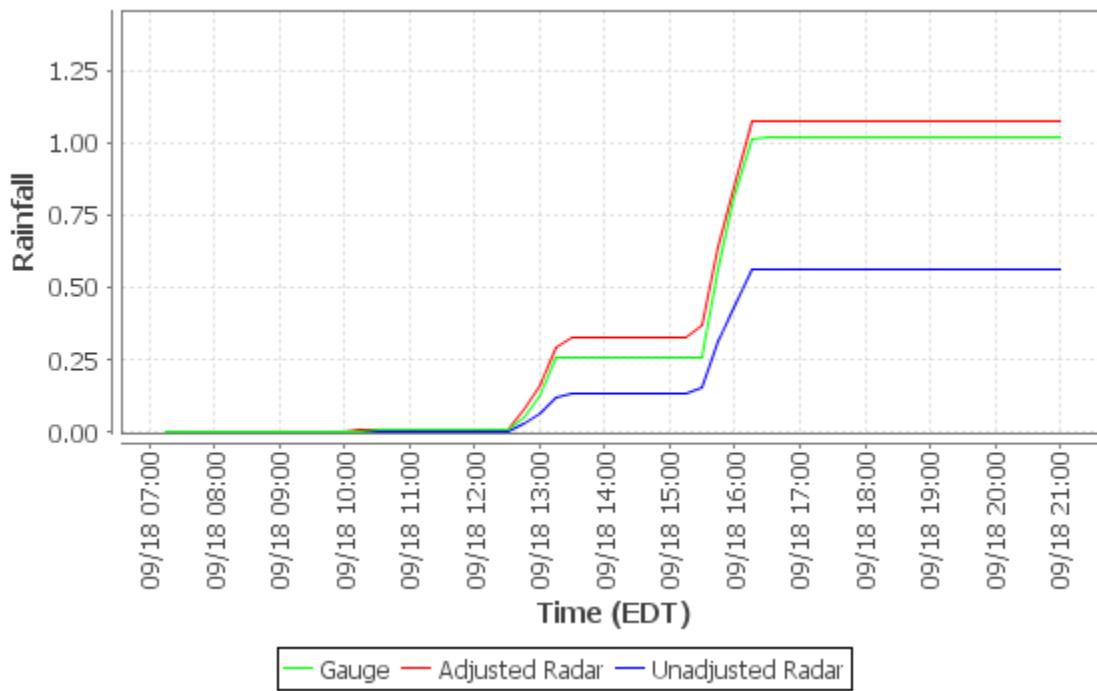
### Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



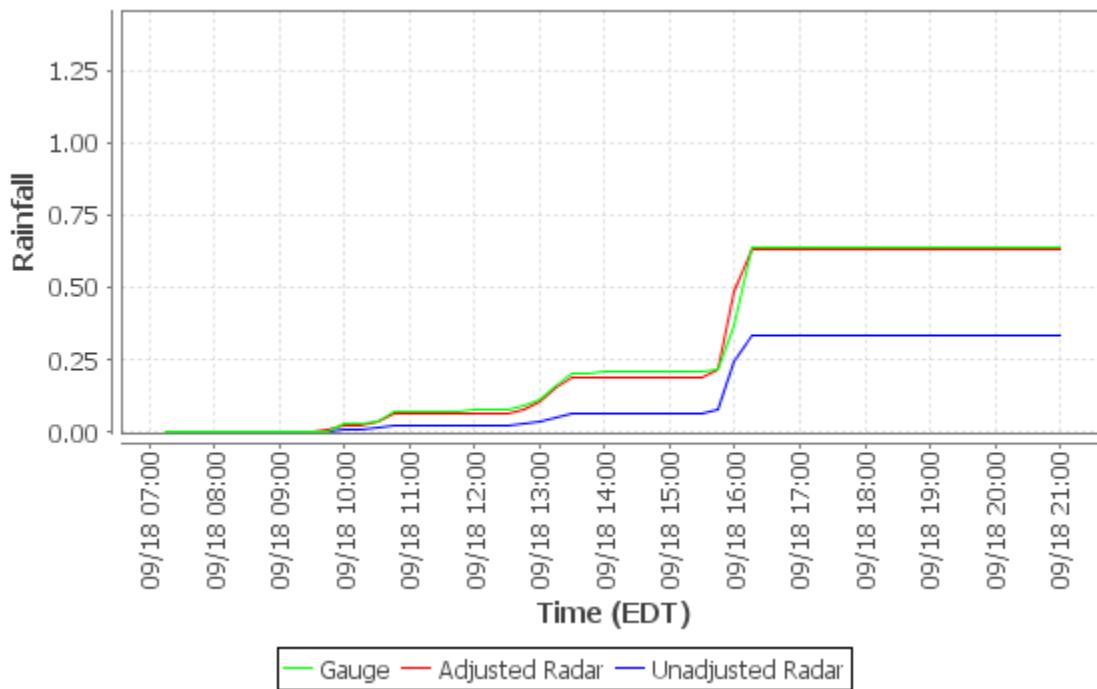
### Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



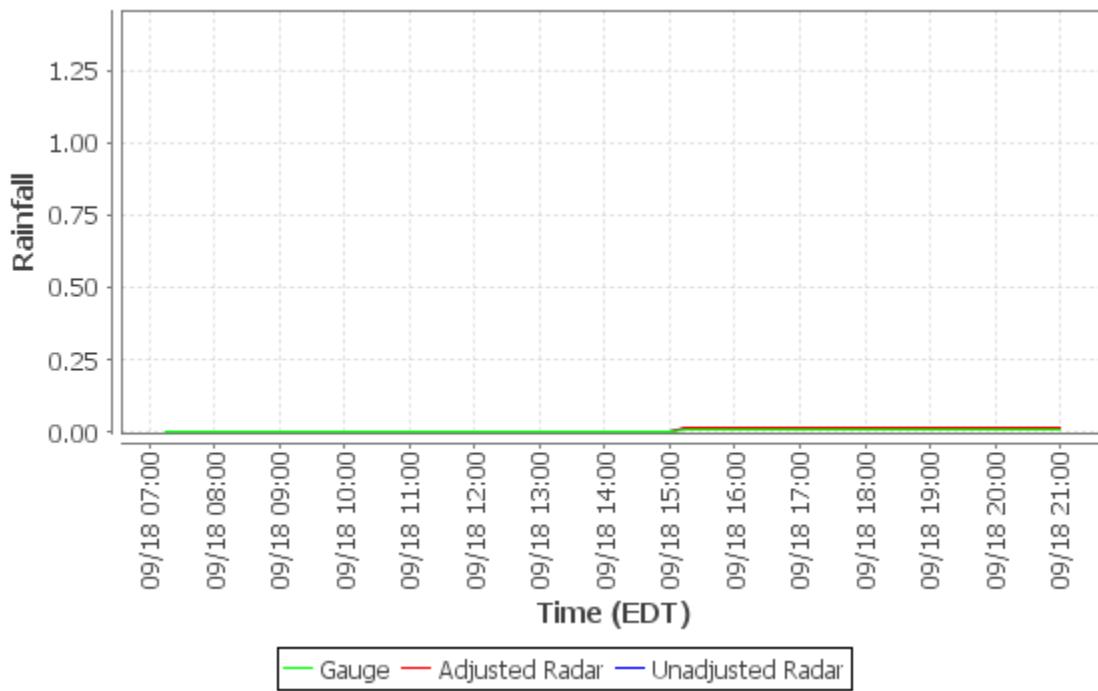
### Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



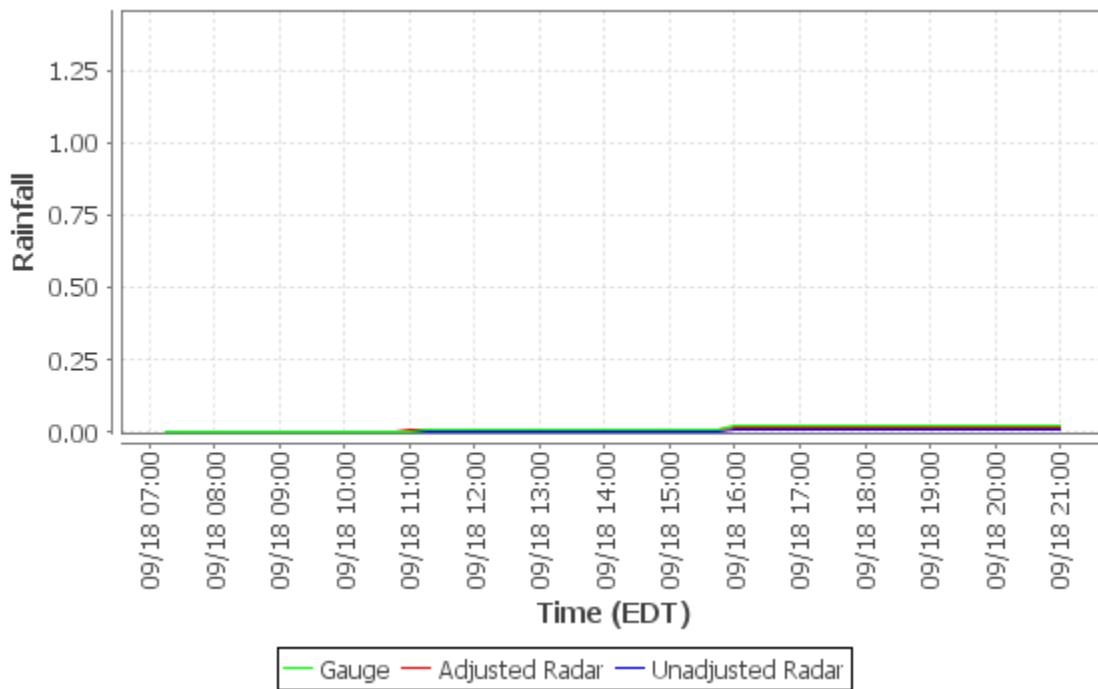
### Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



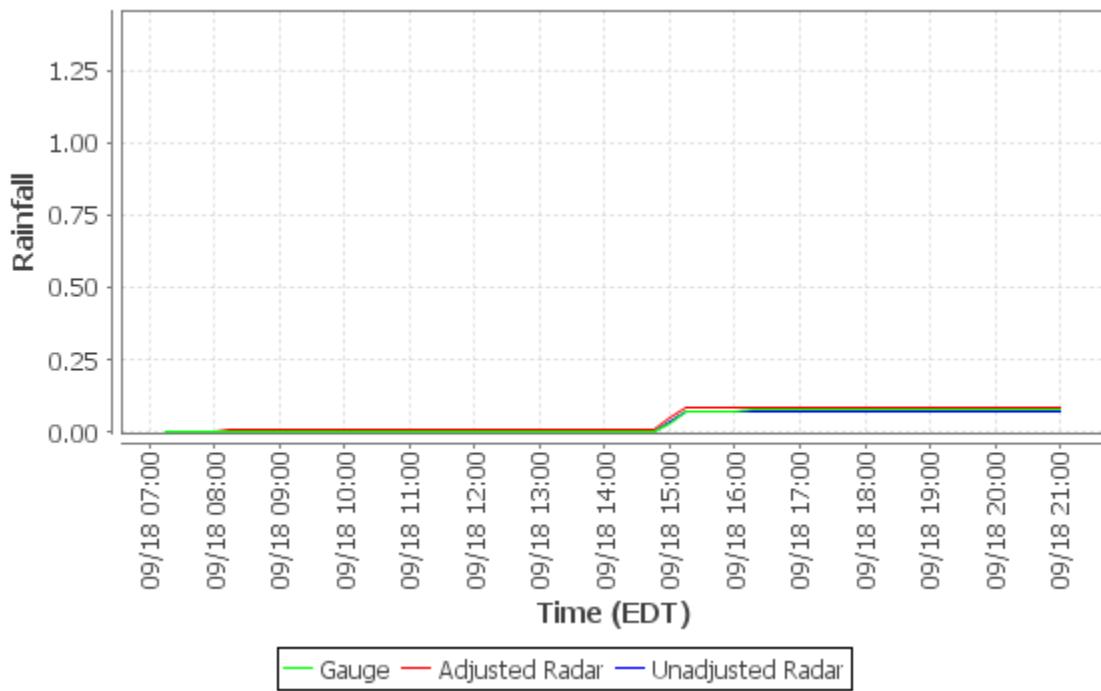
**Cumulative Distribution Plot - Moon TWP (Loc21)**



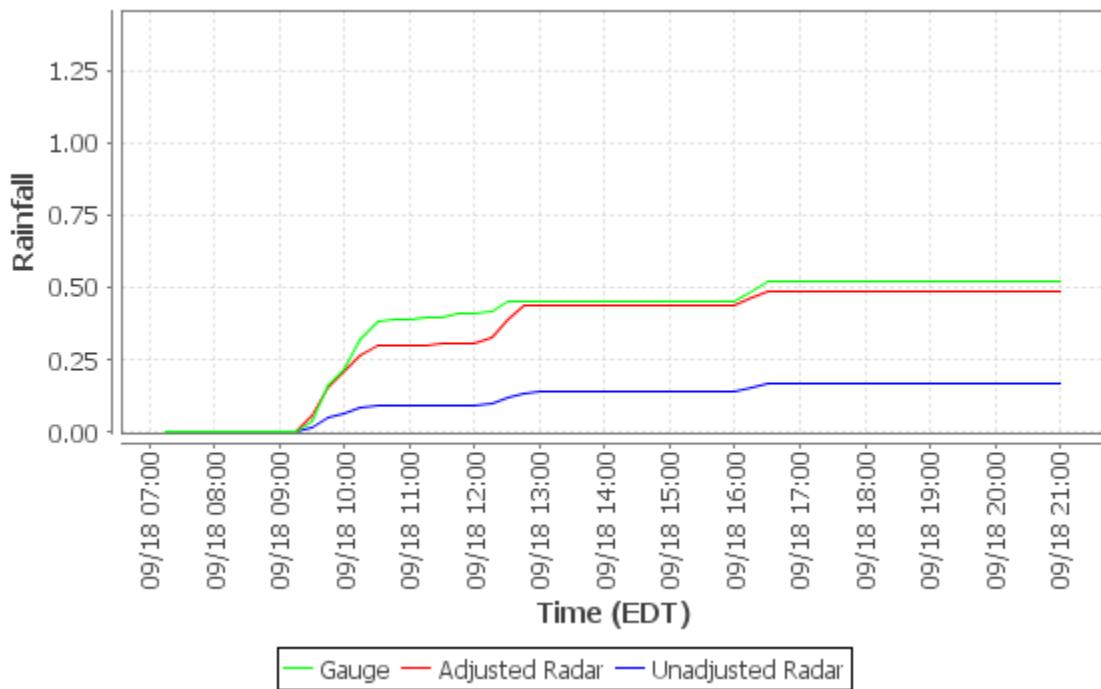
**Cumulative Distribution Plot - North Fayette TWP (Loc22)**



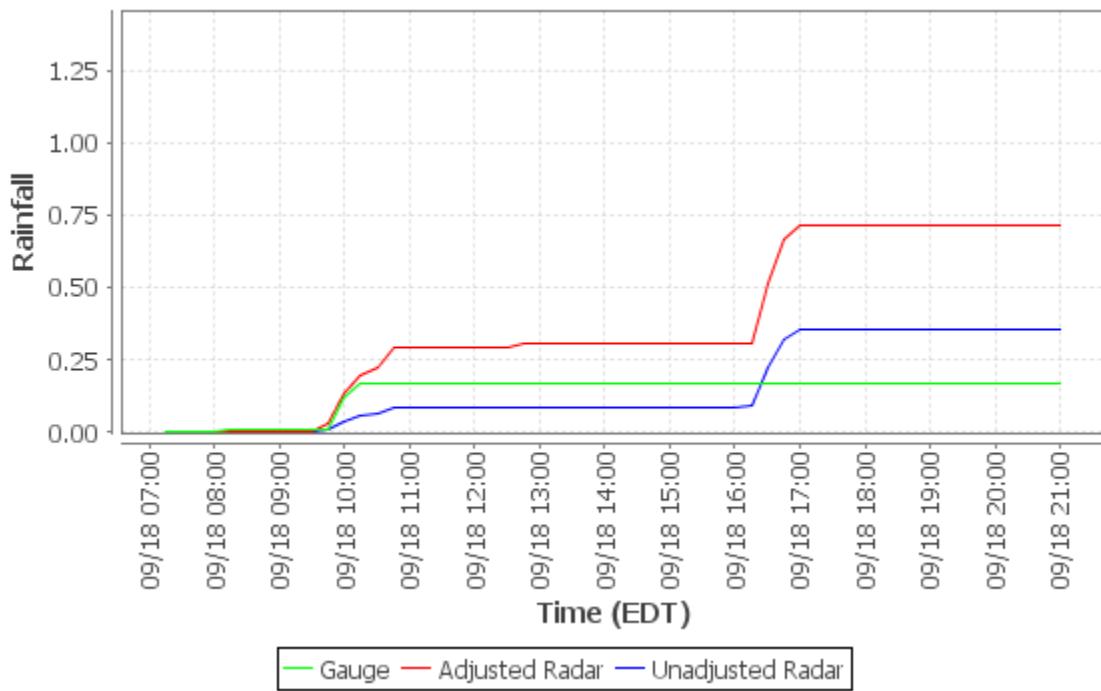
**Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)**



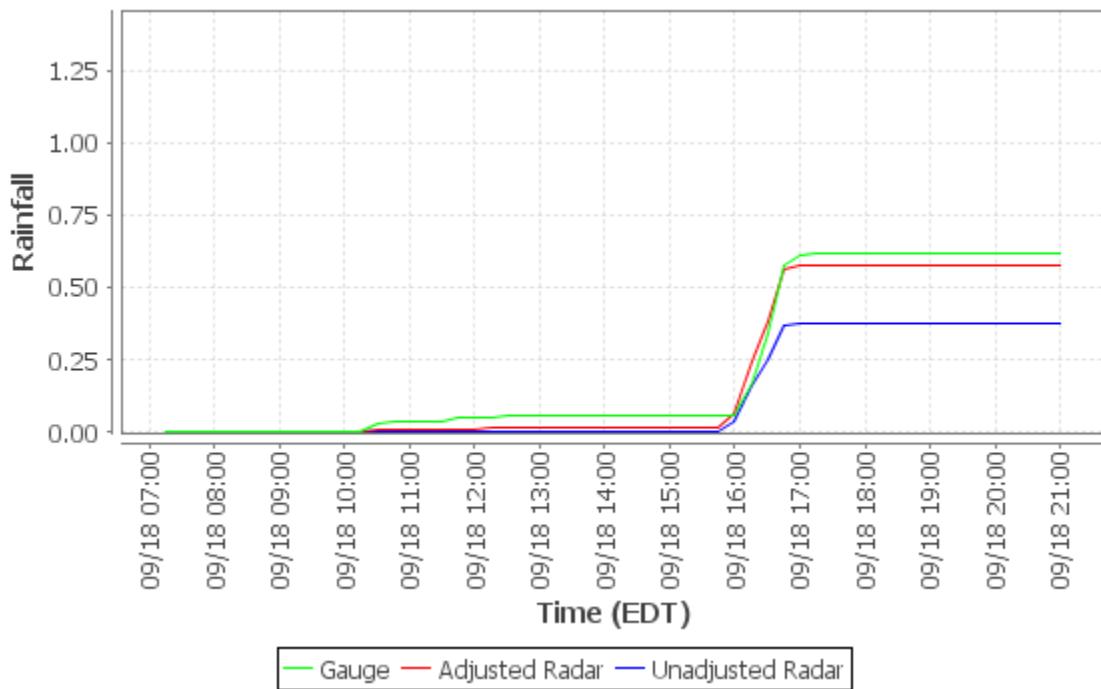
**Cumulative Distribution Plot - Jefferson Hills (Loc24)**



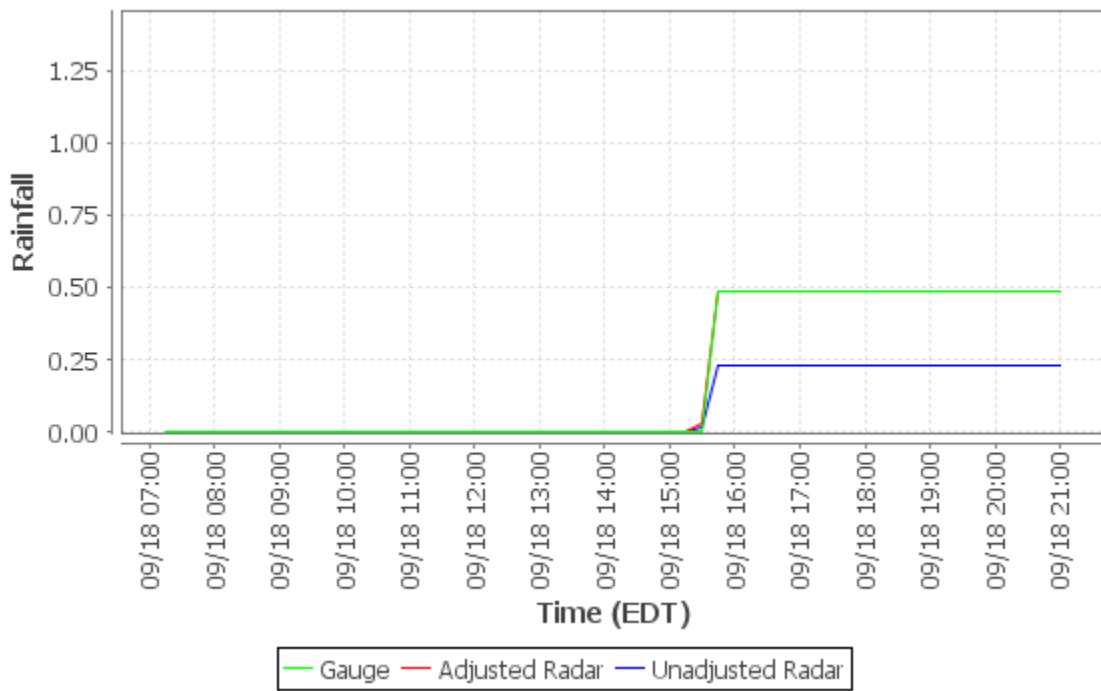
### Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



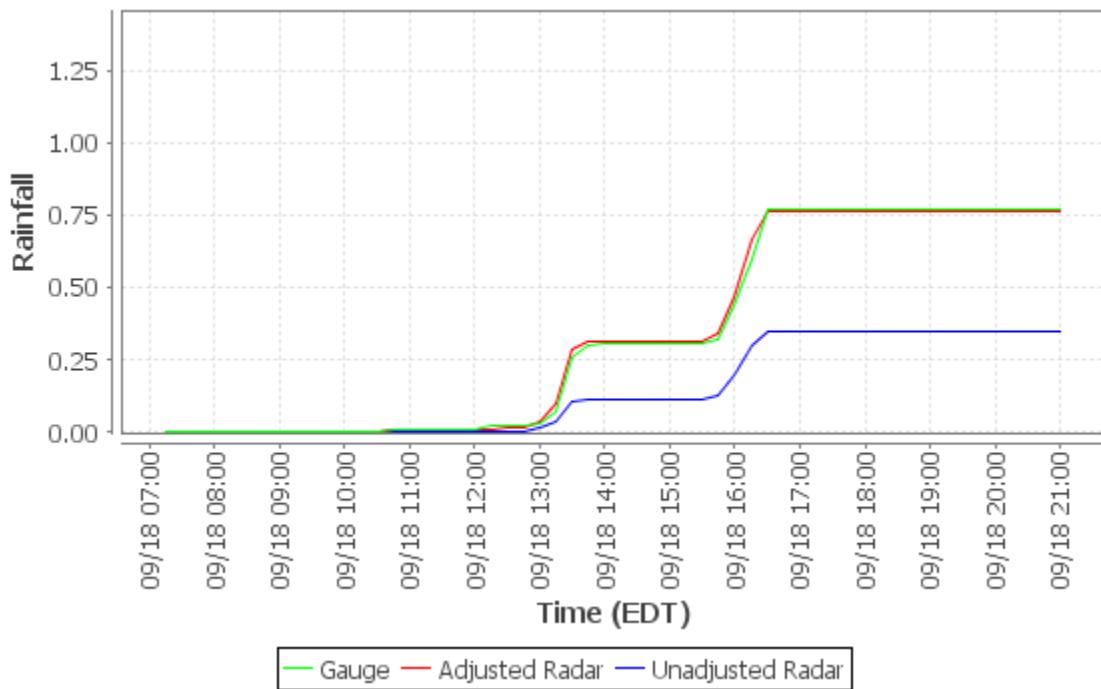
### Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



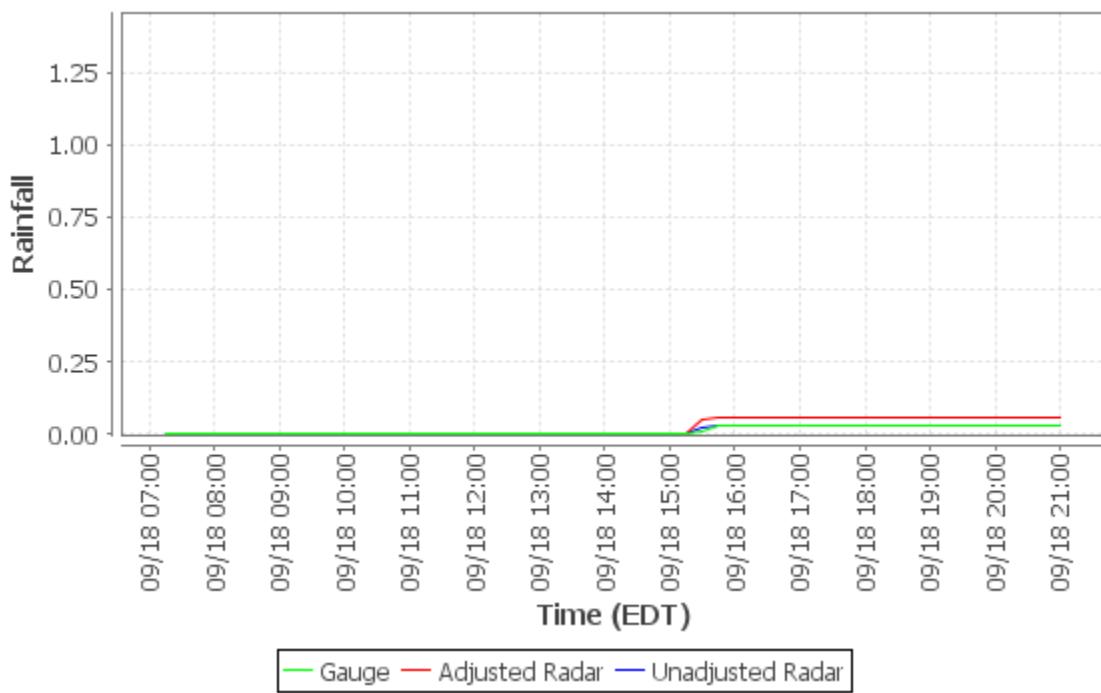
### Cumulative Distribution Plot - Marshall TWP (Loc27)



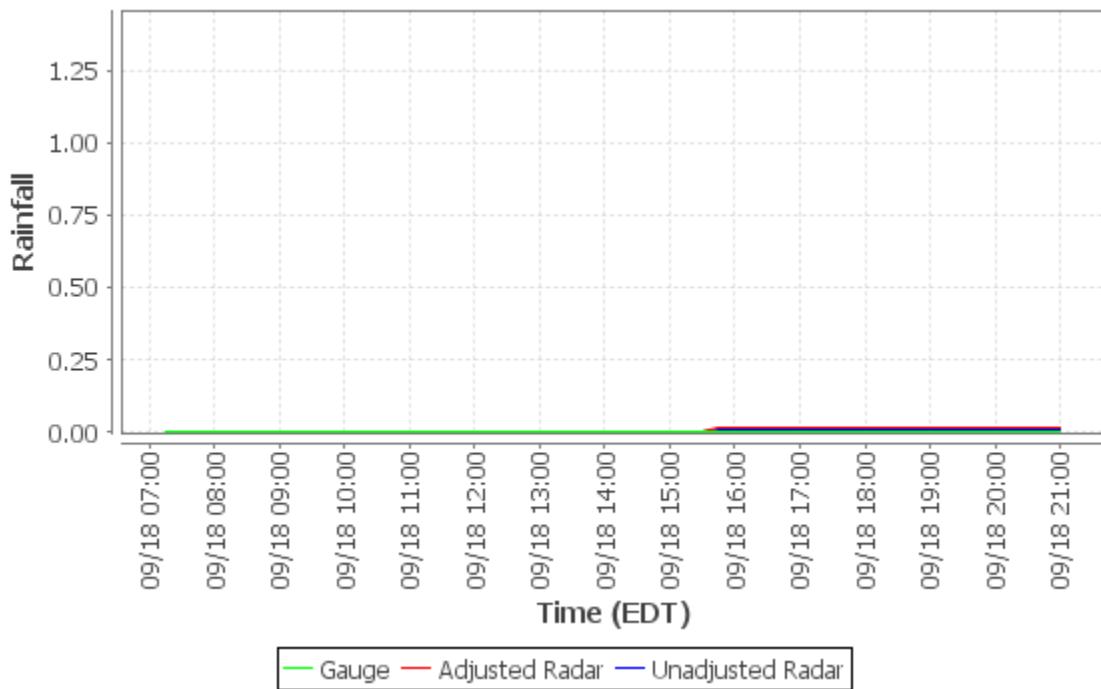
### Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



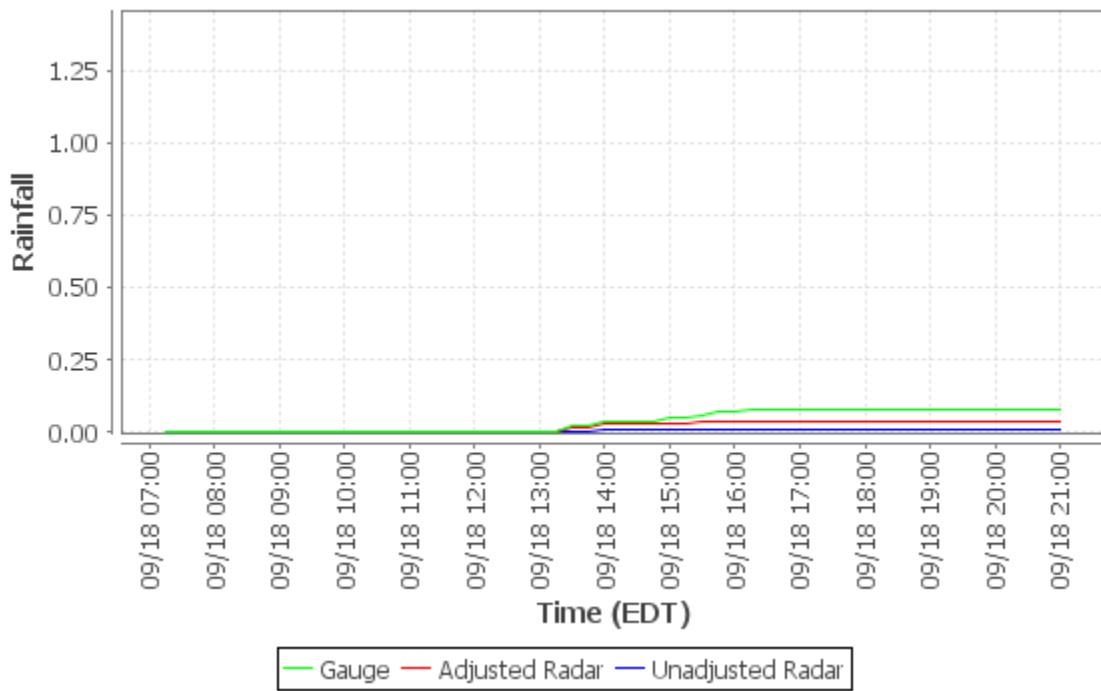
### Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



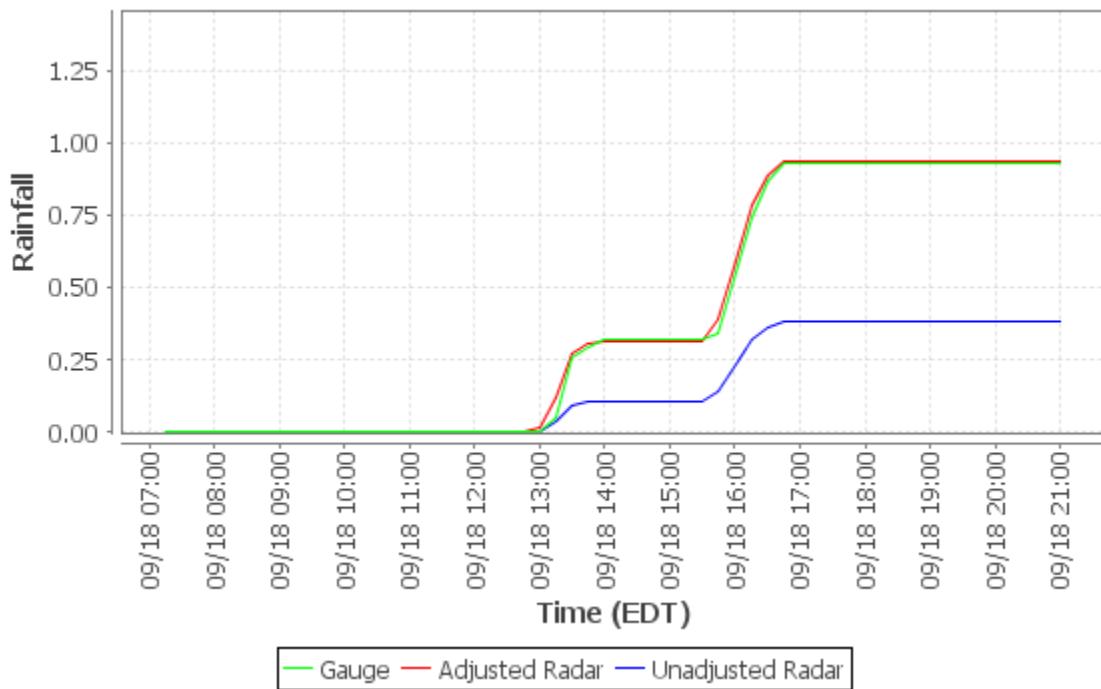
### Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



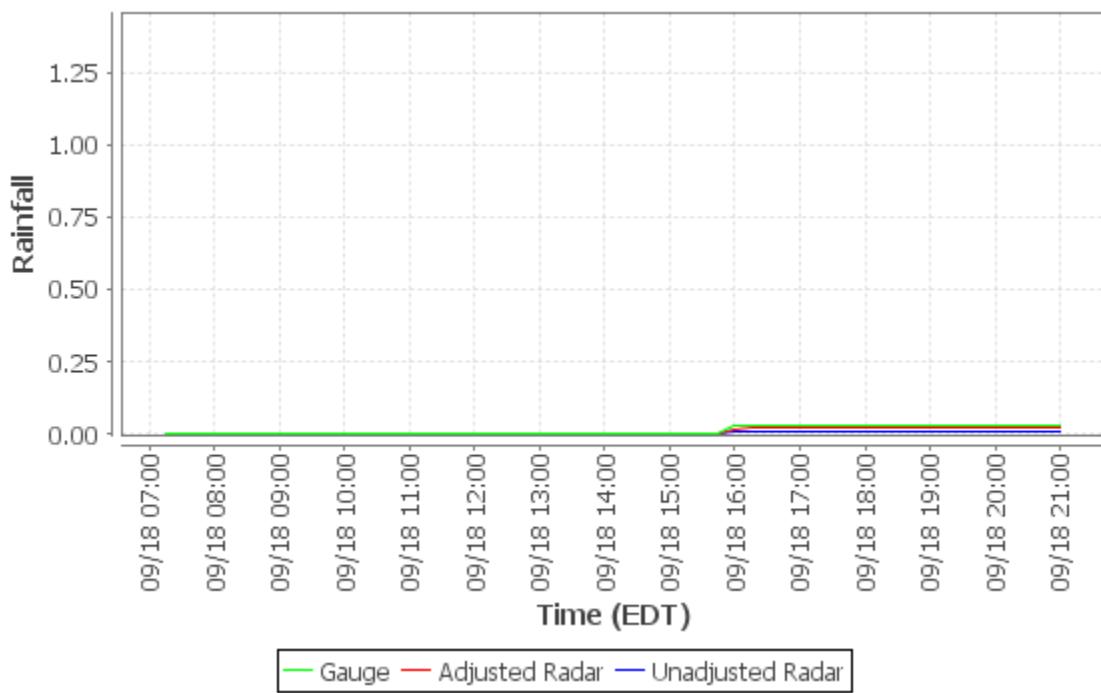
### Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



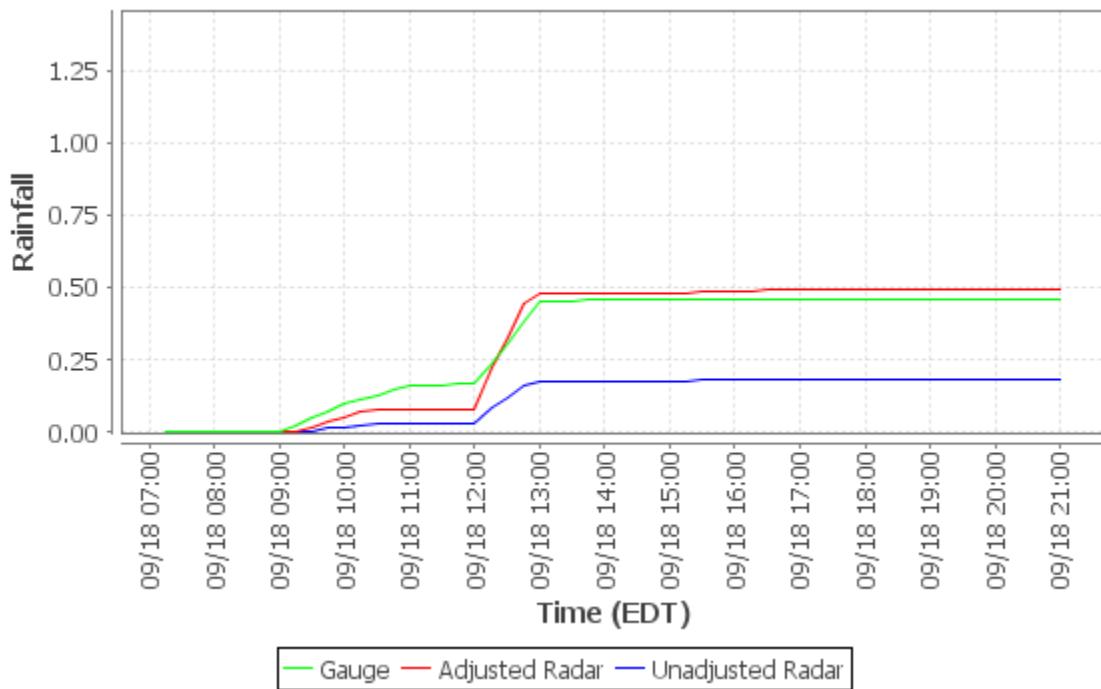
### Cumulative Distribution Plot - Arnold (Loc32)



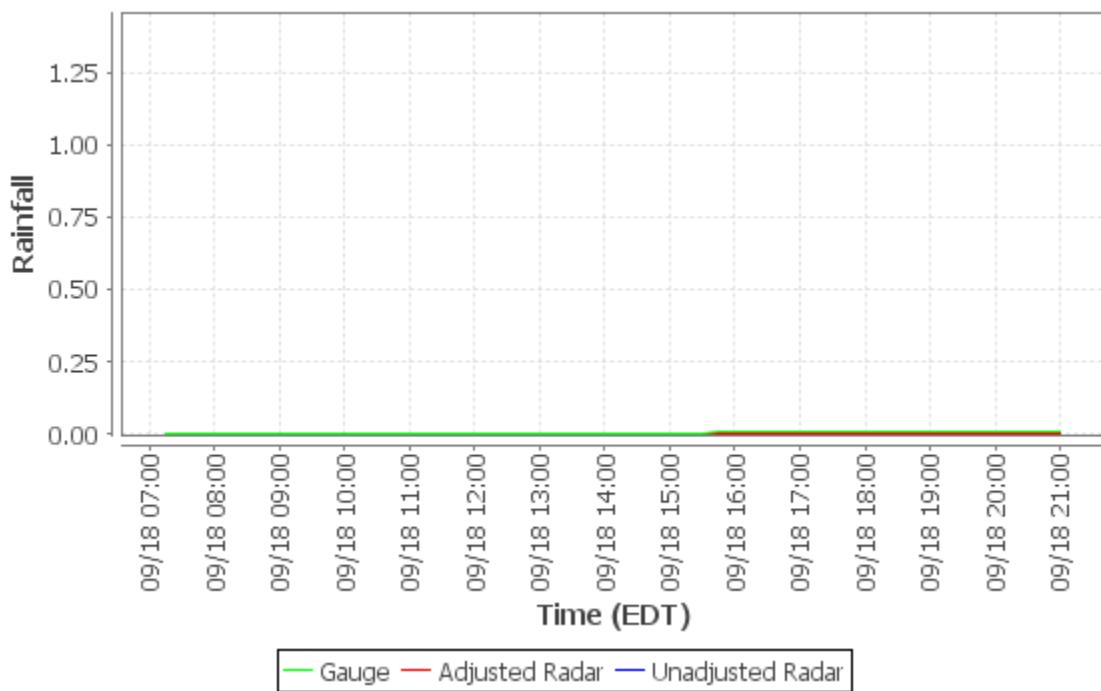
### Cumulative Distribution Plot - Richland TWP (Loc33)



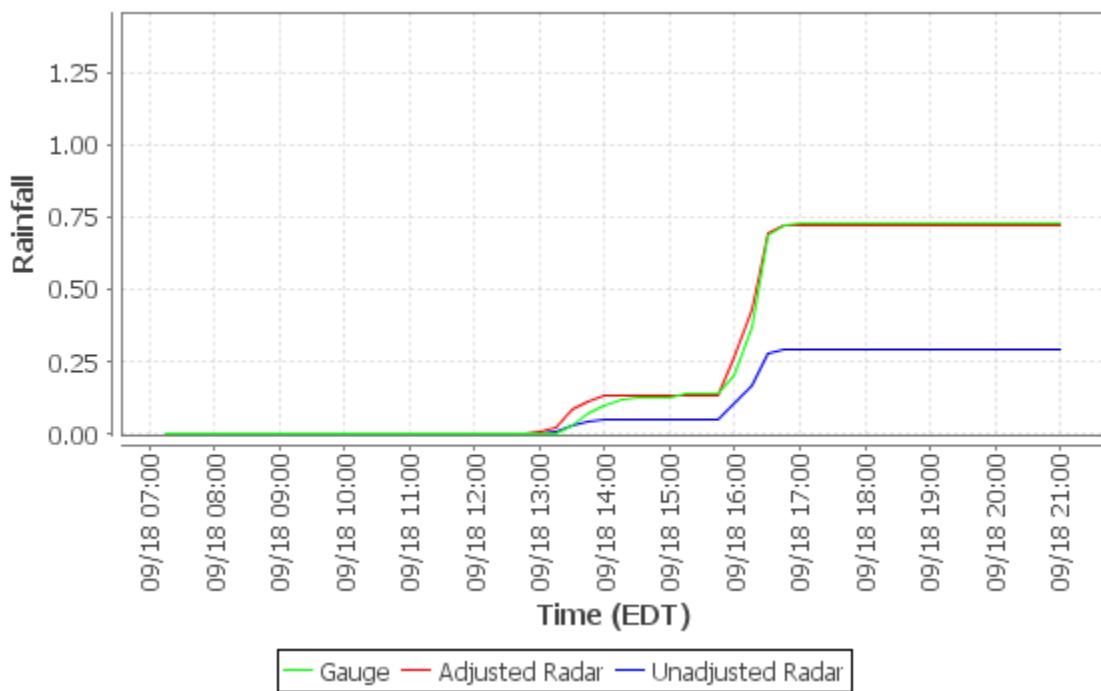
### Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



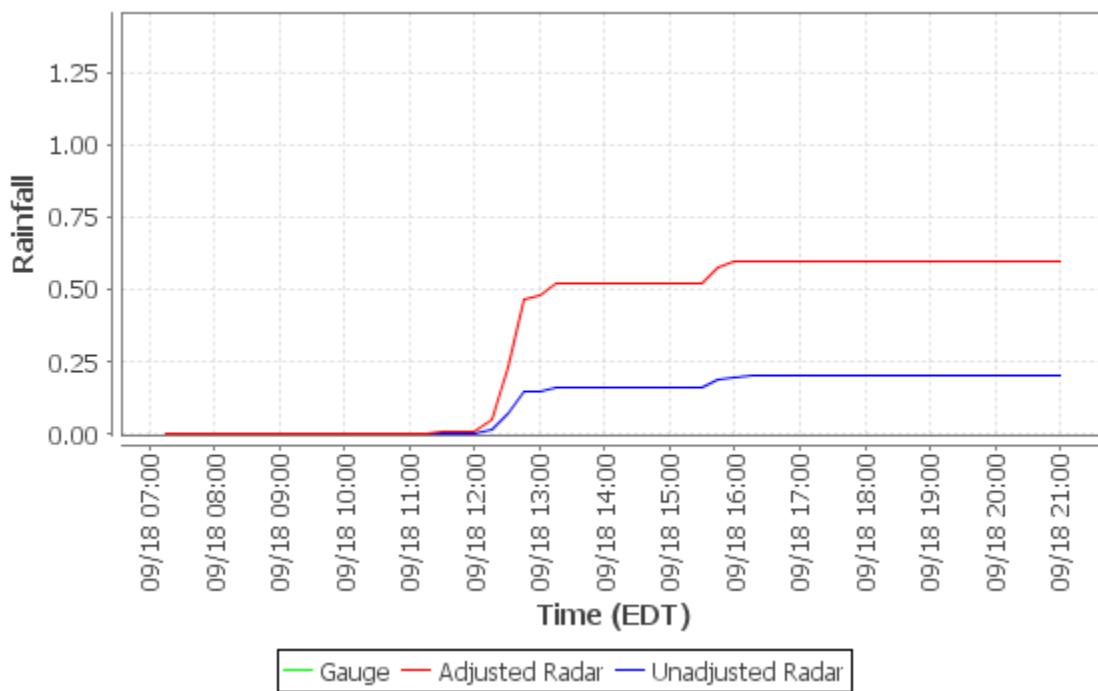
### Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



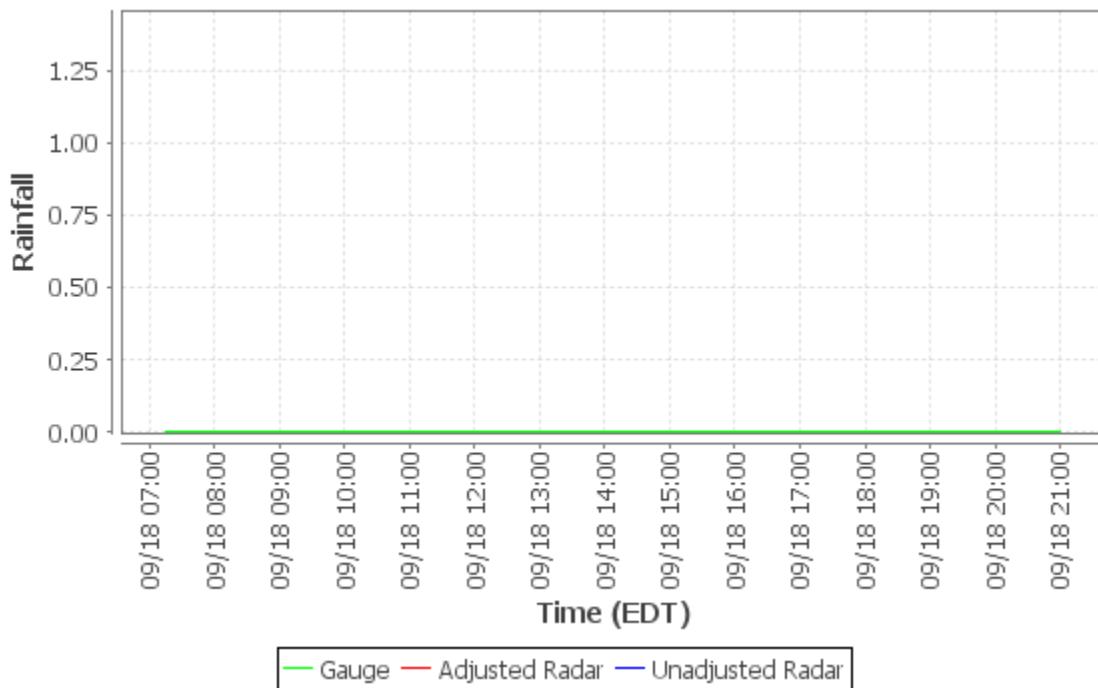
### Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



### Cumulative Distribution Plot - Chartiers Creek at Carnegie (03085500)

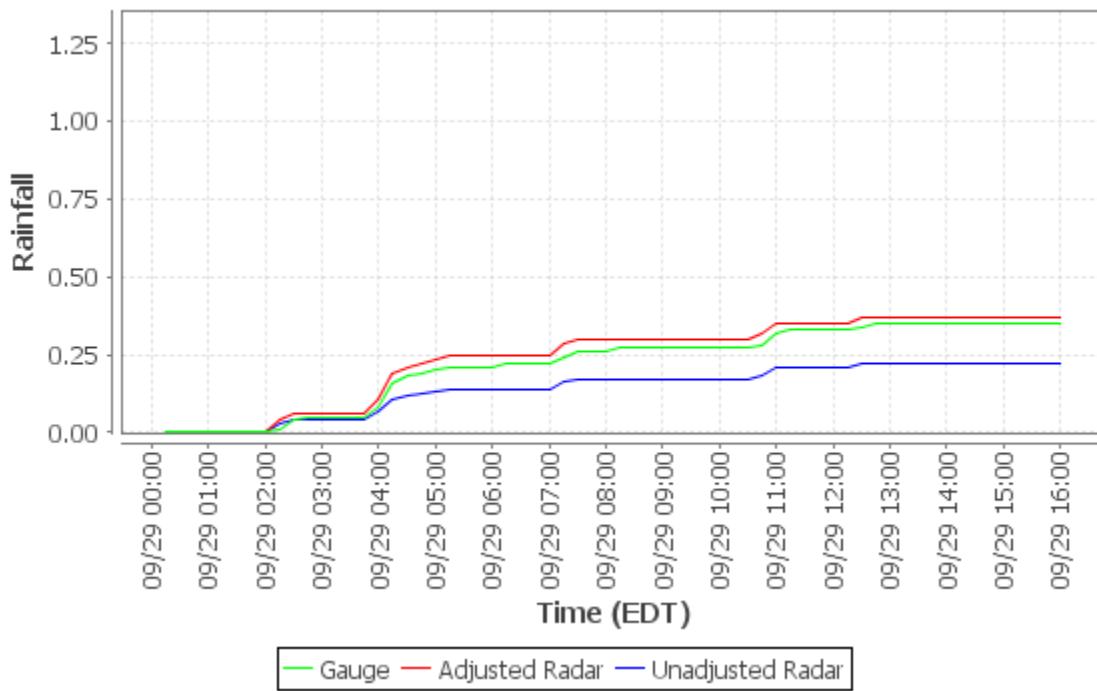


### Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

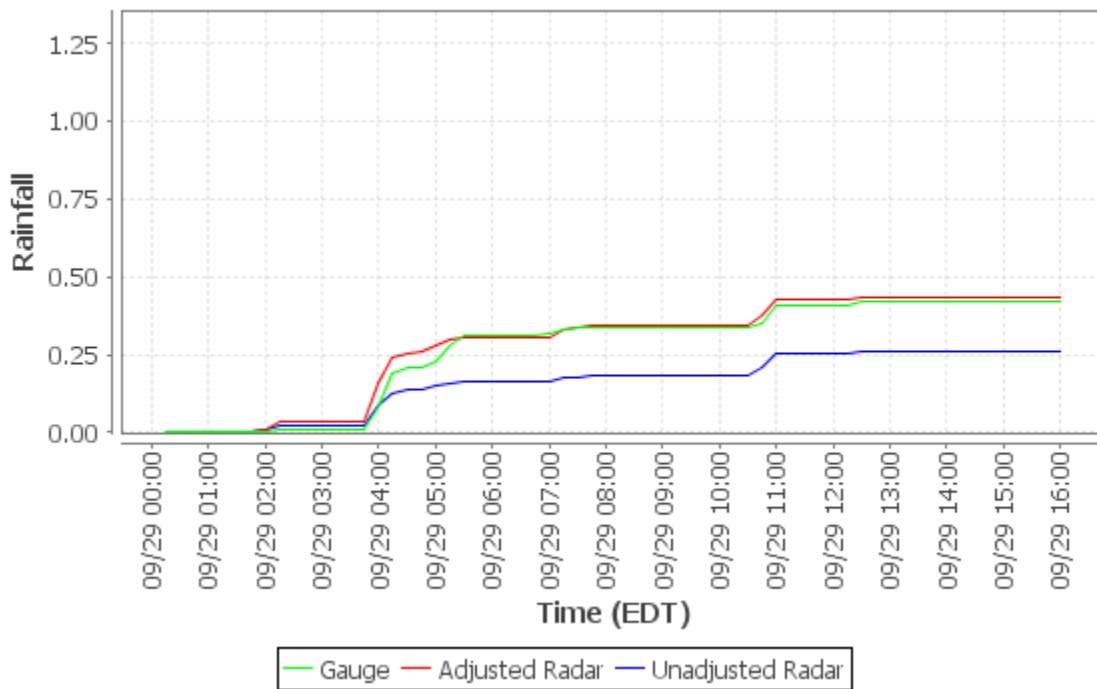


## **Appendix D - Event 3 (2016-09-29 AM) CDPs**

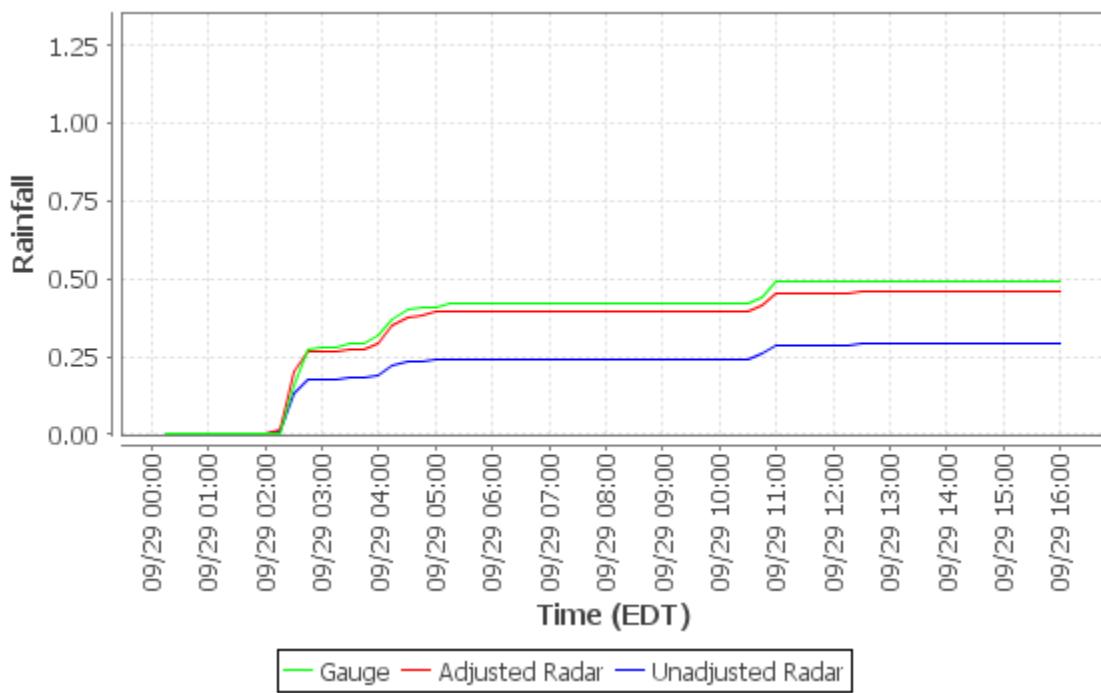
### Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



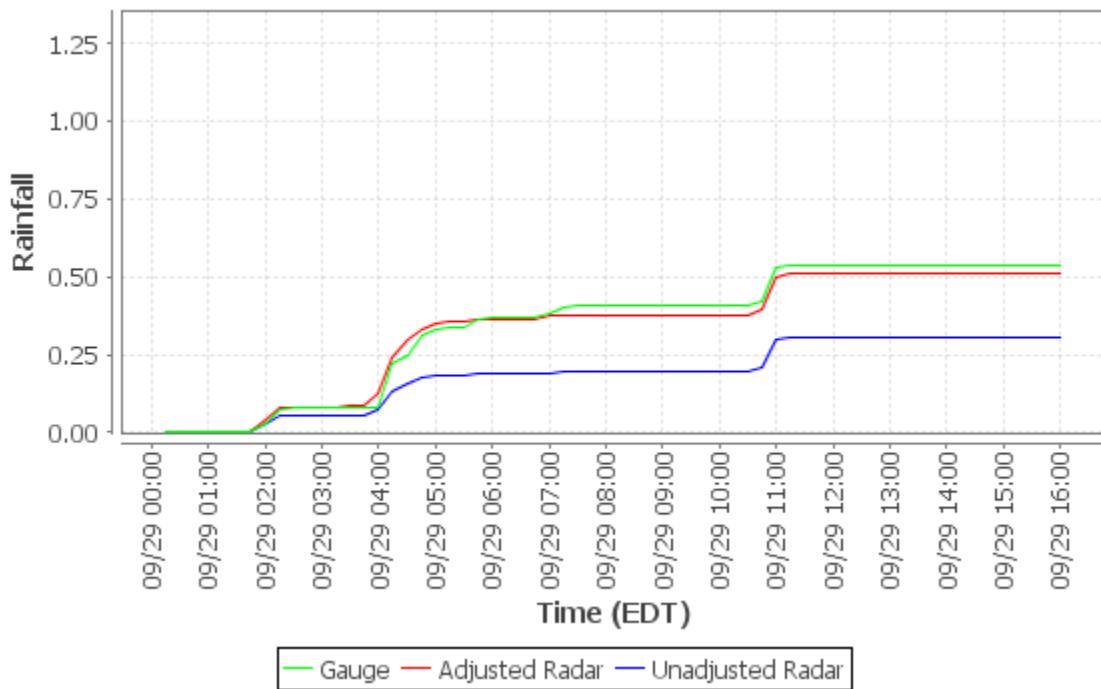
### Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



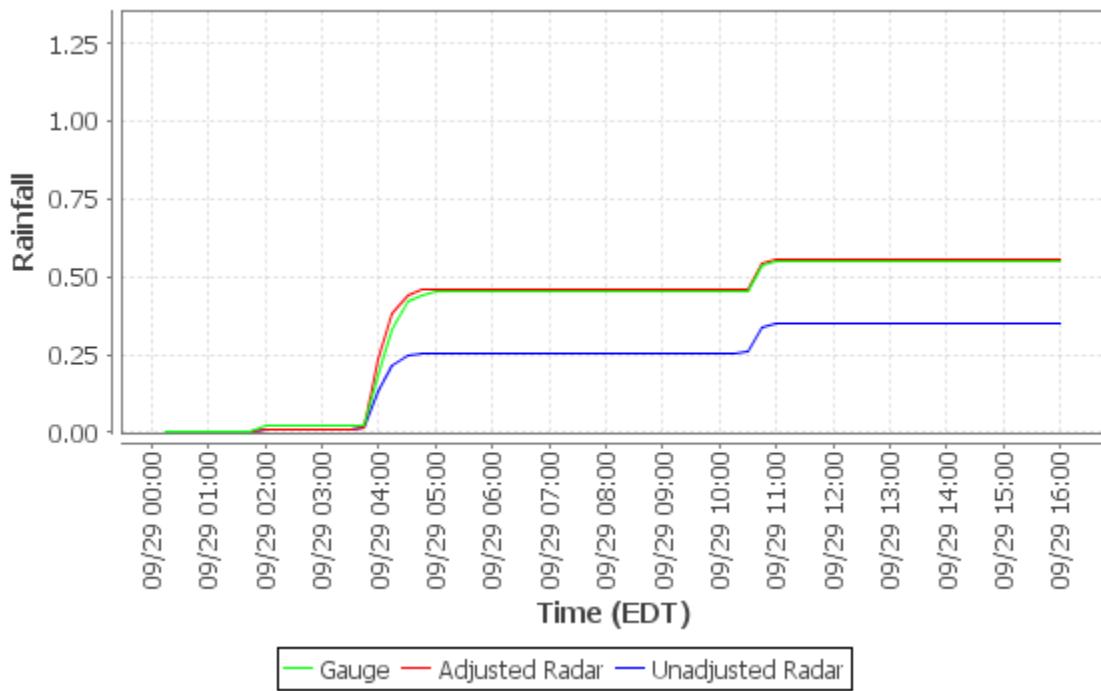
### Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



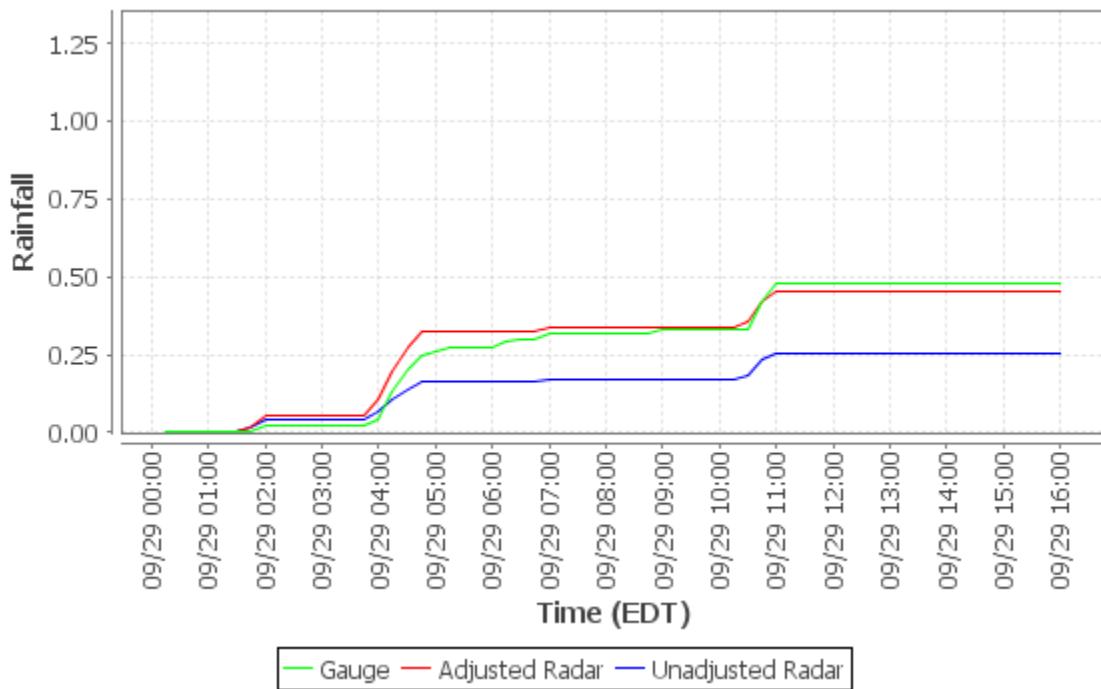
### Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



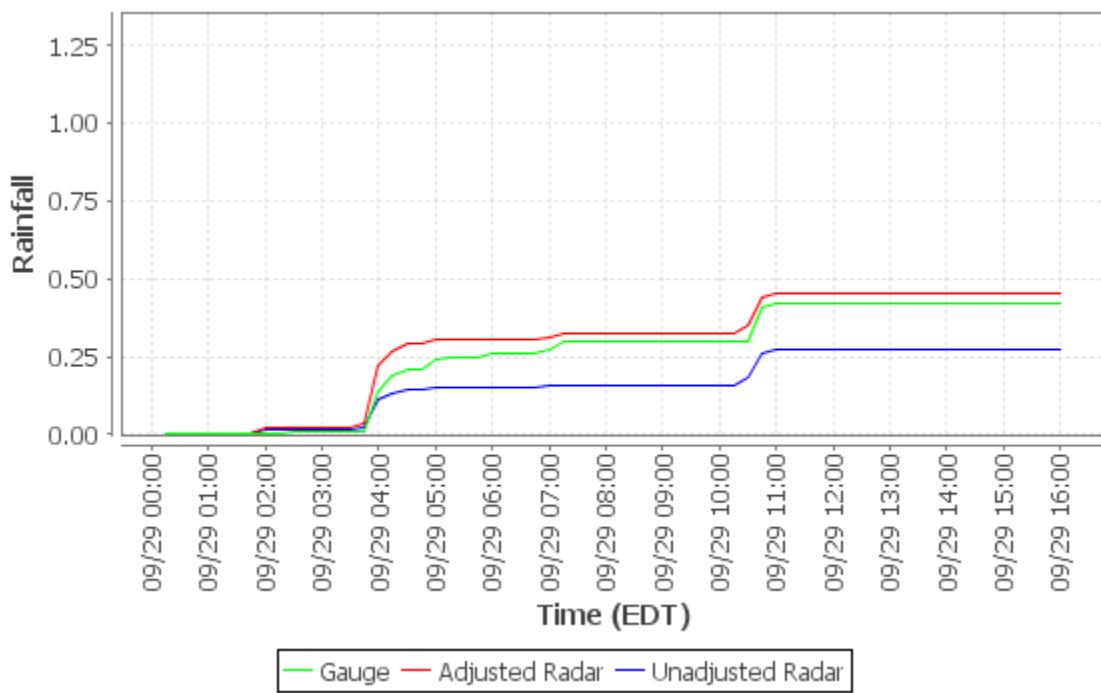
### Cumulative Distribution Plot - Upper St. Clair (Loc05)



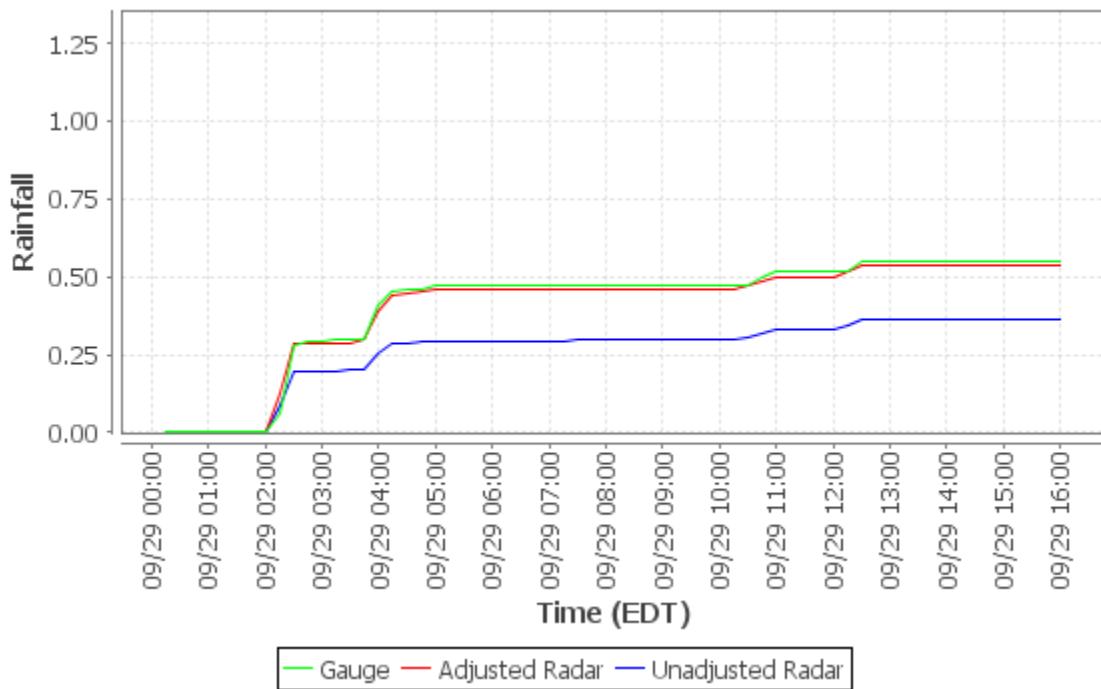
### Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



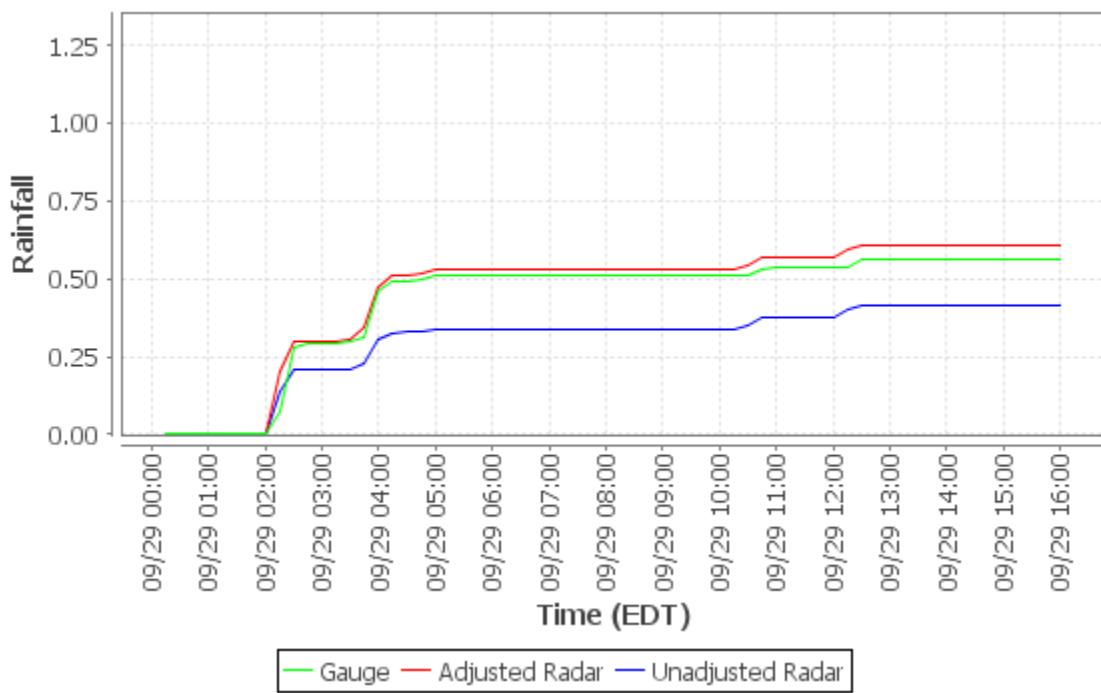
### Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



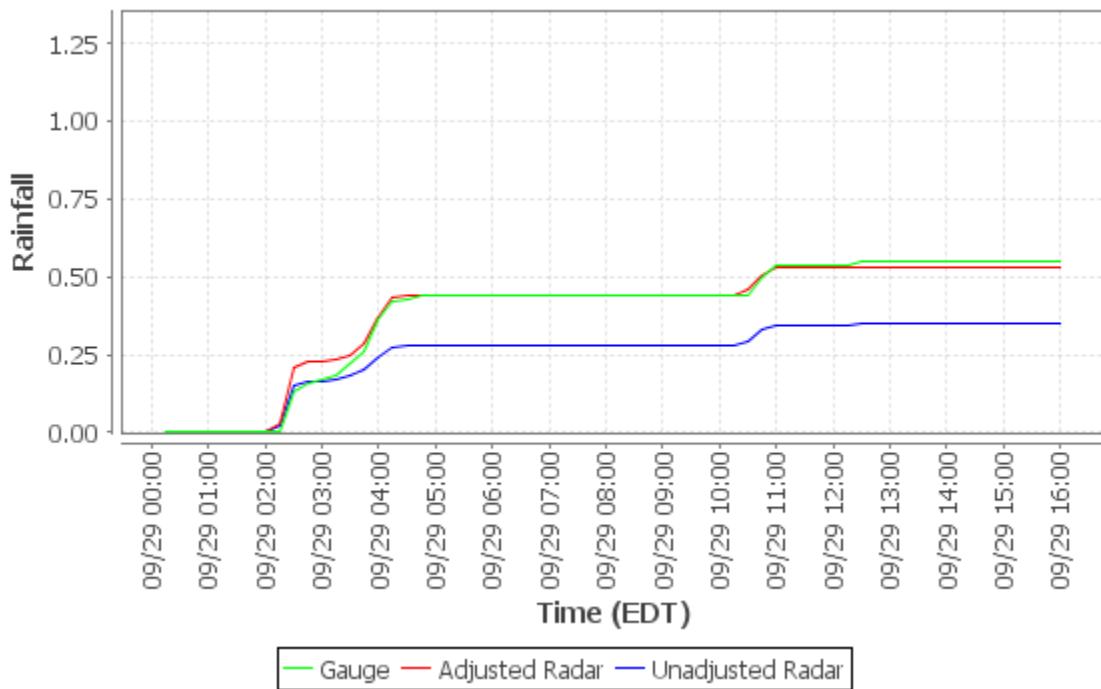
### Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



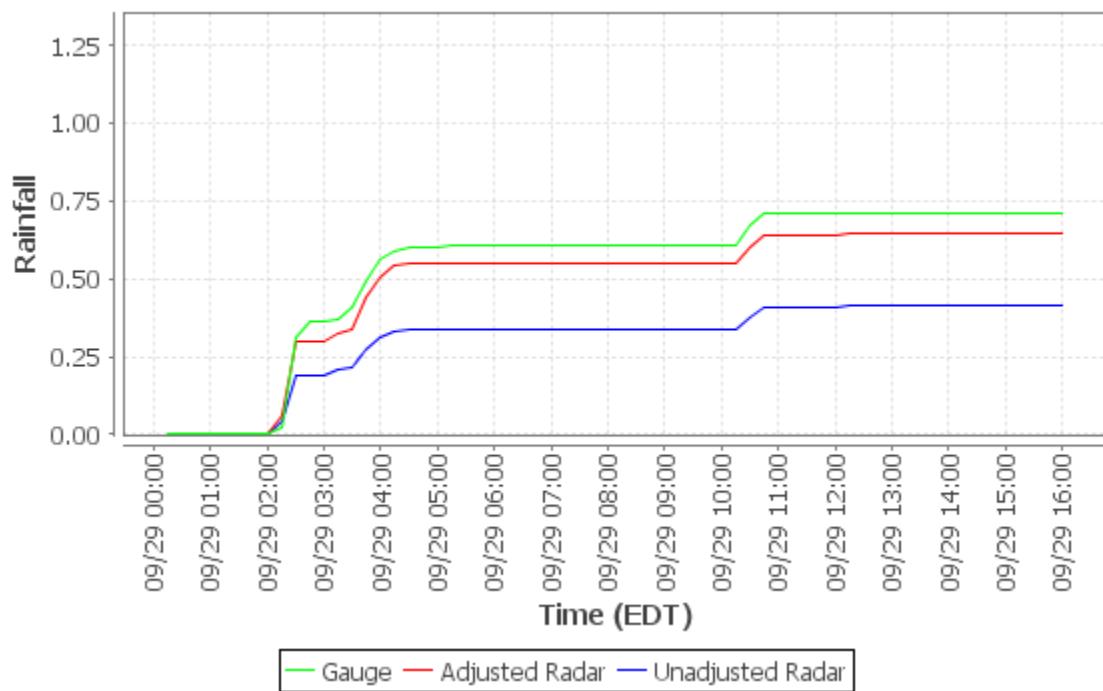
### Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



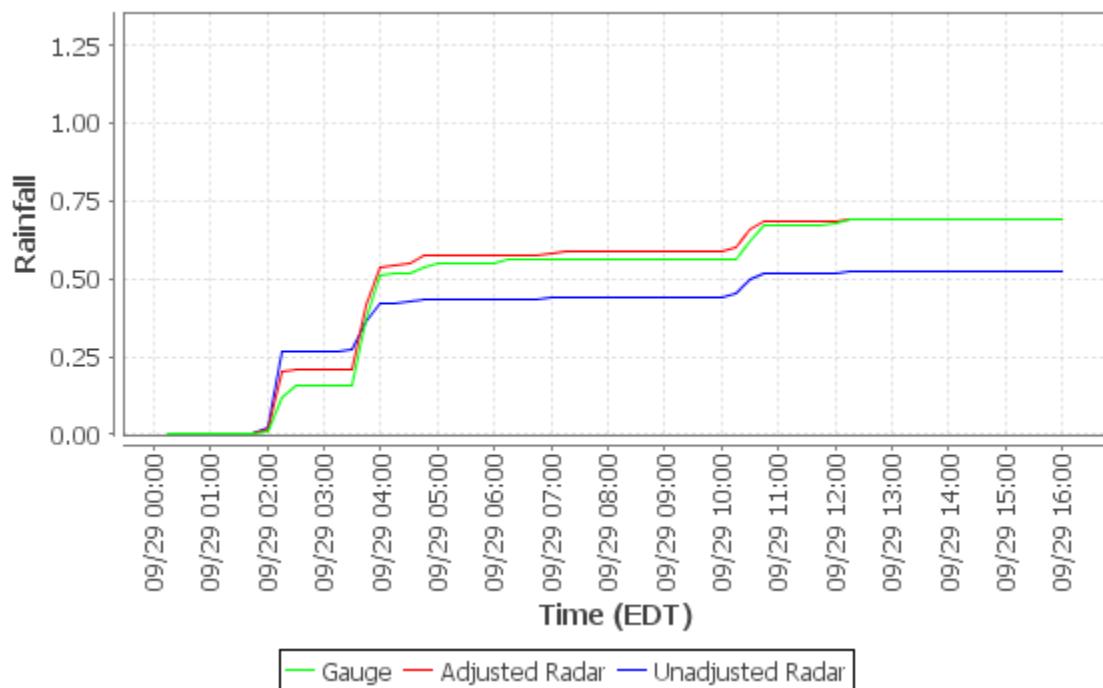
### Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



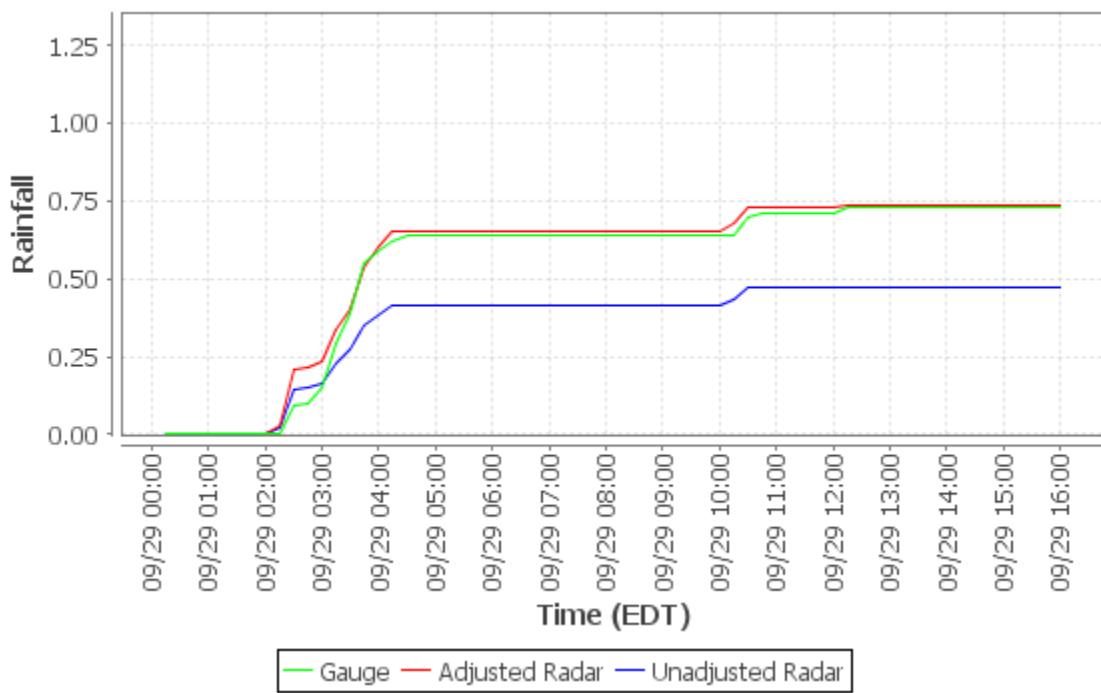
### Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



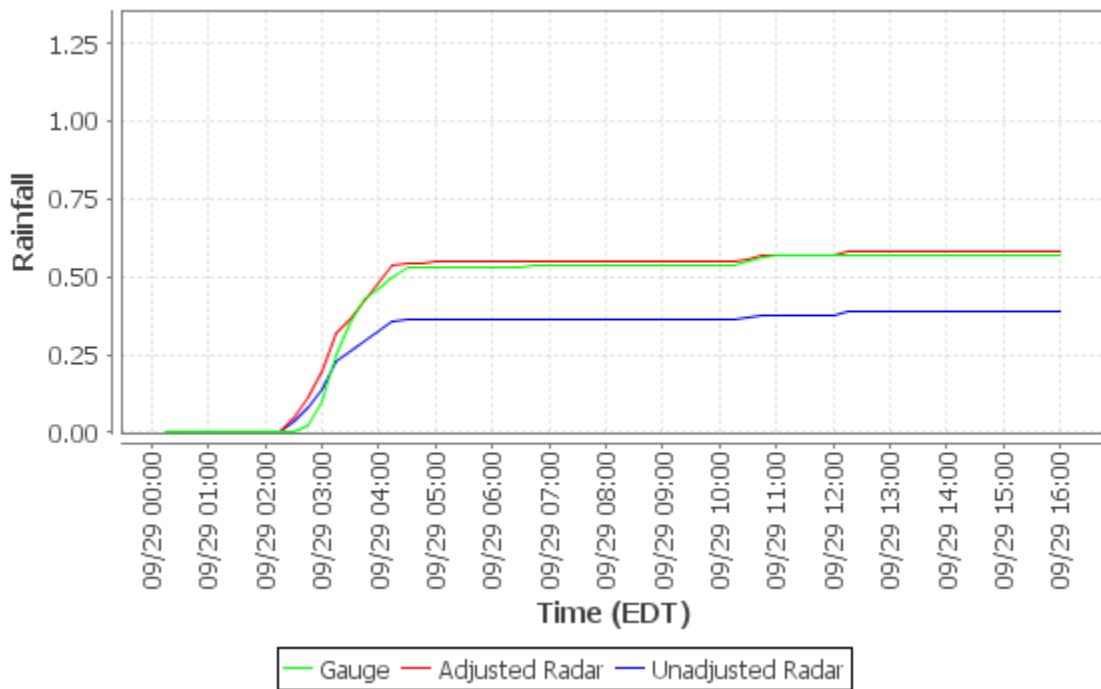
### Cumulative Distribution Plot - Baldwin (Loc12)



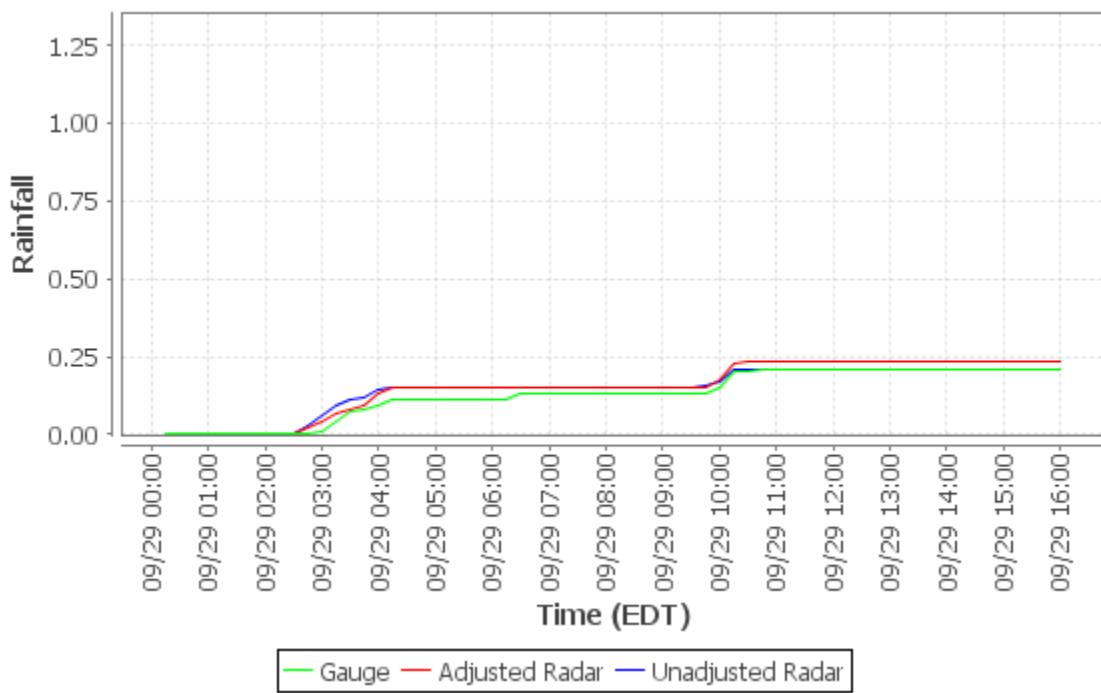
### Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



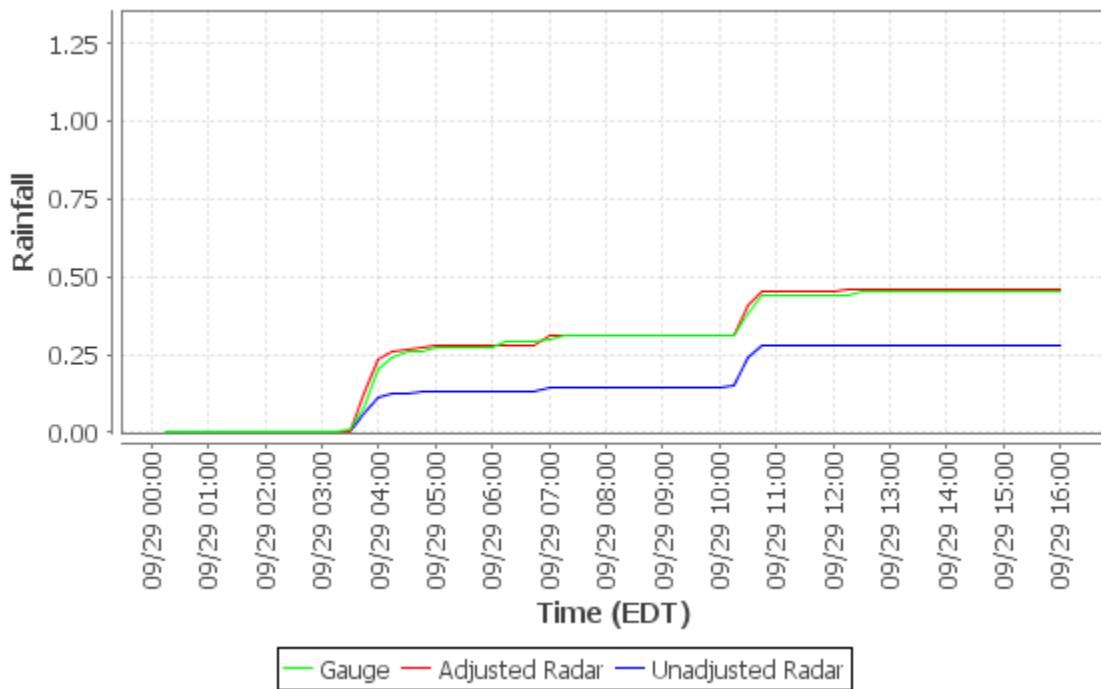
### Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



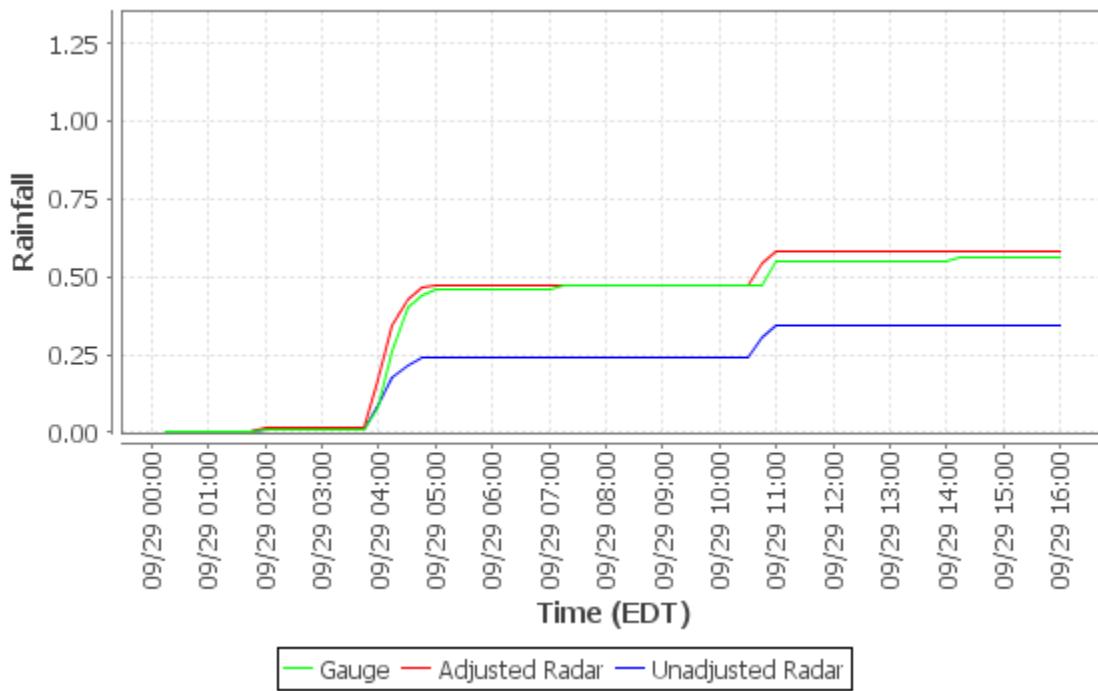
### Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



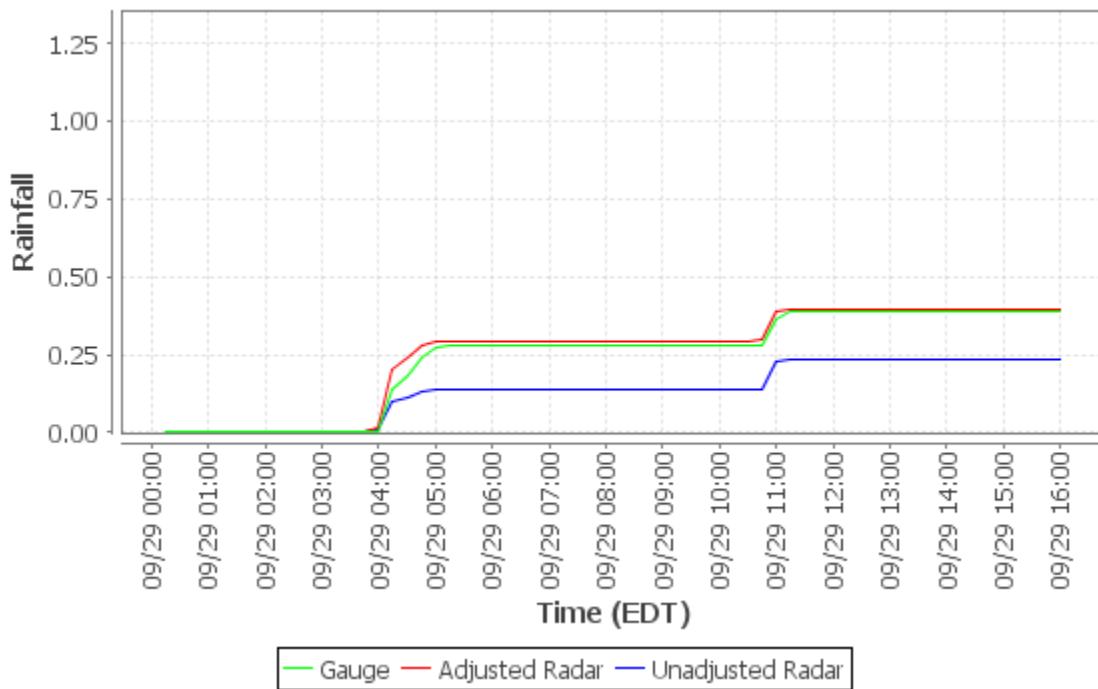
### Cumulative Distribution Plot - Castle Shannon (Loc16)



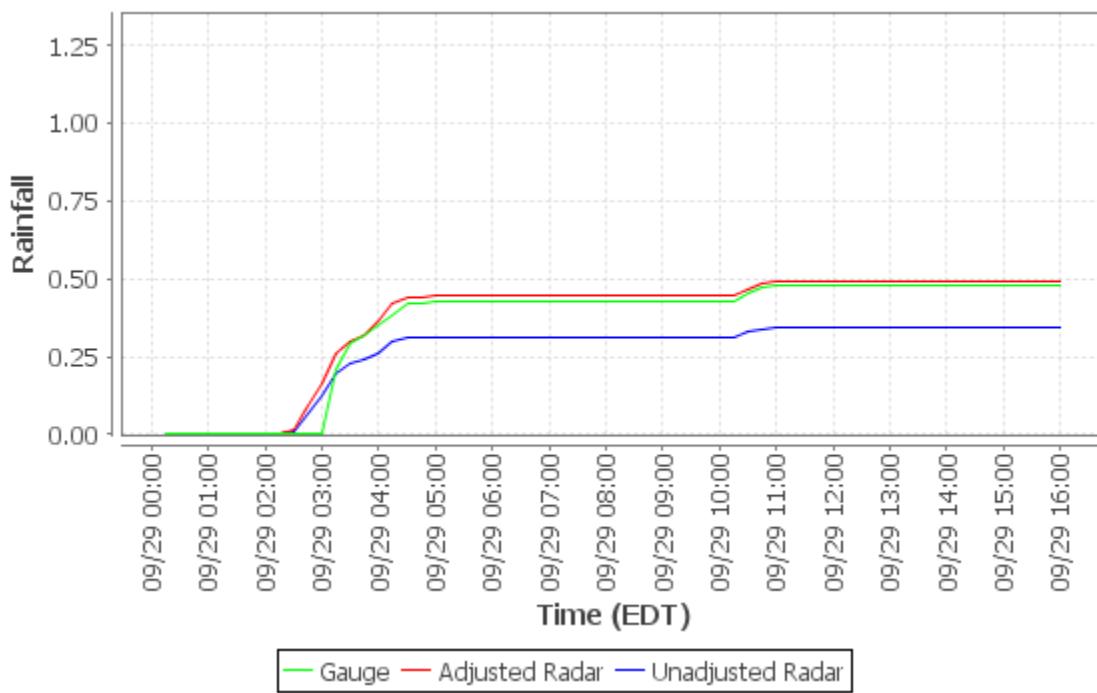
### Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



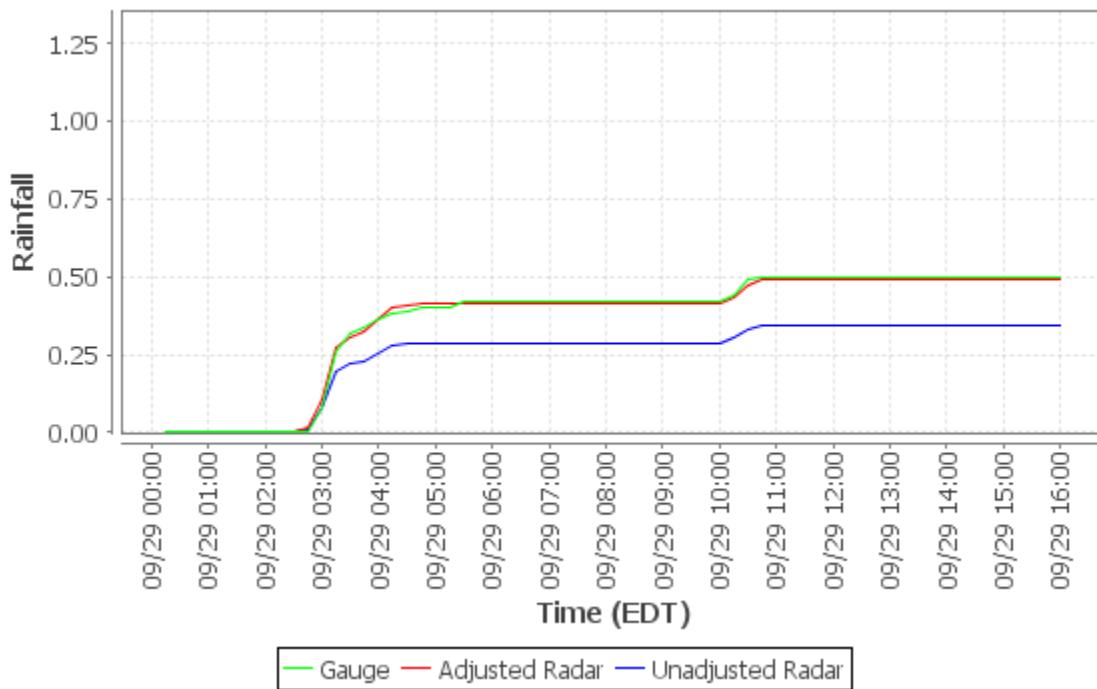
### Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



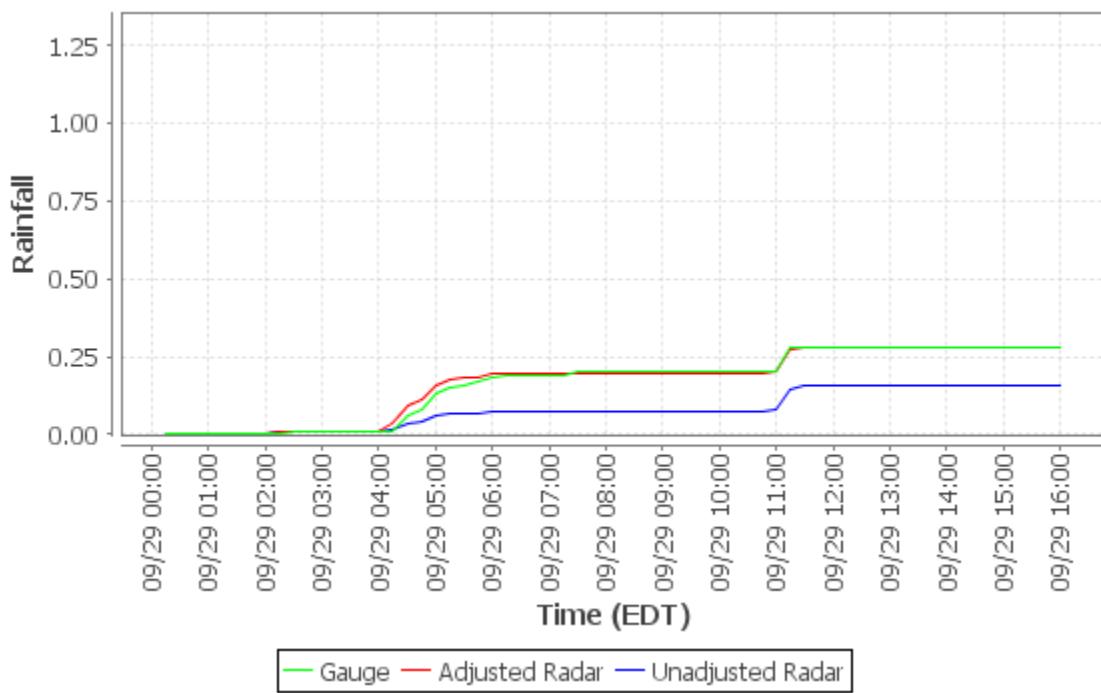
### Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



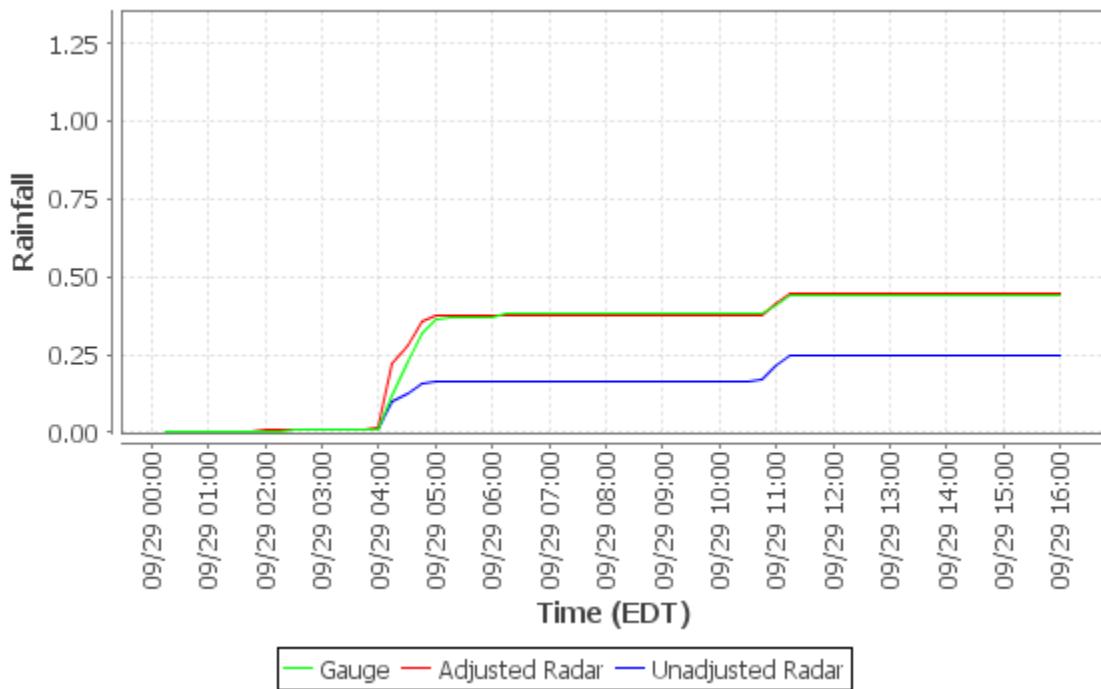
### Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



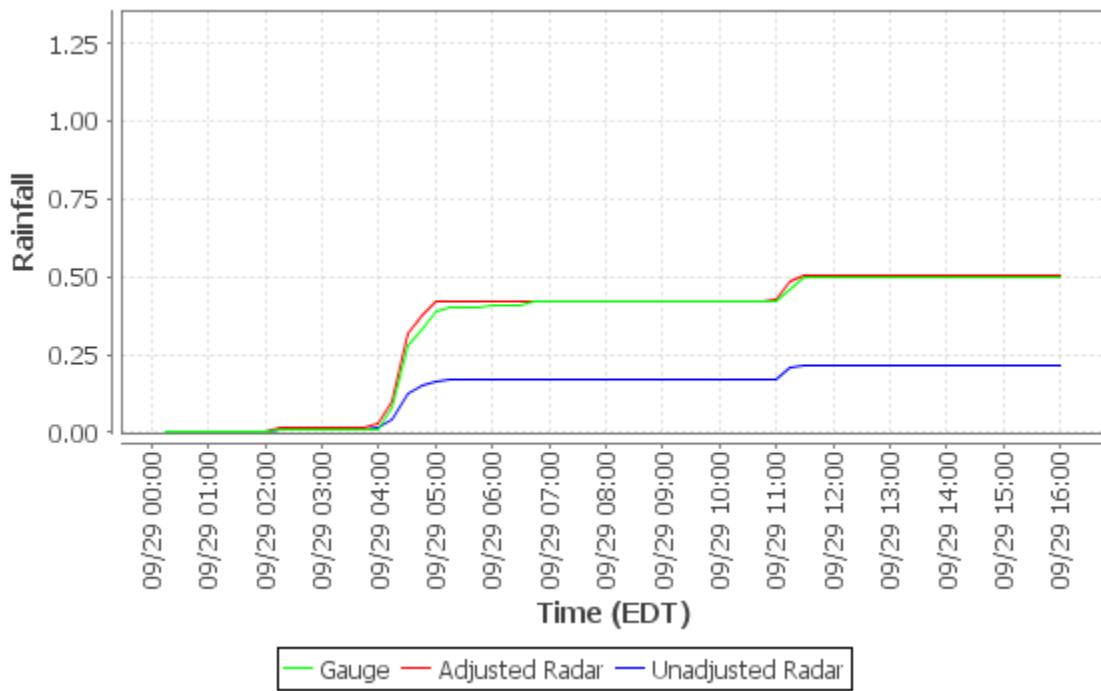
### Cumulative Distribution Plot - Moon TWP (Loc21)



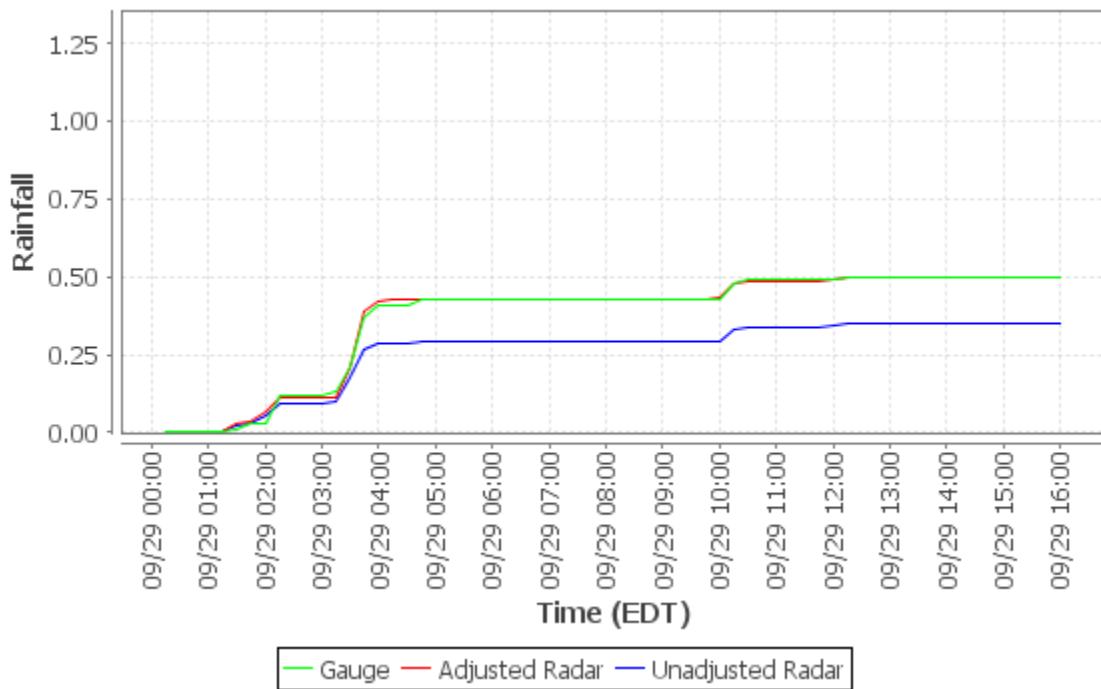
### Cumulative Distribution Plot - North Fayette TWP (Loc22)



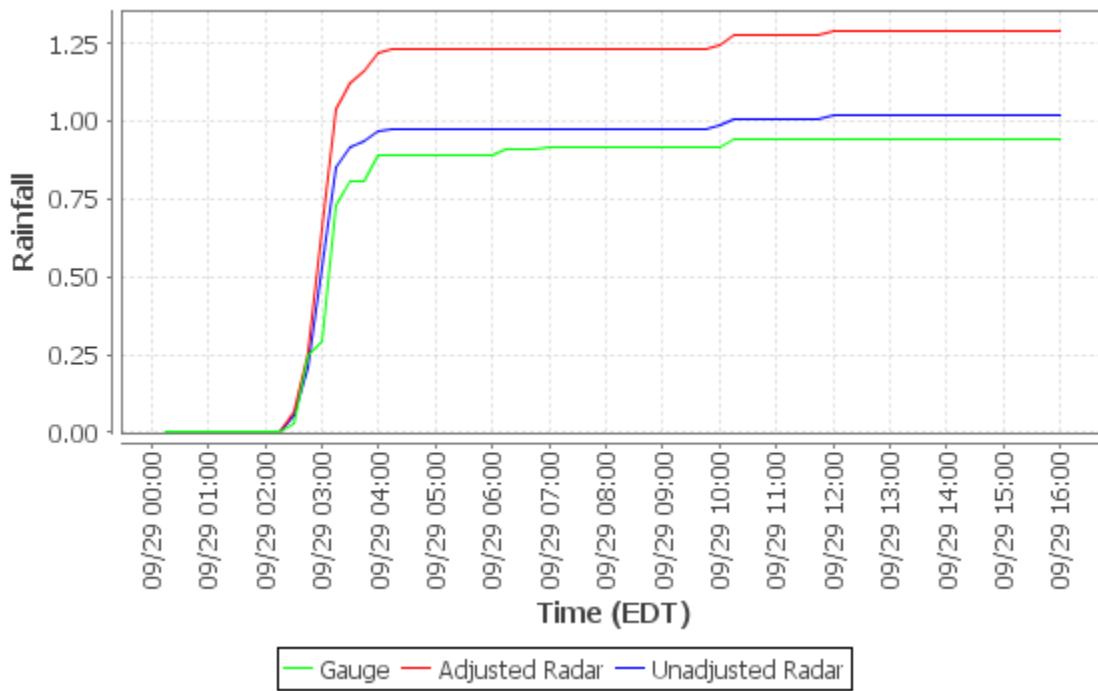
### Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



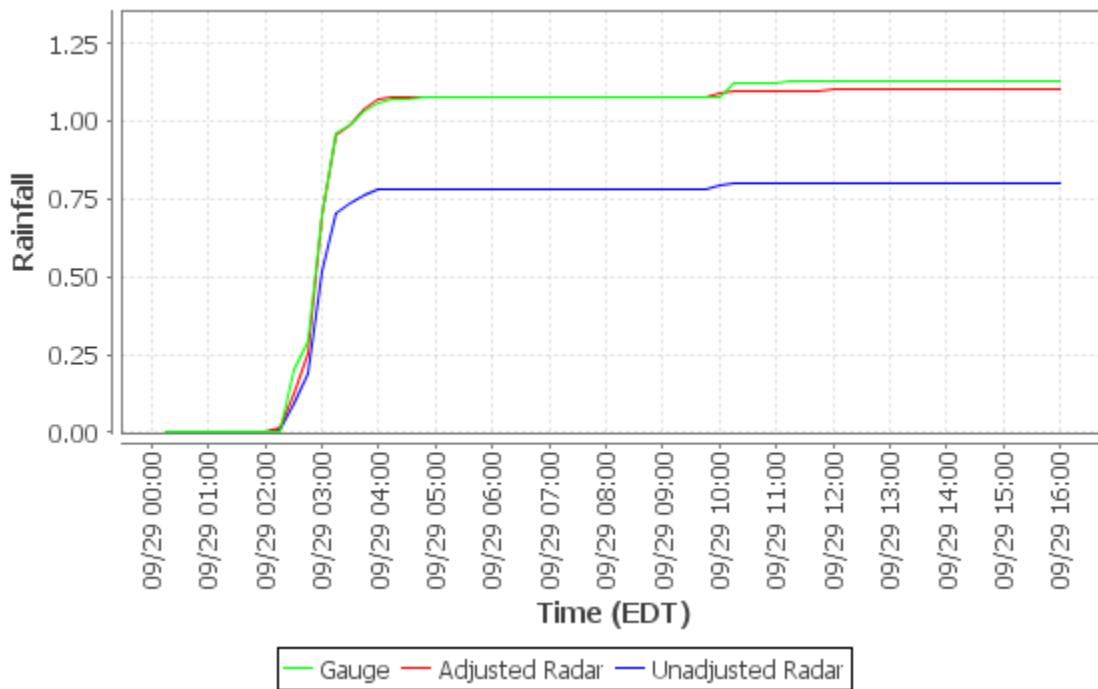
### Cumulative Distribution Plot - Jefferson Hills (Loc24)



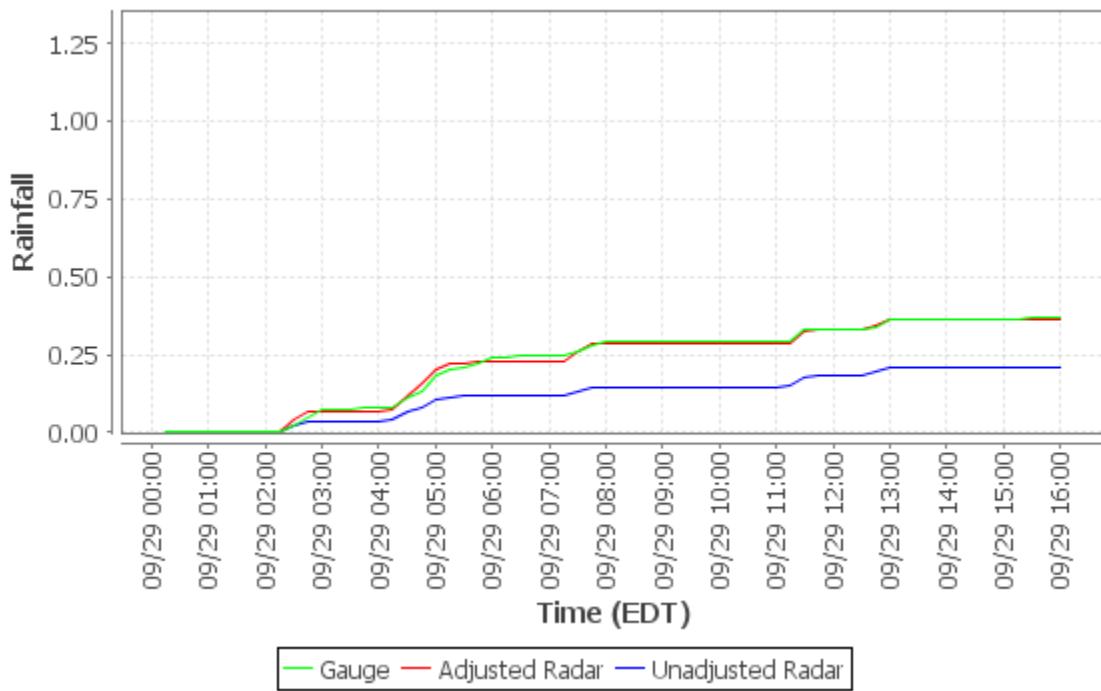
### Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



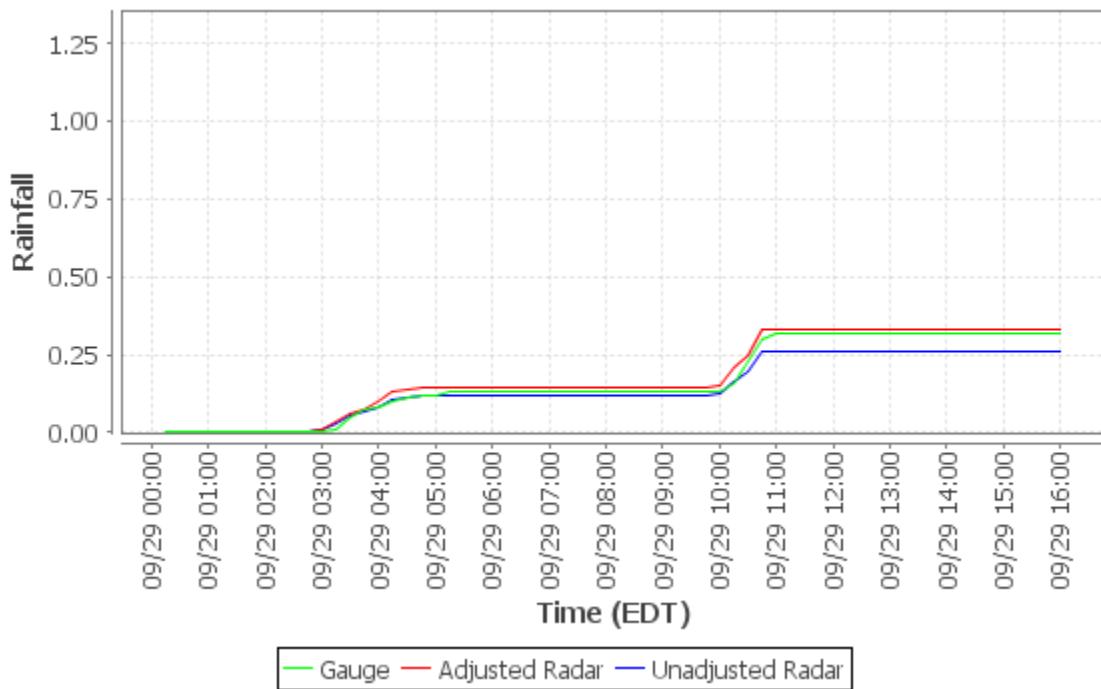
### Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



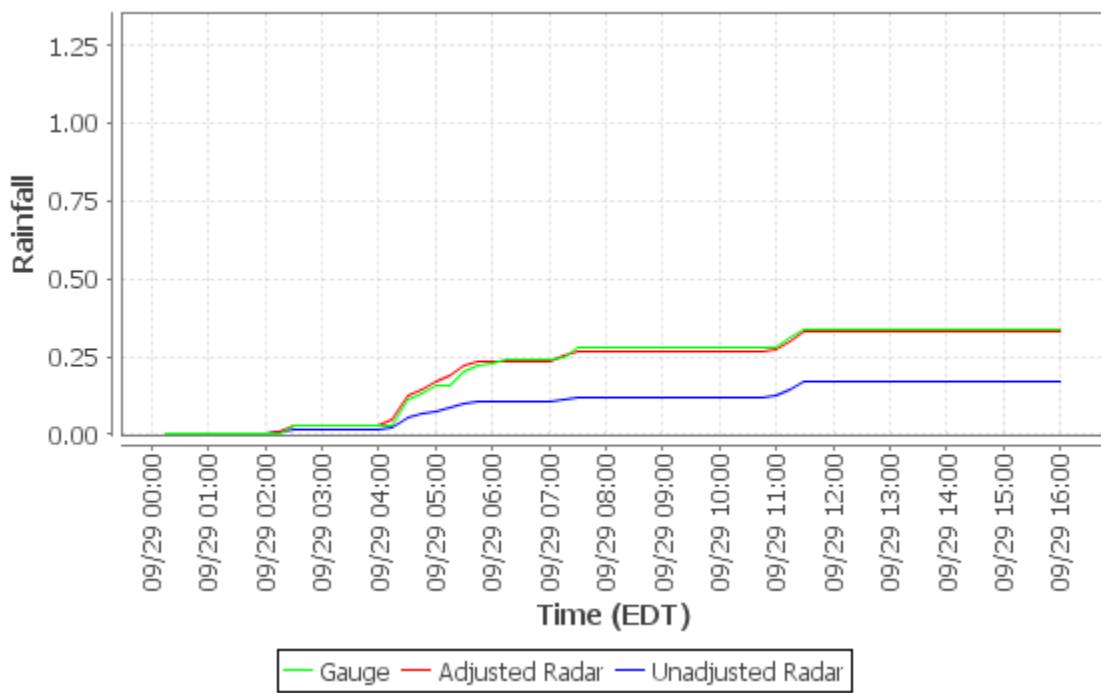
### Cumulative Distribution Plot - Marshall TWP (Loc27)



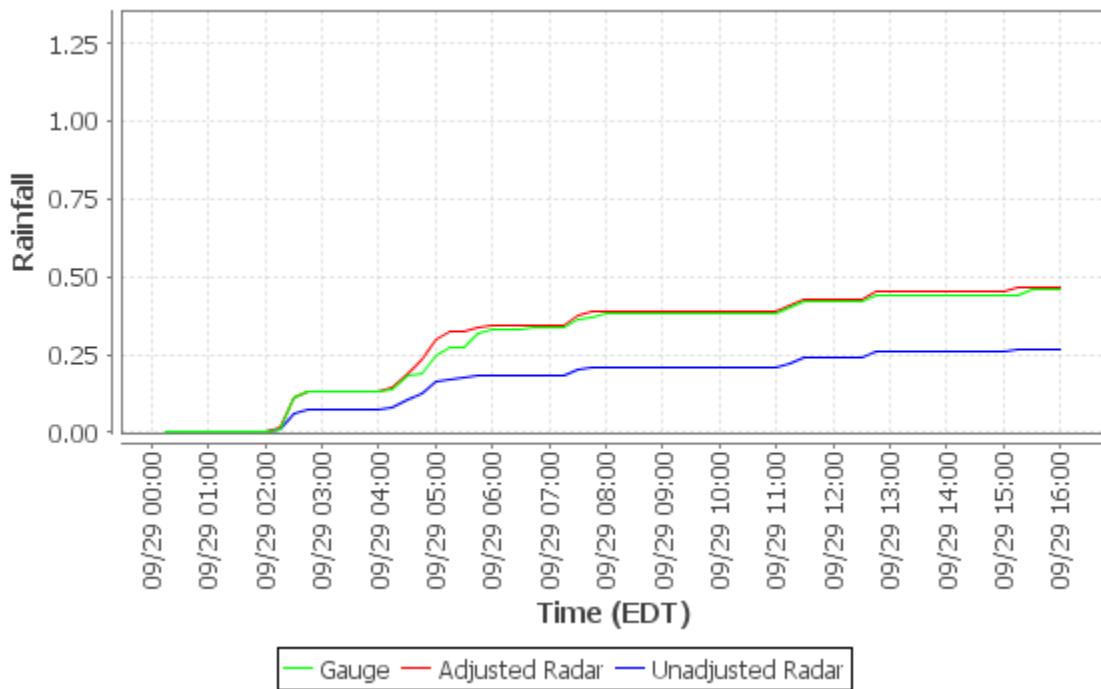
### Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



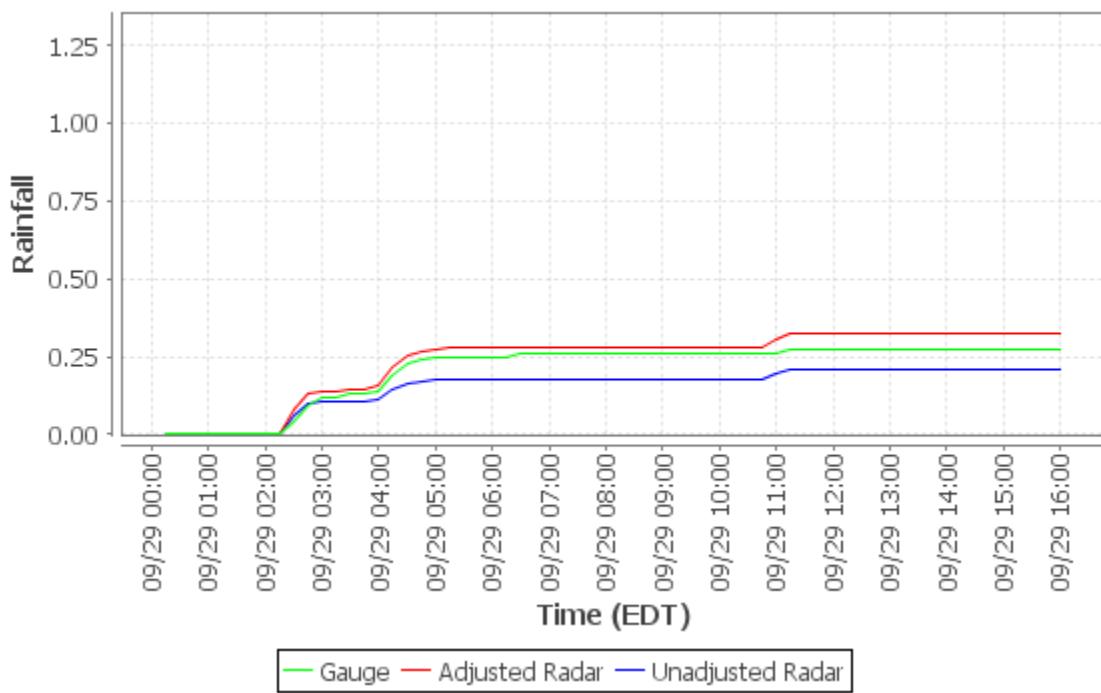
### Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



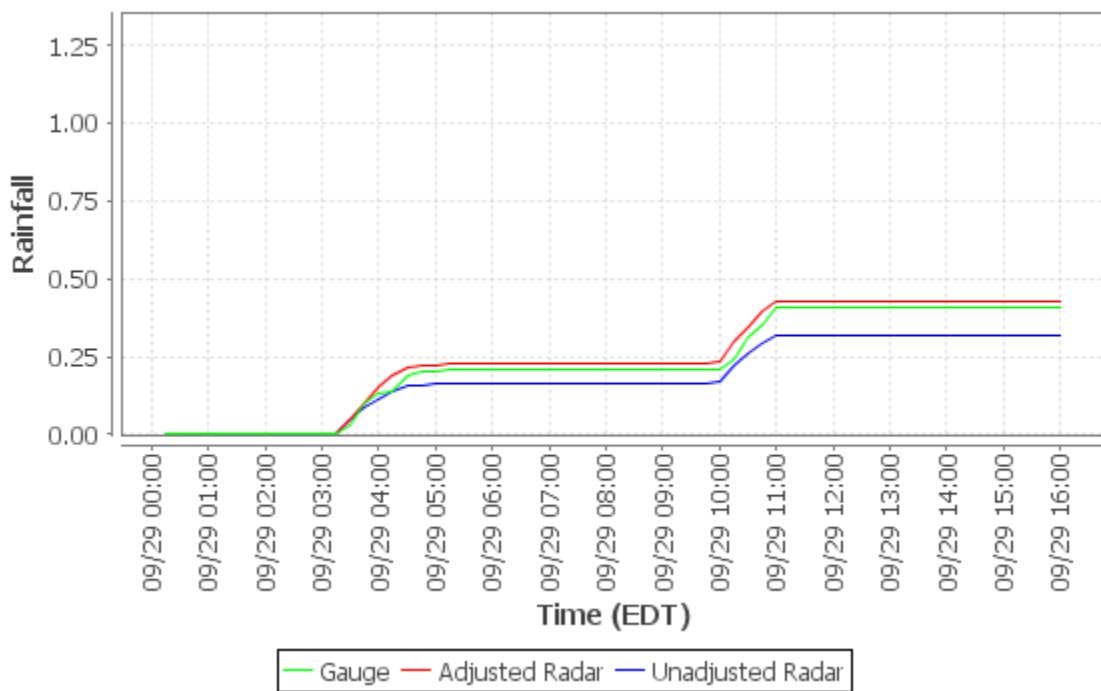
### Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



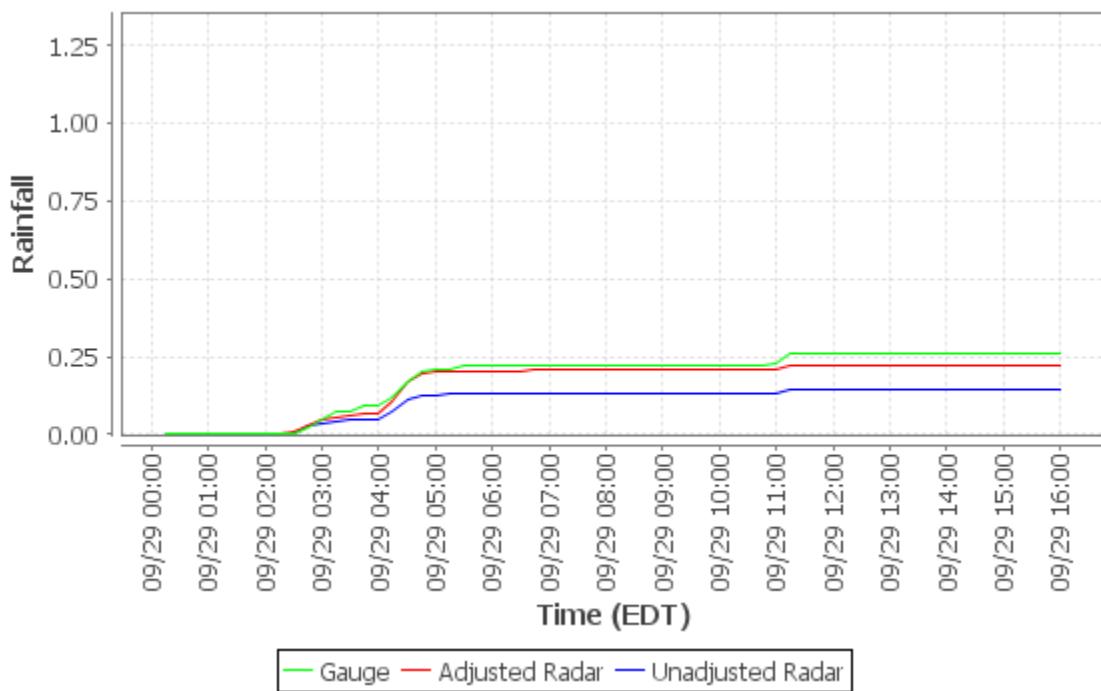
### Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



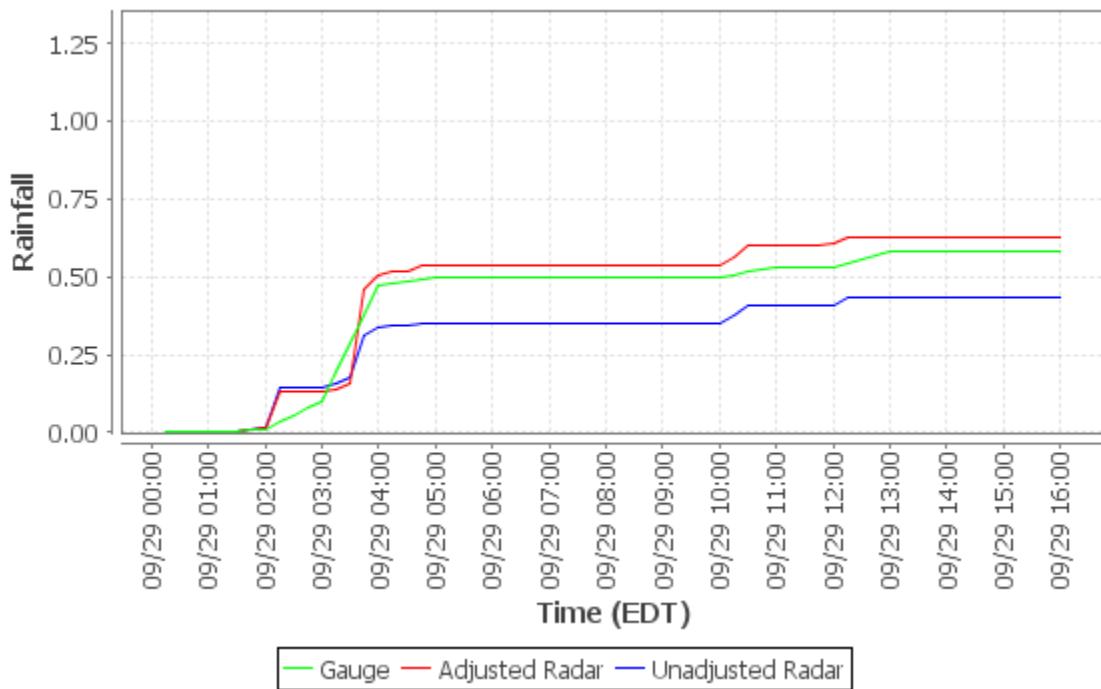
### Cumulative Distribution Plot - Arnold (Loc32)



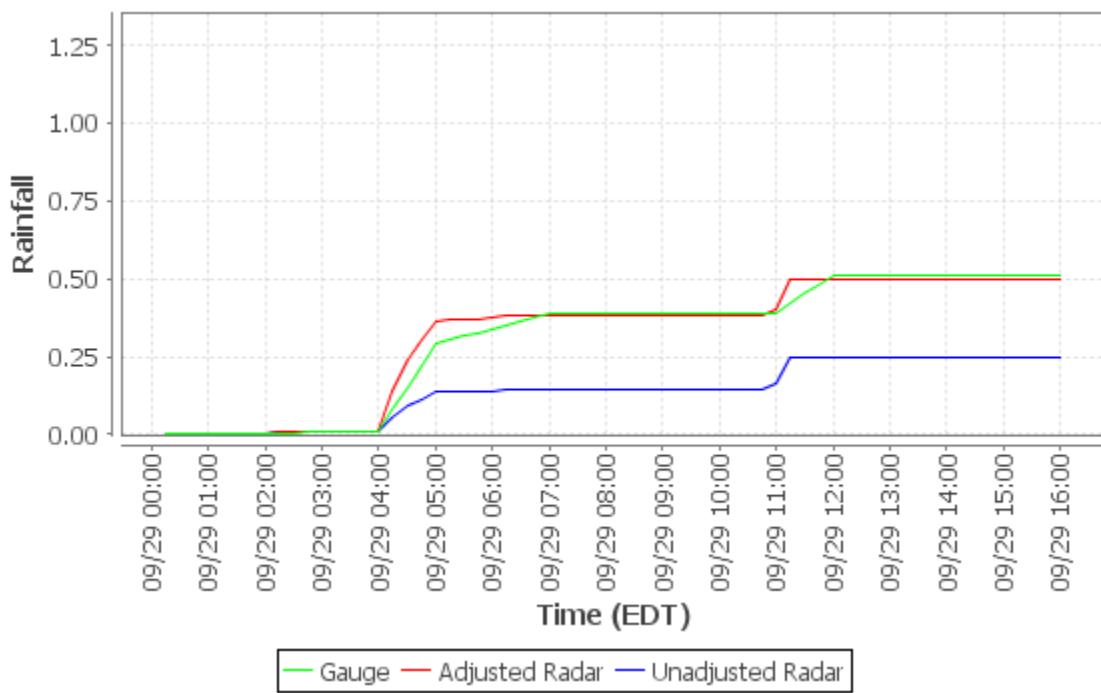
### Cumulative Distribution Plot - Richland TWP (Loc33)



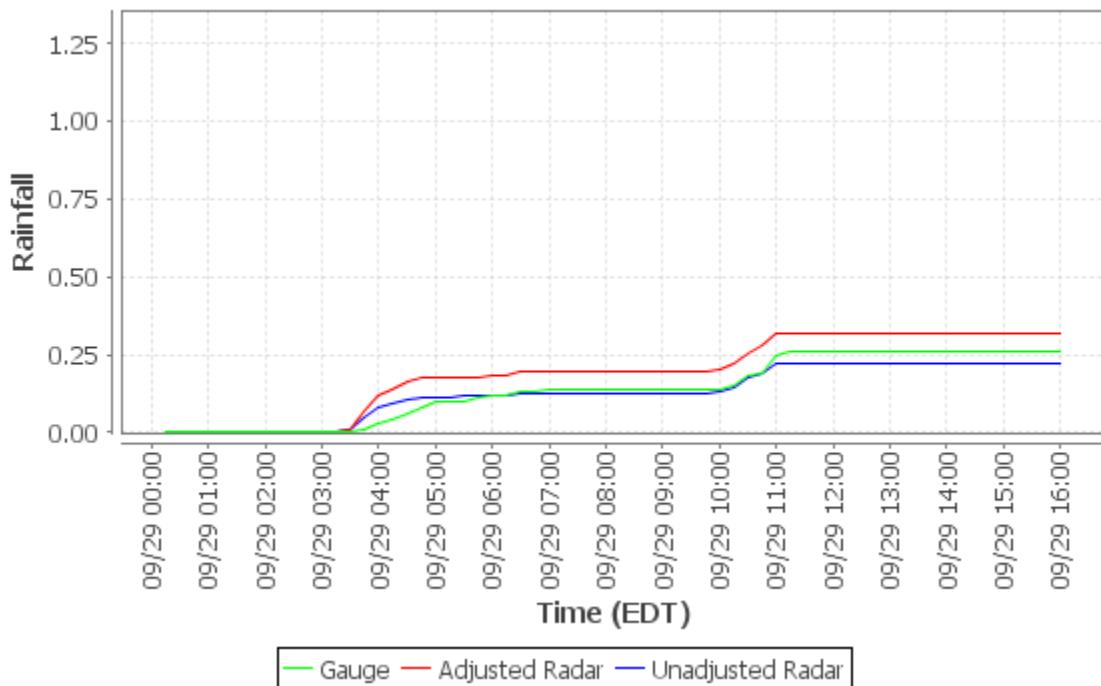
### Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



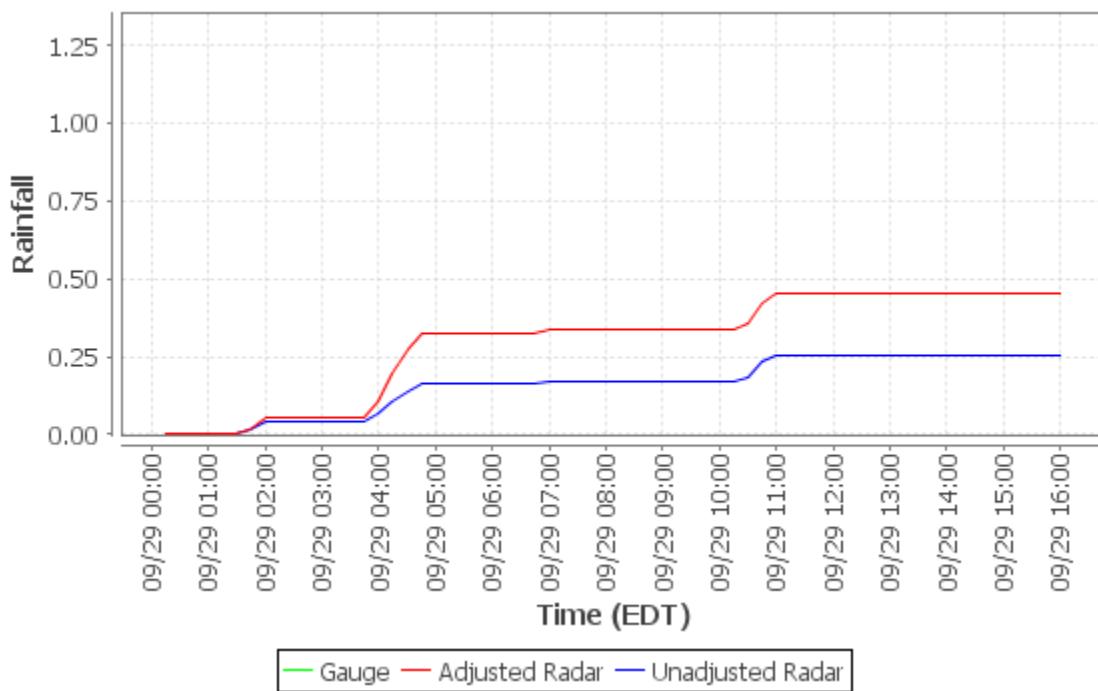
### Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



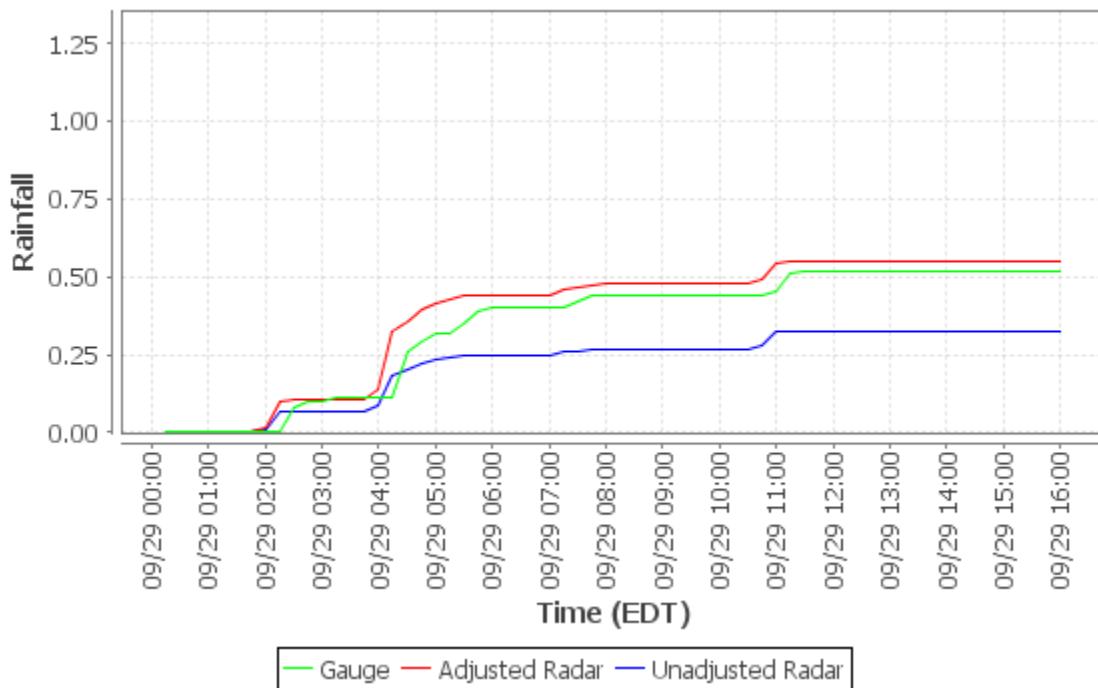
### Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



### Cumulative Distribution Plot - Chartiers Creek at Carnegie (03085500)

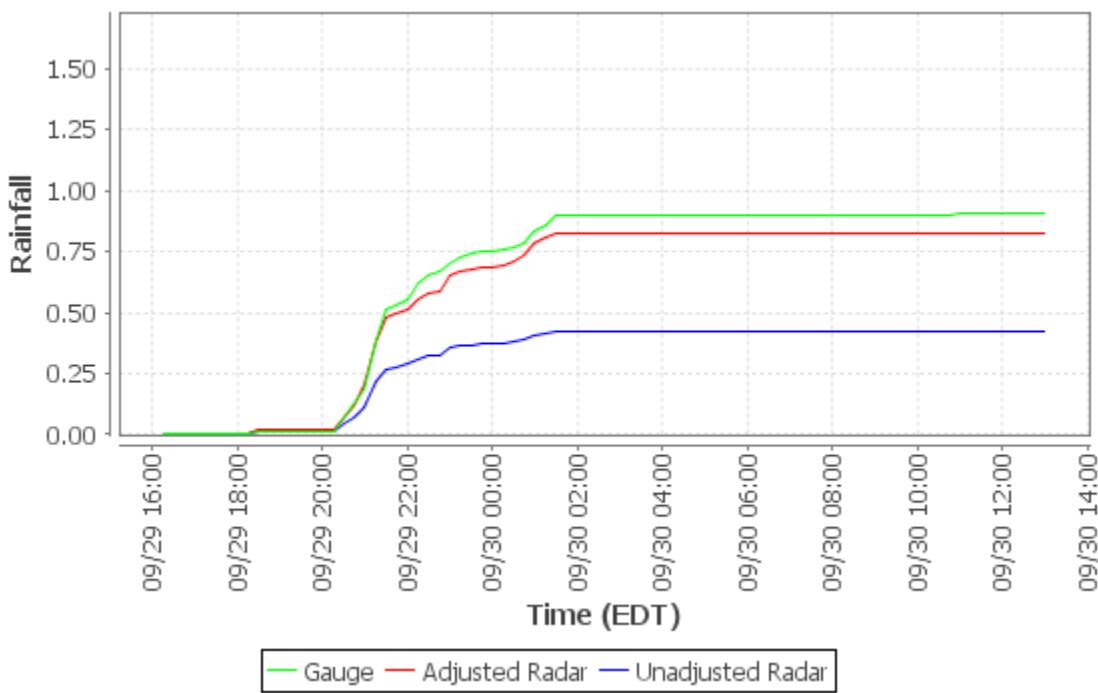


### Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

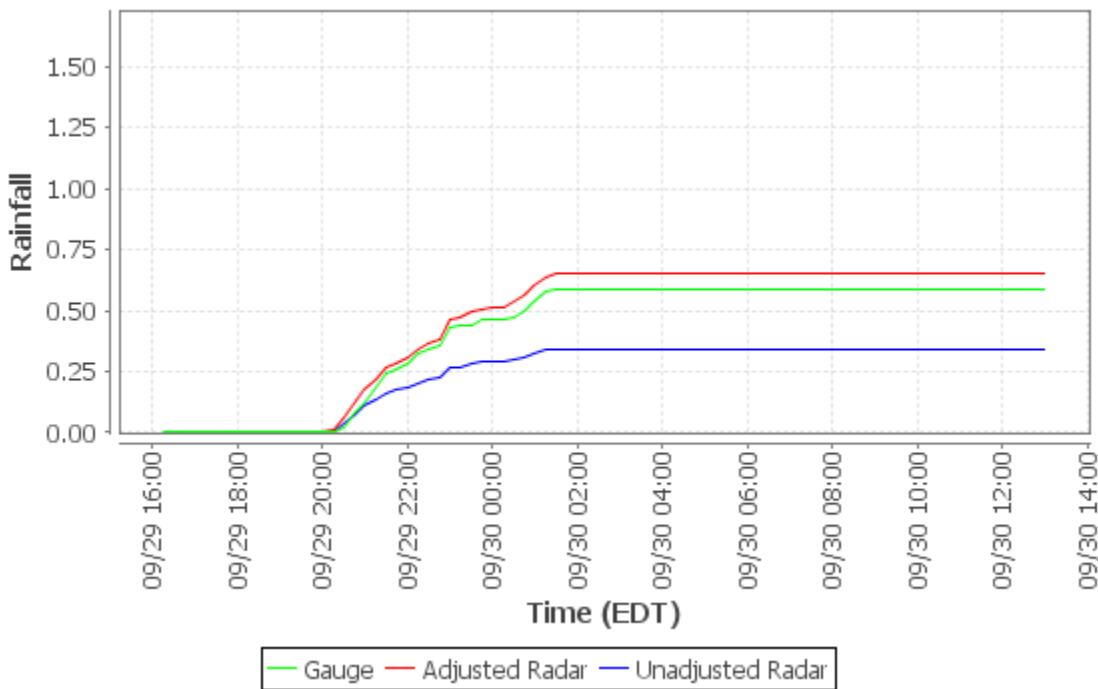


## **Appendix E - Event 4 (2016-09-29 PM) CDPs**

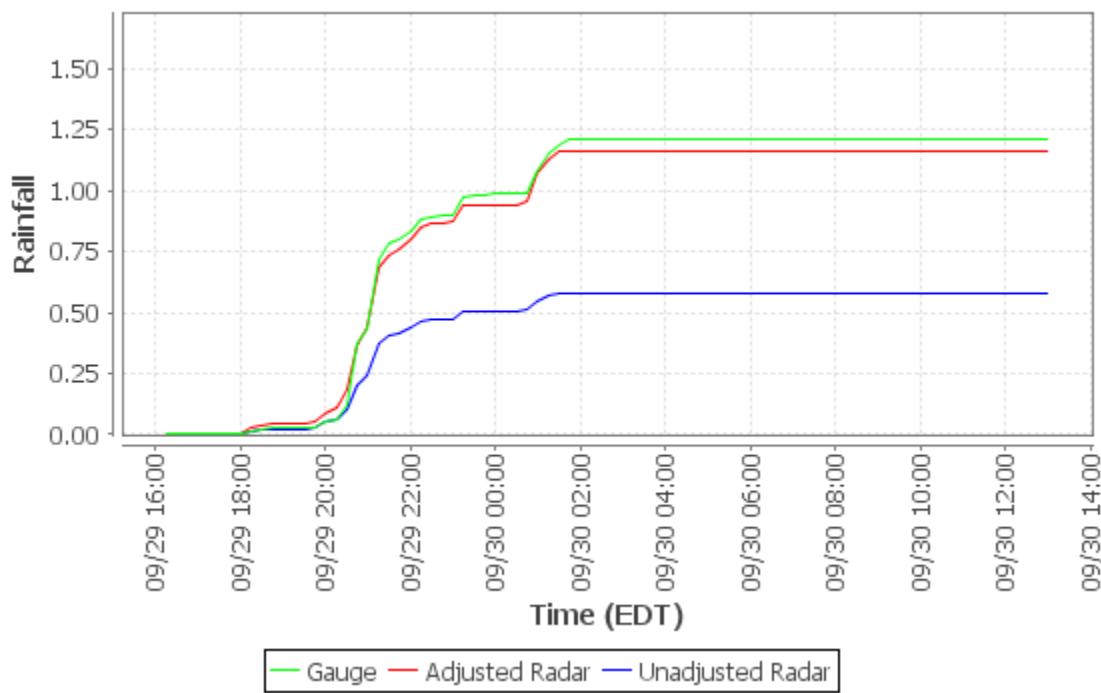
### Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



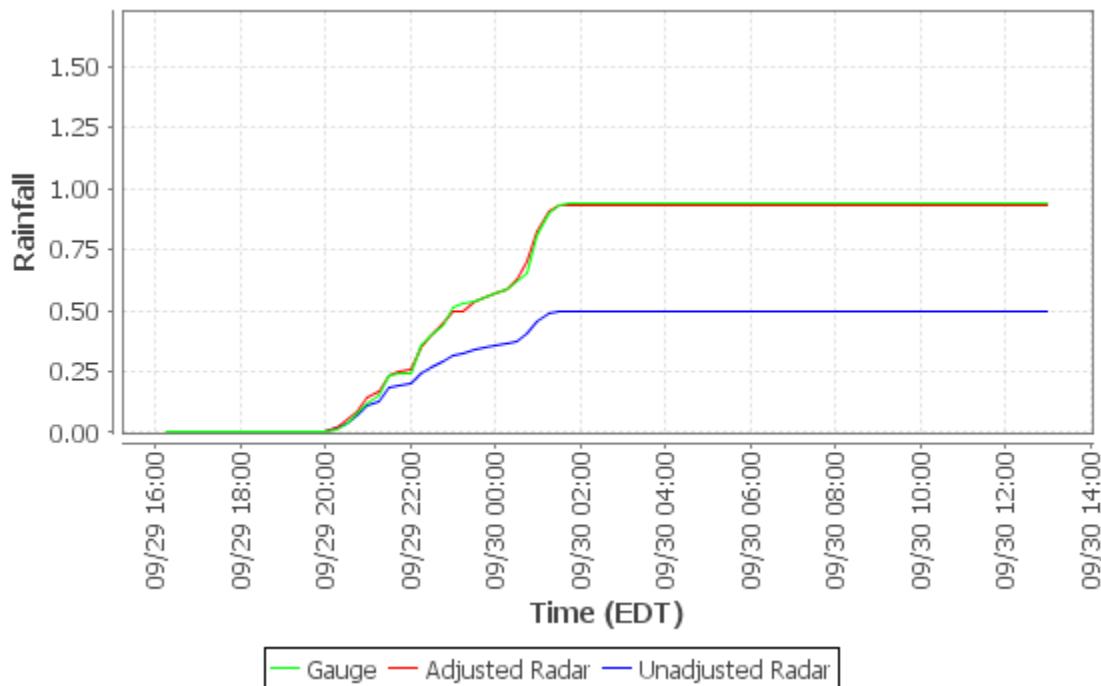
### Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



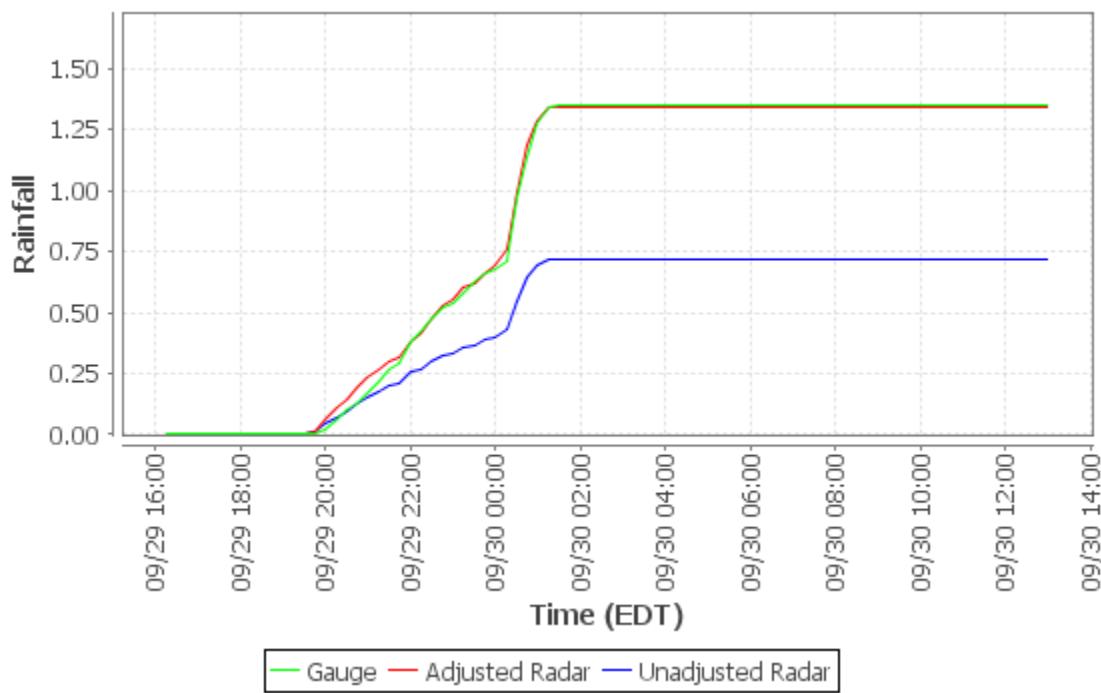
### Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



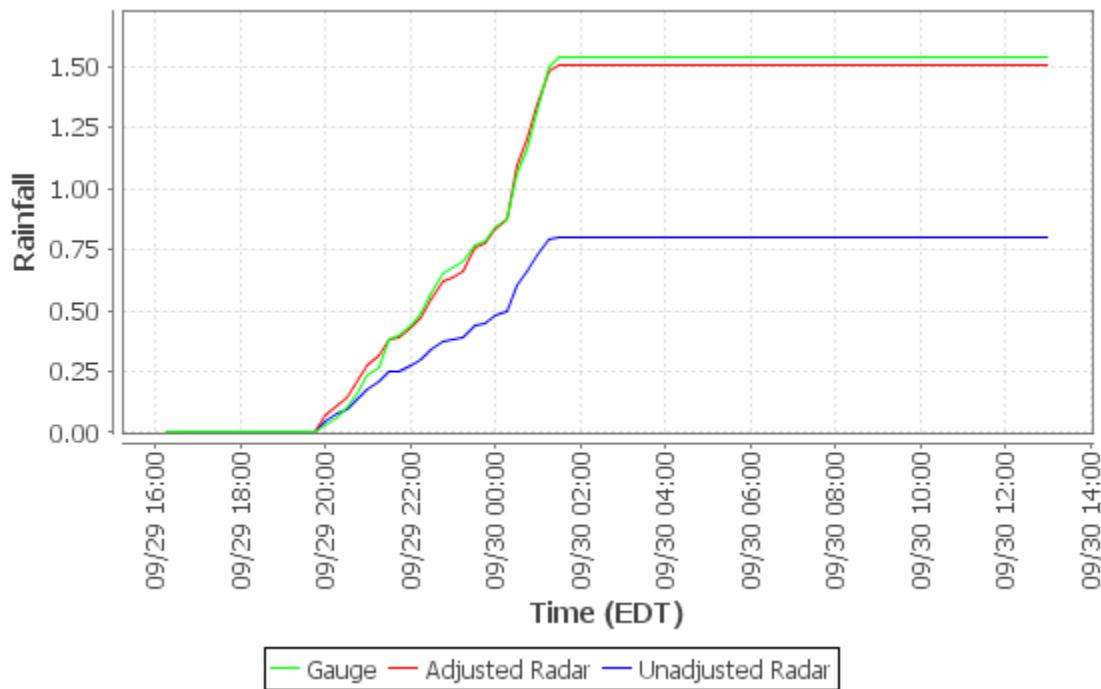
### Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



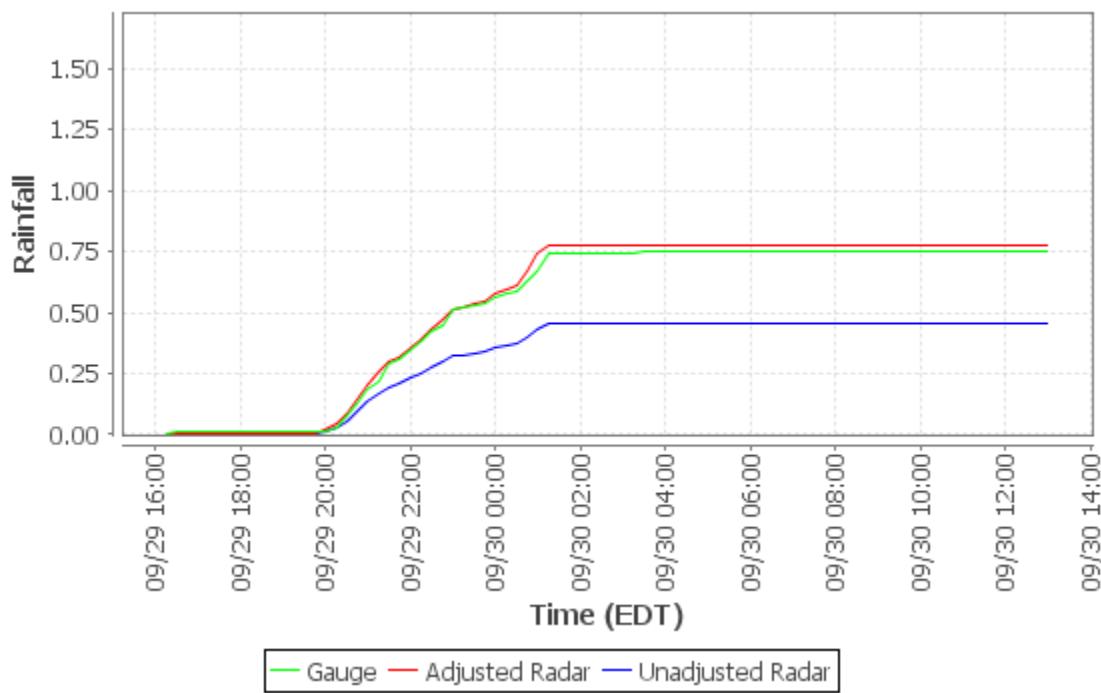
### Cumulative Distribution Plot - Upper St. Clair (Loc05)



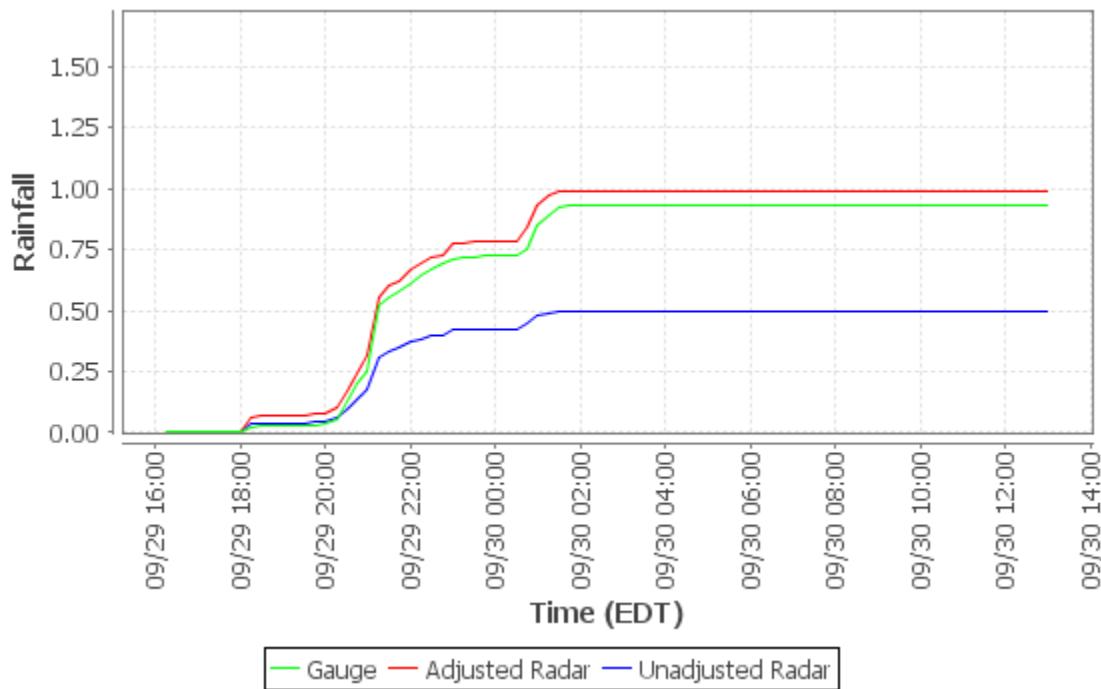
### Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



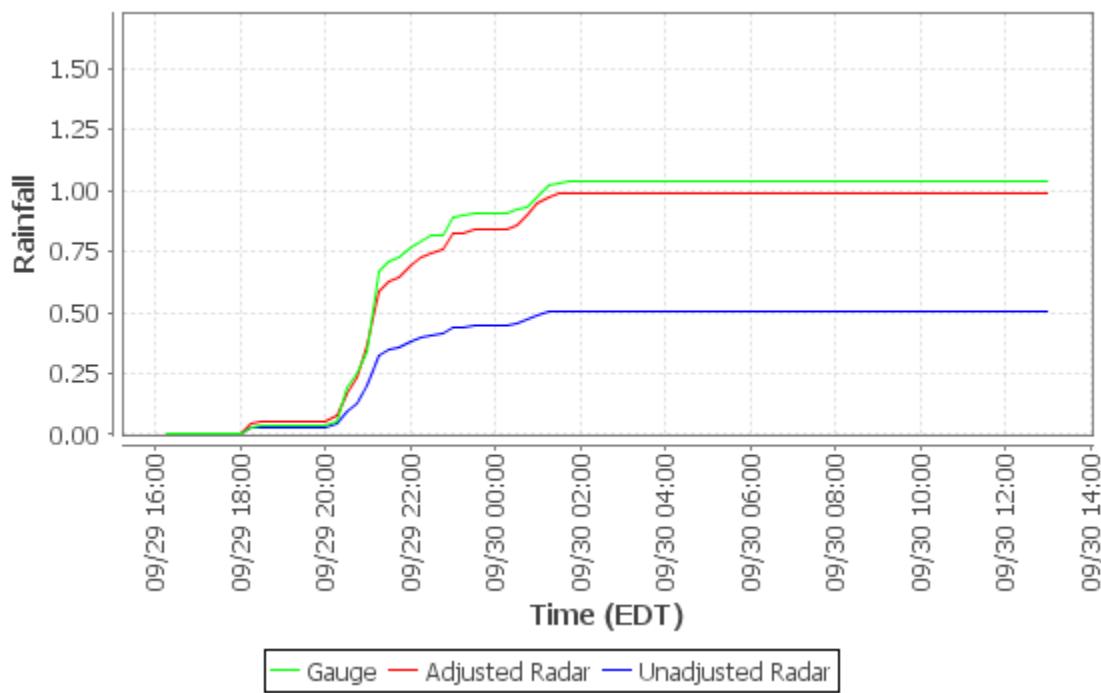
### Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



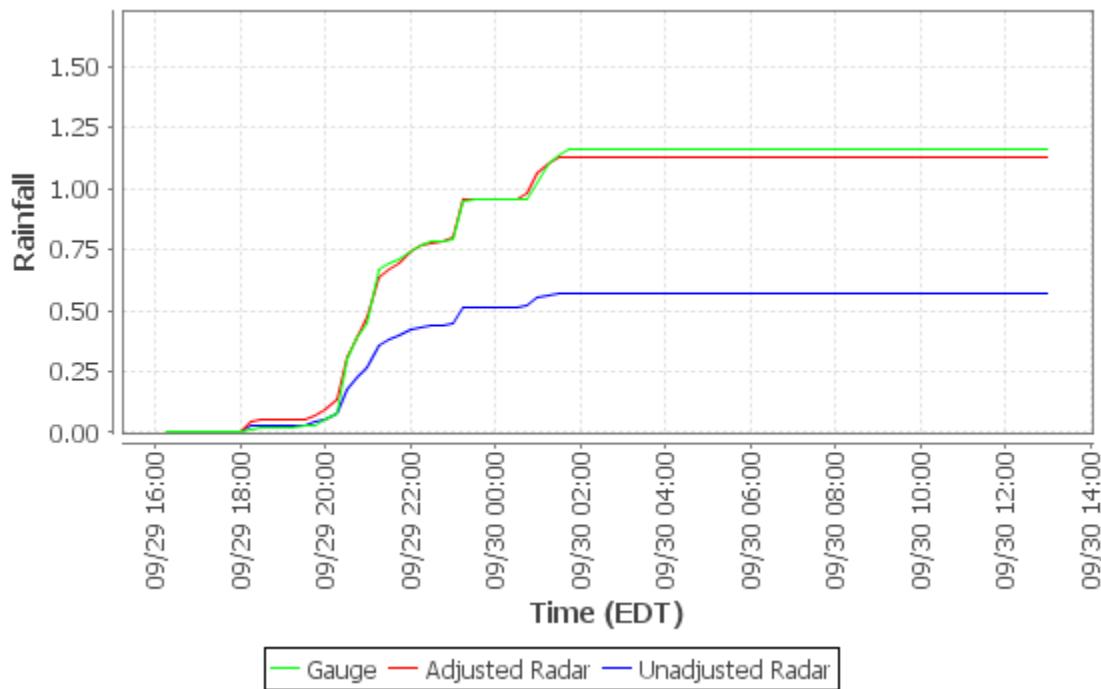
### Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



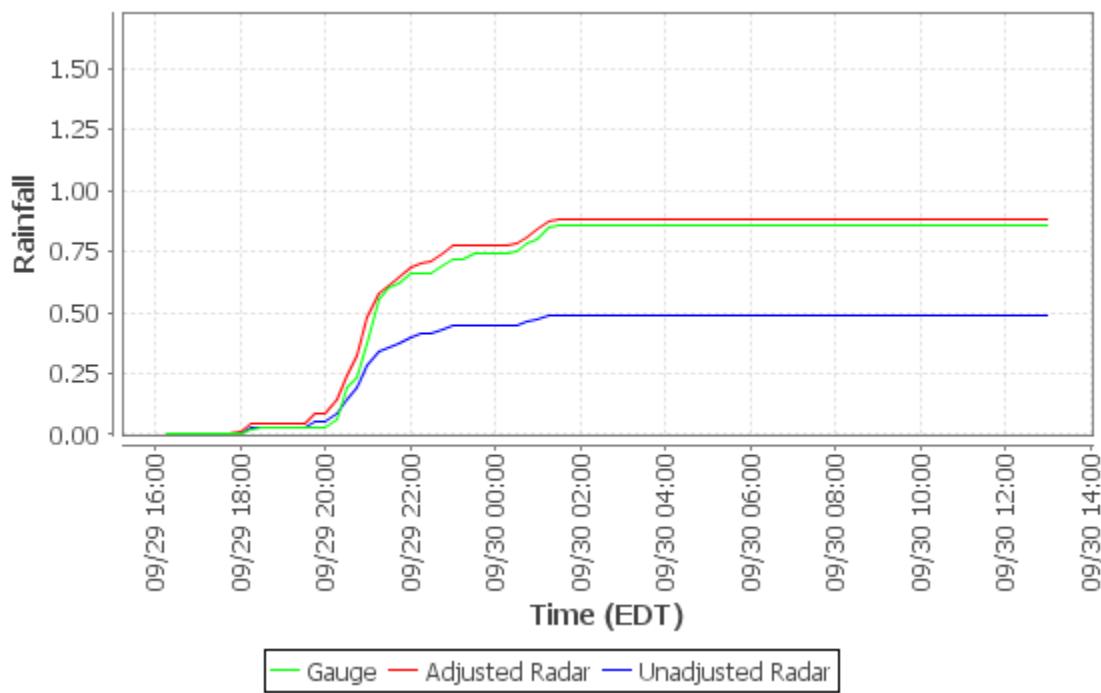
### Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



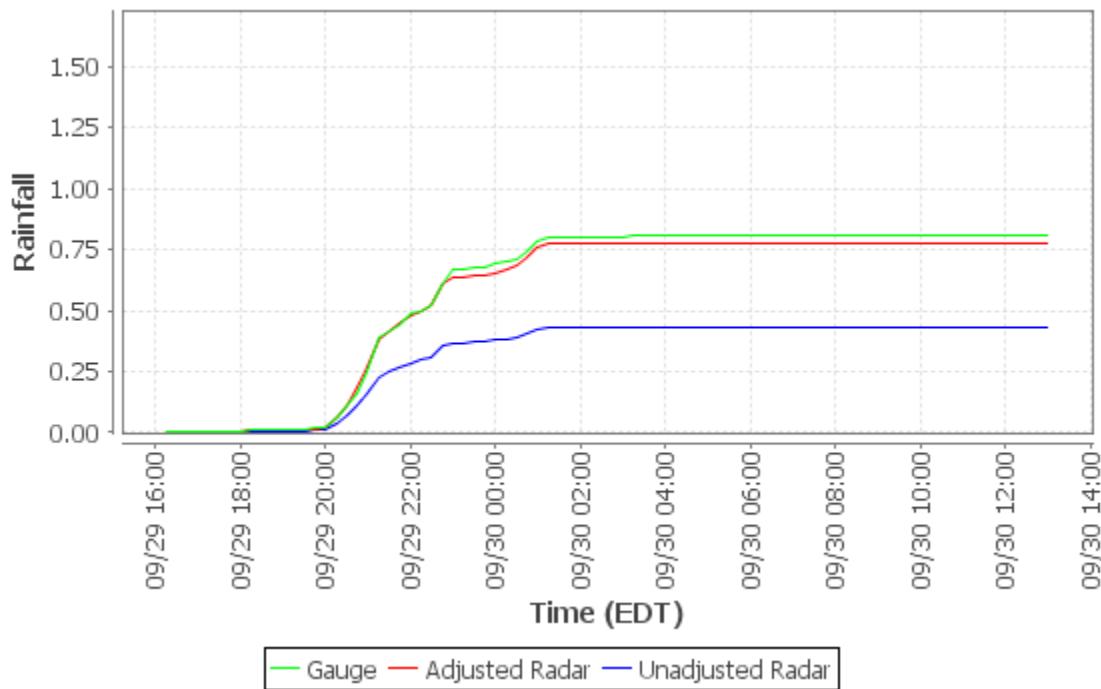
### Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



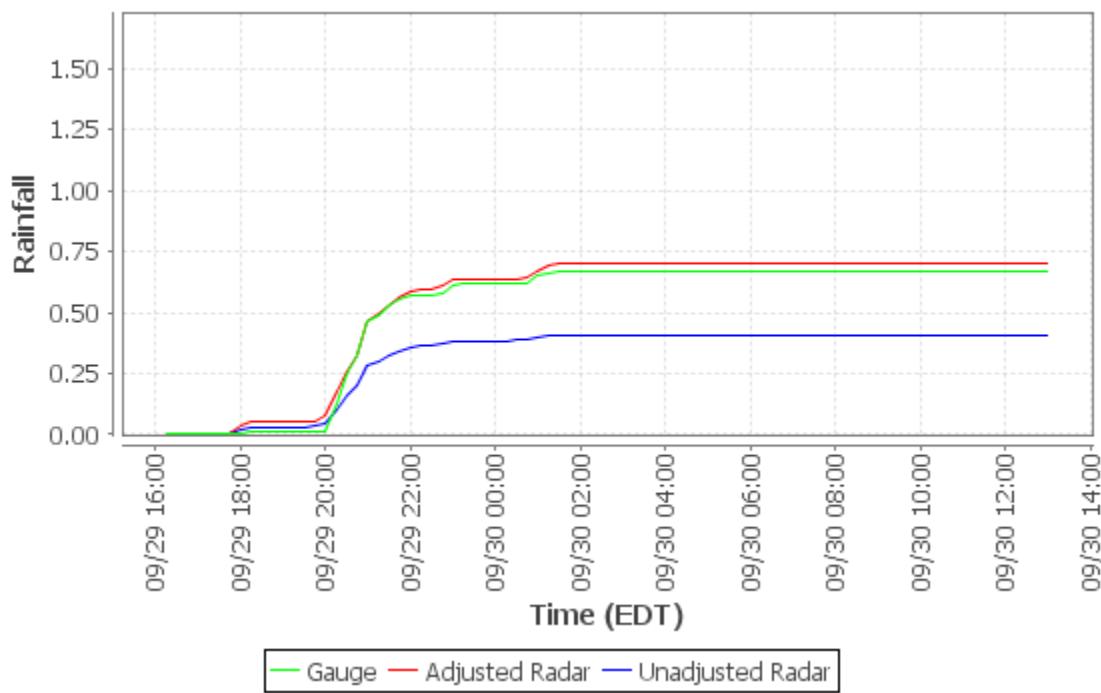
### Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



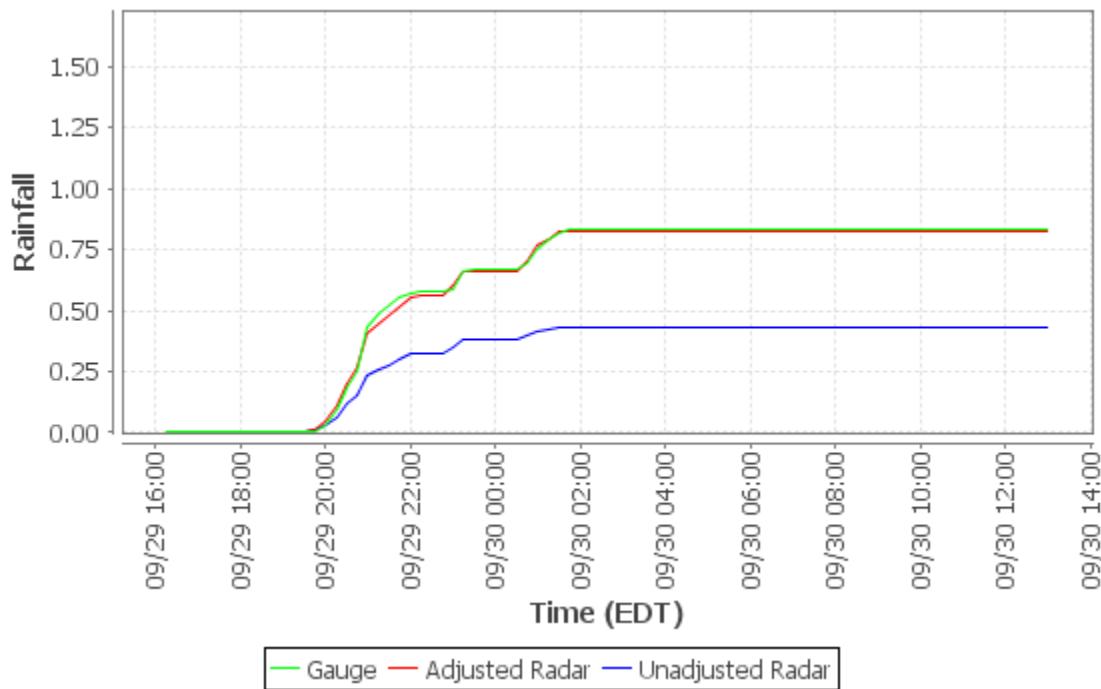
### Cumulative Distribution Plot - Baldwin (Loc12)



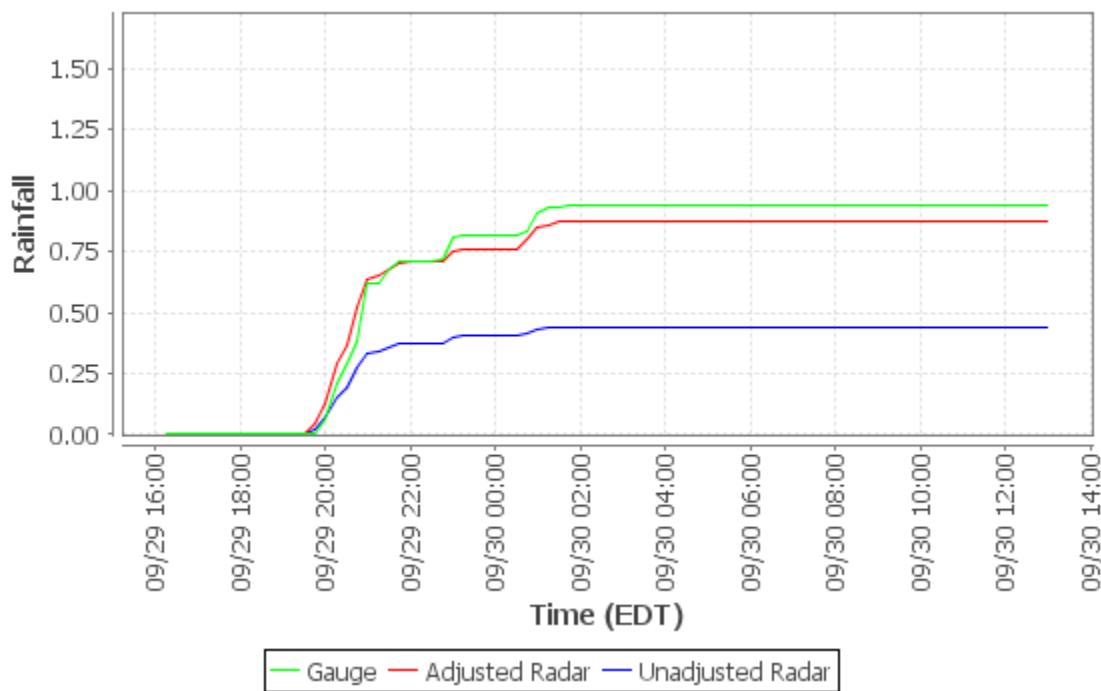
### Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



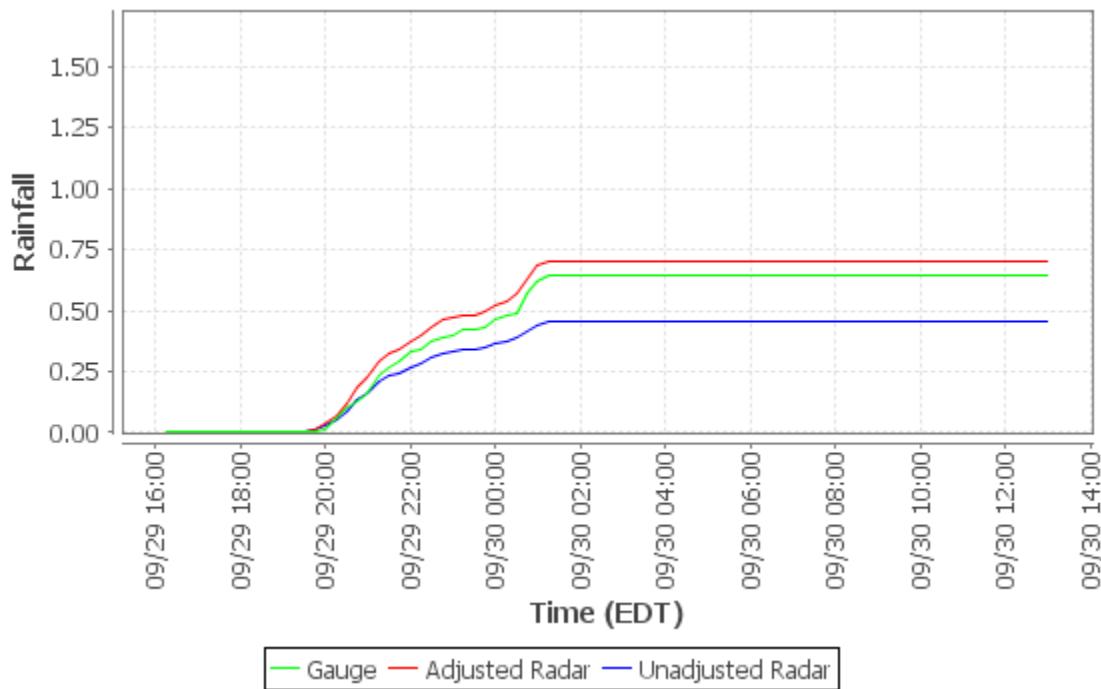
### Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



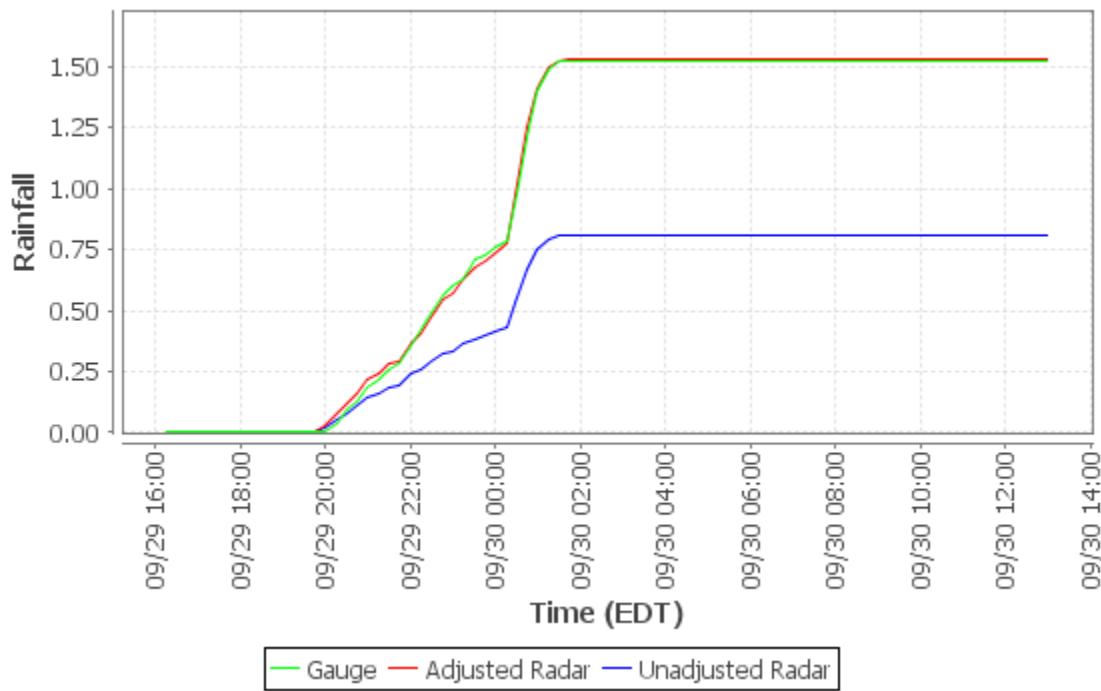
### Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



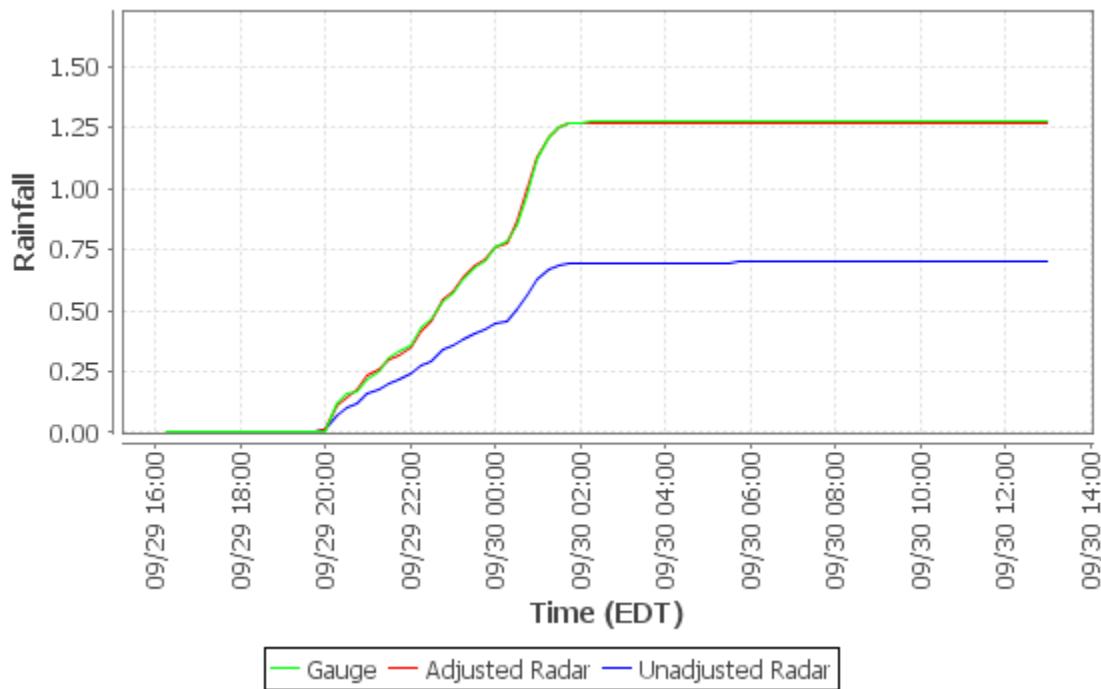
### Cumulative Distribution Plot - Castle Shannon (Loc16)



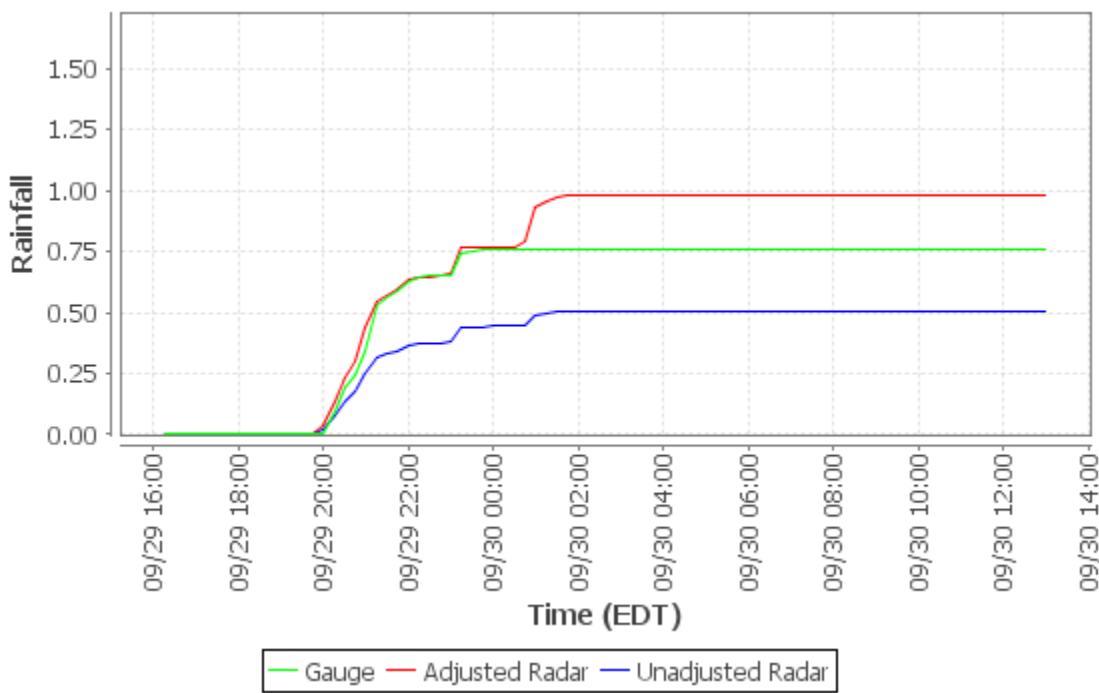
### Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



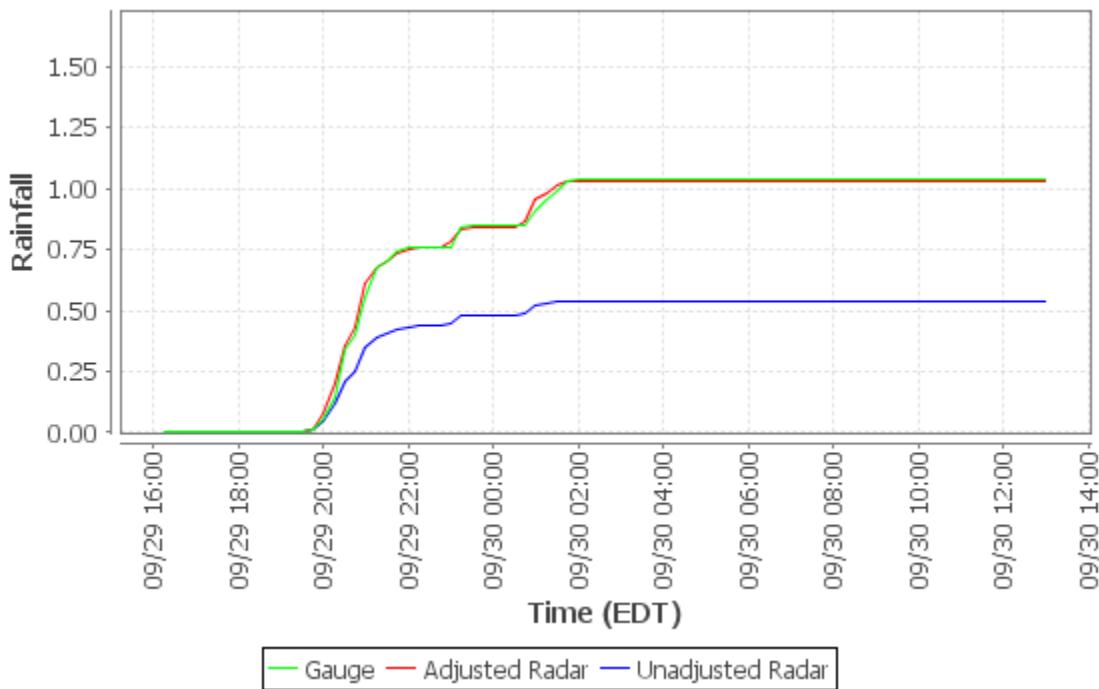
### Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



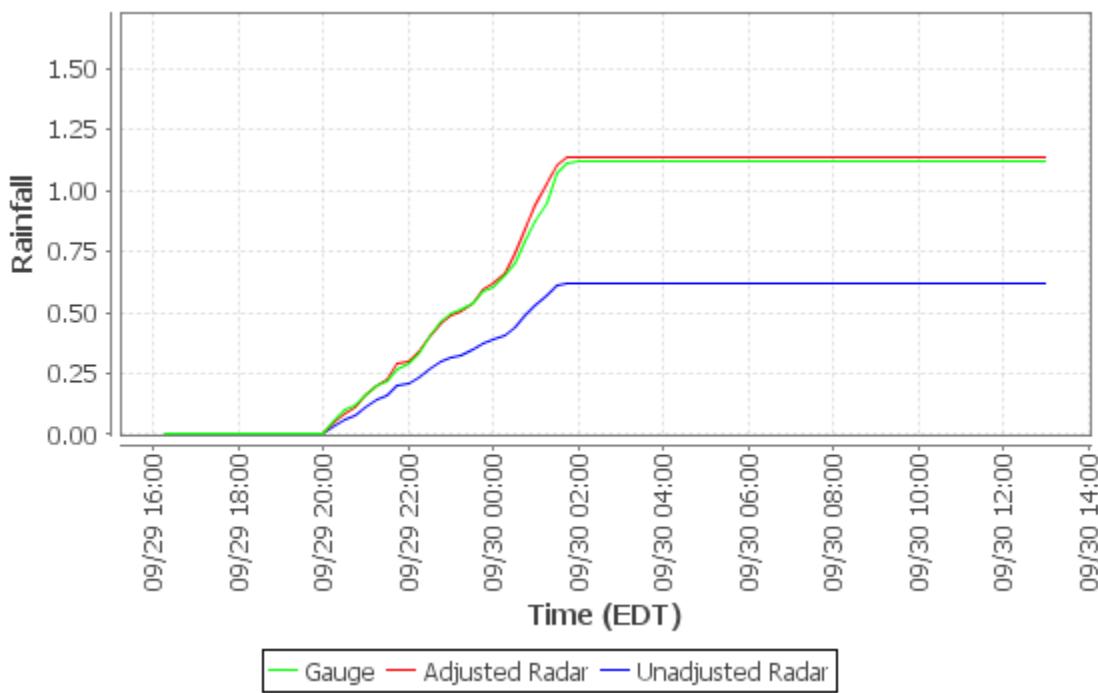
### Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



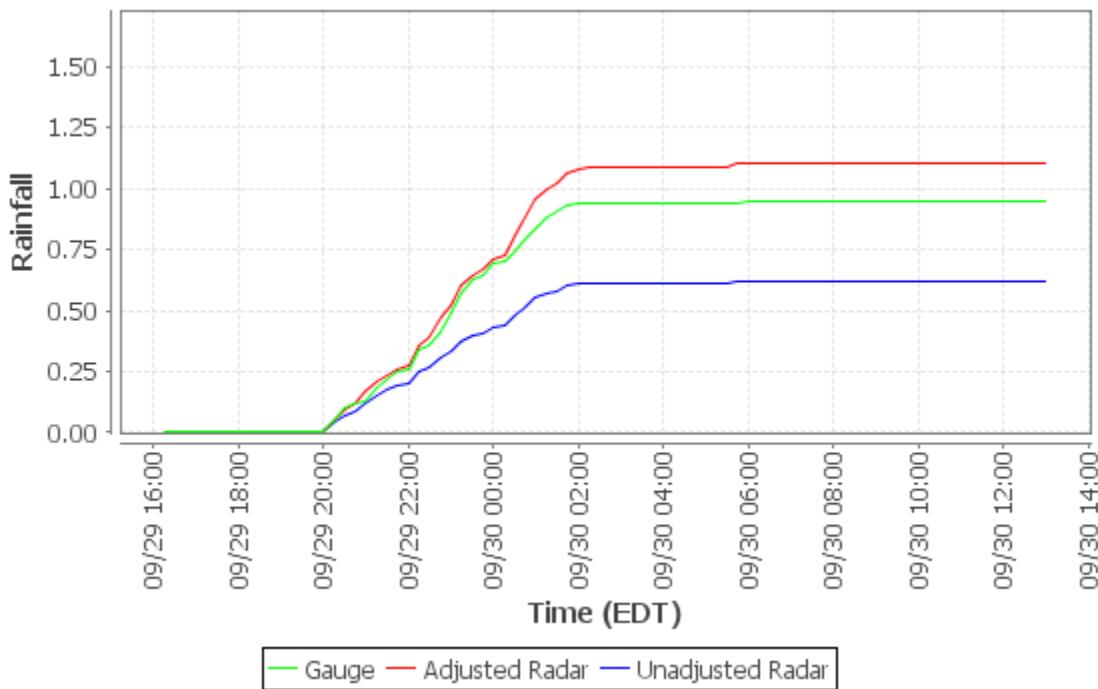
### Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



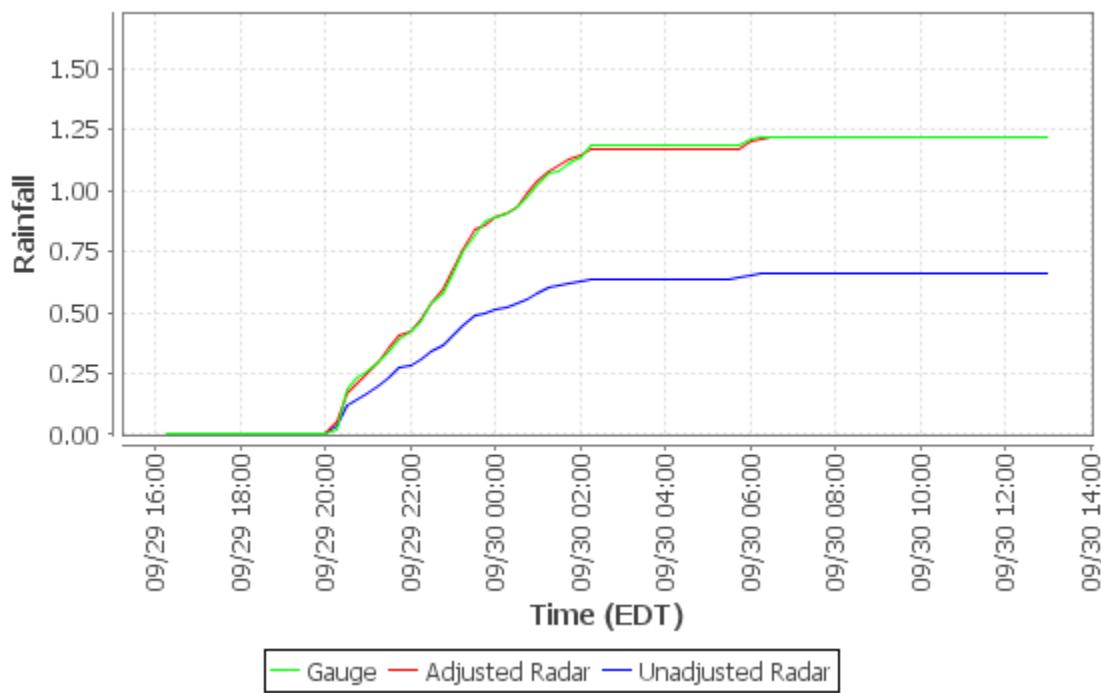
### Cumulative Distribution Plot - Moon TWP (Loc21)



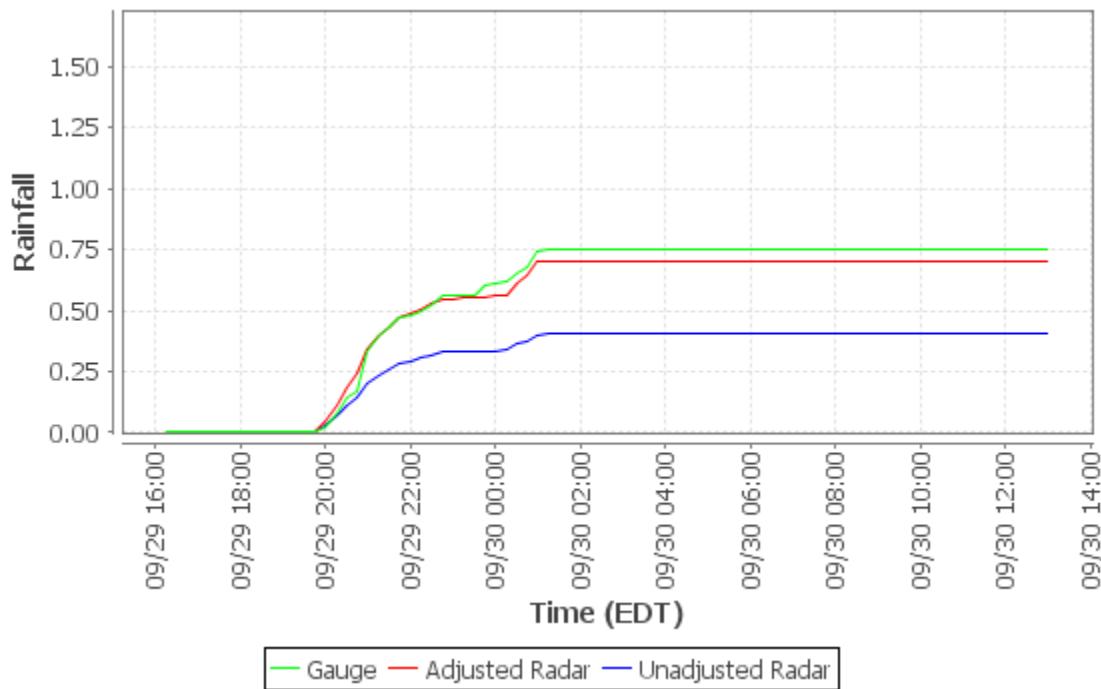
### Cumulative Distribution Plot - North Fayette TWP (Loc22)



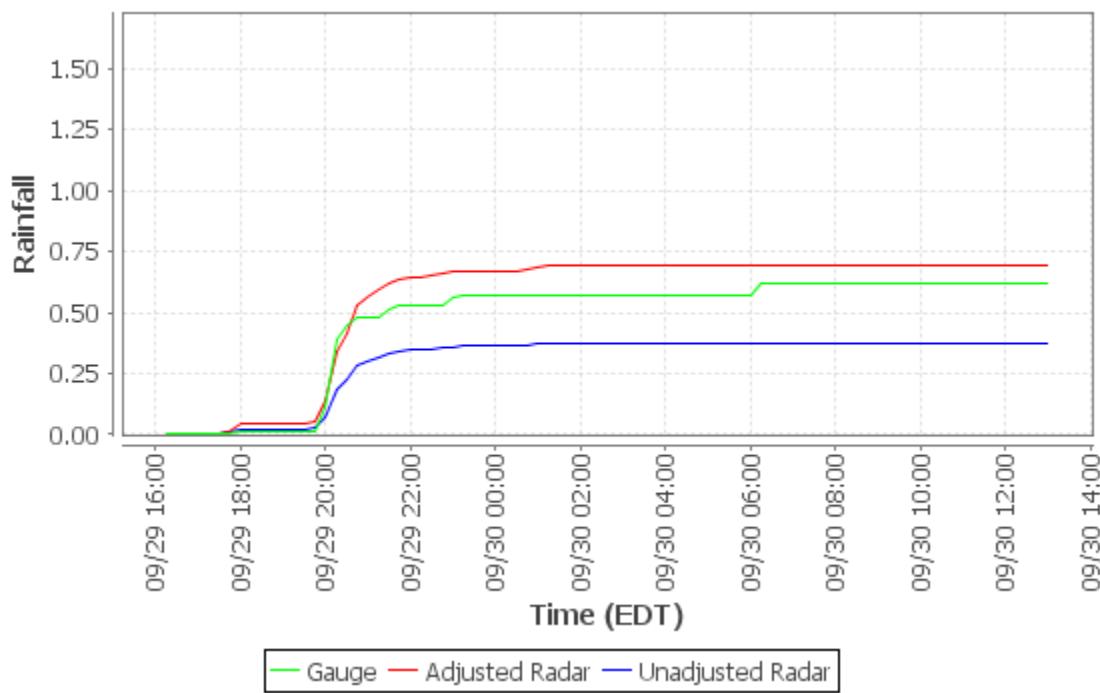
### Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



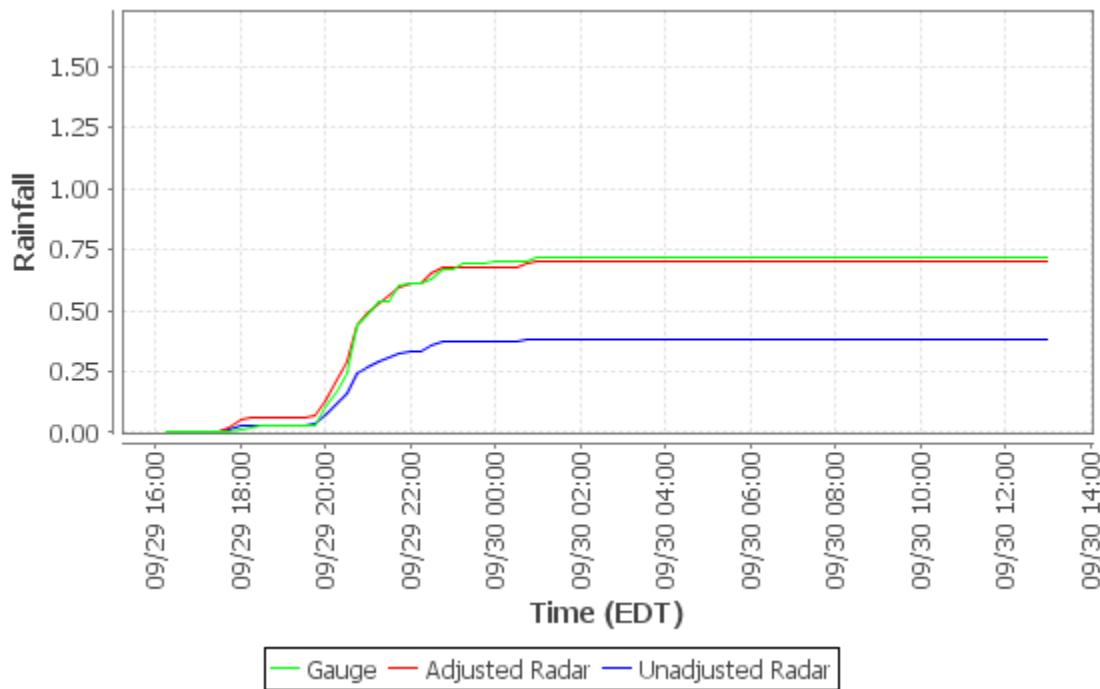
### Cumulative Distribution Plot - Jefferson Hills (Loc24)



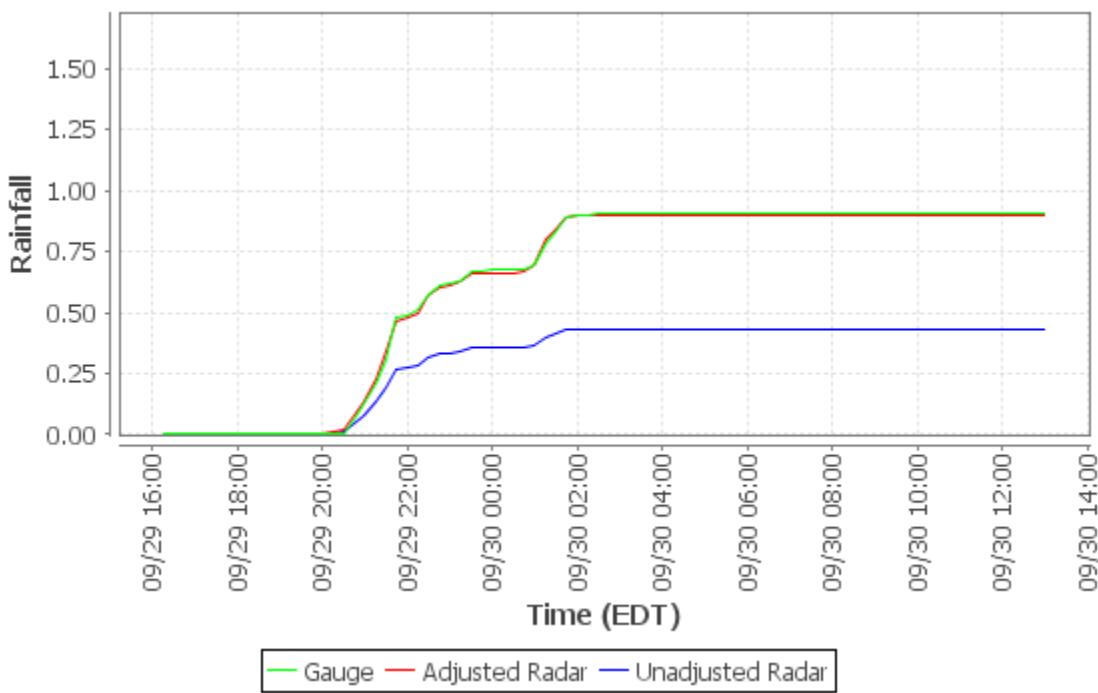
### Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



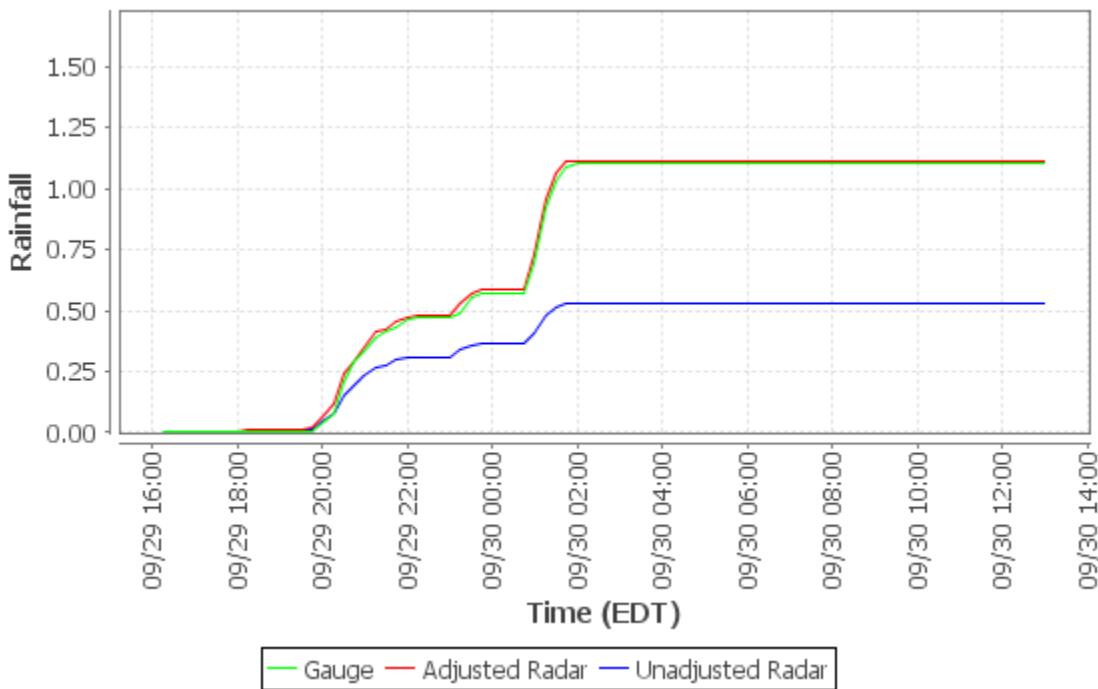
### Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



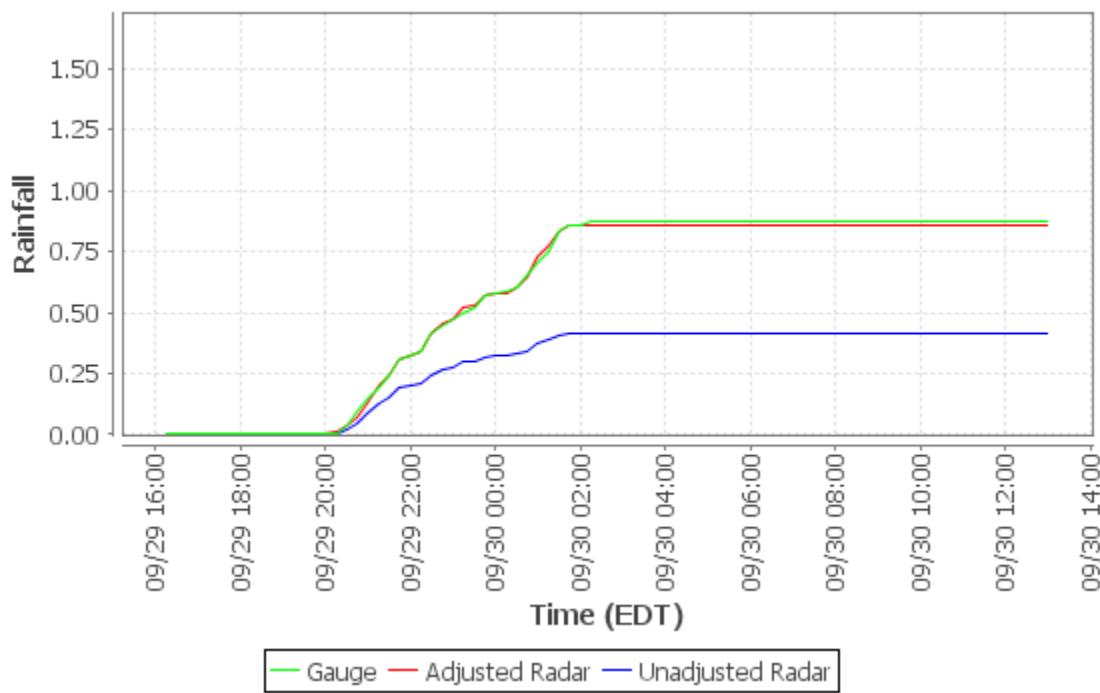
### Cumulative Distribution Plot - Marshall TWP (Loc27)



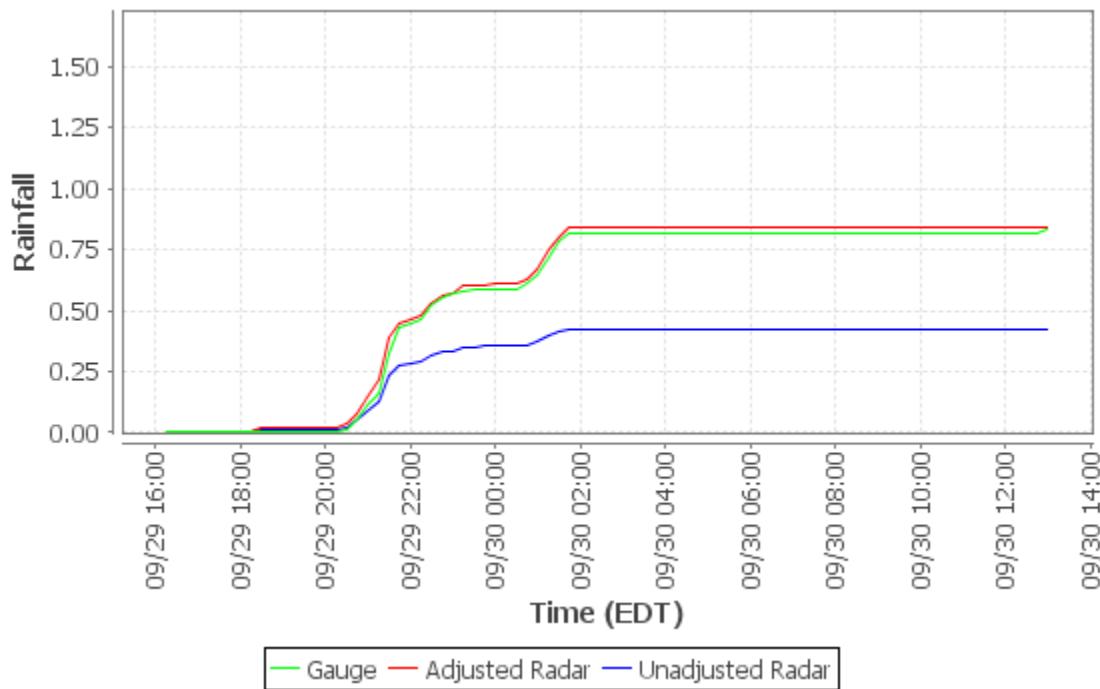
### Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



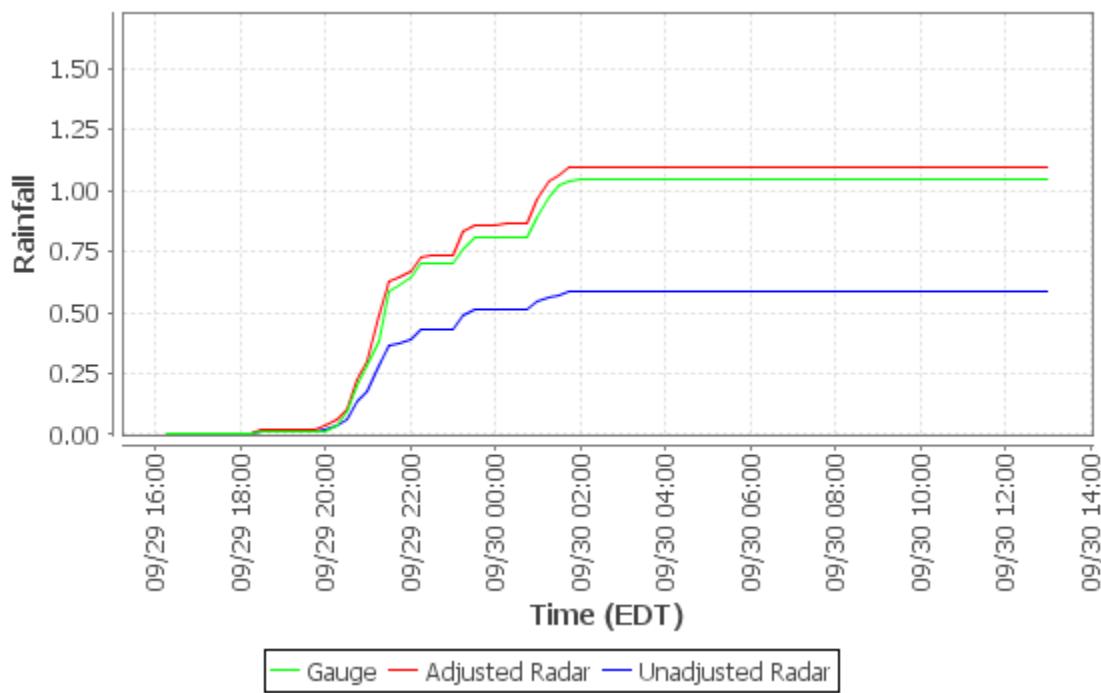
### Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



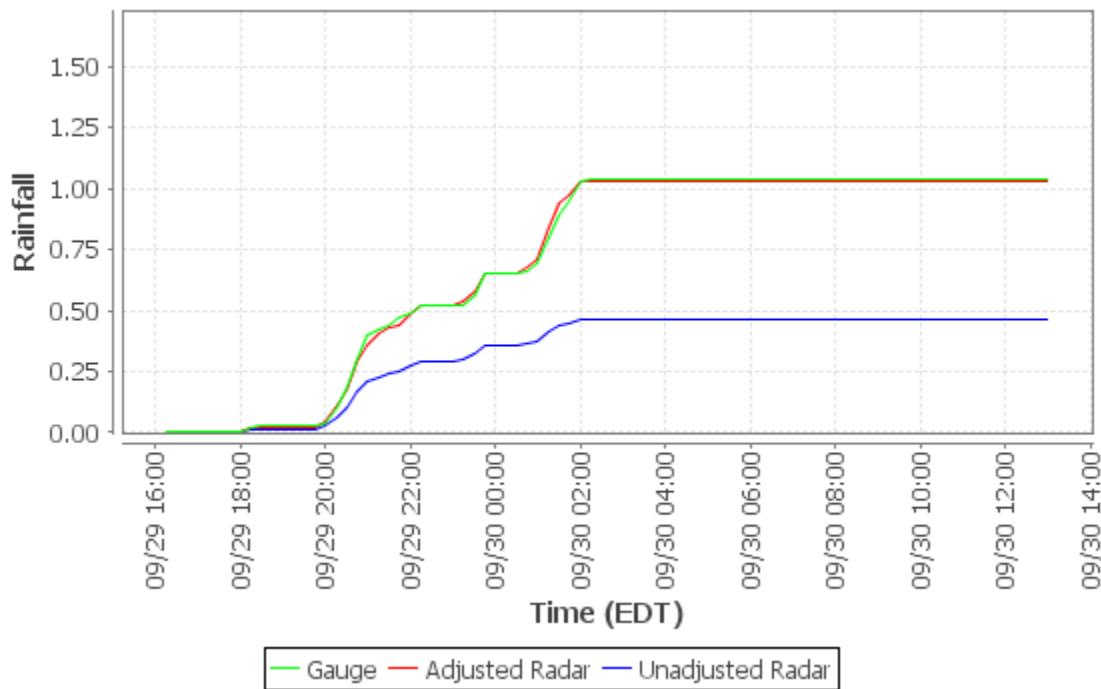
### Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



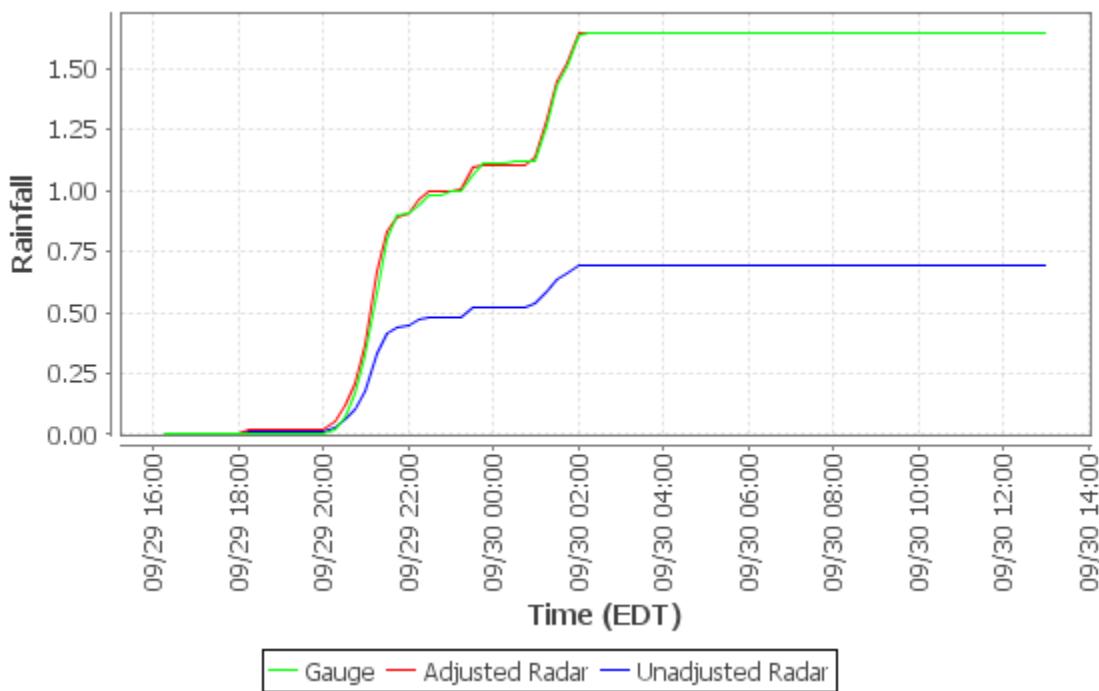
### Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



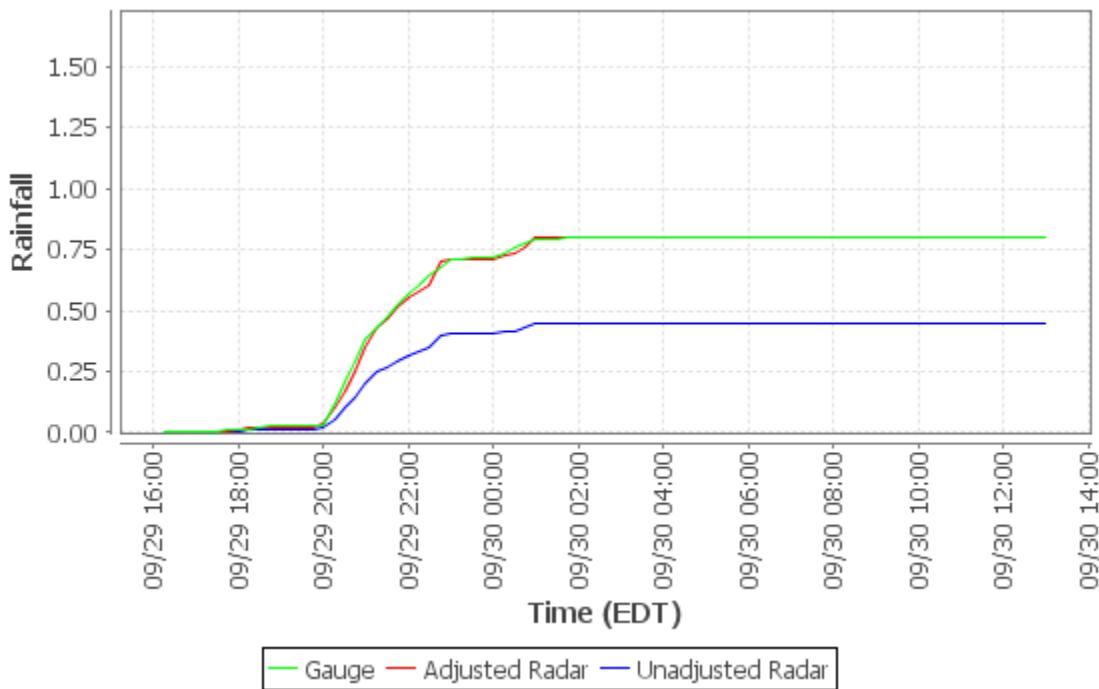
### Cumulative Distribution Plot - Arnold (Loc32)



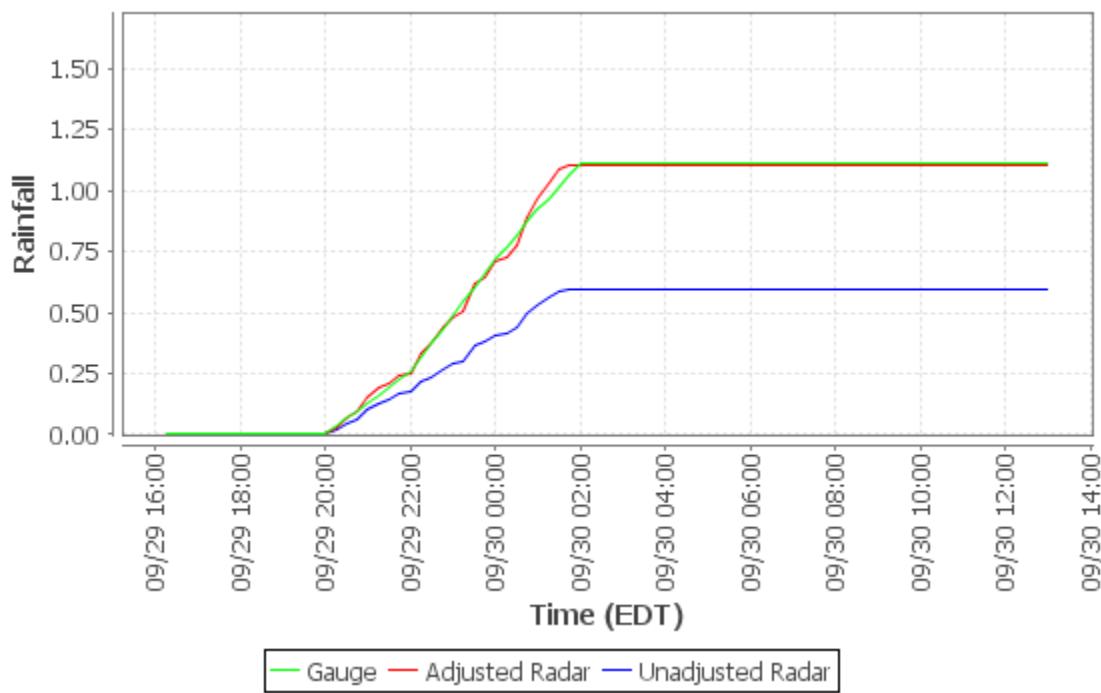
### Cumulative Distribution Plot - Richland TWP (Loc33)



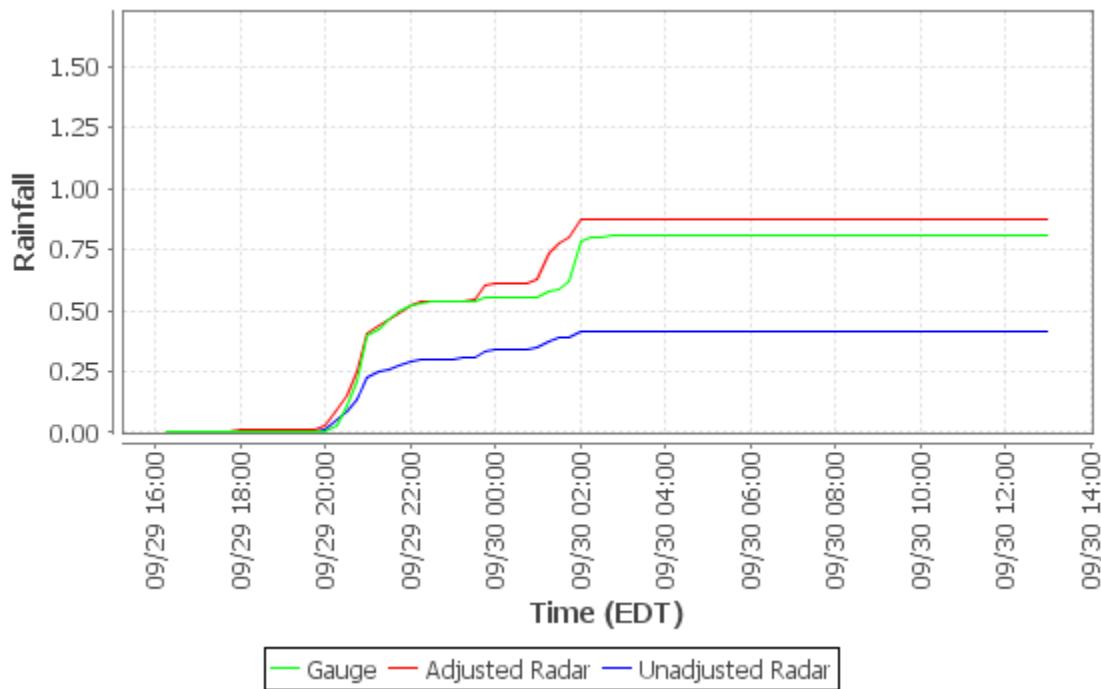
### Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



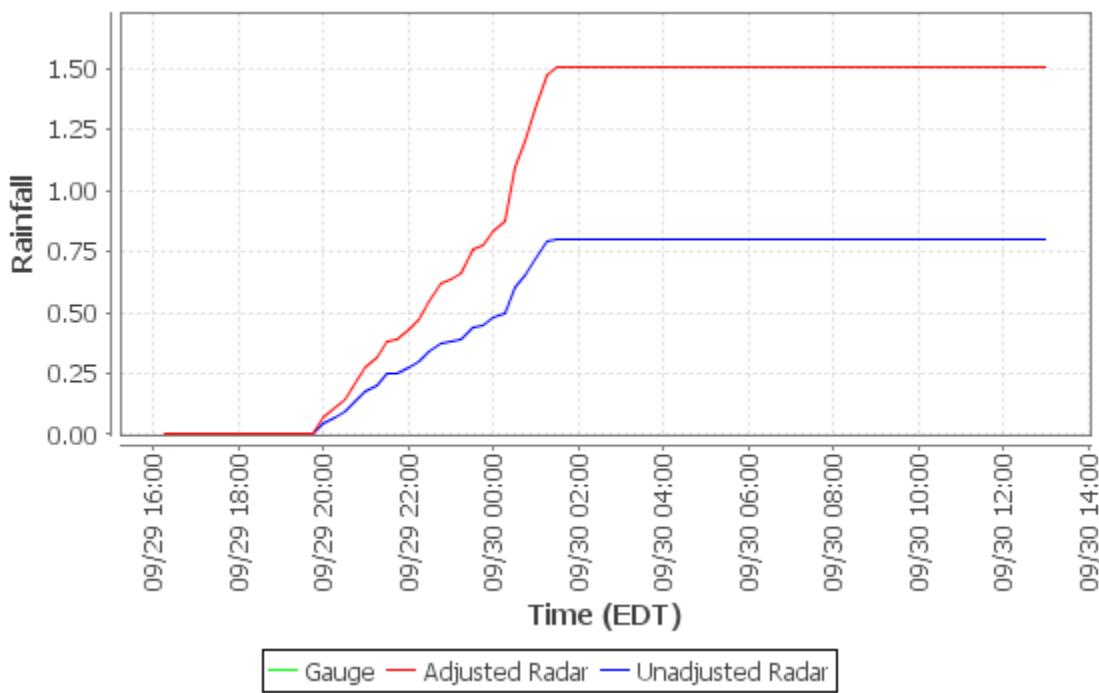
### Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



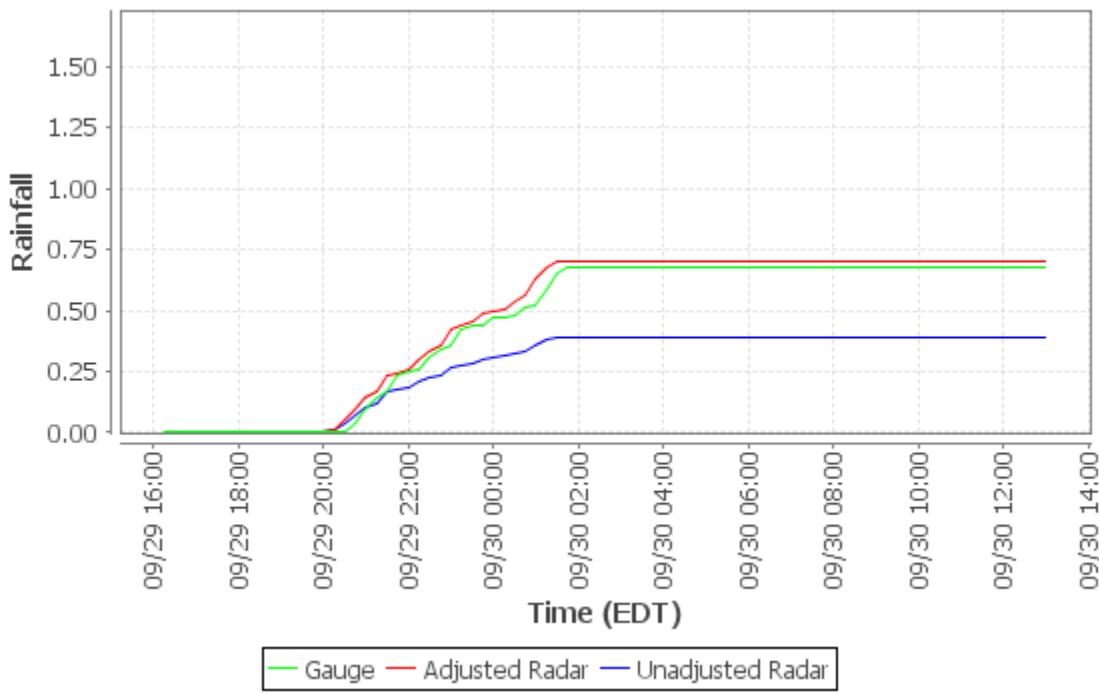
### Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



### Cumulative Distribution Plot - Chartiers Creek at Carnegie (03085500)

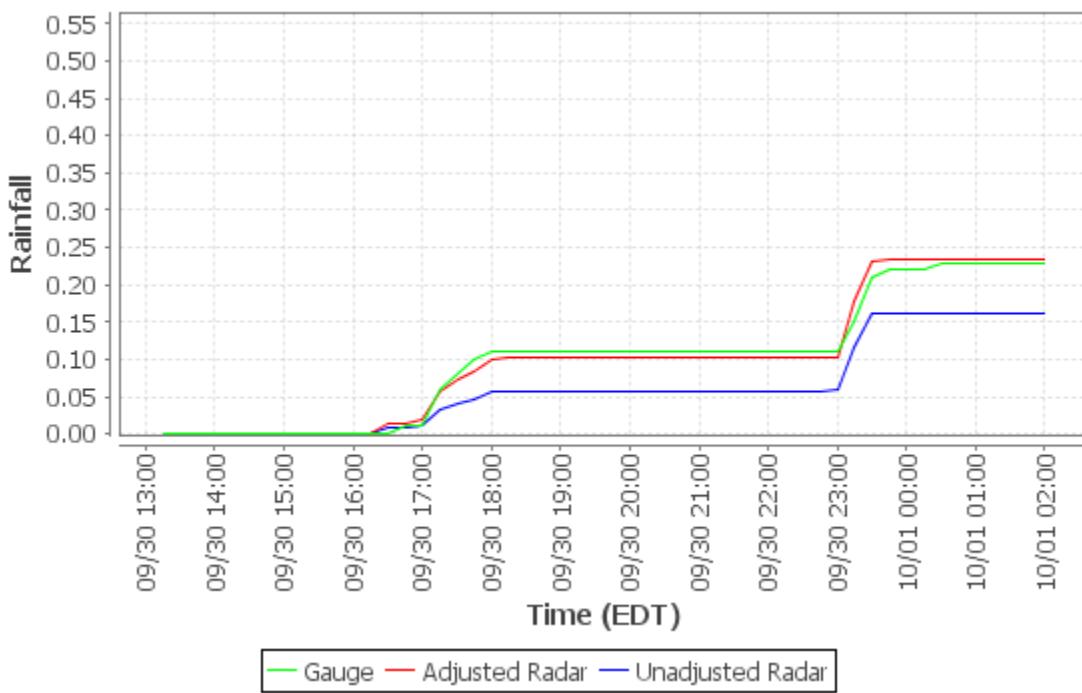


### Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

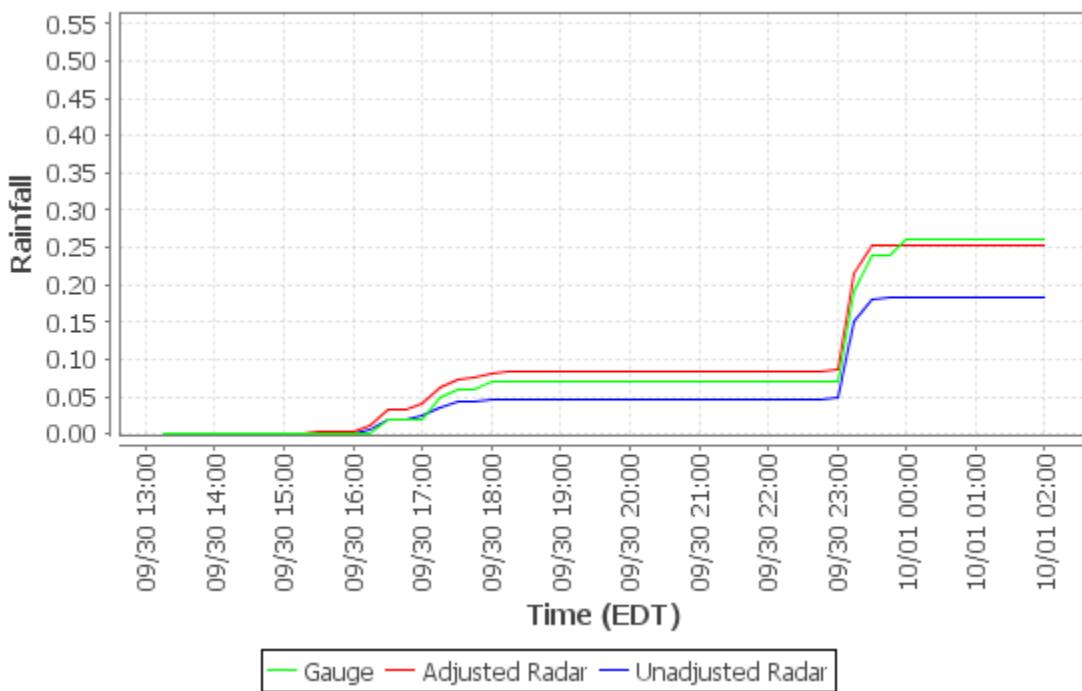


## **Appendix F - Event 5 (2016-09-30) CDPs**

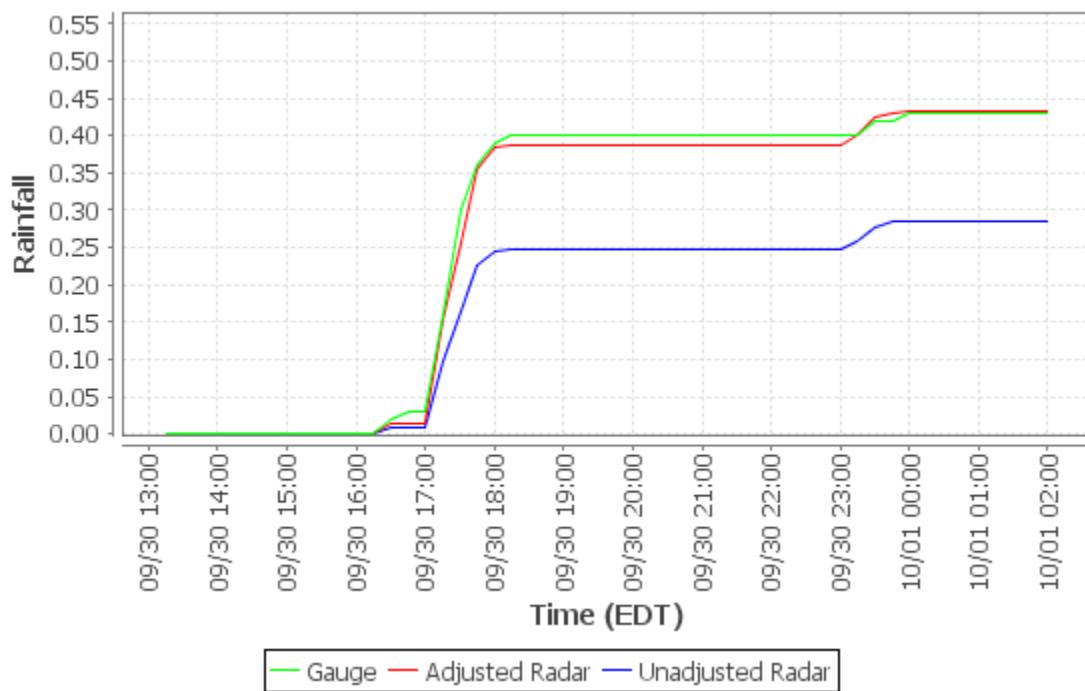
### Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



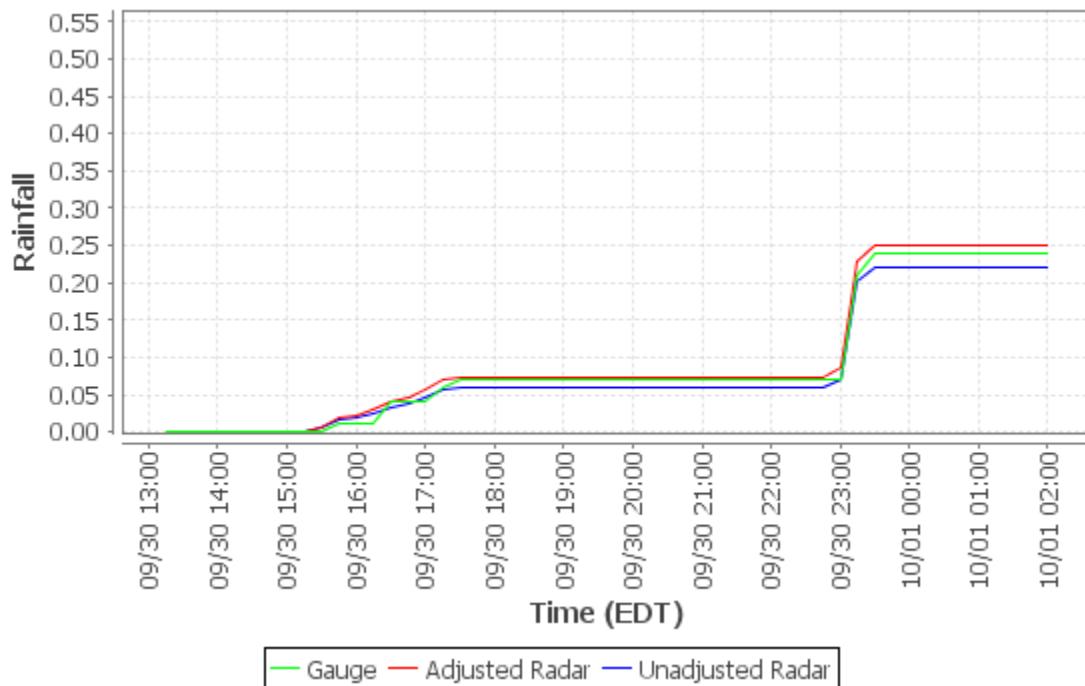
### Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



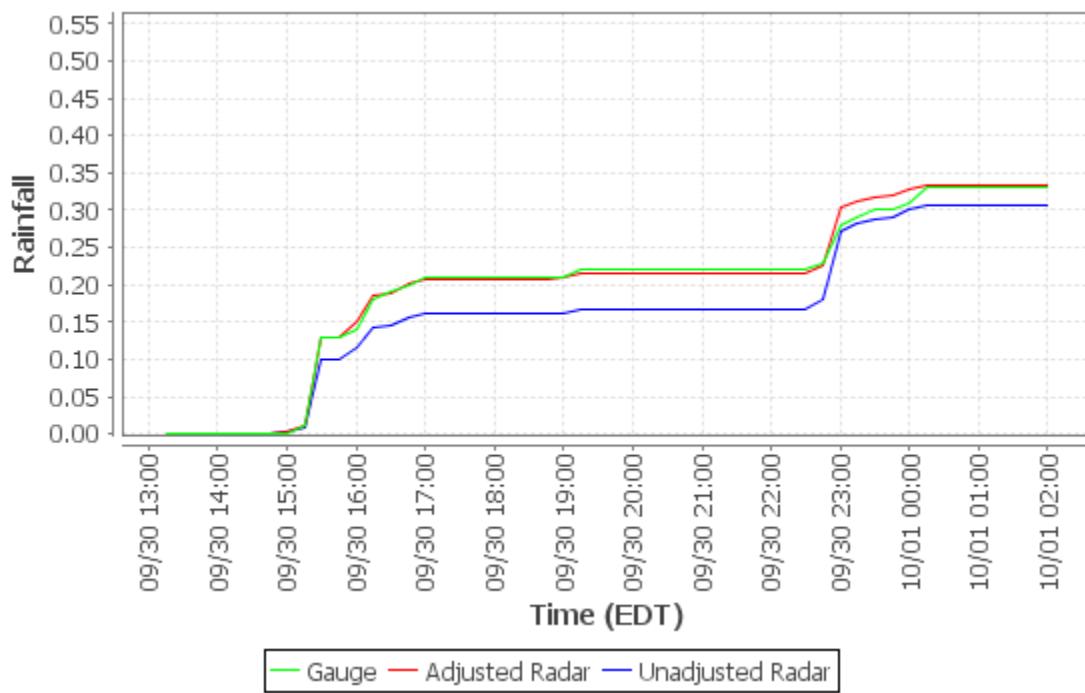
### Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



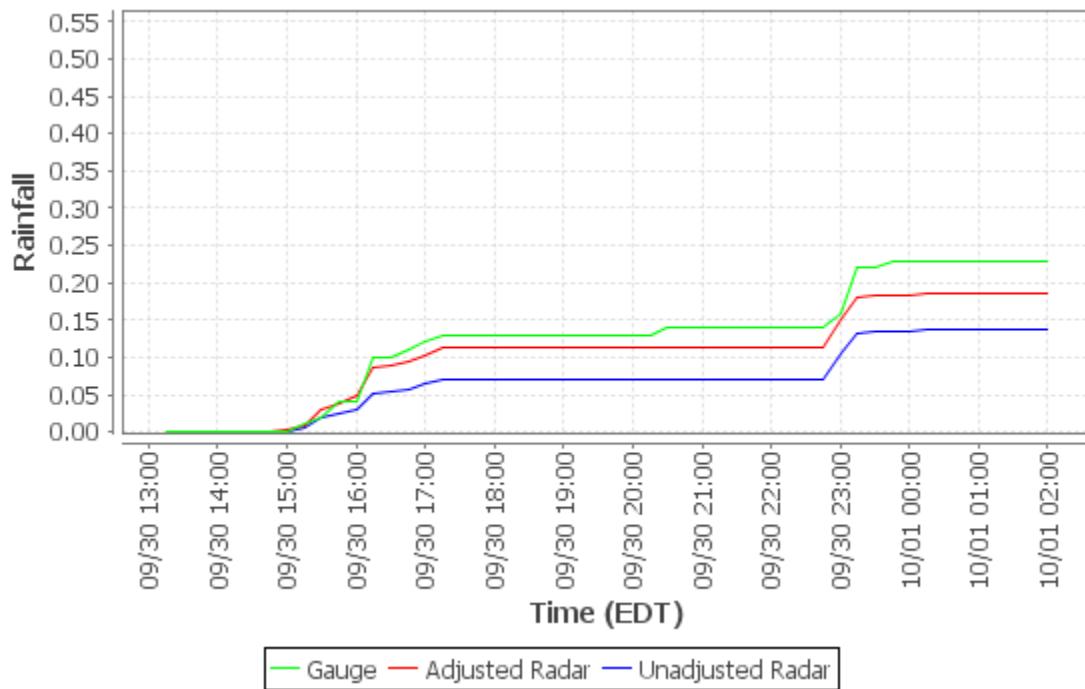
### Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



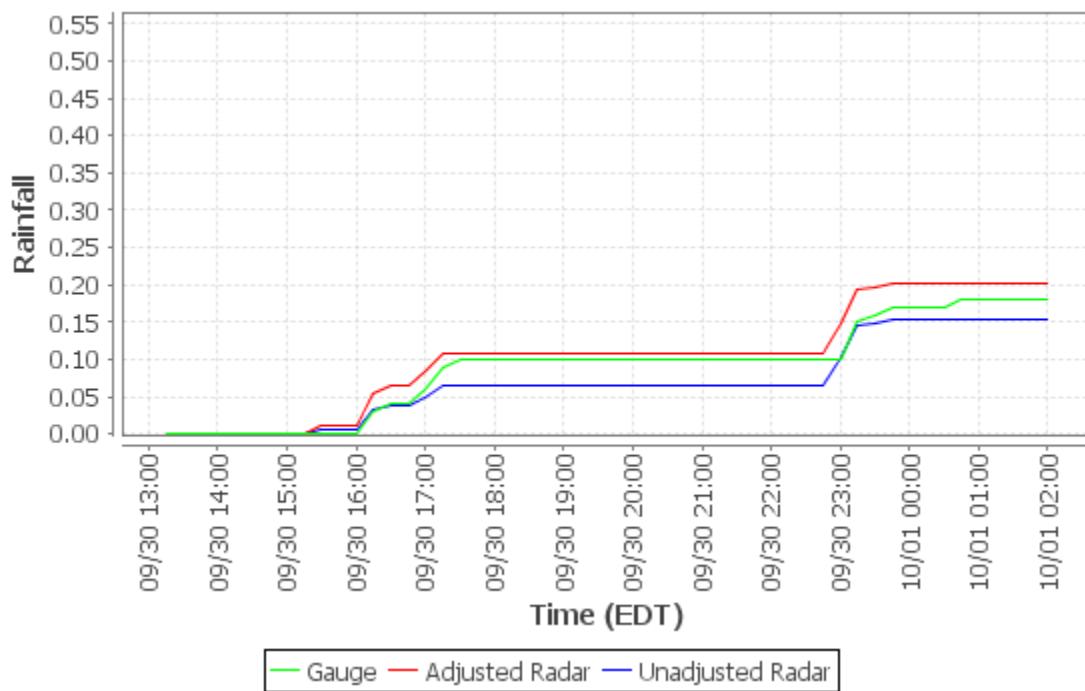
### Cumulative Distribution Plot - Upper St. Clair (Loc05)



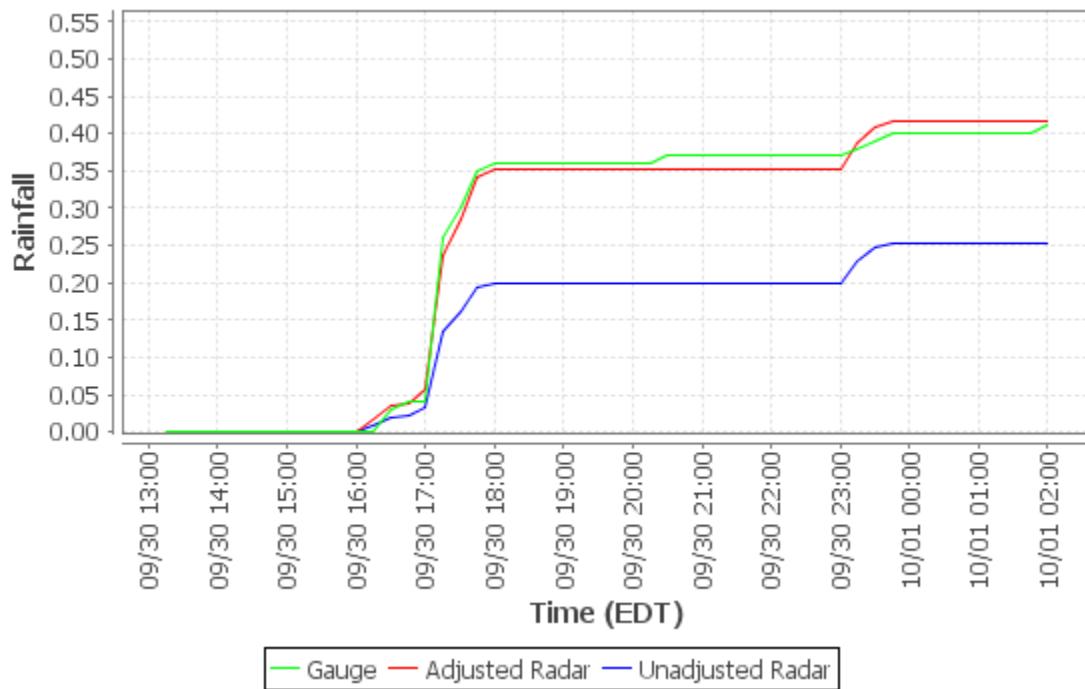
### Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



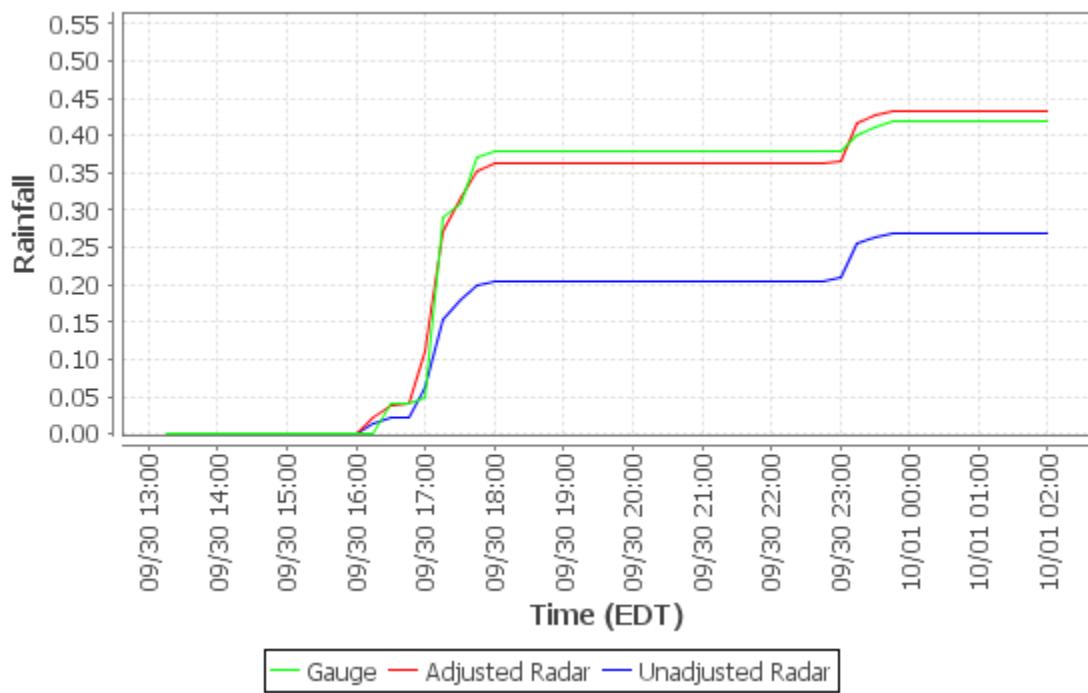
### Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



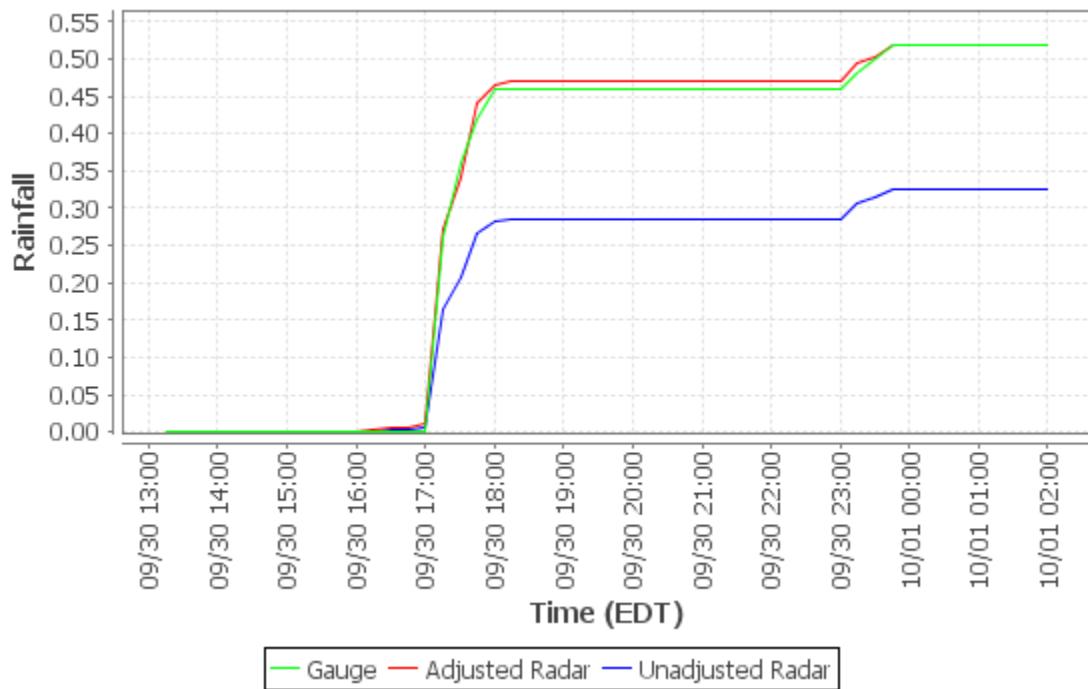
### Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



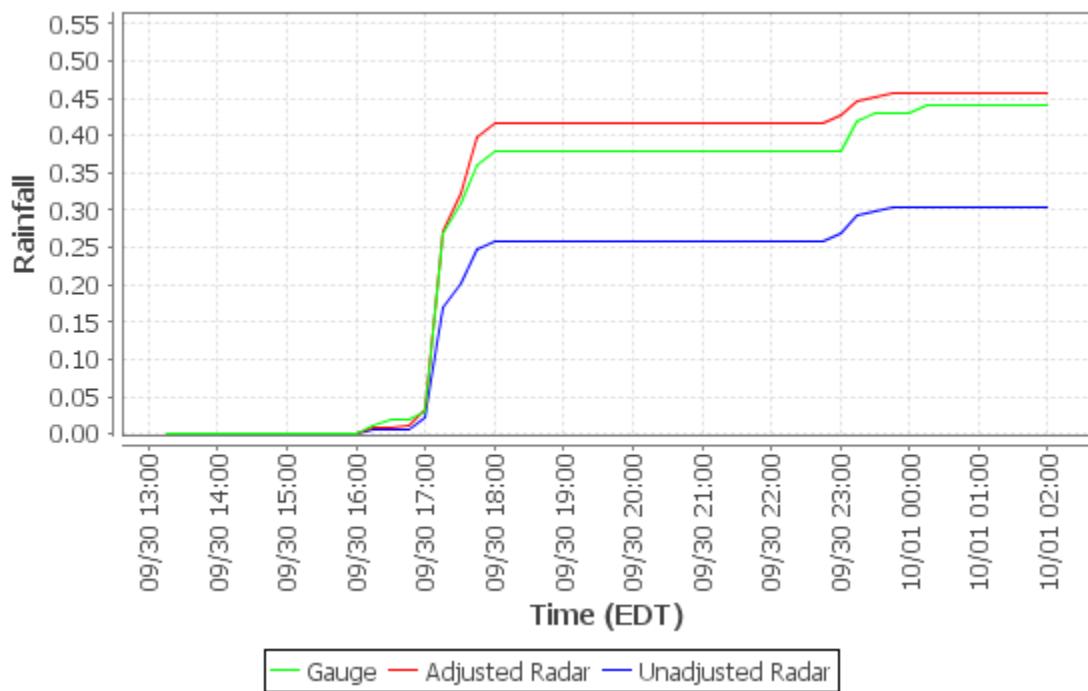
### Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



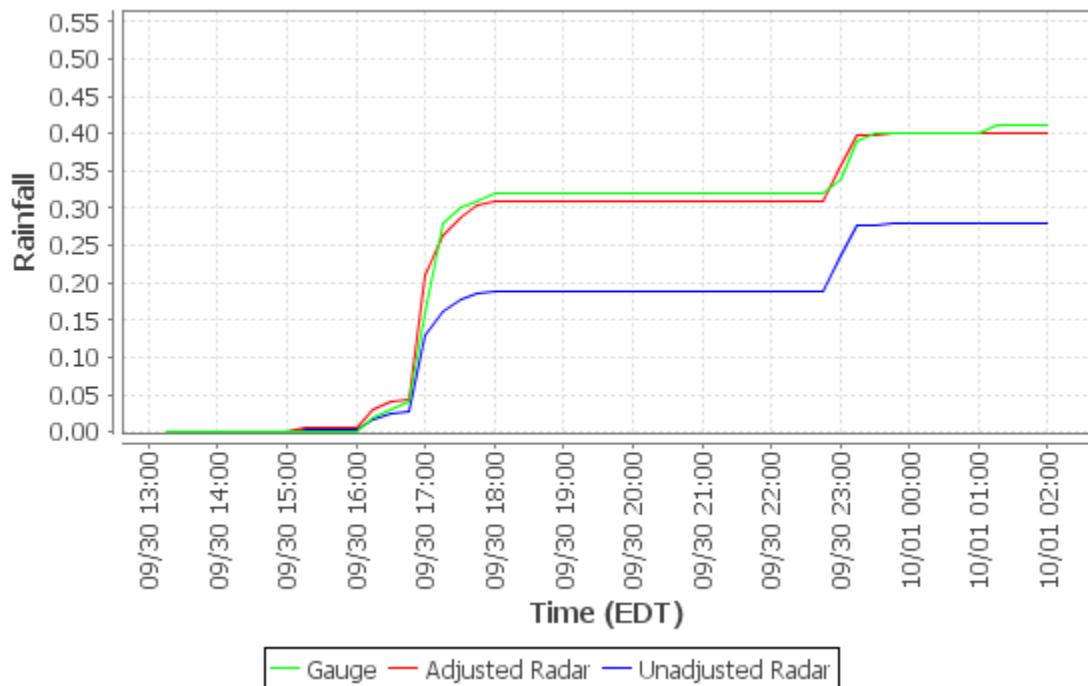
### Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



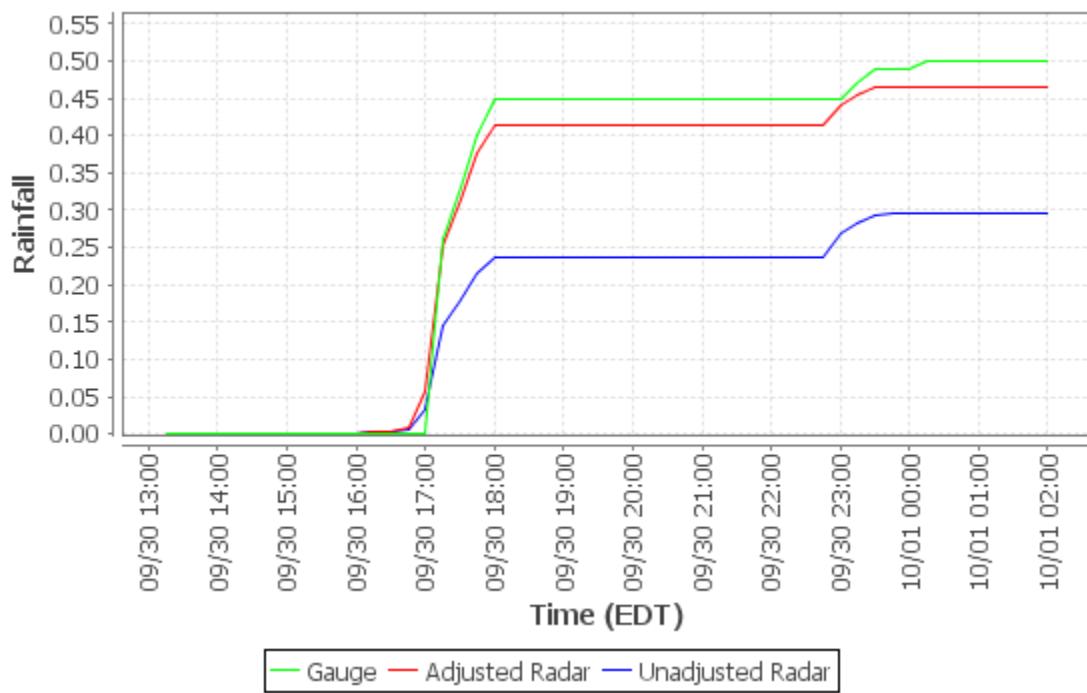
### Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



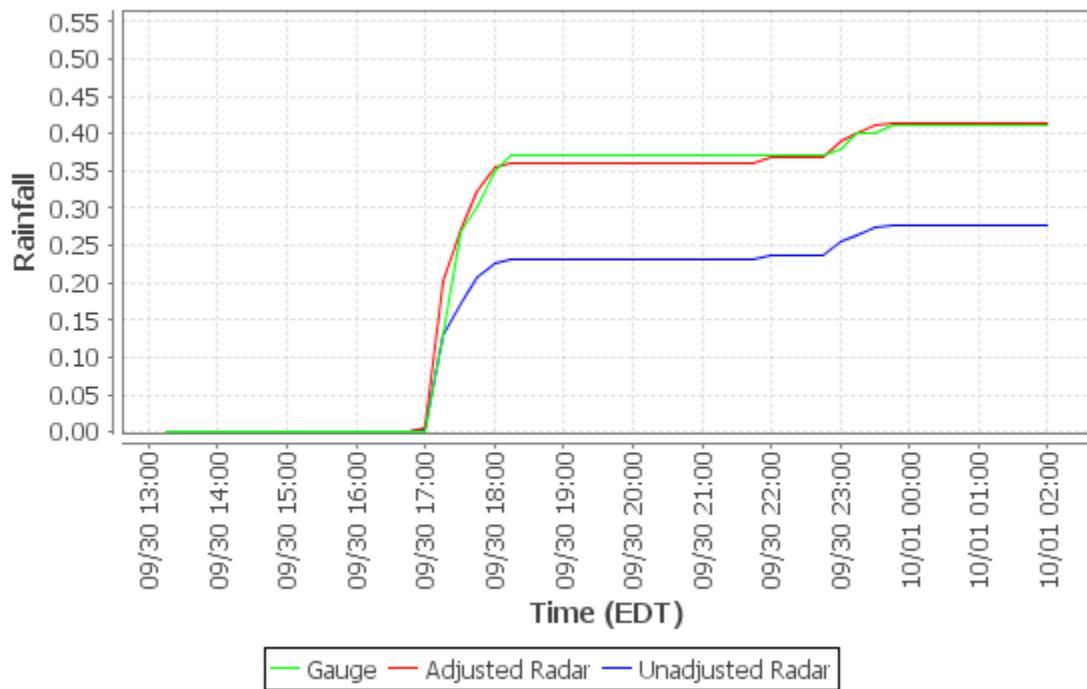
### Cumulative Distribution Plot - Baldwin (Loc12)



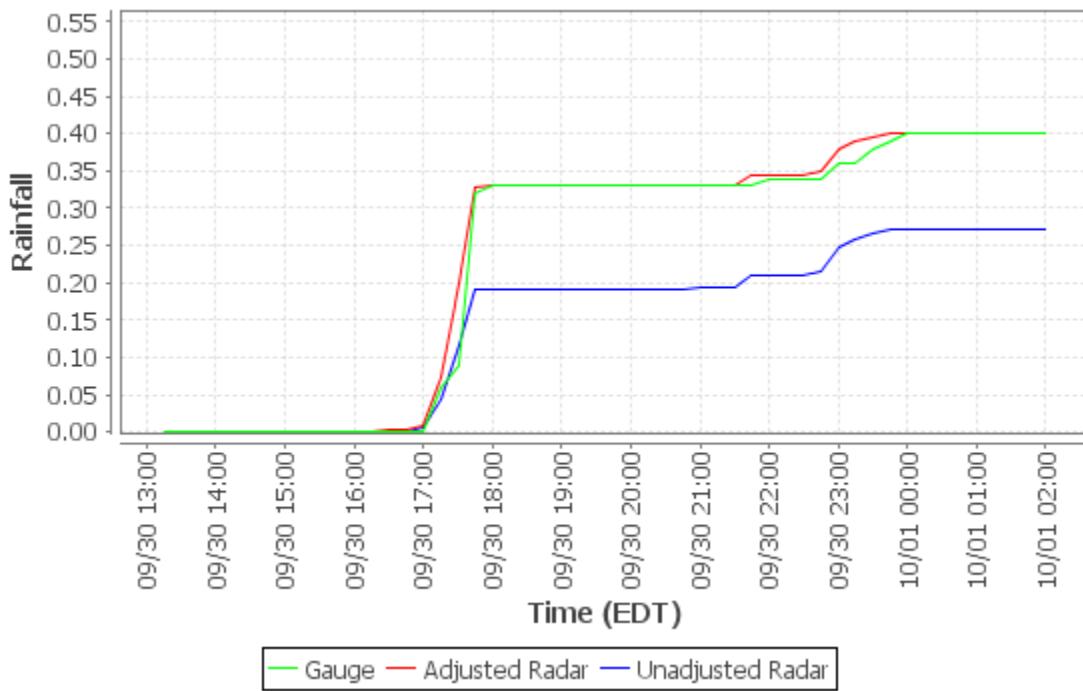
### Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



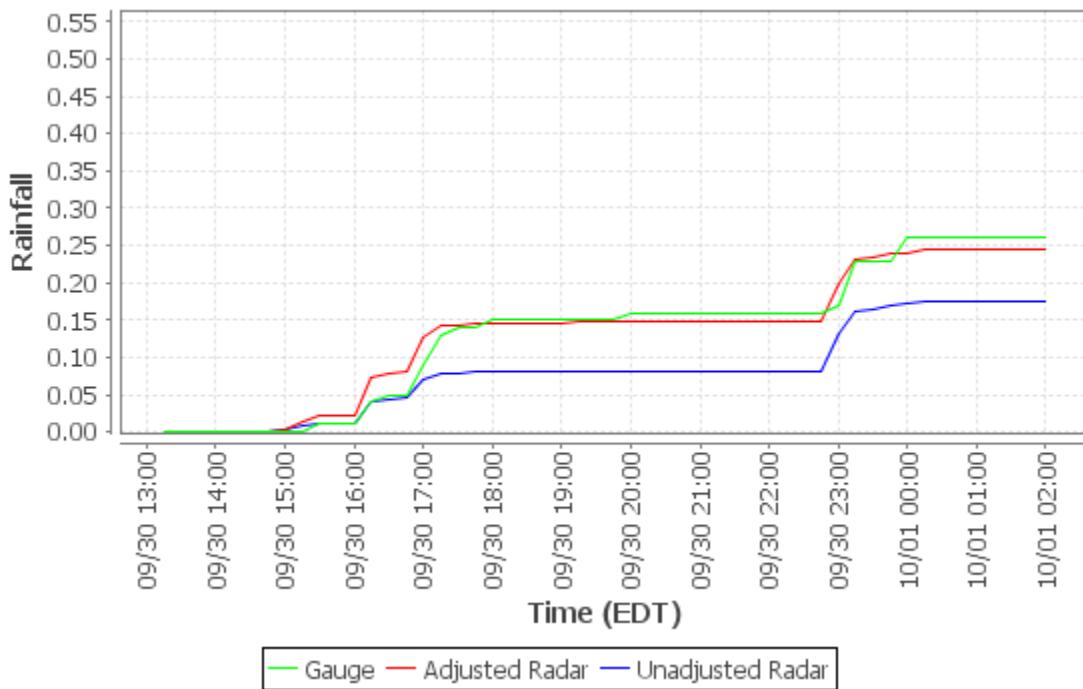
### Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



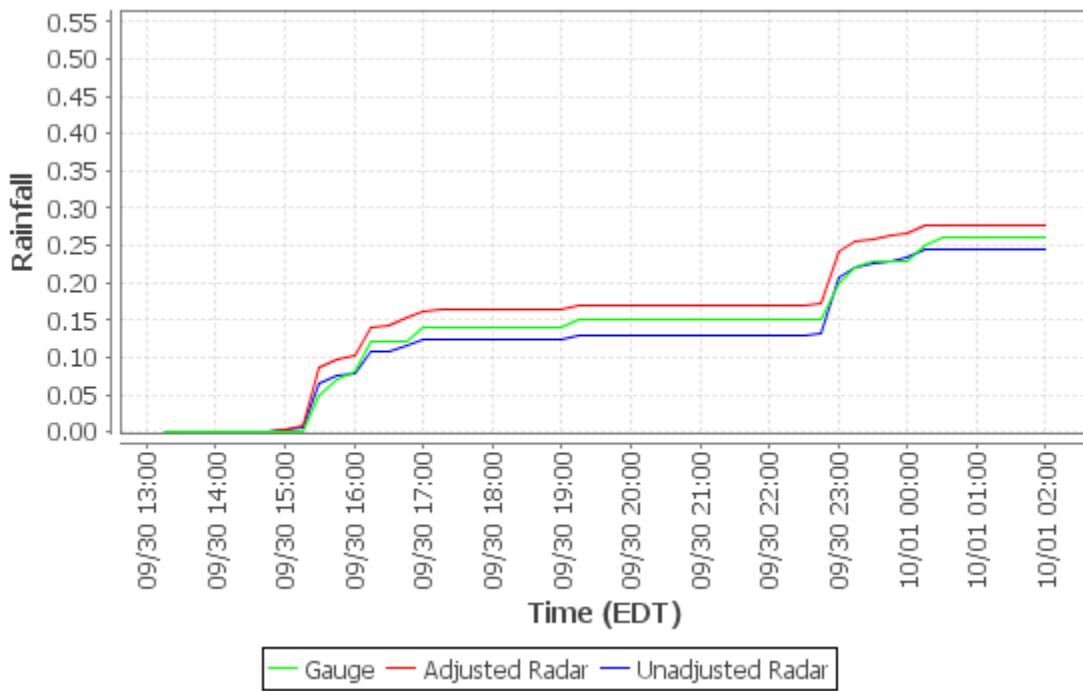
### Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



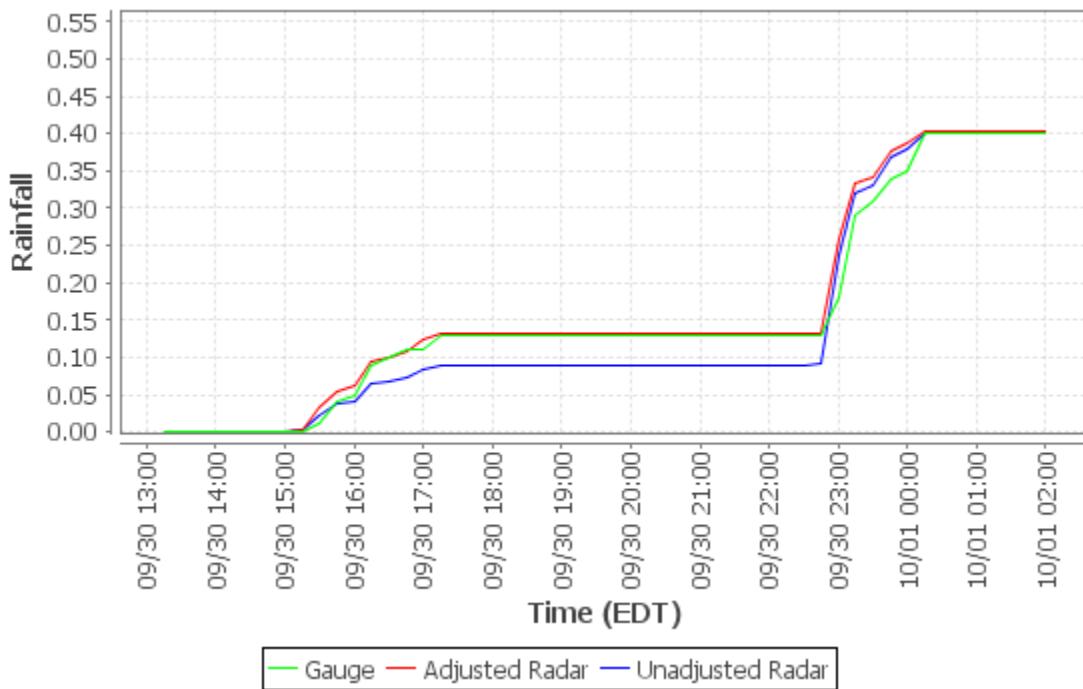
### Cumulative Distribution Plot - Castle Shannon (Loc16)



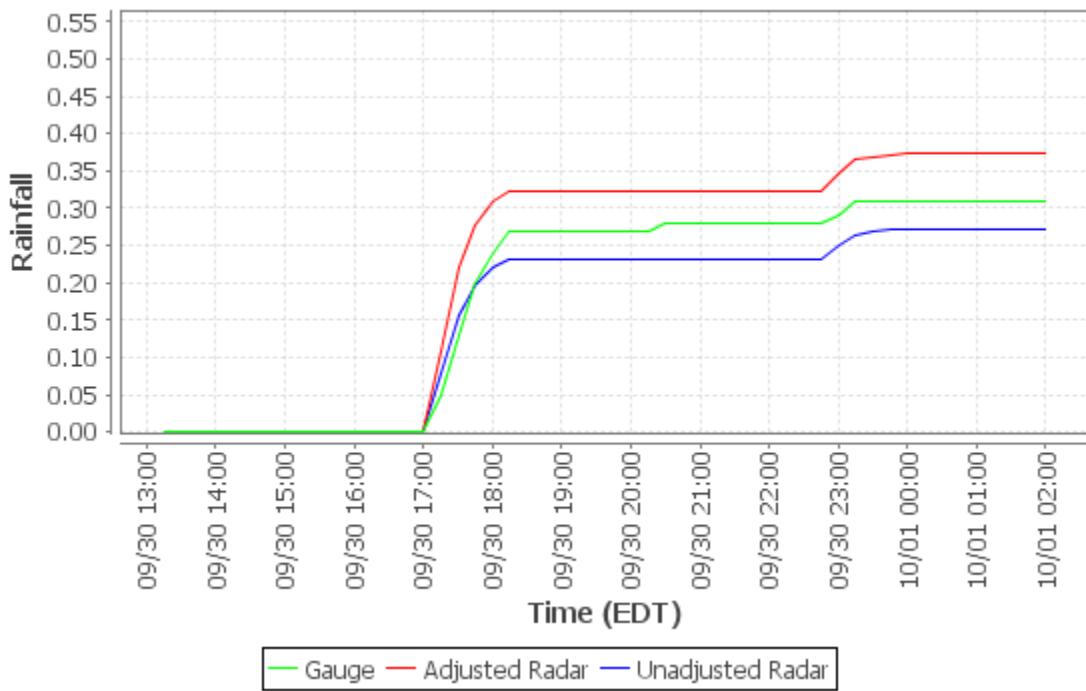
### Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



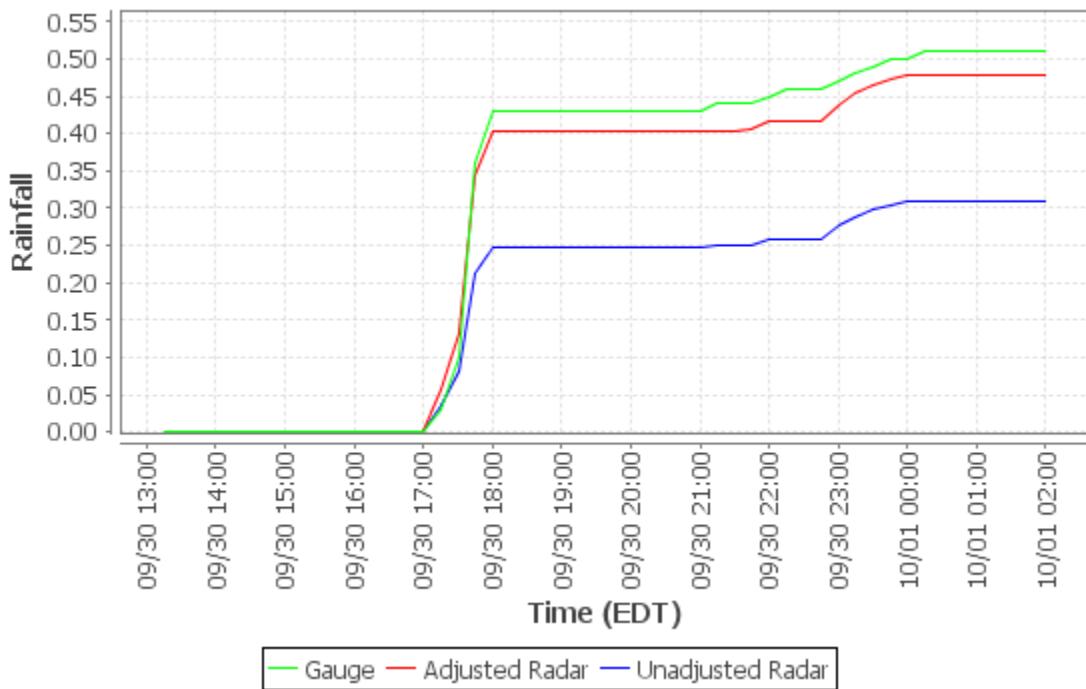
### Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



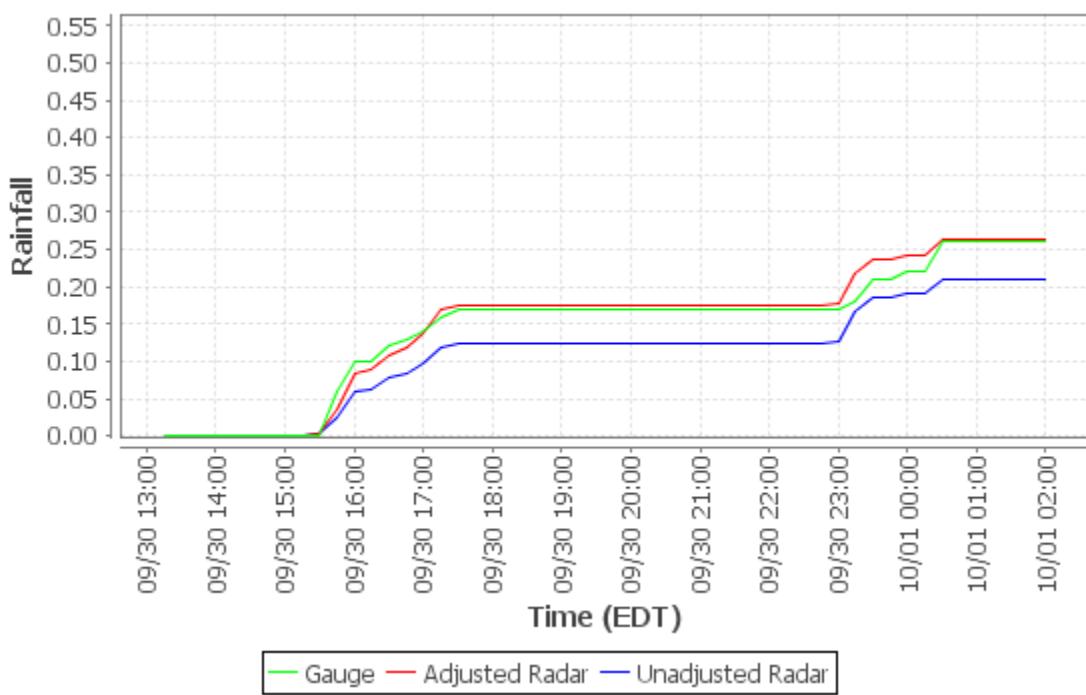
### Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



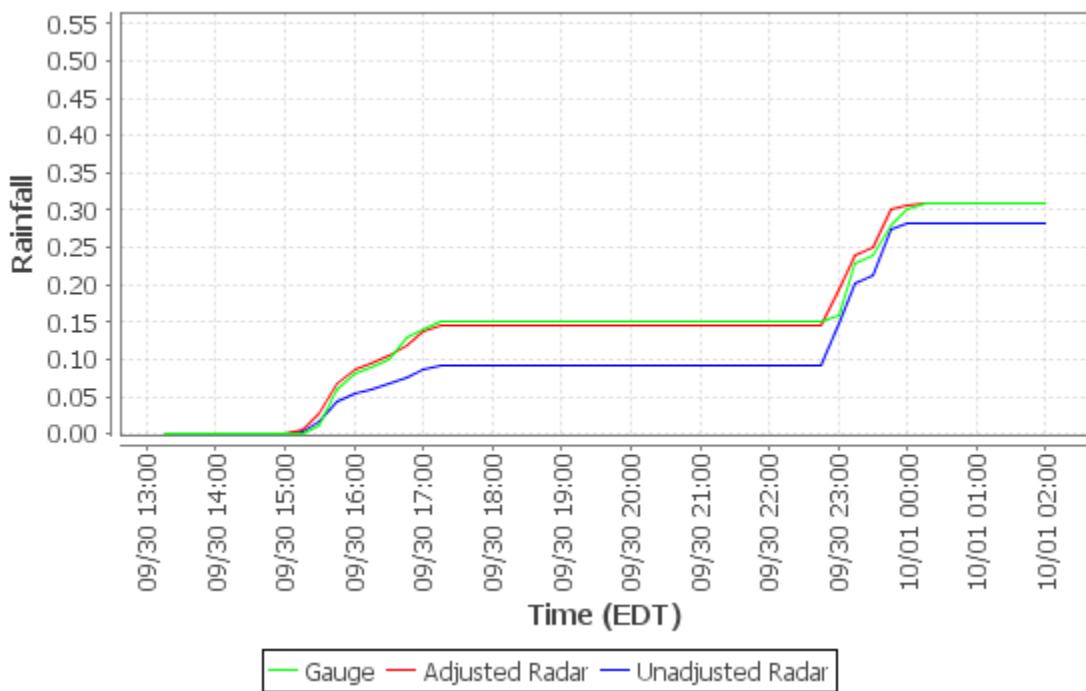
### Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



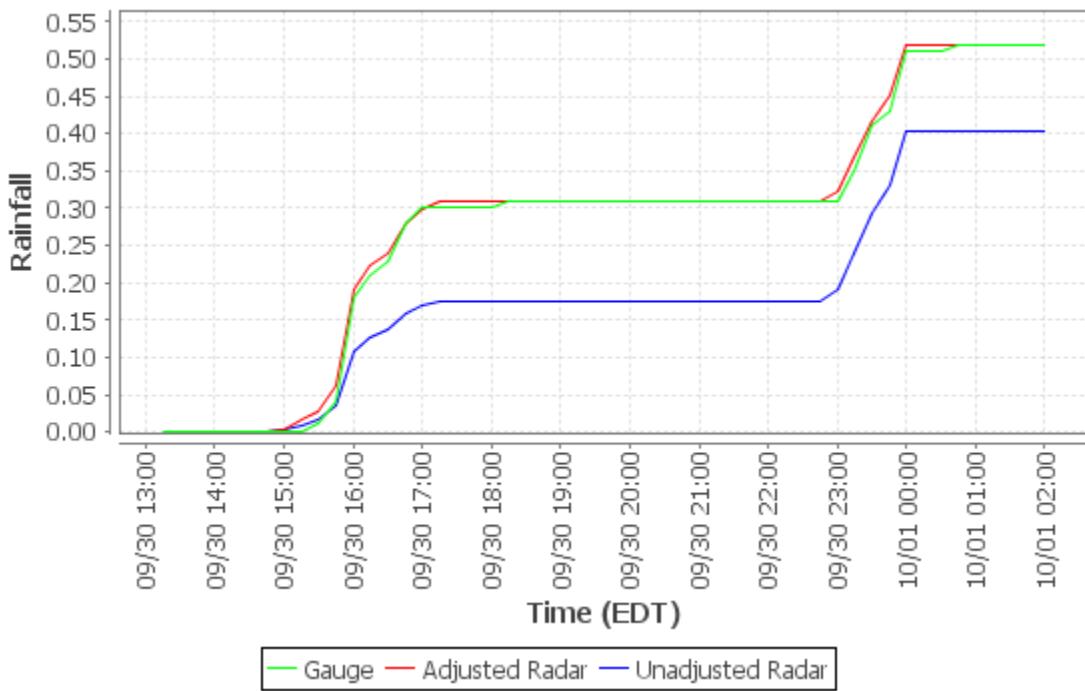
### Cumulative Distribution Plot - Moon TWP (Loc21)



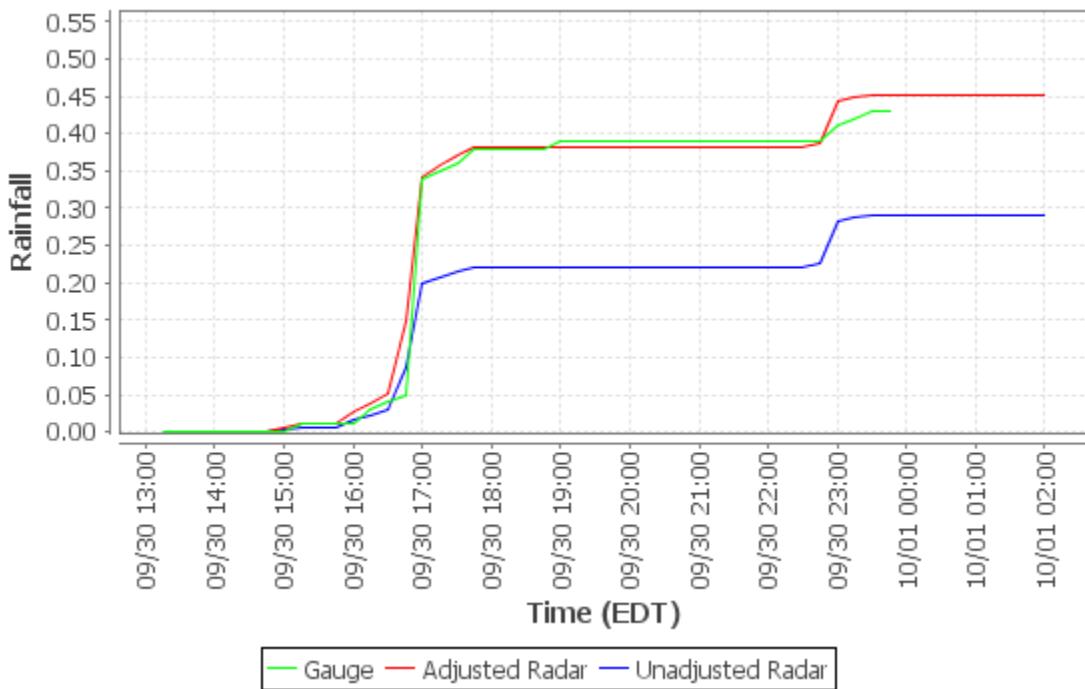
### Cumulative Distribution Plot - North Fayette TWP (Loc22)



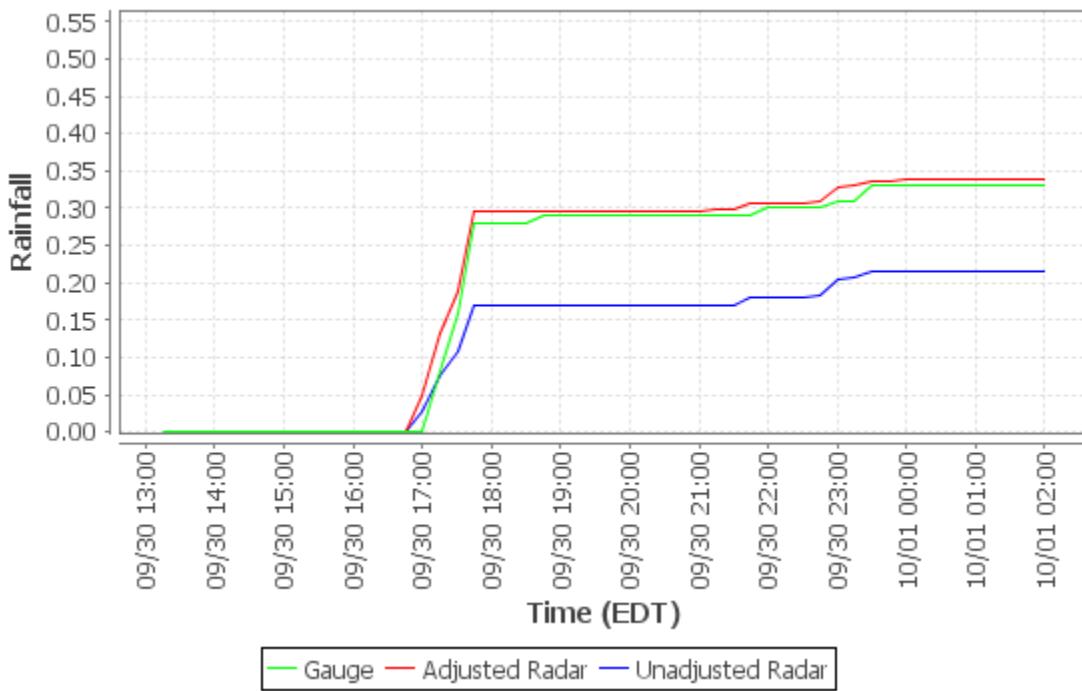
### Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



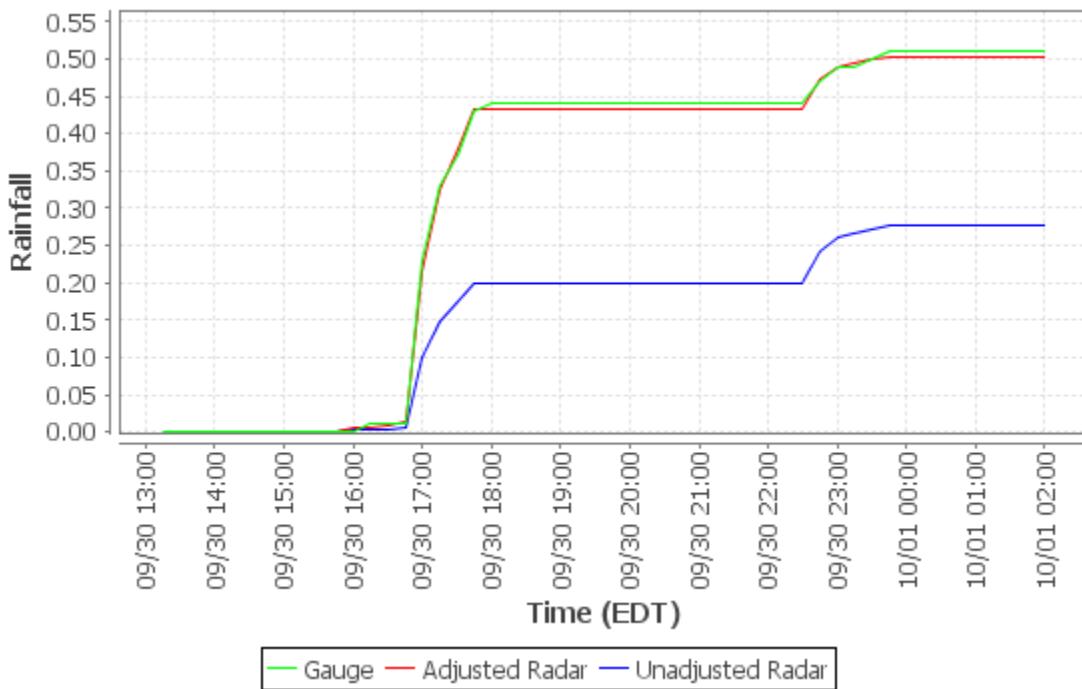
### Cumulative Distribution Plot - Jefferson Hills (Loc24)



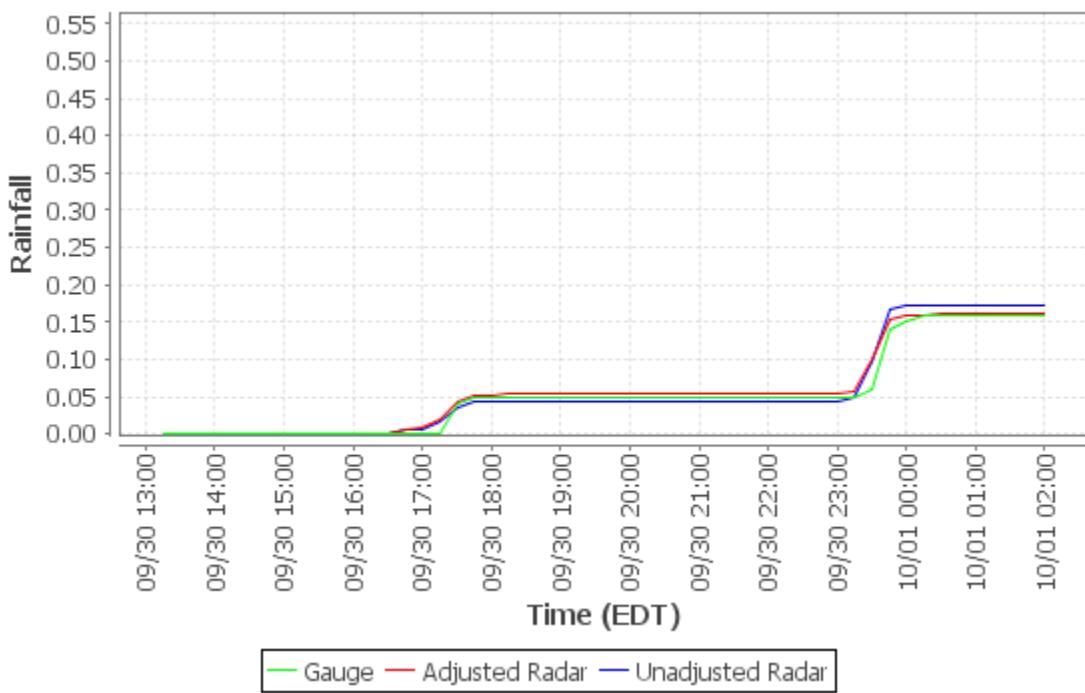
### Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



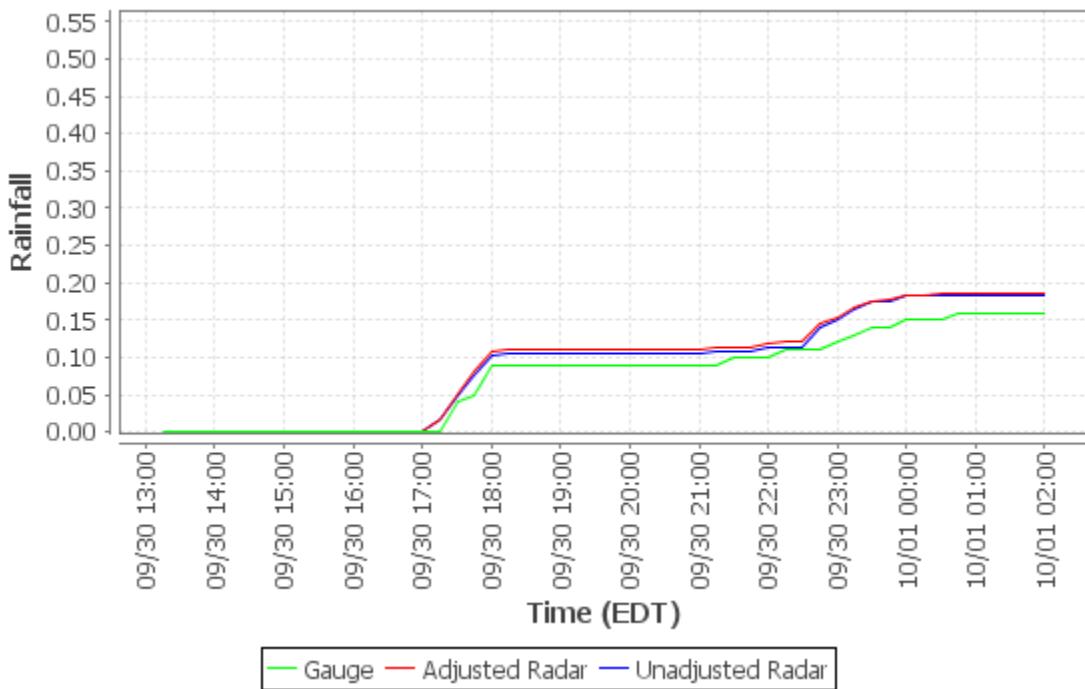
### Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



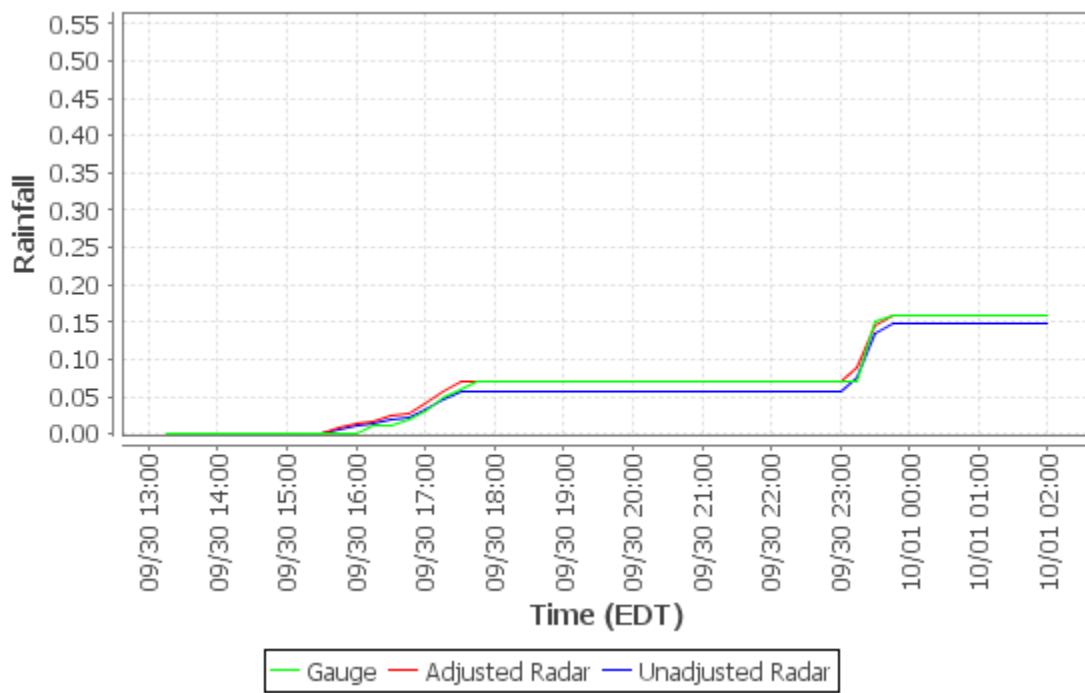
### Cumulative Distribution Plot - Marshall TWP (Loc27)



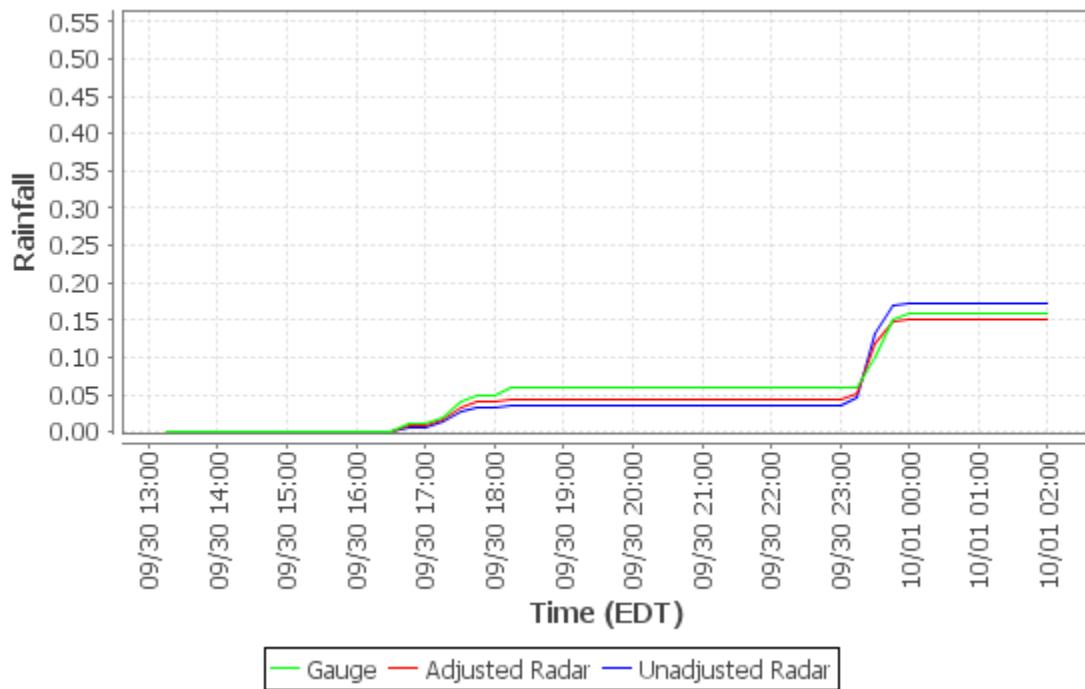
### Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



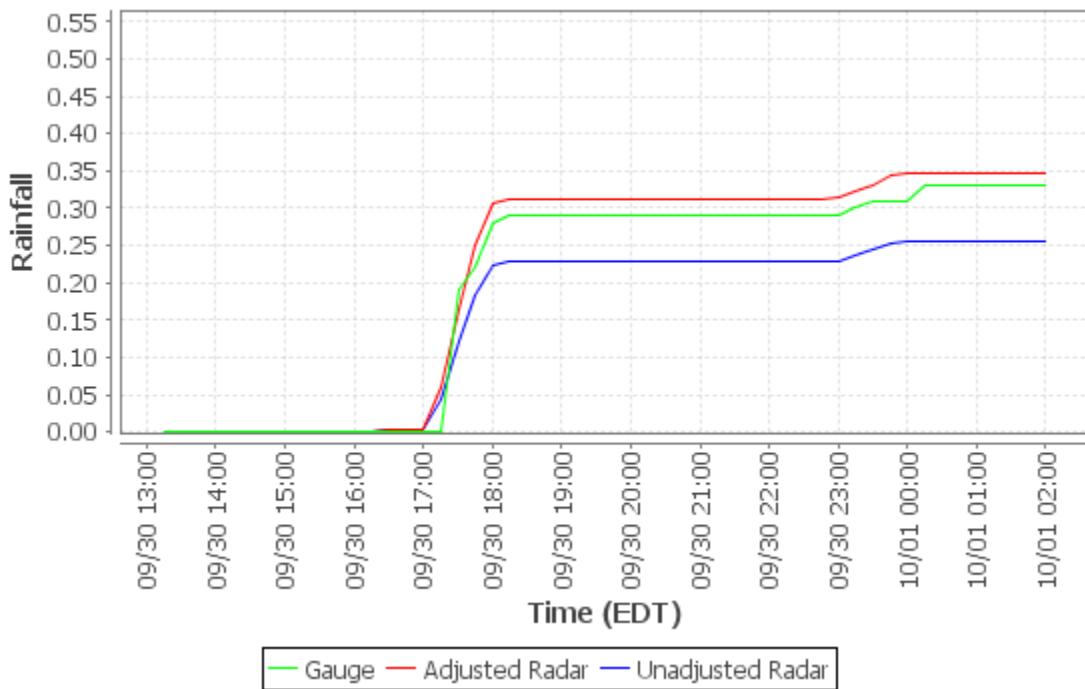
### Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



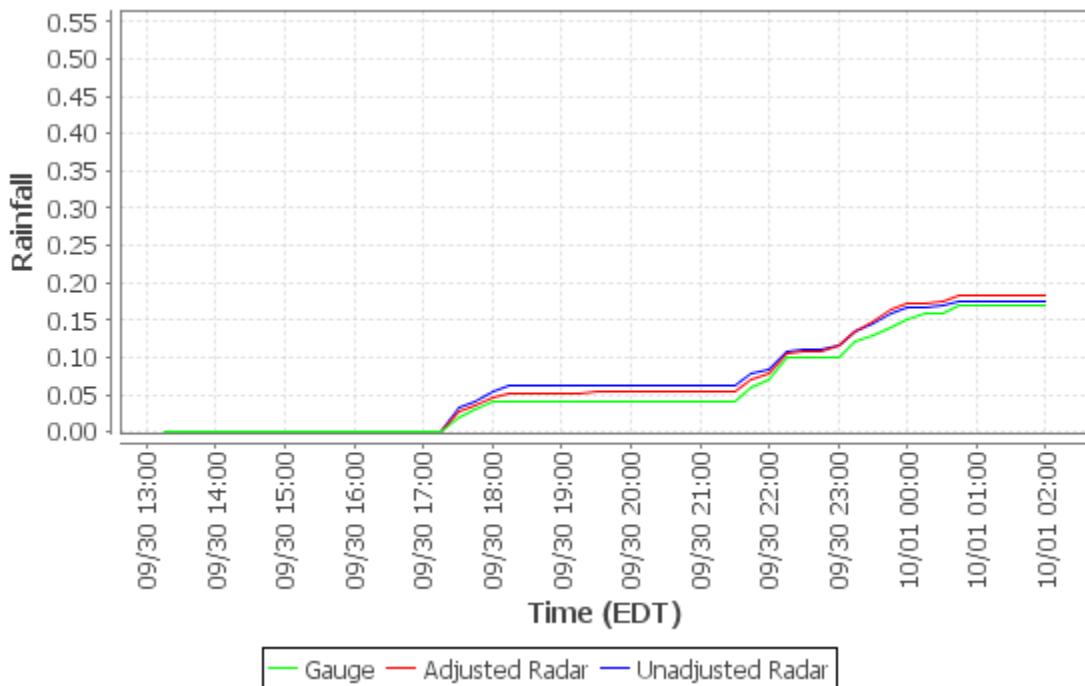
### Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



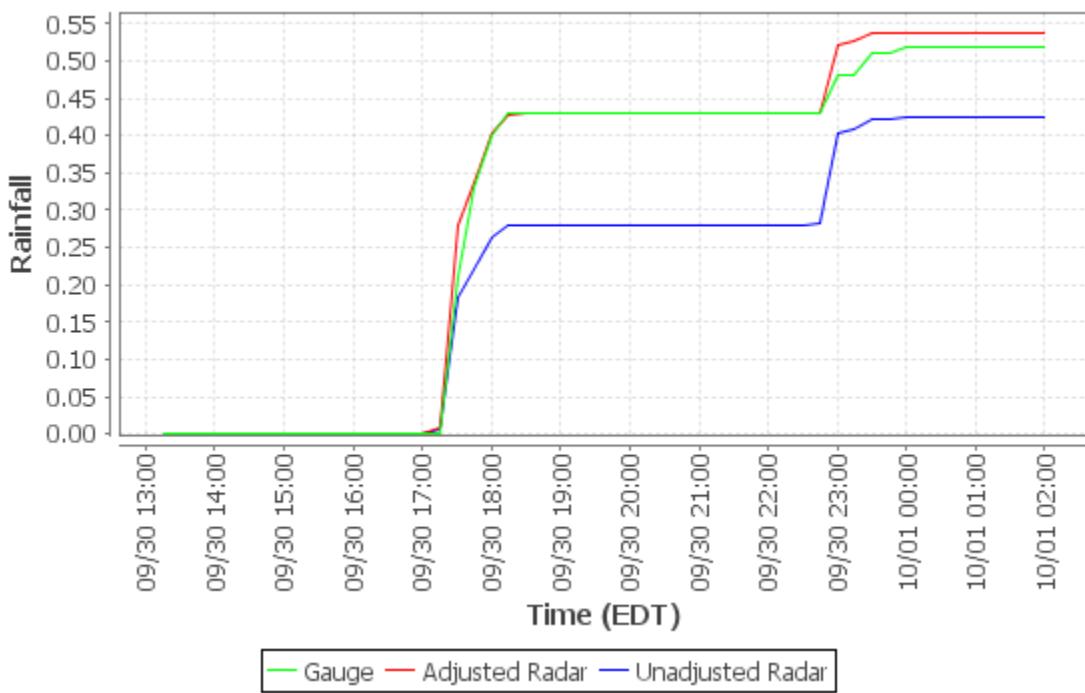
### Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



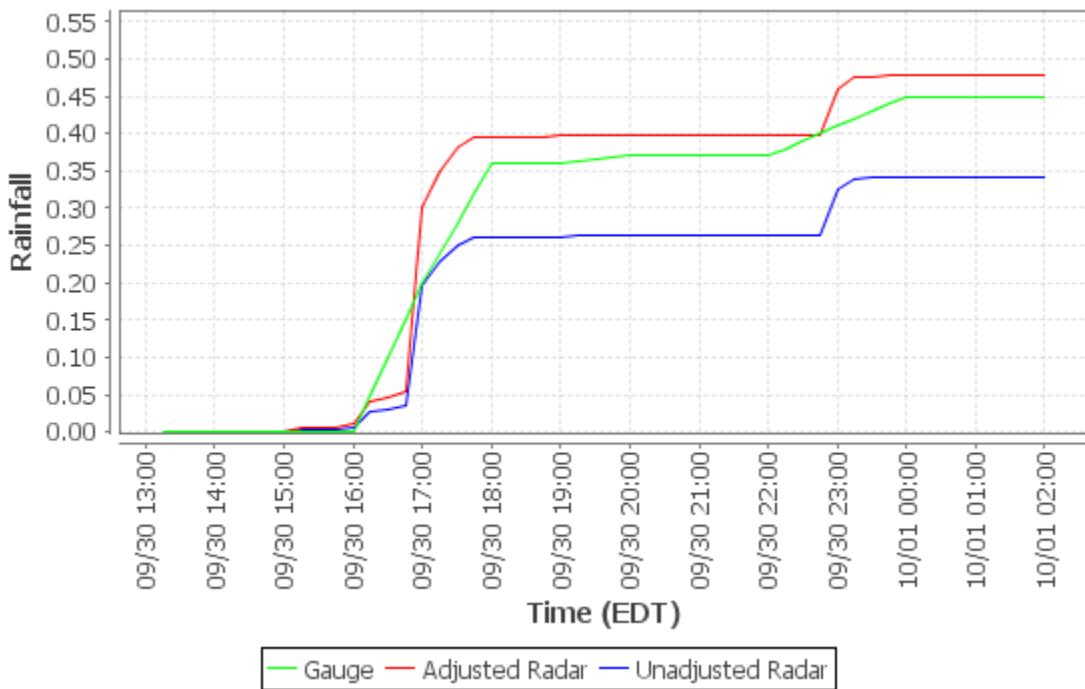
### Cumulative Distribution Plot - Arnold (Loc32)



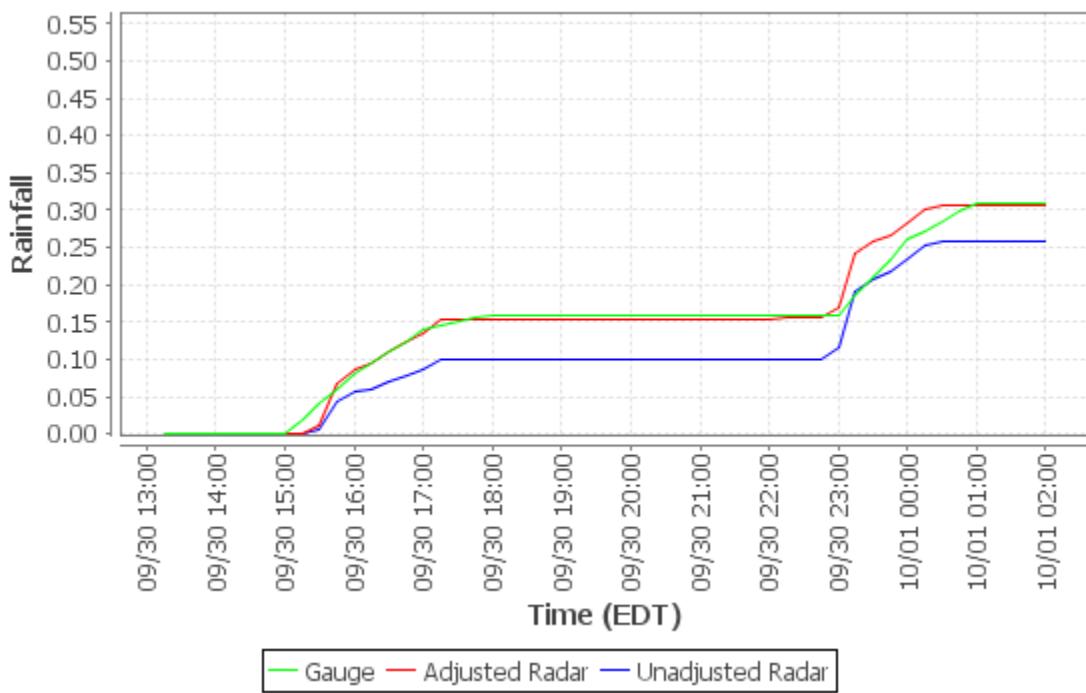
### Cumulative Distribution Plot - Richland TWP (Loc33)



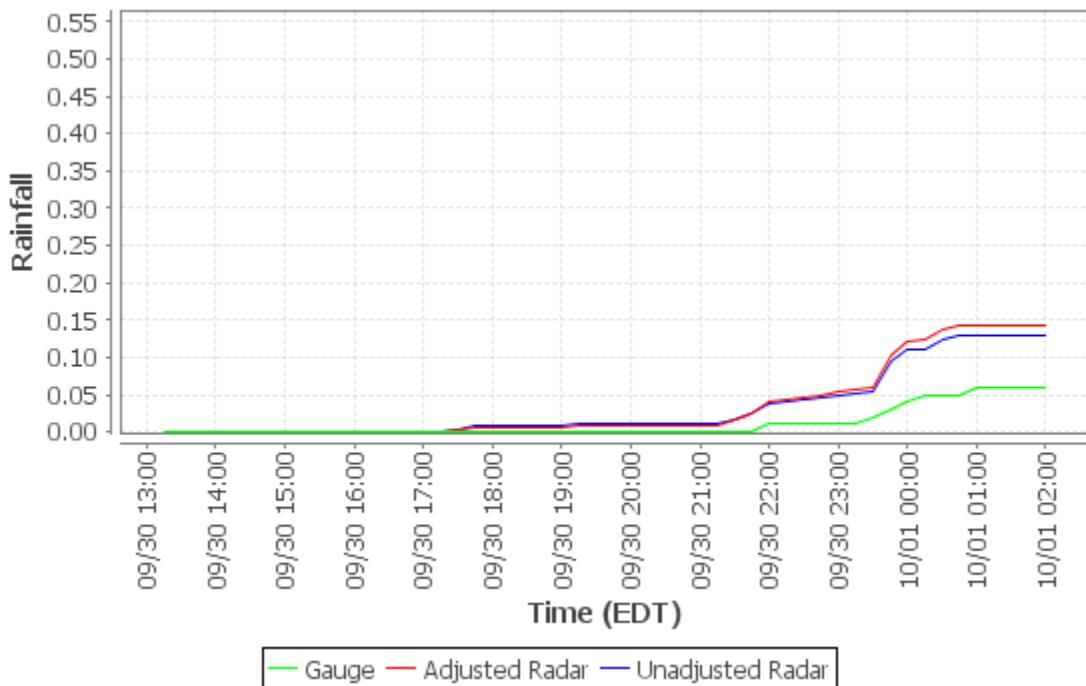
### Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



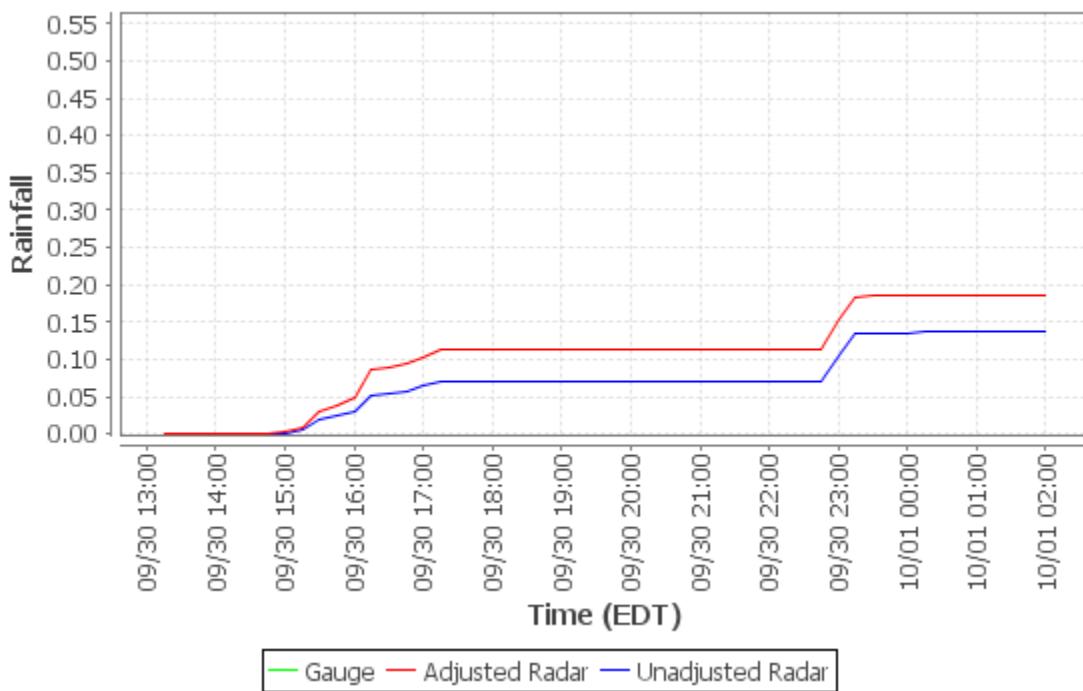
### Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



### Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



### Cumulative Distribution Plot - Chartiers Creek at Carnegie (03085500)



### Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

