Radar Rainfall Analysis

January 2021 Summary Report

Prepared for 3 Rivers Wet Weather

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Glossary

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 ($mm^6\ m^{-3}$) and rain rate R ($mm\ hr^{-1}$). 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 segmented into qualified storm event periods and then Quality Controlled (QC). To produce QC gauge-adjusted radar rainfall (GARR), both radar and rain gauge data are reviewed manually to remove inconsistent data. While only qualified rainfall events are included in this report, the RainVieux online database contains continuous data where QC rain gauge and radar data are available during the inter-event periods. QC is performed to remove anomalous radar data and inconsistent rain gauges during both the qualified and inter-event periods.

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 reflectivity 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 III Q0 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 five-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^2 grid domain shapefile containing 2313 1-km^2 pixels covering the study area. CDM Smith provided two basin shapefiles consisting of 440 RFM basins and 871 RFM sheds that are located within the 1-km^2 pixel domain.

Rain gauge data from as many as 37 gauges were used to adjust the radar. 3RWW provided rain data in 5-minute increments for 33 stations. In addition, rain gauge data were obtained from two 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, RFM basins and 1-km^2 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^2 pixels were achieved using software developed at Vieux.

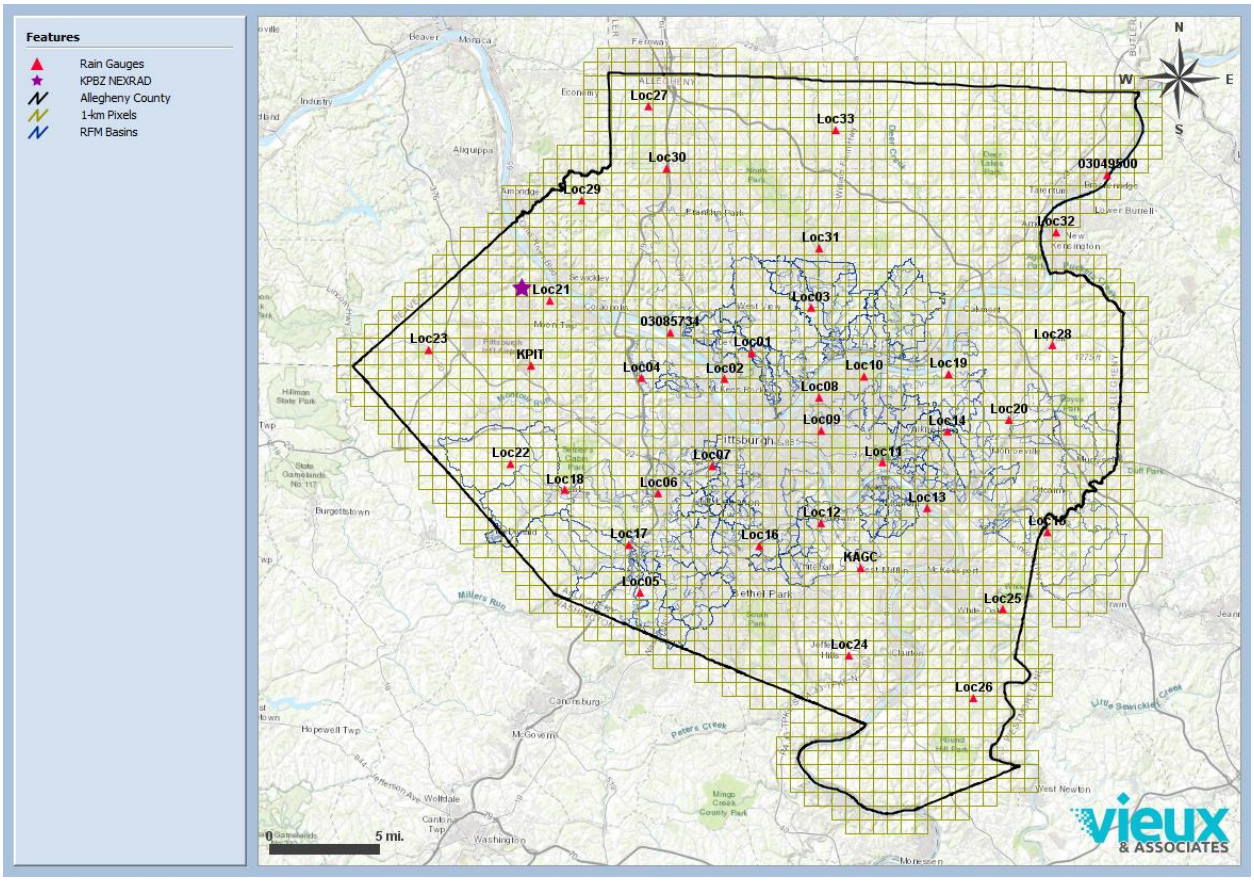


Figure 1. Spatial Distribution of the Rain Gauge Network, KPBZ NEXRAD, RFM Basins and 1-km^2 Pixels

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

Gauge ID	Gauge Name	Source
Loc14	Churchill Munic Bldg	3RWW
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
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	USGS

The 37 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

Radar and rain gauge data are segmented into qualified storm event periods and then Quality Controlled (QC). Qualified rainfall events are defined based on the storm event definition where, for any given hour, at least 50% of all working 3RWW gauges have an accumulation of 0.05 inches. Only qualified rainfall events are included in the report, while the RainVieux online database contains continuous data. Both the qualified and inter-event periods receive QC to remove anomalous radar data and inconsistent rain gauges.

Statistical control of the data makes radar rainfall measurements more accurate. By statistical comparison between the radar and rain gauge accumulations during a GARR period, certain gauges may be identified as statistical outliers and excluded for all or part of an event. 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.

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, outlier check or gauge performance review, there must be at least two remaining RG pairs to proceed with gauge-adjustment of the radar. 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. GARR is then spatially aggregated from the final adjusted radar bins to the basins and 1-km^2 pixels 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 pixels, 440 RFM basins and 871 RFM sheds in 15-minute intervals. The data are provided in CSV format for the period from 2021-01-01 00:00 EST to 2021-02-01 00:00 EST. Shapefiles of the 1-km pixels, RFM basins and RFM sheds are located in the Shapefiles subfolder.

1-km^2 Pixel CSV metadata:

- Individual CSV files are provided for each pixel.
- The pixel filenames use a "Ryymm_" (i.e. R, year, month) prefix in front of the pixel ID.
- The comma-delimited text files contain a header row in the 1st row and time/data values beginning on the 2nd row.
- The time/data columns consist of Month, Day, Year, Hour, Minute, Rainfall and Source, where R represents EOM GARR quality.
- Time stamps are in EST/EDT.
- Data values represent 15-min accumulation (inches) at end of interval.
- The 1-km Pixel ID field that was used from the shapefile DBF is "PIXEL".

Basin CSV metadata:

- Individual CSV files are provided for each RFM Basin and RFM Shed.
- The RFM Basin filenames use a "P-" prefix and a "yyyymmG" (i.e. year, month, G) suffix in front and after the RFM Basin ID.
- The RFM Shed filenames use a "P-" prefix and a "yyyymmN" (i.e. year, month, N) suffix in front and after the RFM Shed ID.
- The comma-delimited text files contain a header row in the 1st row and time/data values beginning on the 2nd row.
- The 1st column contains the date (yyyy/mm/dd hh:mm) and the 2nd column contains the corresponding rainfall value.
- Time stamps are in EST/EDT.
- Data values represent 15-min accumulation (inches) at end of interval.
- The RFM Basin ID field that was used from the shapefile DBF is "DS_METERNA".
- The RFM Shed ID field that was used from the shapefile DBF is "DELINID".

Shapefile metadata:

- NAD 1983, State Plane Pennsylvania South (feet).

Gauge-Adjusted Radar Rainfall (GARR)

Rainfall totals for January 2021 are shown in Figure 2. The rainfall amounts for the 2313 1-km^2 pixels range from 1.3 to 2.1 inches with a mean of 1.8 inches. The rainfall amounts for the 440 RFM basins range from 1.5 to 2.1 inches with a mean of 1.8 inches. The rainfall amounts for the 871 RFM sheds range from 1.5 to 2.1 inches with a mean of 1.8 inches.

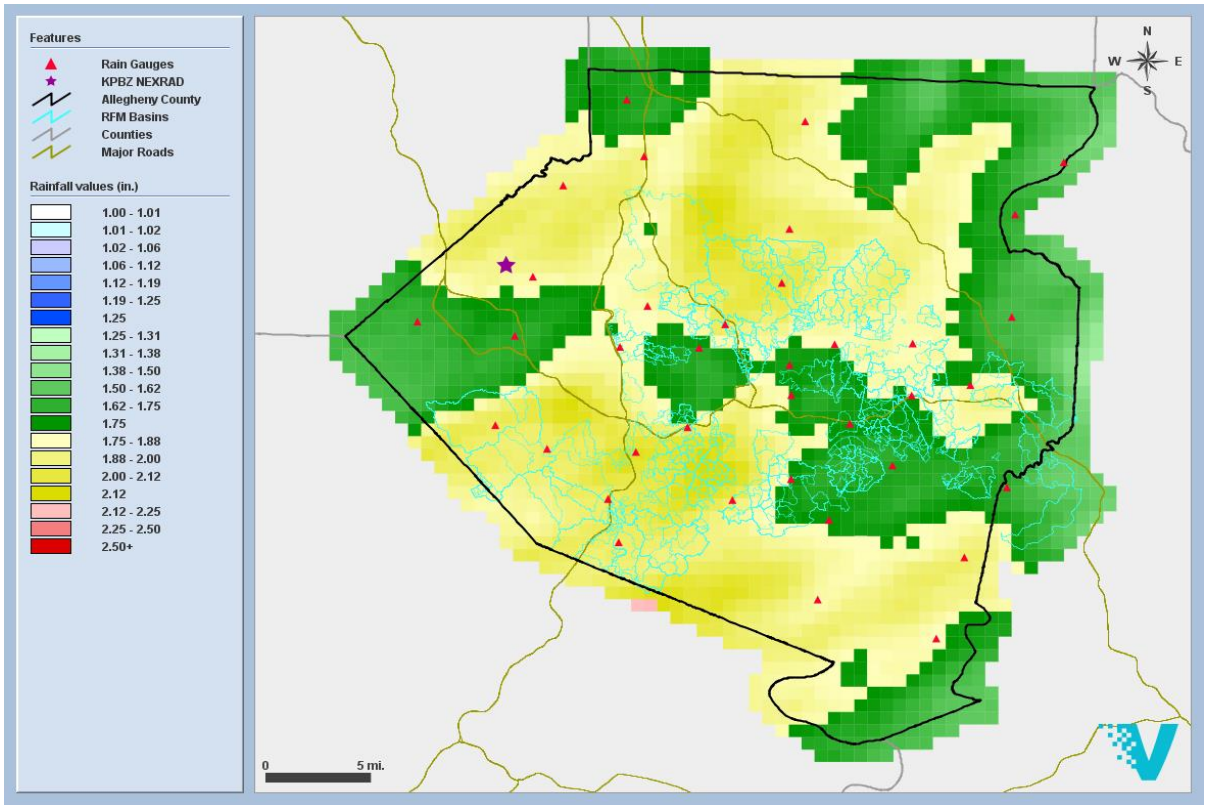


Figure 2. GARR Storm Total for January 2021

GARR was processed continuously at five-minute increments and covers the period from 2021-01-01 00:00 EST to 2021-02-01 00:00 EST. Three rainfall events were identified as having met the storm definition during January 2021. The GARR statistics for each event are listed in Table 2. Two of the events were split into multiple sub-event periods to improve gauge-adjustment of the radar, resulting in a total of 7 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 three 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 7 event and sub-event periods, the event CAD averaged 1.8%, indicating that the mean GARR agrees with the mean gauge accumulation to within ±0.9%.

Table 2. Storm Events and GARR Statistics

Event #	Source	Event Date	Start Time (EST)	End Time (EST)	Gauges Used (37)	Avg. Depth (in)	Bias	AD (%)	CAD (%)
E1a	KPBZ LII	2021-01-01	2021-01-01 08:05	2021-01-01 12:15	30	0.168	0.810	23.9	1.1
E1b	KPBZ LII	2021-01-01	2021-01-01 12:20	2021-01-01 13:45	32	0.094	0.890	16.8	2.3
E1c	KPBZ LII	2021-01-01	2021-01-01 13:50	2021-01-01 23:00	31	0.452	1.428	29.6	1.2
E2a	KPBZ LII	2021-01-03	2021-01-03 02:05	2021-01-03 08:00	25	0.059	0.698	45.6	1.9
E2b	KPBZ LII	2021-01-03	2021-01-03 08:05	2021-01-03 10:15	25	0.073	0.984	24.8	2.6
E2c	KPBZ LII	2021-01-03	2021-01-03 10:20	2021-01-03 22:00	32	0.280	0.655	54.0	1.1
E3	KPBZ LII	2021-01-15	2021-01-15 11:05	2021-01-15 20:00	29	0.098	0.568	79.2	2.2

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 C - E. CDPs are useful for visualizing rain gauge performance. Figure 3 shows the rainfall accumulation at the Kennedy Twp PS (Loc04) gauge during the 2021-01-03 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.

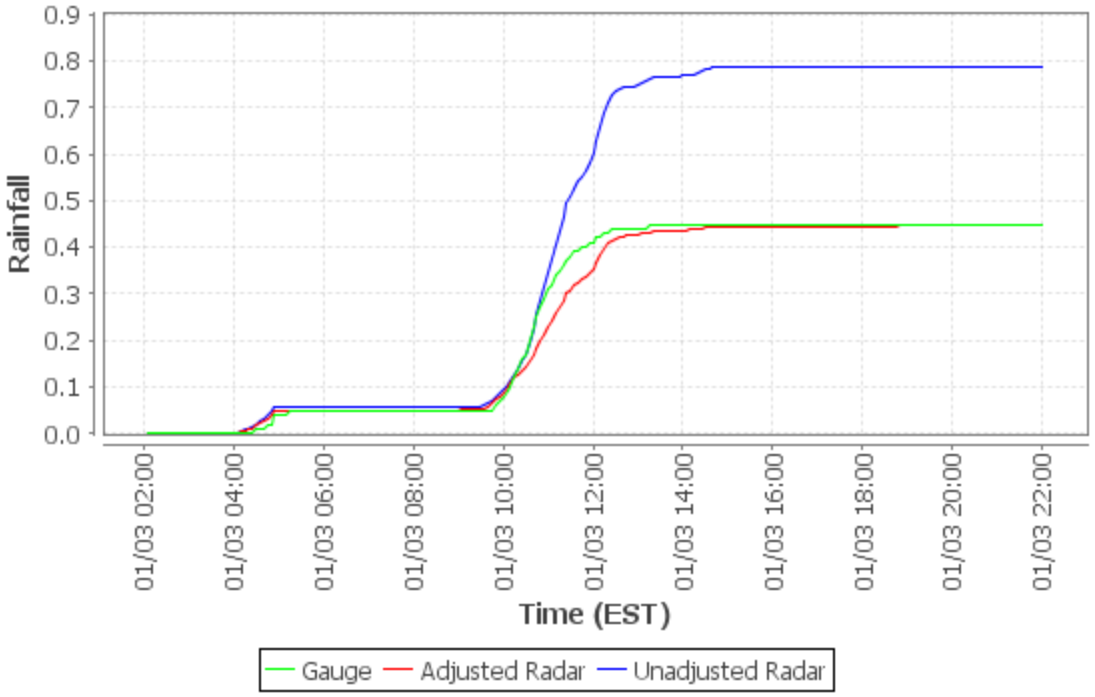


Figure 3. CDP Showing Rain Gauge Versus Unadjusted Radar Versus GARR

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 based on gauge performance 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. A list of reasons for not using a gauge based on statistical criteria is shown in Table 4. The gauges listed in Appendix B did not meet statistical criteria for gauge-adjustment of the radar and were not used to adjust the radar.

Table 3. Reasons for Gauge Exclusion Based on Performance

Reason	Explanation
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

Reason	Explanation
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

Table 4. Reasons for Gauge Exclusion Based on Statistical Criteria

Reason	Explanation
Minimum Storm Total Threshold (MSTT)	The radar or gauge cumulative sum during the event or sub-event period was less than MSTT
Outlier Based on Mean Field Bias (OMFB)	The RG pair bias (G/R) was greater than three standard deviations from the mean bias (e.g. G>>R)
Outlier Based on Average Difference (OAD)	The RG pair average difference ((G-R)/G)) was greater than three standard deviations from the mean average difference (e.g. G<<R)

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: 2021-01-01

The analysis period was from 2021-01-01 08:00 EST to 2021-01-01 23:00 EST. The event was then split into three sub-event periods at 2021-01-01 12:15 EST and 2021-01-01 13:45 EST 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. The gauges listed in Appendix B were not used to adjust the radar since they did not meet statistical criteria for gauge-adjustment.

The Eastern U.S. cool season stratiform Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 5 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 6 - 8 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. Those gauges not used to adjust the radar are shown at the bottom of the table and are highlighted in red. The specific reason for gauge exclusion is displayed in the Flag column. Figures 4 - 6 show the scatter plots of the gauge-adjusted RG pairs. Those gauges not used to adjust the radar are shown in red. Figure 7 depicts the GARR storm total over the 1-km^2 pixels. The GARR amounts for the 2313 1-km^2 pixels range from 0.6 - 0.9 inches with a mean of 0.7 inches. The GARR amounts for the 440 RFM basins range from 0.6 - 0.8 inches with a mean of 0.7 inches. The GARR amounts

for the 871 RFM sheds range from 0.6 - 0.9 inches with a mean of 0.7 inches. Table 9 shows the Depth Duration Frequency (DDF) maximum values for the 1-km^2 pixels.

Table 5. GARR Statistics for Event 1

Event #	Radar	Event Date	Start Time (EST)	End Time (EST)	Gauges Used (37)	Avg. Depth (in)	Bias	AD (%)	CAD (%)
E1a	KPBZ LII	2021-01-01	2021-01-01 08:05	2021-01-01 12:15	30	0.168	0.810	23.9	1.1
E1b	KPBZ LII	2021-01-01	2021-01-01 12:20	2021-01-01 13:45	32	0.094	0.890	16.8	2.3
E1c	KPBZ LII	2021-01-01	2021-01-01 13:50	2021-01-01 23:00	31	0.452	1.428	29.6	1.2

Table 6. Summary of Individual RG Pairs for Event 1a

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc07	Greentree Munic Bldg	0.16	0.21	0.17	-0.01	-6.3	
Loc08	AC Health Dept Bldg	0.16	0.21	0.17	-0.01	-6.3	
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.16	0.22	0.16	0.00	0.0	
KAGC	Pittsburgh Allegheny Cty	0.16	0.20	0.16	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.17	0.23	0.17	0.00	0.0	
Loc01	PWSA-Montana St.	0.18	0.23	0.18	0.00	0.0	
Loc02	ALCOSAN WWTP Lab	0.17	0.23	0.17	0.00	0.0	
Loc03	Shaler Munic Bldg	0.20	0.22	0.20	0.00	0.0	
Loc04	Kennedy Twp PS	0.18	0.23	0.18	0.00	0.0	
Loc09	Univ of Pittsburgh	0.16	0.20	0.16	0.00	0.0	
Loc11	M-46 Access Shaft	0.16	0.20	0.16	0.00	0.0	
Loc12	Baldwin	0.16	0.20	0.16	0.00	0.0	
Loc13	M-59 Access Shaft	0.16	0.20	0.16	0.00	0.0	
Loc14	Churchill Munic Bldg	0.17	0.20	0.17	0.00	0.0	
Loc15	Trafford Maint Bldg	0.16	0.19	0.16	0.00	0.0	
Loc17	Chartiers Pump Station	0.18	0.20	0.18	0.00	0.0	
Loc18	Oakdale Pump Station	0.17	0.21	0.17	0.00	0.0	
Loc19	Sandy Creek Eq Facility	0.17	0.20	0.17	0.00	0.0	
Loc20	Gascola Eq Facility	0.17	0.20	0.17	0.00	0.0	
Loc21	Moon TWP	0.16	0.24	0.16	0.00	0.0	
Loc23	Clinton Munic Bldg	0.16	0.24	0.16	0.00	0.0	
Loc24	Jefferson Hills	0.14	0.17	0.14	0.00	0.0	

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc25	White Oak Public Works Bldg	0.16	0.18	0.16	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.15	0.18	0.15	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.18	0.22	0.18	0.00	0.0	
Loc31	Hampton Municipal Bldg	0.18	0.22	0.18	0.00	0.0	
Loc32	Arnold	0.18	0.22	0.18	0.00	0.0	
Loc33	Richland TWP	0.18	0.20	0.18	0.00	0.0	
Loc06	Carnegie Transit Time	0.20	0.20	0.19	0.01	5.0	
Loc10	PWSA-Highland Park	0.18	0.20	0.17	0.01	5.6	
03049500	Allegheny River at Natrona	0.15	---	---	---	---	U
Loc05	Upper St. Clair	0.15	---	---	---	---	U
Loc16	Castle Shannon	0.14	---	---	---	---	U
Loc22	North Fayette TWP	0.13	---	---	---	---	U
Loc27	Marshall TWP	0.10	---	---	---	---	U
Loc28	Plum Municipal Bldg	0.13	---	---	---	---	U
Loc30	McCandless Twn Hall	0.10	---	---	---	---	U

Table 7. Summary of Individual RG Pairs for Event 1b

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
KAGC	Pittsburgh Allegheny Cty	0.08	0.12	0.09	-0.01	-12.5	
Loc02	ALCOSAN WWTP Lab	0.09	0.11	0.10	-0.01	-11.1	
KPIT	Greater Pittsburgh Int'l	0.10	0.15	0.11	-0.01	-10.0	
Loc05	Upper St. Clair	0.13	0.14	0.14	-0.01	-7.7	
03049500	Allegheny River at Natrona	0.06	0.06	0.06	0.00	0.0	
Loc03	Shaler Munic Bldg	0.09	0.10	0.09	0.00	0.0	
Loc04	Kennedy Twp PS	0.12	0.13	0.12	0.00	0.0	
Loc06	Carnegie Transit Time	0.13	0.12	0.13	0.00	0.0	
Loc07	Greentree Munic Bldg	0.10	0.12	0.10	0.00	0.0	
Loc08	AC Health Dept Bldg	0.09	0.11	0.09	0.00	0.0	
Loc09	Univ of Pittsburgh	0.09	0.11	0.09	0.00	0.0	
Loc11	M-46 Access Shaft	0.09	0.10	0.09	0.00	0.0	
Loc13	M-59 Access Shaft	0.08	0.11	0.08	0.00	0.0	
Loc14	Churchill Munic Bldg	0.08	0.09	0.08	0.00	0.0	
Loc15	Trafford Maint Bldg	0.07	0.09	0.07	0.00	0.0	
Loc16	Castle Shannon	0.11	0.12	0.11	0.00	0.0	

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc17	Chartiers Pump Station	0.14	0.13	0.14	0.00	0.0	
Loc18	Oakdale Pump Station	0.15	0.13	0.15	0.00	0.0	
Loc19	Sandy Creek Eq Facility	0.07	0.09	0.07	0.00	0.0	
Loc20	Gascola Eq Facility	0.09	0.09	0.09	0.00	0.0	
Loc21	Moon TWP	0.10	0.14	0.10	0.00	0.0	
Loc23	Clinton Munic Bldg	0.12	0.14	0.12	0.00	0.0	
Loc24	Jefferson Hills	0.09	0.10	0.09	0.00	0.0	
Loc25	White Oak Public Works Bldg	0.07	0.09	0.07	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.08	0.09	0.08	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.09	0.11	0.09	0.00	0.0	
Loc31	Hampton Municipal Bldg	0.09	0.10	0.09	0.00	0.0	
Loc32	Arnold	0.06	0.06	0.06	0.00	0.0	
Loc33	Richland TWP	0.08	0.07	0.08	0.00	0.0	
Loc01	PWSA-Montana St.	0.11	0.11	0.10	0.01	9.1	
Loc12	Baldwin	0.11	0.11	0.10	0.01	9.1	
Loc10	PWSA-Highland Park	0.10	0.09	0.09	0.01	10.0	
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.08	---	---	---	---	U
Loc22	North Fayette TWP	0.09	---	---	---	---	U
Loc27	Marshall TWP	0.05	---	---	---	---	U
Loc28	Plum Municipal Bldg	0.04	---	---	---	---	U
Loc30	McCandless Twn Hall	0.04	---	---	---	---	U

Table 8. Summary of Individual RG Pairs for Event 1c

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc08	AC Health Dept Bldg	0.41	0.32	0.43	-0.02	-4.9	
Loc05	Upper St. Clair	0.45	0.31	0.47	-0.02	-4.4	
Loc07	Greentree Munic Bldg	0.44	0.32	0.45	-0.01	-2.3	
Loc02	ALCOSAN WWTP Lab	0.45	0.35	0.46	-0.01	-2.2	
Loc19	Sandy Creek Eq Facility	0.46	0.30	0.47	-0.01	-2.2	
03049500	Allegheny River at Natrona	0.37	0.28	0.37	0.00	0.0	
KAGC	Pittsburgh Allegheny Cty	0.48	0.32	0.48	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.39	0.32	0.39	0.00	0.0	
Loc01	PWSA-Montana St.	0.47	0.35	0.47	0.00	0.0	

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc03	Shaler Munic Bldg	0.51	0.35	0.51	0.00	0.0	
Loc04	Kennedy Twp PS	0.45	0.32	0.45	0.00	0.0	
Loc06	Carnegie Transit Time	0.49	0.33	0.49	0.00	0.0	
Loc09	Univ of Pittsburgh	0.42	0.31	0.42	0.00	0.0	
Loc11	M-46 Access Shaft	0.42	0.29	0.42	0.00	0.0	
Loc13	M-59 Access Shaft	0.50	0.33	0.50	0.00	0.0	
Loc15	Trafford Maint Bldg	0.41	0.27	0.41	0.00	0.0	
Loc18	Oakdale Pump Station	0.47	0.33	0.47	0.00	0.0	
Loc21	Moon TWP	0.44	0.38	0.44	0.00	0.0	
Loc23	Clinton Munic Bldg	0.44	0.37	0.44	0.00	0.0	
Loc24	Jefferson Hills	0.46	0.28	0.46	0.00	0.0	
Loc25	White Oak Public Works Bldg	0.46	0.32	0.46	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.50	0.34	0.50	0.00	0.0	
Loc28	Plum Municipal Bldg	0.39	0.30	0.39	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.55	0.37	0.55	0.00	0.0	
Loc32	Arnold	0.37	0.29	0.37	0.00	0.0	
Loc33	Richland TWP	0.46	0.33	0.46	0.00	0.0	
Loc20	Gascola Eq Facility	0.52	0.32	0.51	0.01	1.9	
Loc14	Churchill Munic Bldg	0.48	0.30	0.47	0.01	2.1	
Loc12	Baldwin	0.46	0.29	0.45	0.01	2.2	
Loc17	Chartiers Pump Station	0.50	0.30	0.48	0.02	4.0	
Loc10	PWSA-Highland Park	0.50	0.30	0.47	0.03	6.0	
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.32	---	---	---	---	U
Loc16	Castle Shannon	0.40	---	---	---	---	U
Loc22	North Fayette TWP	0.40	---	---	---	---	U
Loc27	Marshall TWP	0.26	---	---	---	---	U
Loc30	McCandless Twn Hall	0.28	---	---	---	---	U
Loc31	Hampton Municipal Bldg	0.37	---	---	---	---	U

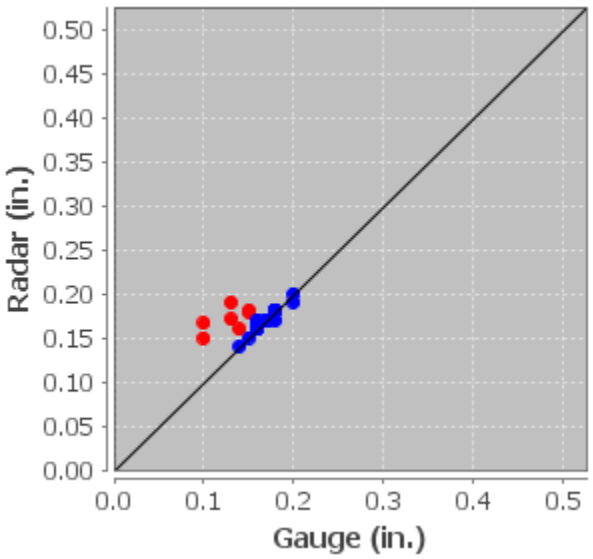


Figure 4. Scatter Plot of RG Pairs for Event 1a

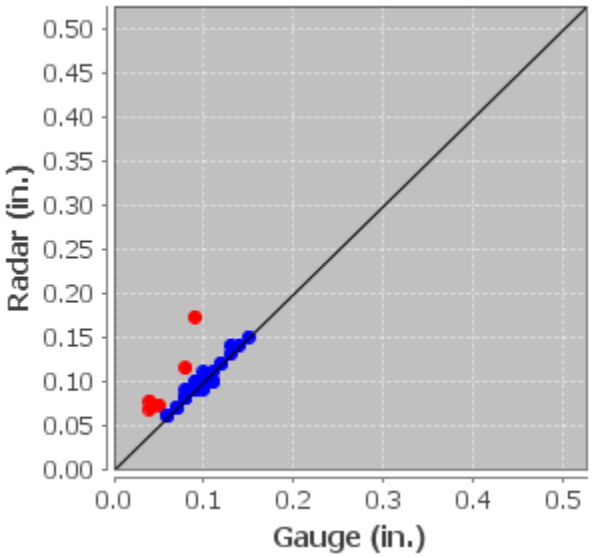


Figure 5. Scatter Plot of RG Pairs for Event 1b

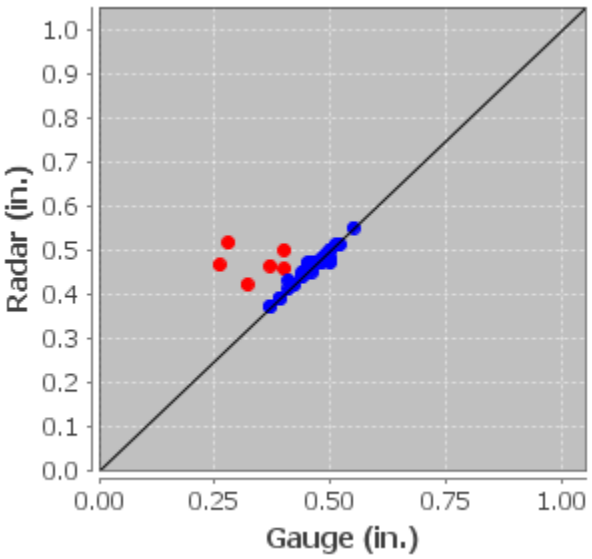


Figure 6. Scatter Plot of RG Pairs for Event 1c

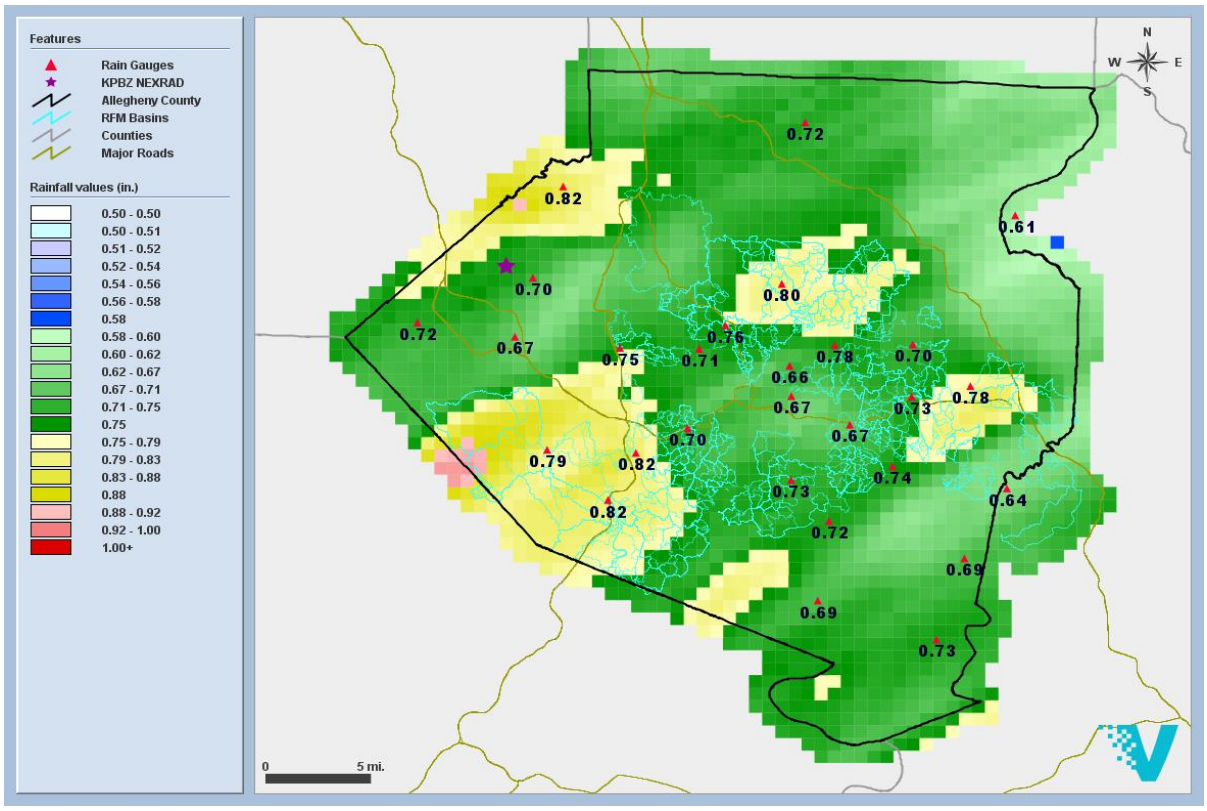


Figure 7. GARR Storm Total for Event 1

Table 9. Depth Duration Frequency Analyses for Event 1

Duration	Depth (in)	Pixel	Time (EST)	Frequency
15 minutes	0.159	161141	2021-01-01 14:45	<1 yr.
30 minutes	0.281	144155	2021-01-01 14:30	<1 yr.
1 hour	0.457	124145	2021-01-01 14:45	<1 yr.
2 hour	0.612	124145	2021-01-01 14:55	<1 yr.
3 hour	0.694	124145	2021-01-01 15:00	<1 yr.
6 hour	0.899	125144	2021-01-01 16:00	<1 yr.
12 hour	0.903	125144	2021-01-01 20:00	<1 yr.

Event 2: 2021-01-03

The analysis period was from 2021-01-03 02:00 EST to 2021-01-03 22:00 EST. The event was then split into three sub-event periods at 2021-01-03 08:00 EST and 2021-01-03 10:15 EST 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. The gauges listed in Appendix B were not used to adjust the radar since they did not meet statistical criteria for gauge-adjustment.

The Eastern U.S. cool season stratiform Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 10 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Tables 11 - 13 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. Those gauges not used to adjust the radar are shown at the bottom of the table and are highlighted in red. The specific reason for gauge exclusion is displayed in the Flag column. Figures 8 - 10 show the scatter plots of the gauge-adjusted RG pairs. Those gauges not used to adjust the radar are shown in red. Figure 11 depicts the GARR storm total over the 1-km^2 pixels. The GARR amounts for the 2313 1-km^2 pixels range from 0.1 - 0.6 inches with a mean of 0.4 inches. The GARR amounts for the 440 RFM basins range from 0.2 - 0.5 inches with a mean of 0.4 inches. The GARR amounts for the 871 RFM sheds range from 0.2 - 0.5 inches with a mean of 0.4 inches. Table 14 shows the Depth Duration Frequency (DDF) maximum values for the 1-km^2 pixels.

Table 10. GARR Statistics for Event 2

Event #	Radar	Event Date	Start Time (EST)	End Time (EST)	Gauges Used (37)	Avg. Depth (in)	Bias	AD (%)	CAD (%)
E2a	KPBZ LII	2021-01-03	2021-01-03 02:05	2021-01-03 08:00	25	0.059	0.698	45.6	1.9
E2b	KPBZ LII	2021-01-03	2021-01-03 08:05	2021-01-03 10:15	25	0.073	0.984	24.8	2.6

Event #	Radar	Event Date	Start Time (EST)	End Time (EST)	Gauges Used (37)	Avg. Depth (in)	Bias	AD (%)	CAD (%)
E2c	KPBZ LII	2021-01-03	2021-01-03 10:20	2021-01-03 22:00	32	0.280	0.655	54.0	1.1

Table 11. Summary of Individual RG Pairs for Event 2a

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
KAGC	Pittsburgh Allegheny Cty	0.10	0.11	0.10	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.06	0.08	0.06	0.00	0.0	
Loc04	Kennedy Twp PS	0.05	0.06	0.05	0.00	0.0	
Loc05	Upper St. Clair	0.05	0.07	0.05	0.00	0.0	
Loc06	Carnegie Transit Time	0.06	0.06	0.06	0.00	0.0	
Loc07	Greentree Munic Bldg	0.05	0.06	0.05	0.00	0.0	
Loc09	Univ of Pittsburgh	0.06	0.06	0.06	0.00	0.0	
Loc10	PWSA-Highland Park	0.06	0.06	0.06	0.00	0.0	
Loc11	M-46 Access Shaft	0.07	0.09	0.07	0.00	0.0	
Loc12	Baldwin	0.07	0.08	0.07	0.00	0.0	
Loc13	M-59 Access Shaft	0.08	0.11	0.08	0.00	0.0	
Loc14	Churchill Munic Bldg	0.07	0.09	0.07	0.00	0.0	
Loc15	Trafford Maint Bldg	0.06	0.15	0.06	0.00	0.0	
Loc16	Castle Shannon	0.07	0.08	0.07	0.00	0.0	
Loc17	Chartiers Pump Station	0.06	0.06	0.06	0.00	0.0	
Loc19	Sandy Creek Eq Facility	0.07	0.09	0.07	0.00	0.0	
Loc20	Gascola Eq Facility	0.08	0.13	0.08	0.00	0.0	
Loc21	Moon TWP	0.05	0.08	0.05	0.00	0.0	
Loc23	Clinton Munic Bldg	0.06	0.08	0.06	0.00	0.0	
Loc24	Jefferson Hills	0.11	0.15	0.11	0.00	0.0	
Loc25	White Oak Public Works Bldg	0.06	0.14	0.06	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.05	0.14	0.05	0.00	0.0	
Loc28	Plum Municipal Bldg	0.06	0.11	0.06	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.05	0.07	0.05	0.00	0.0	
Loc32	Arnold	0.07	0.14	0.07	0.00	0.0	
03049500	Allegheny River at Natrona	0.05	---	---	---	---	U
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.03	---	---	---	---	MSTT
Loc01	PWSA-Montana St.	0.04	---	---	---	---	MSTT

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc02	ALCOSAN WWTP Lab	0.04	---	---	---	---	MSTT
Loc03	Shaler Munic Bldg	0.04	---	---	---	---	MSTT
Loc08	AC Health Dept Bldg	0.04	---	---	---	---	MSTT
Loc18	Oakdale Pump Station	0.04	---	---	---	---	MSTT
Loc22	North Fayette TWP	0.03	---	---	---	---	U
Loc27	Marshall TWP	0.03	---	---	---	---	MSTT
Loc30	McCandless Twn Hall	0.03	---	---	---	---	MSTT
Loc31	Hampton Municipal Bldg	0.04	---	---	---	---	MSTT
Loc33	Richland TWP	0.04	---	---	---	---	MSTT

Table 12. Summary of Individual RG Pairs for Event 2b

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc22	North Fayette TWP	0.10	0.08	0.11	-0.01	-10.0	
KAGC	Pittsburgh Allegheny Cty	0.11	0.11	0.11	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.05	0.05	0.05	0.00	0.0	
Loc01	PWSA-Montana St.	0.08	0.07	0.08	0.00	0.0	
Loc02	ALCOSAN WWTP Lab	0.08	0.07	0.08	0.00	0.0	
Loc03	Shaler Munic Bldg	0.06	0.05	0.06	0.00	0.0	
Loc04	Kennedy Twp PS	0.07	0.07	0.07	0.00	0.0	
Loc05	Upper St. Clair	0.15	0.11	0.15	0.00	0.0	
Loc06	Carnegie Transit Time	0.12	0.10	0.12	0.00	0.0	
Loc07	Greentree Munic Bldg	0.09	0.08	0.09	0.00	0.0	
Loc08	AC Health Dept Bldg	0.07	0.06	0.07	0.00	0.0	
Loc09	Univ of Pittsburgh	0.08	0.07	0.08	0.00	0.0	
Loc10	PWSA-Highland Park	0.07	0.06	0.07	0.00	0.0	
Loc11	M-46 Access Shaft	0.06	0.08	0.06	0.00	0.0	
Loc12	Baldwin	0.10	0.10	0.10	0.00	0.0	
Loc14	Churchill Munic Bldg	0.08	0.09	0.08	0.00	0.0	
Loc15	Trafford Maint Bldg	0.11	0.19	0.11	0.00	0.0	
Loc16	Castle Shannon	0.13	0.10	0.13	0.00	0.0	
Loc20	Gascola Eq Facility	0.07	0.12	0.07	0.00	0.0	
Loc23	Clinton Munic Bldg	0.06	0.05	0.06	0.00	0.0	
Loc24	Jefferson Hills	0.12	0.18	0.12	0.00	0.0	
Loc25	White Oak Public Works Bldg	0.14	0.19	0.14	0.00	0.0	

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc26	Elizabeth TWP Municipal Bldg	0.08	0.13	0.08	0.00	0.0	
Loc18	Oakdale Pump Station	0.20	0.13	0.19	0.01	5.0	
Loc17	Chartiers Pump Station	0.15	0.10	0.14	0.01	6.7	
03049500	Allegheny River at Natrona	0.00	---	---	---	---	MSTT
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.05	---	---	---	---	MSTT
Loc13	M-59 Access Shaft	0.05	---	---	---	---	U
Loc19	Sandy Creek Eq Facility	0.04	---	---	---	---	MSTT
Loc21	Moon TWP	0.03	---	---	---	---	MSTT
Loc27	Marshall TWP	0.00	---	---	---	---	MSTT
Loc28	Plum Municipal Bldg	0.04	---	---	---	---	MSTT
Loc29	Bell Acres Munic Bldg	0.01	---	---	---	---	MSTT
Loc30	McCandless Twn Hall	0.00	---	---	---	---	MSTT
Loc31	Hampton Municipal Bldg	0.03	---	---	---	---	MSTT
Loc32	Arnold	0.01	---	---	---	---	MSTT
Loc33	Richland TWP	0.01	---	---	---	---	MSTT

Table 13. Summary of Individual RG Pairs for Event 2c

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc05	Upper St. Clair	0.18	0.37	0.19	-0.01	-5.6	
Loc11	M-46 Access Shaft	0.26	0.40	0.27	-0.01	-3.8	
Loc19	Sandy Creek Eq Facility	0.31	0.42	0.32	-0.01	-3.2	
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.33	0.72	0.34	-0.01	-3.0	
Loc03	Shaler Munic Bldg	0.34	0.59	0.35	-0.01	-2.9	
KAGC	Pittsburgh Allegheny Cty	0.20	0.32	0.20	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.33	0.40	0.33	0.00	0.0	
Loc02	ALCOSAN WWTP Lab	0.29	0.61	0.29	0.00	0.0	
Loc04	Kennedy Twp PS	0.33	0.66	0.33	0.00	0.0	
Loc07	Greentree Munic Bldg	0.25	0.45	0.25	0.00	0.0	
Loc08	AC Health Dept Bldg	0.30	0.49	0.30	0.00	0.0	
Loc09	Univ of Pittsburgh	0.27	0.45	0.27	0.00	0.0	
Loc10	PWSA-Highland Park	0.30	0.47	0.30	0.00	0.0	
Loc12	Baldwin	0.25	0.39	0.25	0.00	0.0	

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc13	M-59 Access Shaft	0.20	0.28	0.20	0.00	0.0	
Loc14	Churchill Munic Bldg	0.27	0.34	0.27	0.00	0.0	
Loc16	Castle Shannon	0.28	0.41	0.28	0.00	0.0	
Loc17	Chartiers Pump Station	0.21	0.39	0.21	0.00	0.0	
Loc18	Oakdale Pump Station	0.29	0.54	0.29	0.00	0.0	
Loc21	Moon TWP	0.36	0.43	0.36	0.00	0.0	
Loc22	North Fayette TWP	0.30	0.51	0.30	0.00	0.0	
Loc23	Clinton Munic Bldg	0.25	0.33	0.25	0.00	0.0	
Loc24	Jefferson Hills	0.18	0.20	0.18	0.00	0.0	
Loc25	White Oak Public Works Bldg	0.16	0.11	0.16	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.14	0.10	0.14	0.00	0.0	
Loc28	Plum Municipal Bldg	0.27	0.27	0.27	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.35	0.64	0.35	0.00	0.0	
Loc31	Hampton Municipal Bldg	0.37	0.59	0.37	0.00	0.0	
Loc32	Arnold	0.35	0.39	0.35	0.00	0.0	
Loc33	Richland TWP	0.44	0.60	0.44	0.00	0.0	
Loc06	Carnegie Transit Time	0.26	0.43	0.25	0.01	3.8	
Loc20	Gascola Eq Facility	0.24	0.24	0.23	0.01	4.2	
03049500	Allegheny River at Natrona	0.31	---	---	---	---	U
Loc01	PWSA-Montana St.	0.26	---	---	---	---	U
Loc15	Trafford Maint Bldg	0.21	---	---	---	---	OMFB
Loc27	Marshall TWP	0.24	---	---	---	---	U
Loc30	McCandless Twn Hall	0.25	---	---	---	---	U

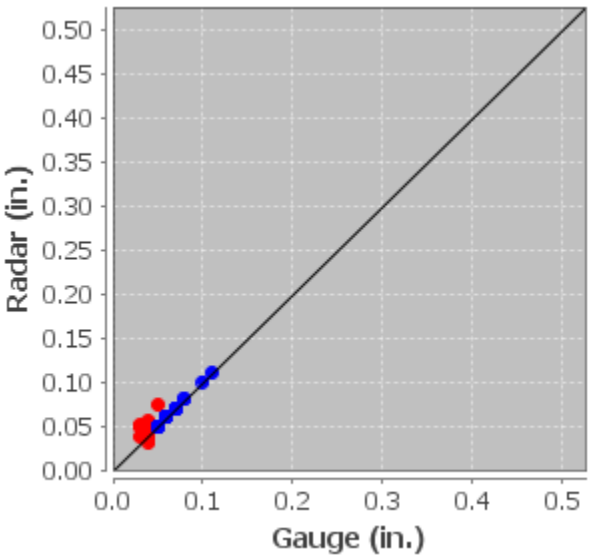


Figure 8. Scatter Plot of RG Pairs for Event 2a

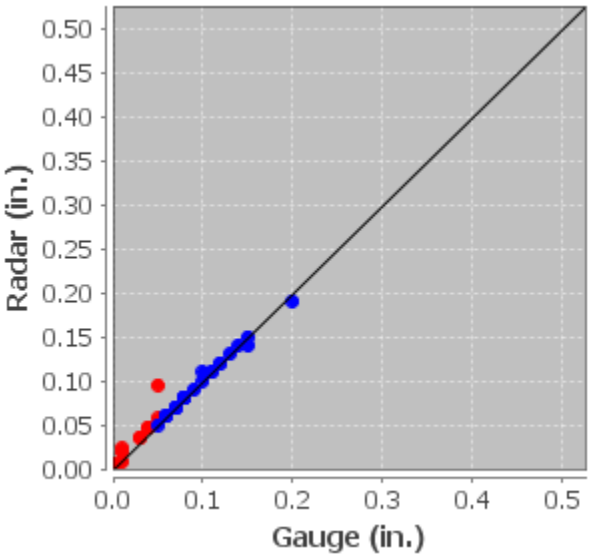


Figure 9. Scatter Plot of RG Pairs for Event 2b

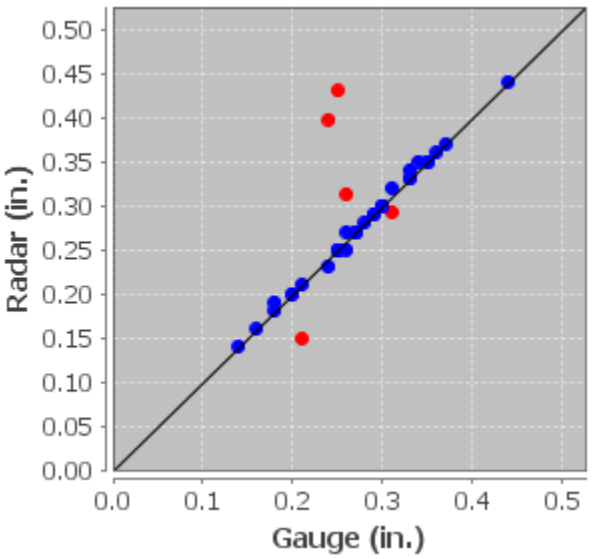


Figure 10. Scatter Plot of RG Pairs for Event 2c

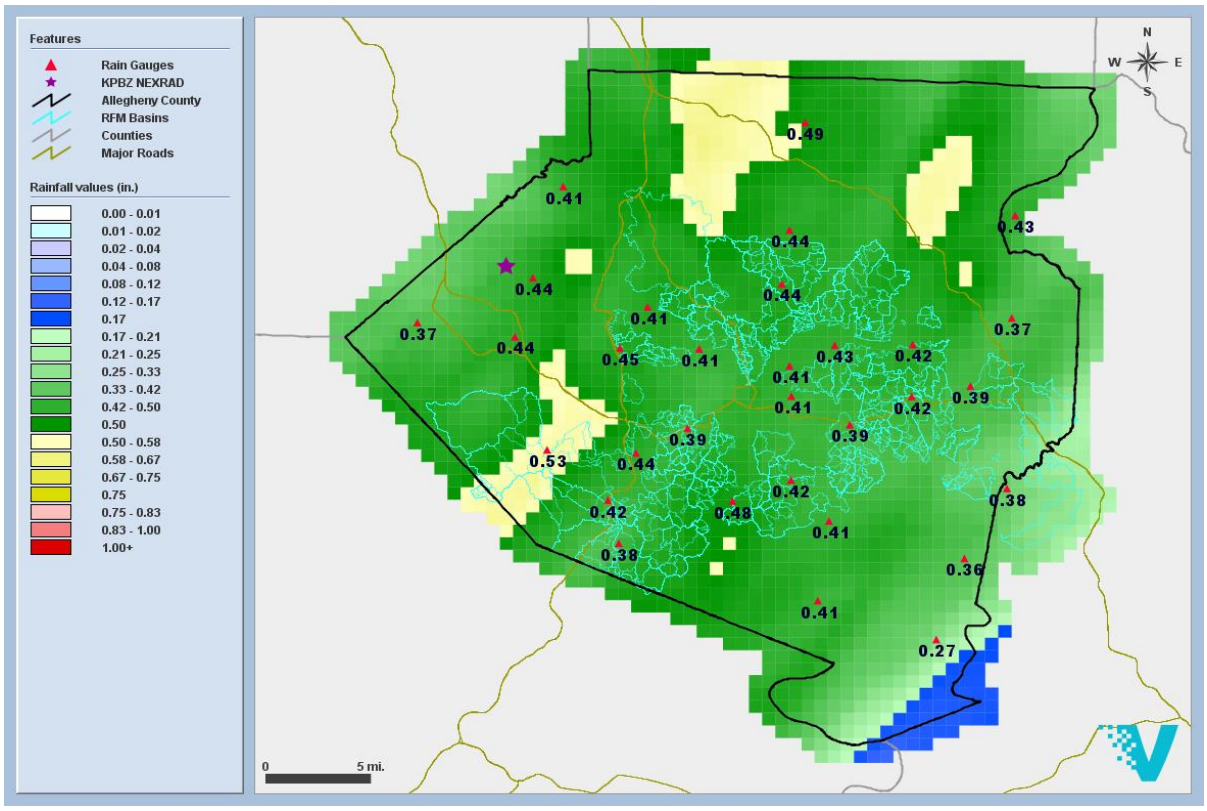


Figure 11. GARR Storm Total for Event 2

Table 14. Depth Duration Frequency Analyses for Event 2

Duration	Depth (in)	Pixel	Time (EST)	Frequency
15 minutes	0.117	157159	2021-01-03 10:30	<1 yr.
30 minutes	0.168	163129	2021-01-03 11:35	<1 yr.
1 hour	0.312	163129	2021-01-03 11:40	<1 yr.
2 hour	0.463	143117	2021-01-03 12:30	<1 yr.
3 hour	0.525	143118	2021-01-03 12:55	<1 yr.
6 hour	0.539	143118	2021-01-03 14:30	<1 yr.
12 hour	0.580	143118	2021-01-03 14:30	<1 yr.

Event 3: 2021-01-15

The analysis period was from 2021-01-15 11:00 EST to 2021-01-15 20:00 EST.

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. The gauges listed in Appendix B were not used to adjust the radar since they did not meet statistical criteria for gauge-adjustment.

The Eastern U.S. cool season stratiform Z-R relationship was used to convert radar reflectivity to rainfall rates. Table 15 shows the mean bias and average depth of the event along with the AD and CAD, respectively. Table 16 summarizes 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, Diff* (in) is the difference in inches between the gauge and GARR estimate, and Diff* (%) is the percent difference between the gauge and GARR estimate. Those gauges not used to adjust the radar are shown at the bottom of the table and are highlighted in red. The specific reason for gauge exclusion is displayed in the Flag column. Figure 12 shows the scatter plot of the RG pairs. Those gauges not used to adjust the radar are shown in red. Figure 13 depicts the GARR storm total over the 1-km^2 pixels. The GARR amounts for the 2313 1-km^2 pixels range from 0.0 - 0.2 inches with a mean of 0.1 inches. The GARR amounts for the 440 RFM basins range from 0.1 - 0.2 inches with a mean of 0.1 inches. The GARR amounts for the 871 RFM sheds range from 0.1 - 0.2 inches with a mean of 0.1 inches. Table 17 shows the Depth Duration Frequency (DDF) maximum values for the 1-km^2 pixels.

Table 15. GARR Statistics for Event 3

Event #	Radar	Event Date	Start Time (EST)	End Time (EST)	Gauges Used (37)	Avg. Depth (in)	Bias	AD (%)	CAD (%)
E3	KPBZ LII	2021-01-15	2021-01-15 11:05	2021-01-15 20:00	29	0.098	0.568	79.2	2.2

Table 16. Summary of Individual RG Pairs for Event 3

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc22	North Fayette TWP	0.10	0.27	0.11	-0.01	-10.0	
KAGC	Pittsburgh Allegheny Cty	0.08	0.11	0.08	0.00	0.0	
KPIT	Greater Pittsburgh Int'l	0.13	0.36	0.13	0.00	0.0	
Loc03	Shaler Munic Bldg	0.08	0.17	0.08	0.00	0.0	
Loc04	Kennedy Twp PS	0.10	0.29	0.10	0.00	0.0	
Loc05	Upper St. Clair	0.07	0.09	0.07	0.00	0.0	
Loc06	Carnegie Transit Time	0.10	0.14	0.10	0.00	0.0	
Loc07	Greentree Munic Bldg	0.08	0.13	0.08	0.00	0.0	
Loc09	Univ of Pittsburgh	0.07	0.16	0.07	0.00	0.0	
Loc10	PWSA-Highland Park	0.08	0.14	0.08	0.00	0.0	
Loc11	M-46 Access Shaft	0.07	0.12	0.07	0.00	0.0	
Loc14	Churchill Munic Bldg	0.09	0.12	0.09	0.00	0.0	
Loc15	Trafford Maint Bldg	0.15	0.11	0.15	0.00	0.0	
Loc16	Castle Shannon	0.07	0.12	0.07	0.00	0.0	
Loc17	Chartiers Pump Station	0.09	0.11	0.09	0.00	0.0	
Loc20	Gascola Eq Facility	0.11	0.11	0.11	0.00	0.0	
Loc21	Moon TWP	0.14	0.42	0.14	0.00	0.0	
Loc23	Clinton Munic Bldg	0.10	0.35	0.10	0.00	0.0	
Loc24	Jefferson Hills	0.07	0.11	0.07	0.00	0.0	
Loc26	Elizabeth TWP Municipal Bldg	0.13	0.13	0.13	0.00	0.0	
Loc27	Marshall TWP	0.10	0.22	0.10	0.00	0.0	
Loc28	Plum Municipal Bldg	0.10	0.10	0.10	0.00	0.0	
Loc29	Bell Acres Munic Bldg	0.15	0.39	0.15	0.00	0.0	
Loc31	Hampton Municipal Bldg	0.09	0.16	0.09	0.00	0.0	
Loc32	Arnold	0.12	0.08	0.12	0.00	0.0	
Loc33	Richland TWP	0.08	0.14	0.08	0.00	0.0	
Loc18	Oakdale Pump Station	0.13	0.22	0.12	0.01	7.7	
Loc19	Sandy Creek Eq Facility	0.11	0.11	0.10	0.01	9.1	
Loc13	M-59 Access Shaft	0.10	0.12	0.09	0.01	10.0	
03049500	Allegheny River at Natrona	0.06	---	---	---	---	F/M
03085734	Ohio River at Emsworth Dam Lower Pool at Emsworth	0.07	---	---	---	---	F/M
Loc01	PWSA-Montana St.	0.04	---	---	---	---	F/M
Loc02	ALCOSAN WWTP Lab	0.06	---	---	---	---	F/M
Loc08	AC Health Dept Bldg	0.06	---	---	---	---	F/M
Loc12	Baldwin	0.05	---	---	---	---	F/M

Gauge ID	Name	G_i (in)	R_i (in)	R_i* (in)	Diff* (in)	Diff* (%)	Flag
Loc25	White Oak Public Works Bldg	ND	---	---	---	---	ND
Loc30	McCandless Twn Hall	0.08	---	---	---	---	F/M

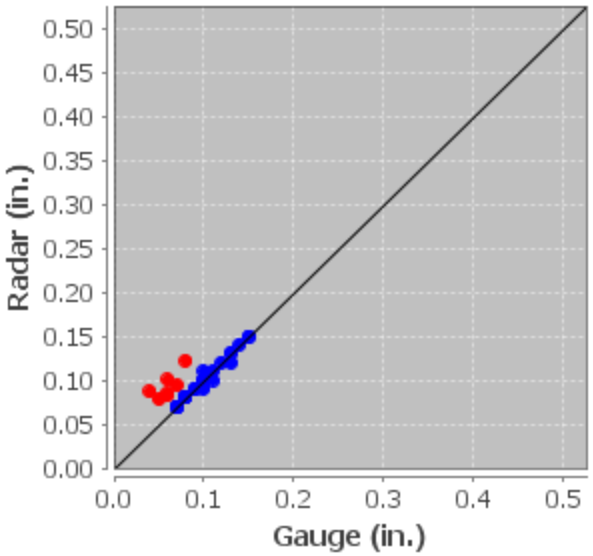


Figure 12. Scatter Plot of RG Pairs for Event 3

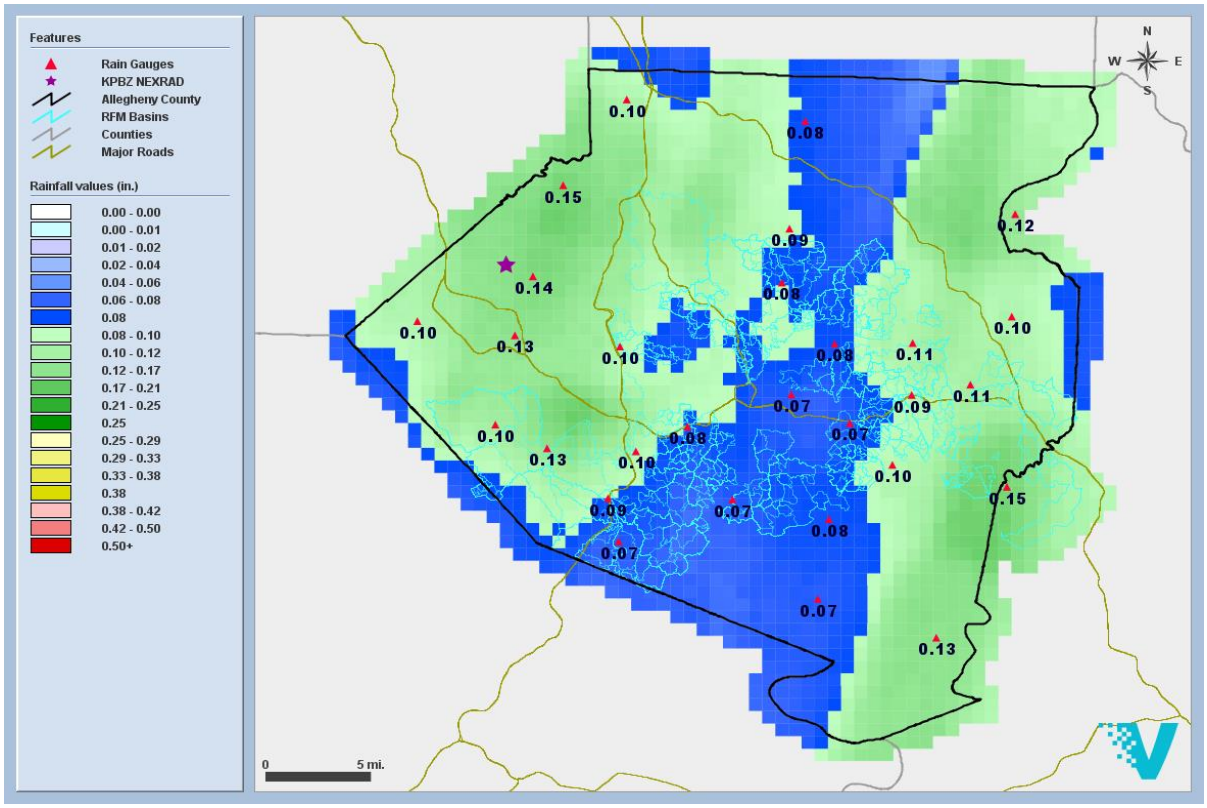


Figure 13. GARR Storm Total for Event 3

Table 17. Depth Duration Frequency Analyses for Event 3

Duration	Depth (in)	Pixel	Time (EST)	Frequency
15 minutes	0.045	135140	2021-01-15 15:25	<1 yr.
30 minutes	0.071	135140	2021-01-15 15:35	<1 yr.
1 hour	0.102	131124	2021-01-15 16:15	<1 yr.
2 hour	0.151	133140	2021-01-15 16:00	<1 yr.
3 hour	0.159	165150	2021-01-15 16:35	<1 yr.
6 hour	0.159	133140	2021-01-15 17:20	<1 yr.

Appendices

Appendix A - Gauge Performance Exclusion Table
Appendix B - Gauge Statistical Criteria Exclusion Table
Appendix C - Event 1 (2021-01-01) CDPs
Appendix D - Event 2 (2021-01-03) CDPs
Appendix E - Event 3 (2021-01-15) CDPs

Appendix A - Gauge Performance Exclusion Table

Reason	Explanation
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

Event #	E1a	E1b	E1c	E2a	E2b
Event Date	**2021-01-01**	**2021-01-01**	**2021-01-01**	**2021-01-03**	**2021-01-03**
Start Time (EST)	2021-01-01 08:05	2021-01-01 12:20	2021-01-01 13:50	2021-01-03 02:05	2021-01-03 08:05
End Time (EST)	2021-01-01 12:15	2021-01-01 13:45	2021-01-01 23:00	2021-01-03 08:00	2021-01-03 10:15
Loc01					
Loc02					
Loc03					
Loc04					
Loc05	U				
Loc06					
Loc07					
Loc08					
Loc09					
Loc10					
Loc11					
Loc12					
Loc13					U
Loc14					
Loc15					
Loc16	U		U		
Loc17					
Loc18					
Loc19					
Loc20					
Loc21					
Loc22	U	U	U	U	
Loc23					
Loc24					
Loc25					
Loc26					
Loc27	U	U	U		
Loc28	U	U			

Event #	E1a	E1b	E1c	E2a	E2b
Event Date	**2021-01-01**	**2021-01-01**	**2021-01-01**	**2021-01-03**	**2021-01-03**
Start Time (EST)	2021-01-01 08:05	2021-01-01 12:20	2021-01-01 13:50	2021-01-03 02:05	2021-01-03 08:05
End Time (EST)	2021-01-01 12:15	2021-01-01 13:45	2021-01-01 23:00	2021-01-03 08:00	2021-01-03 10:15
Loc29					
Loc30	U	U	U		
Loc31			U		
Loc32					
Loc33					
KAGC					
KPIT					
03049500	U			U	
03085734		U	U		

Event #	E2c	E3
Event Date	**2021-01-03**	**2021-01-15**
Start Time (EST)	2021-01-03 10:20	2021-01-15 11:05
End Time (EST)	2021-01-03 22:00	2021-01-15 20:00
Loc01	U	F/M
Loc02		F/M
Loc03		
Loc04		
Loc05		
Loc06		
Loc07		
Loc08		F/M
Loc09		
Loc10		
Loc11		
Loc12		F/M
Loc13		
Loc14		
Loc15		
Loc16		
Loc17		
Loc18		
Loc19		
Loc20		
Loc21		
Loc22		
Loc23		
Loc24		
Loc25		ND
Loc26		
Loc27	U	
Loc28		

Event #	E2c	E3
Event Date	**2021-01-03**	**2021-01-15**
Start Time (EST)	2021-01-03 10:20	2021-01-15 11:05
End Time (EST)	2021-01-03 22:00	2021-01-15 20:00
Loc29		
Loc30	U	F/M
Loc31		
Loc32		
Loc33		
KAGC		
KPIT		
03049500	U	F/M
03085734		F/M

Appendix B - Gauge Statistical Criteria Exclusion Table

Reason	Explanation
Minimum Storm Total Threshold (MSTT)	The radar or gauge cumulative sum during the event or sub-event period was less than MSTT
Outlier Based on Mean Field Bias (OMFB)	The RG pair bias (G/R) was greater than three standard deviations from the mean bias (e.g. G>>R)
Outlier Based on Average Difference (OAD)	The RG pair average difference ((G-R)/G)) was greater than three standard deviations from the mean average difference (e.g. G<<R)

Event #	E1a	E1b	E1c	E2a	E2b
Event Date	**2021-01-01**	**2021-01-01**	**2021-01-01**	**2021-01-03**	**2021-01-03**
Start Time (EST)	2021-01-01 08:05	2021-01-01 12:20	2021-01-01 13:50	2021-01-03 02:05	2021-01-03 08:05
End Time (EST)	2021-01-01 12:15	2021-01-01 13:45	2021-01-01 23:00	2021-01-03 08:00	2021-01-03 10:15
Source	KPBZ LII	KPBZ LII	KPBZ LII	KPBZ LII	KPBZ LII
Loc01				MSTT	
Loc02				MSTT	
Loc03				MSTT	
Loc04					
Loc05					
Loc06					
Loc07					
Loc08				MSTT	
Loc09					
Loc10					
Loc11					
Loc12					
Loc13					
Loc14					
Loc15					
Loc16					
Loc17					
Loc18				MSTT	
Loc19					MSTT
Loc20					
Loc21					MSTT
Loc22					
Loc23					
Loc24					
Loc25					
Loc26					
Loc27				MSTT	MSTT

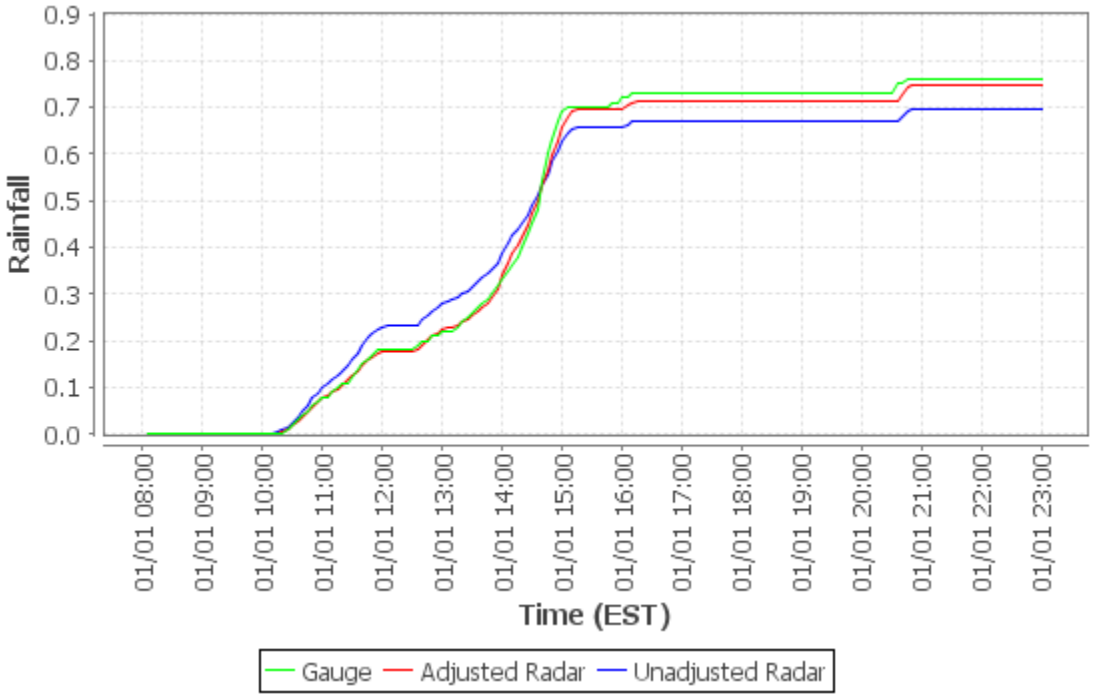
Event #	E1a	E1b	E1c	E2a	E2b
Event Date	**2021-01-01**	**2021-01-01**	**2021-01-01**	**2021-01-03**	**2021-01-03**
Start Time (EST)	2021-01-01 08:05	2021-01-01 12:20	2021-01-01 13:50	2021-01-03 02:05	2021-01-03 08:05
End Time (EST)	2021-01-01 12:15	2021-01-01 13:45	2021-01-01 23:00	2021-01-03 08:00	2021-01-03 10:15
Source	KPBZ LII	KPBZ LII	KPBZ LII	KPBZ LII	KPBZ LII
Loc28					MSTT
Loc29					MSTT
Loc30				MSTT	MSTT
Loc31				MSTT	MSTT
Loc32					MSTT
Loc33				MSTT	MSTT
KAGC					
KPIT					
03049500					MSTT
03085734				MSTT	MSTT

Event #	E2c	E3
Event Date	**2021-01-03**	**2021-01-15**
Start Time (EST)	2021-01-03 10:20	2021-01-15 11:05
End Time (EST)	2021-01-03 22:00	2021-01-15 20:00
Source	KPBZ LII	KPBZ LII
Loc01		
Loc02		
Loc03		
Loc04		
Loc05		
Loc06		
Loc07		
Loc08		
Loc09		
Loc10		
Loc11		
Loc12		
Loc13		
Loc14		
Loc15	OMFB	
Loc16		
Loc17		
Loc18		
Loc19		
Loc20		
Loc21		
Loc22		
Loc23		
Loc24		
Loc25		
Loc26		
Loc27		

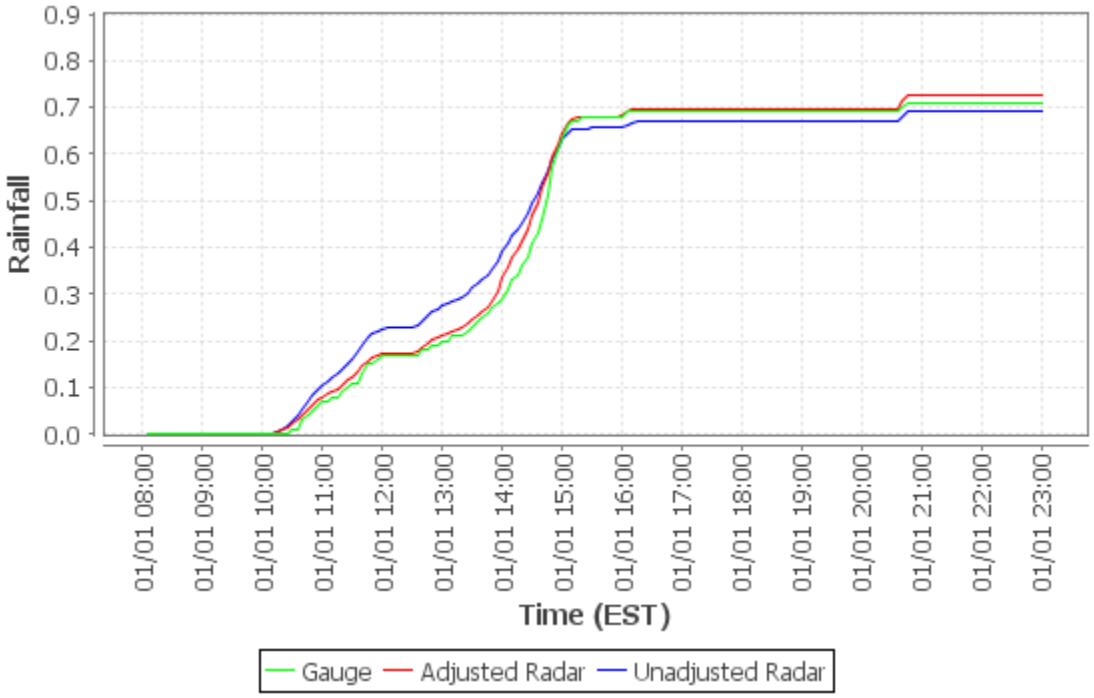
Event #	E2c	E3
Event Date	**2021-01-03**	**2021-01-15**
Start Time (EST)	2021-01-03 10:20	2021-01-15 11:05
End Time (EST)	2021-01-03 22:00	2021-01-15 20:00
Source	KPBZ LII	KPBZ LII
Loc28		
Loc29		
Loc30		
Loc31		
Loc32		
Loc33		
KAGC		
KPIT		
03049500		
03085734		

Appendix C - Event 1 (2021-01-01) CDPs

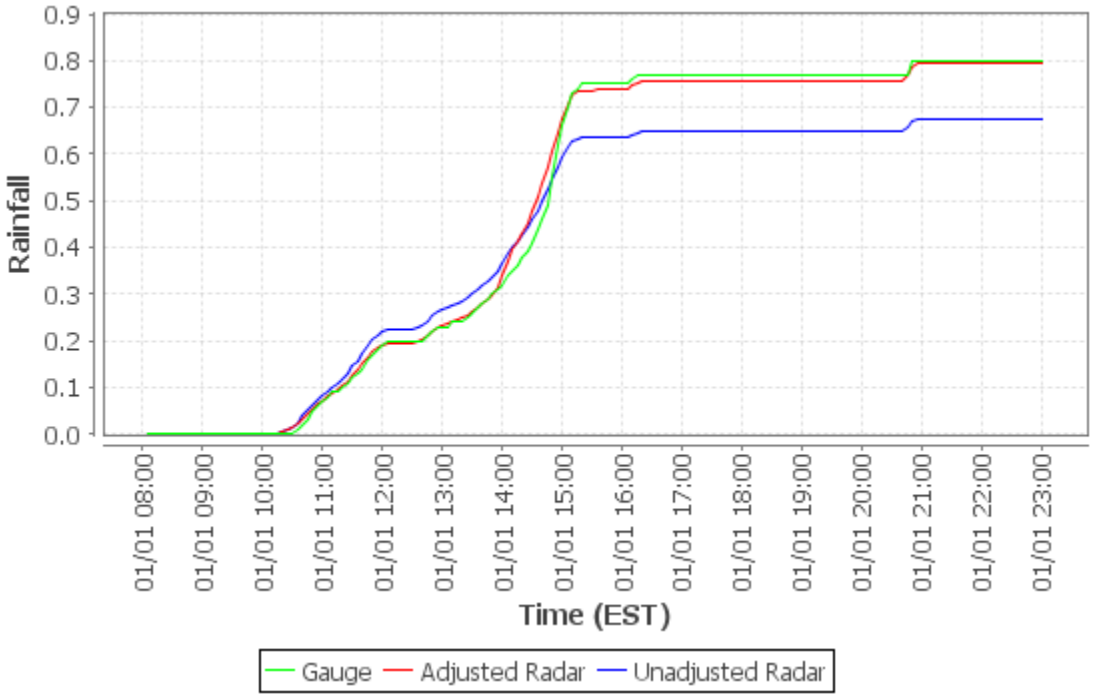
Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



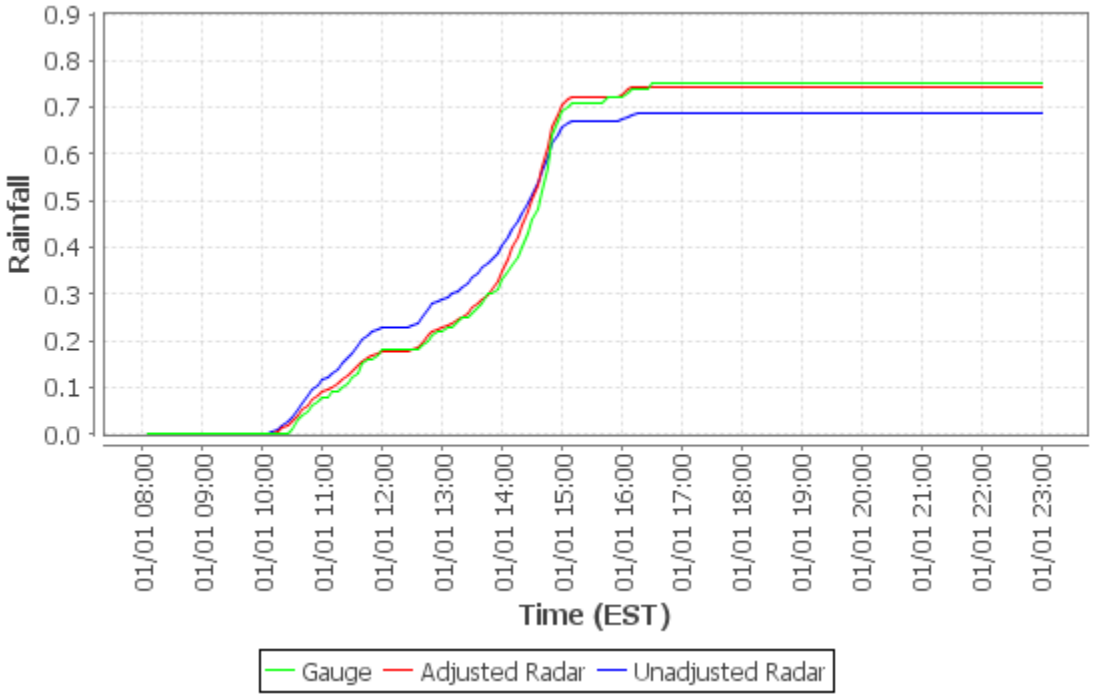
Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



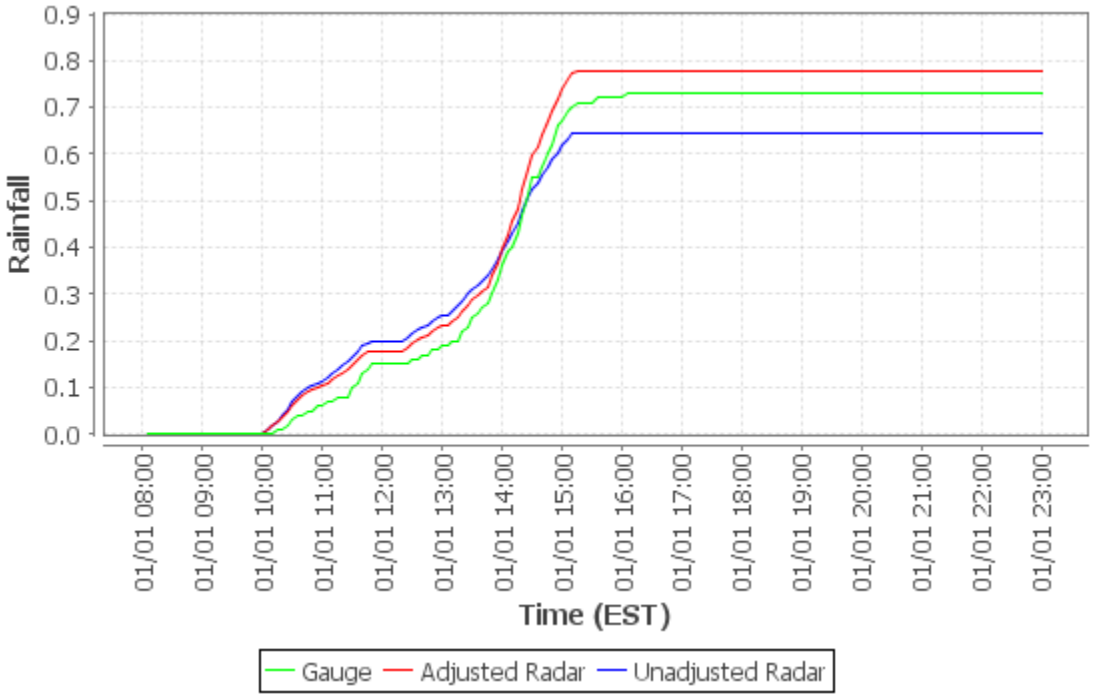
Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



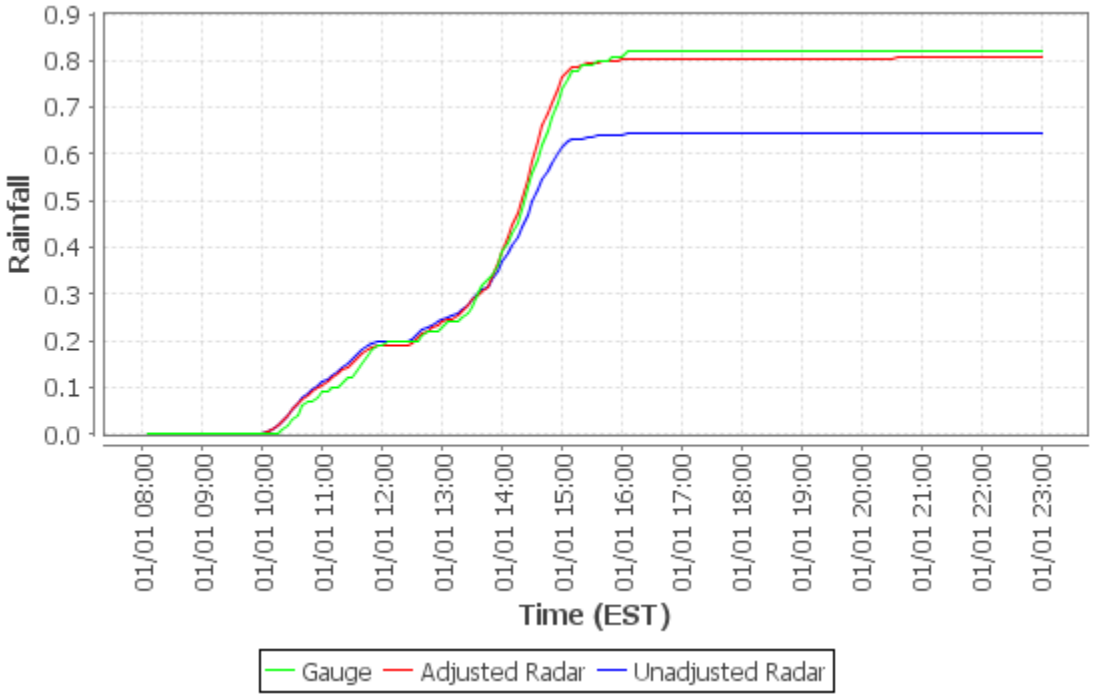
Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



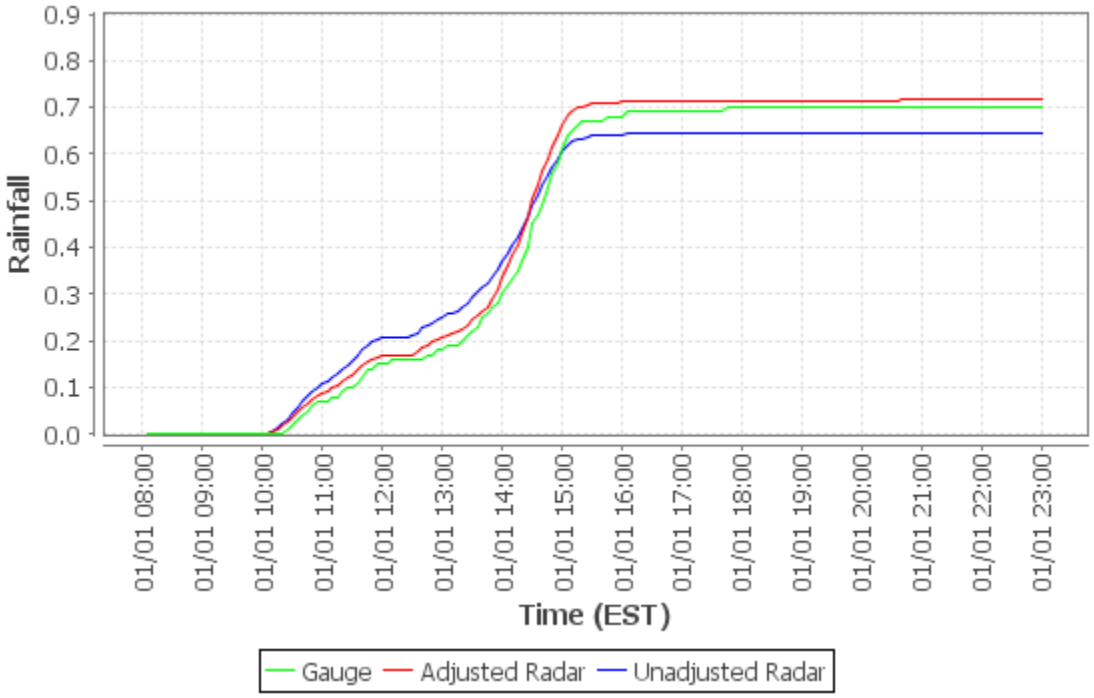
Cumulative Distribution Plot - Upper St. Clair (Loc05)



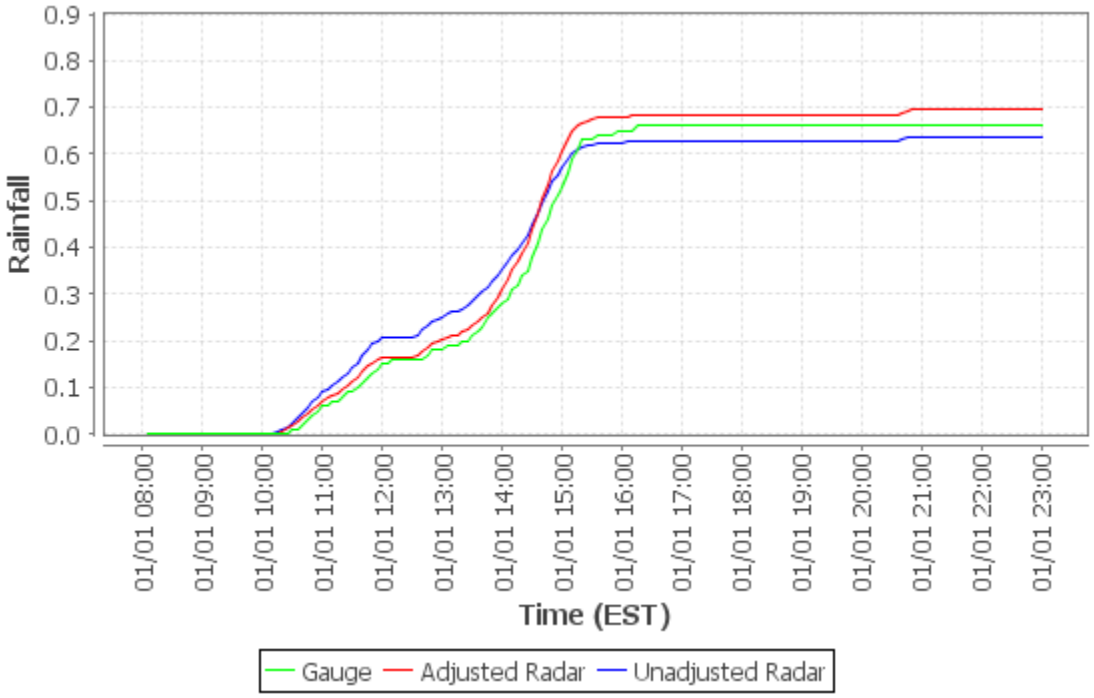
Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



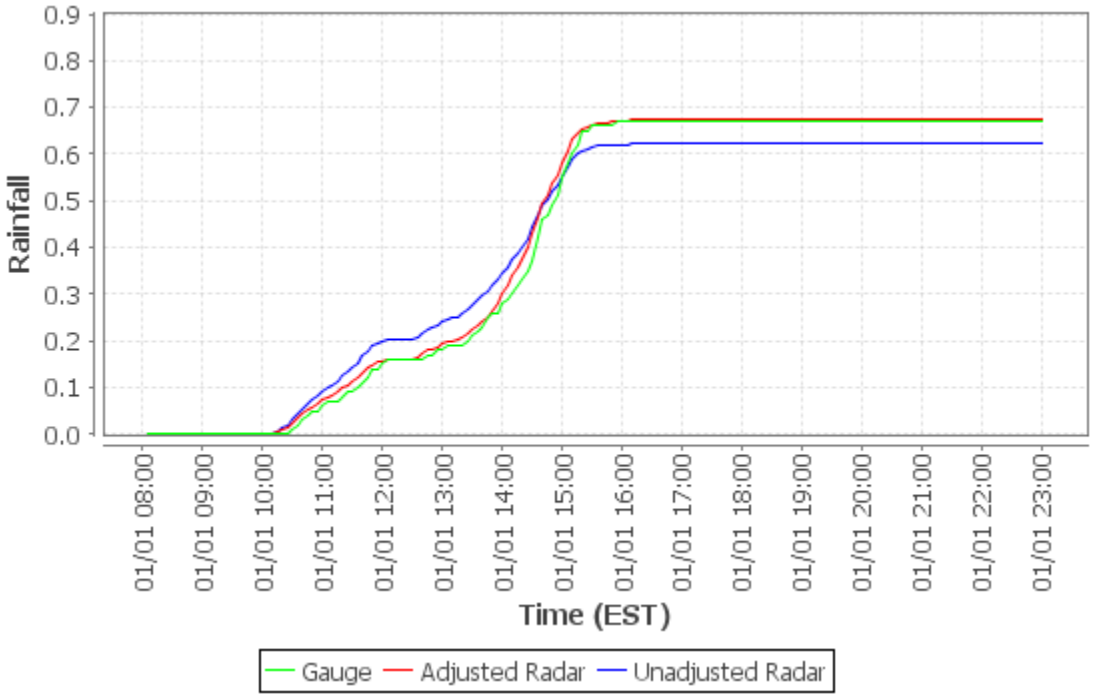
Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



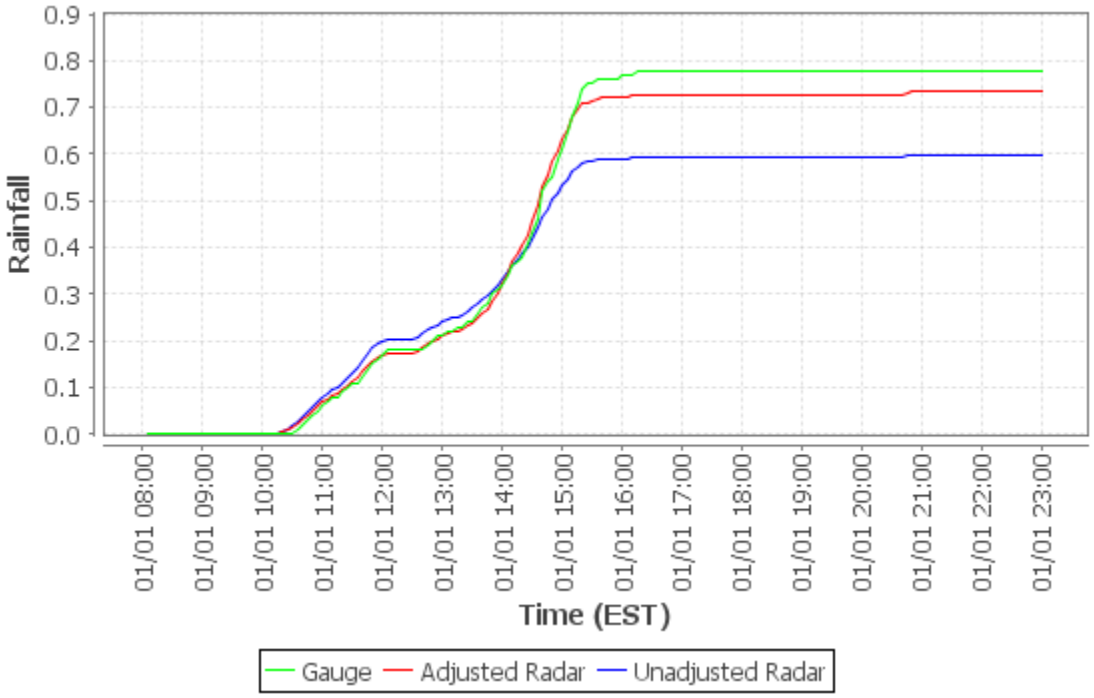
Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



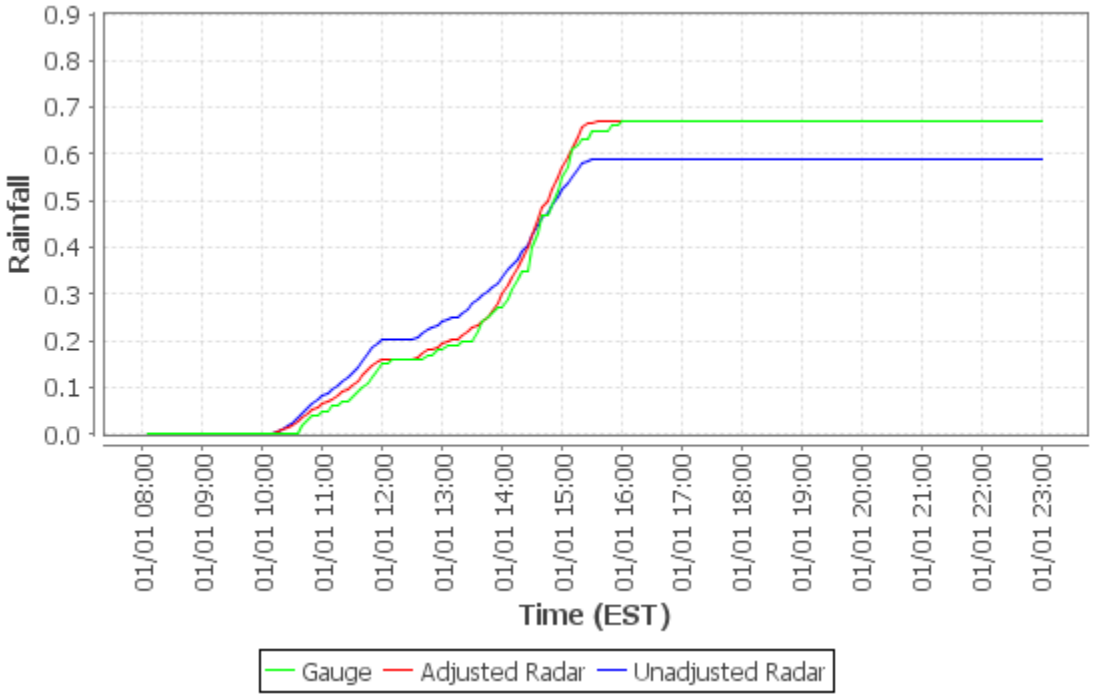
Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



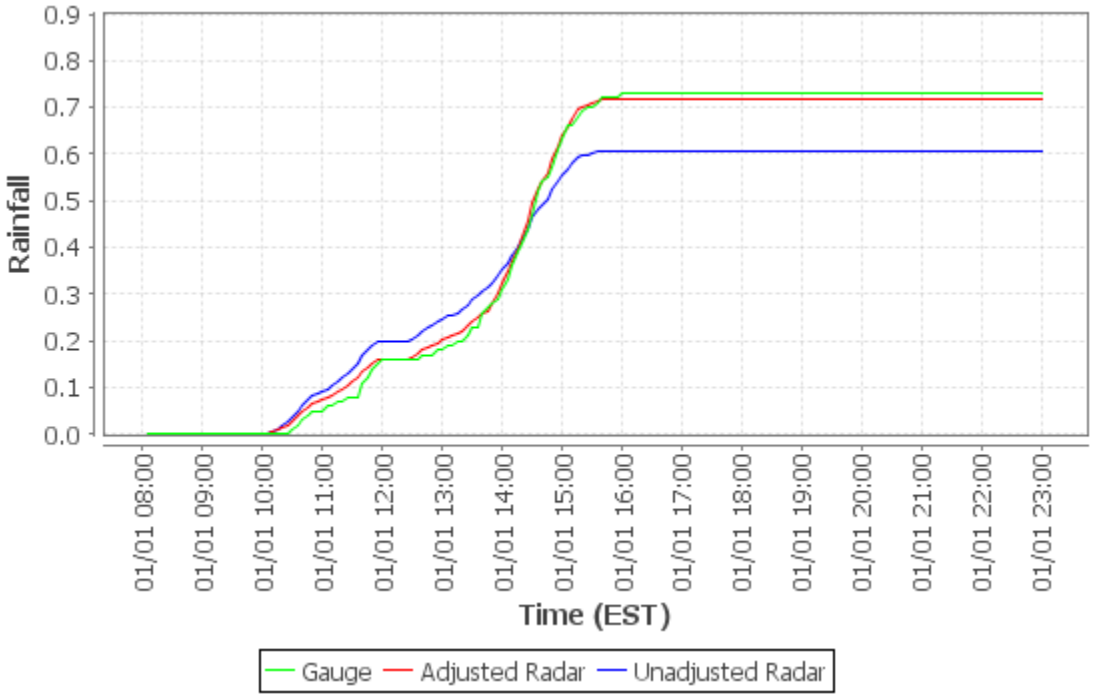
Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



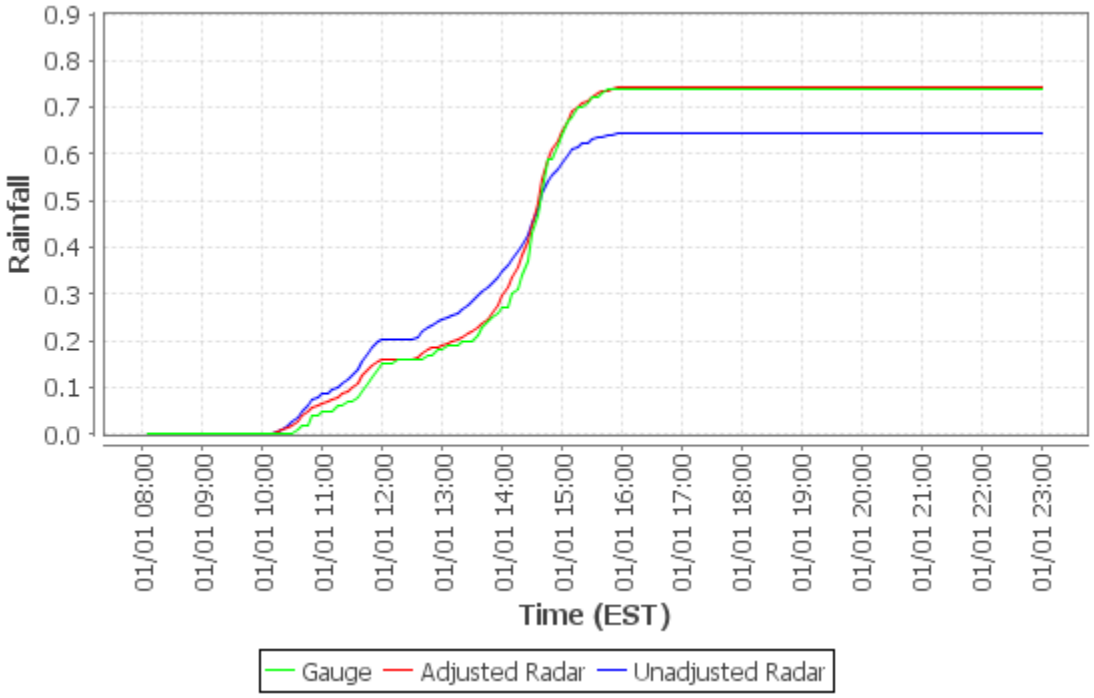
Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



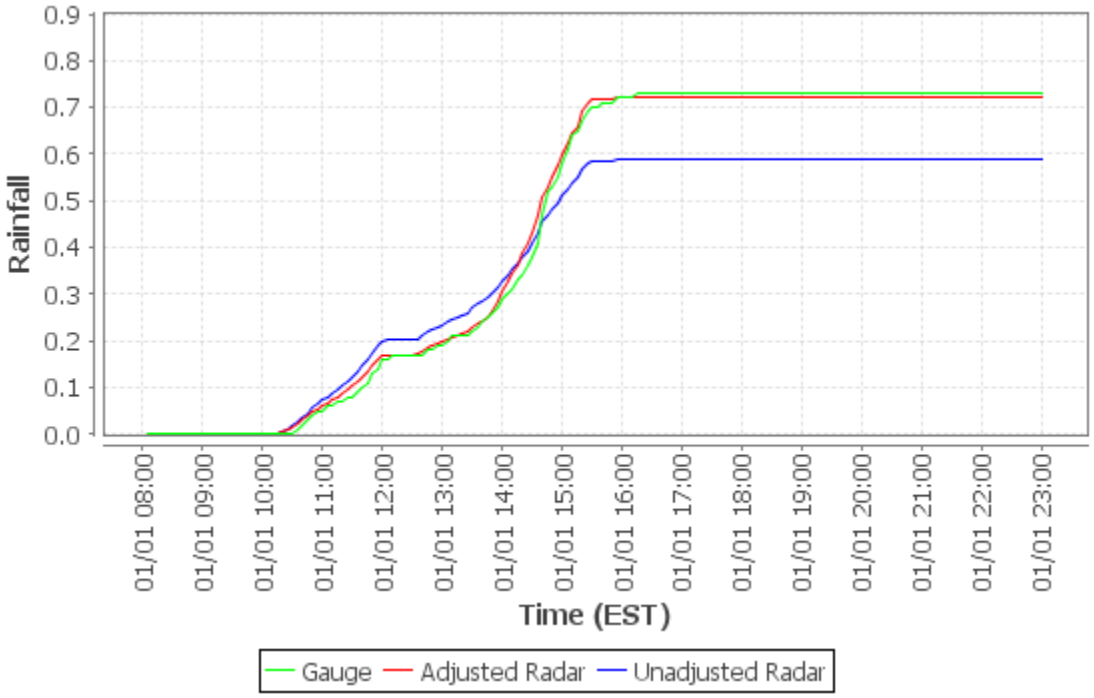
Cumulative Distribution Plot - Baldwin (Loc12)



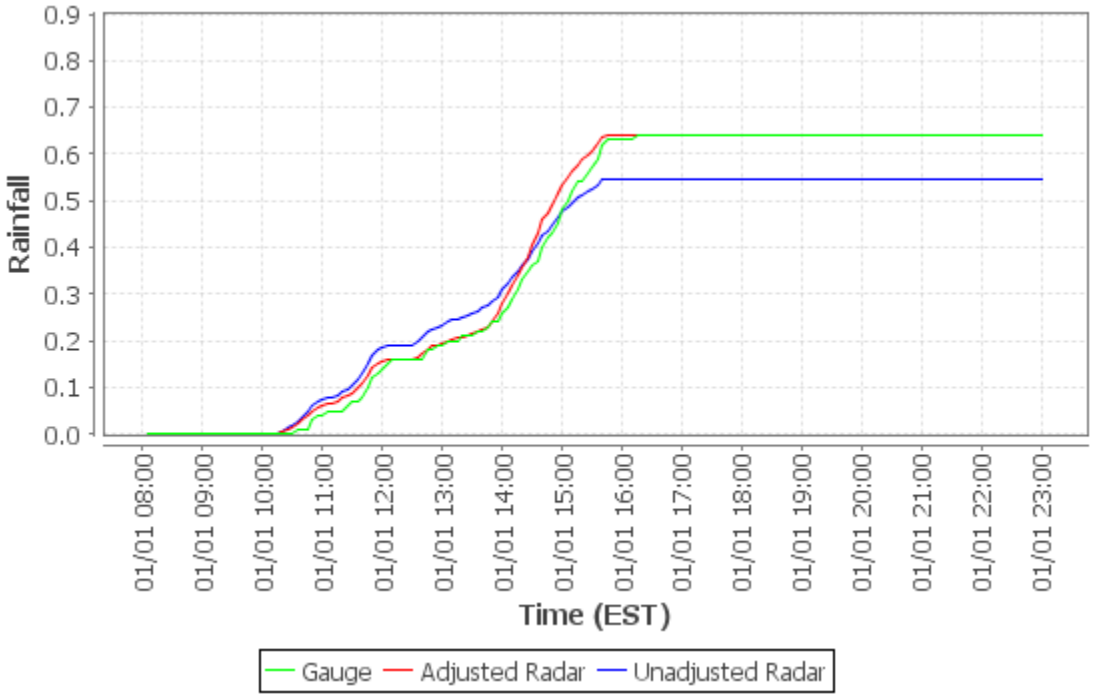
Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



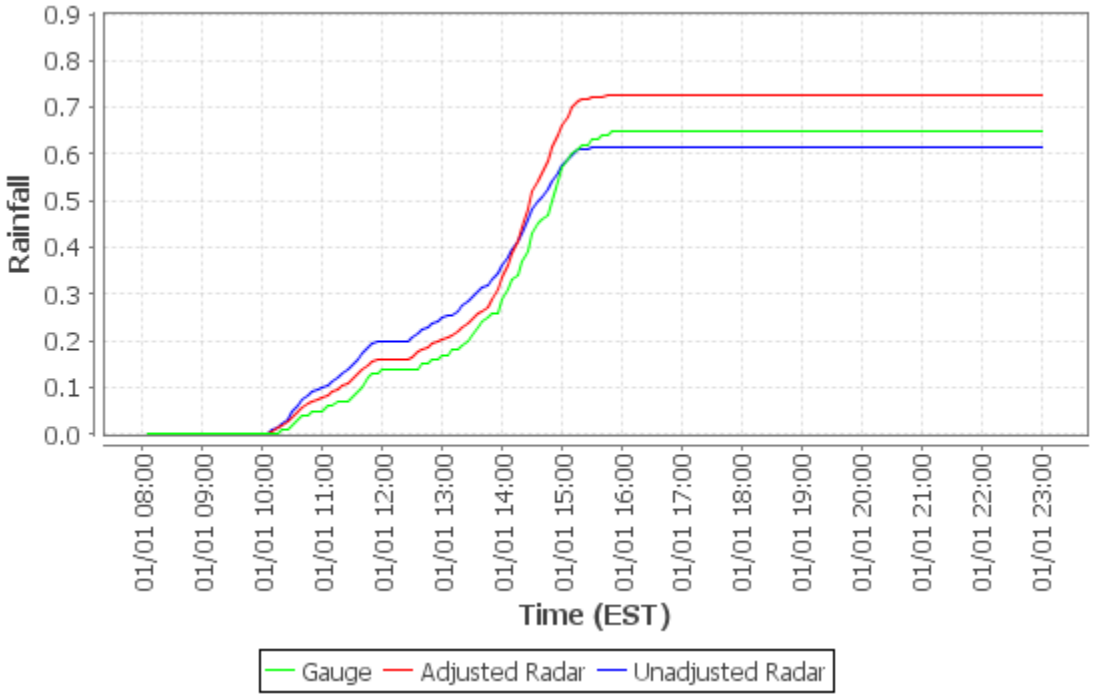
Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



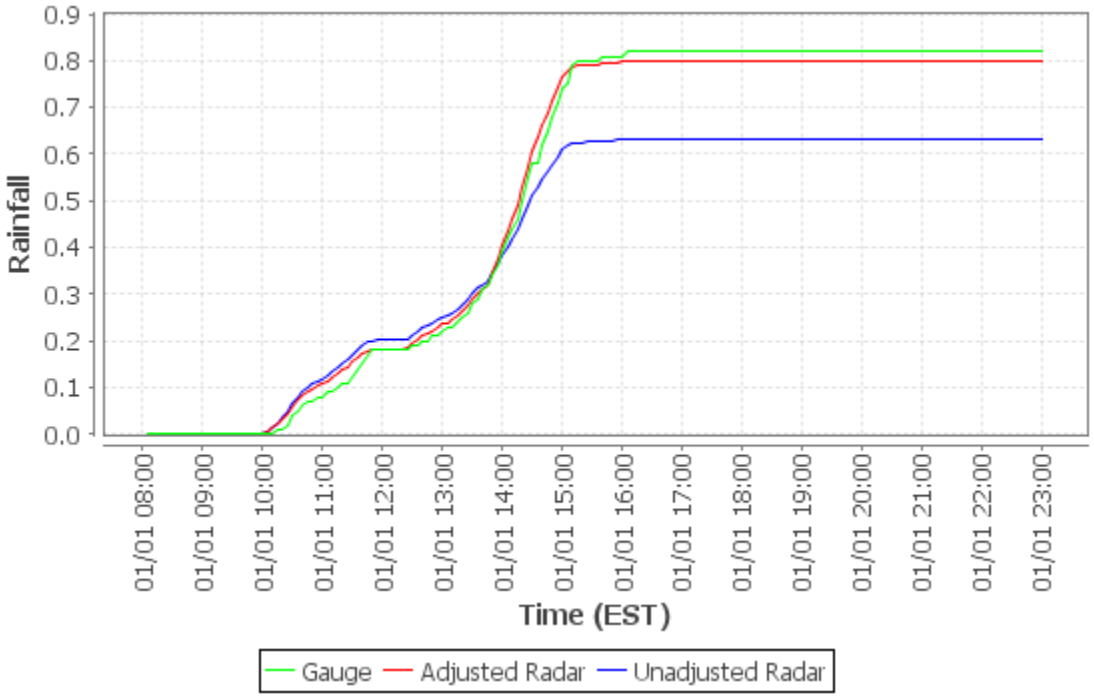
Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



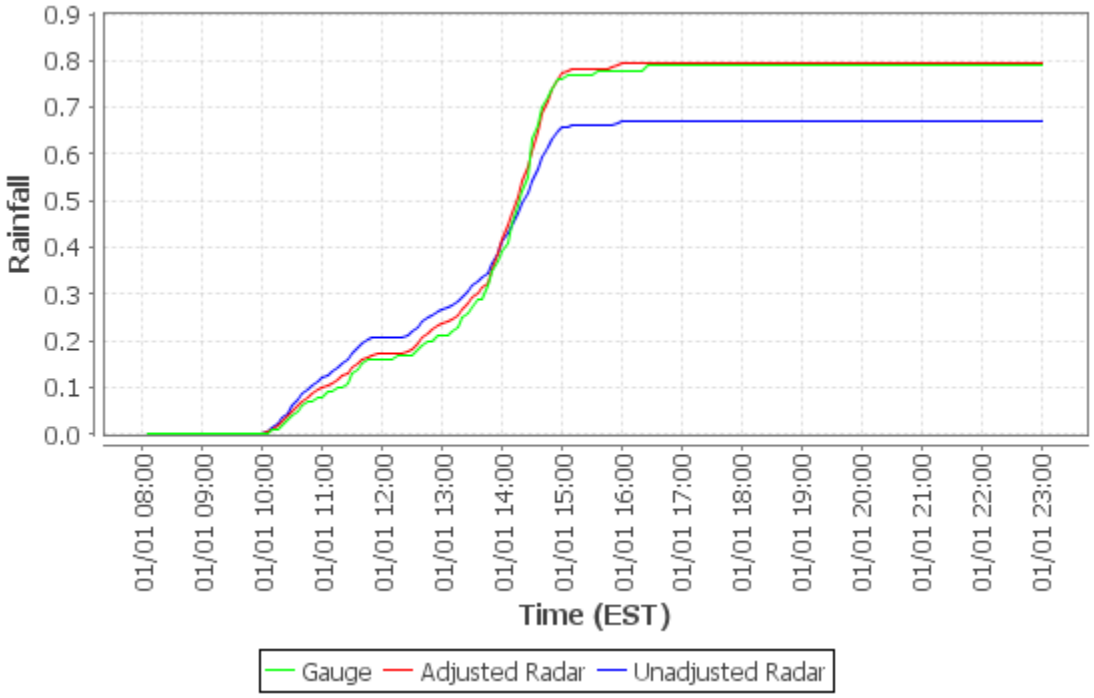
Cumulative Distribution Plot - Castle Shannon (Loc16)



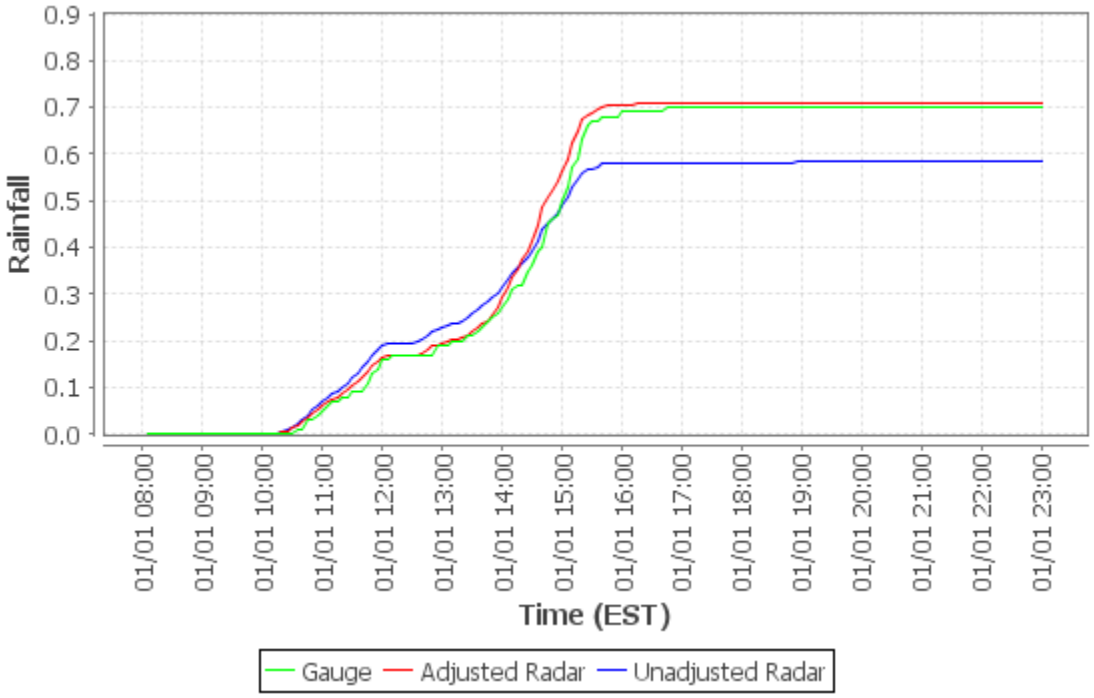
Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



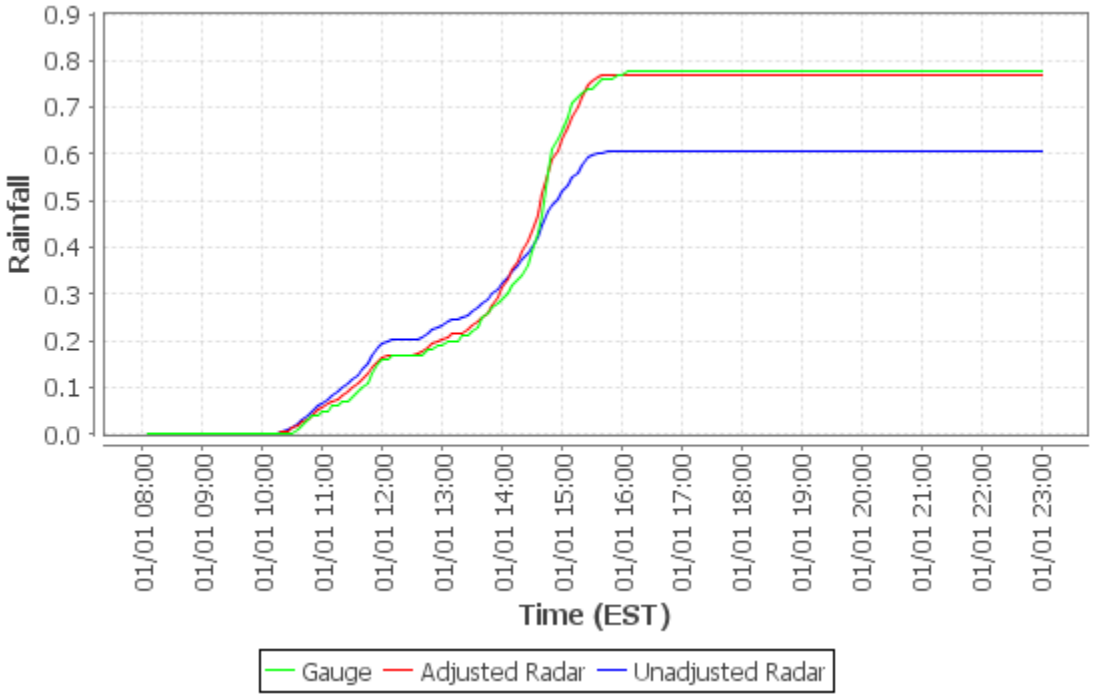
Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



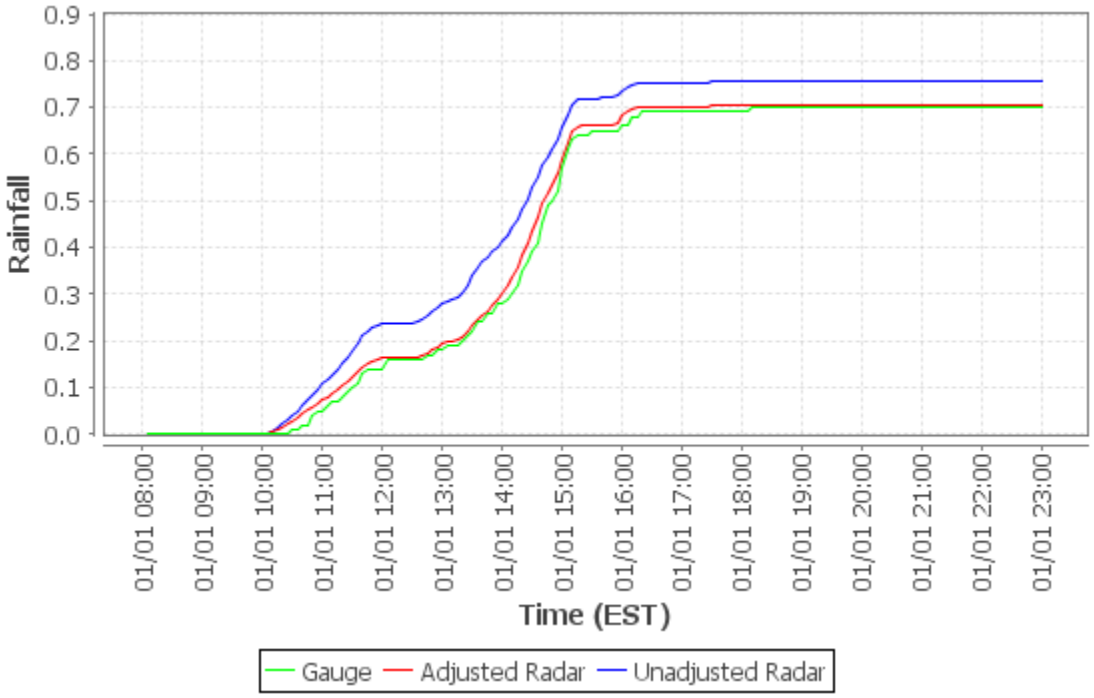
Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



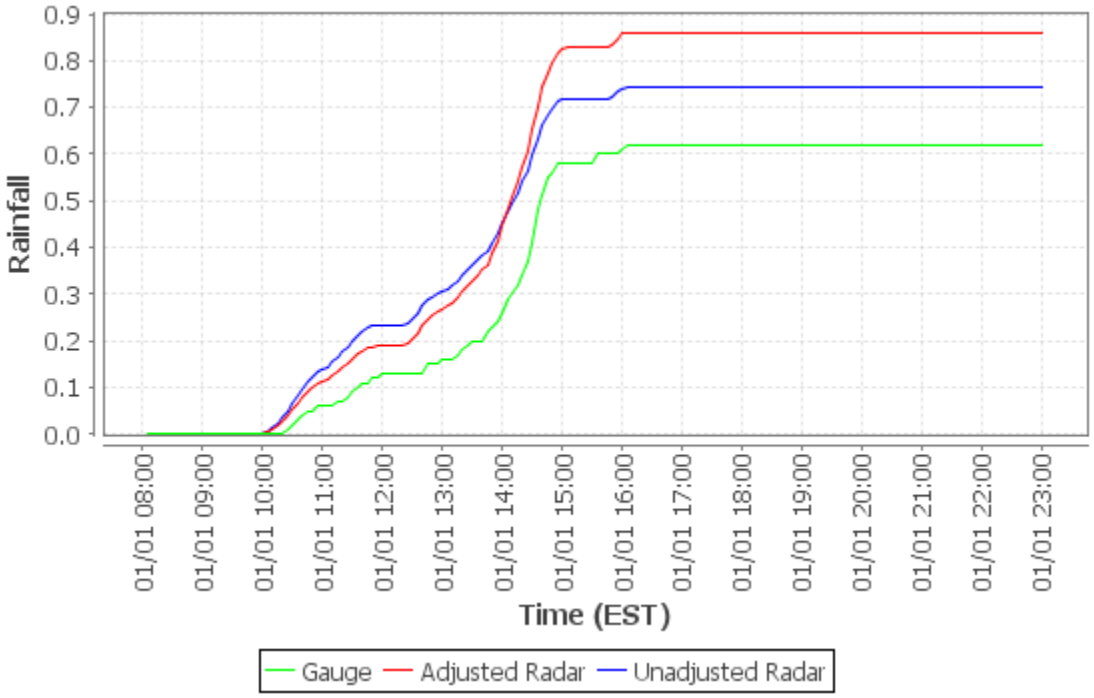
Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



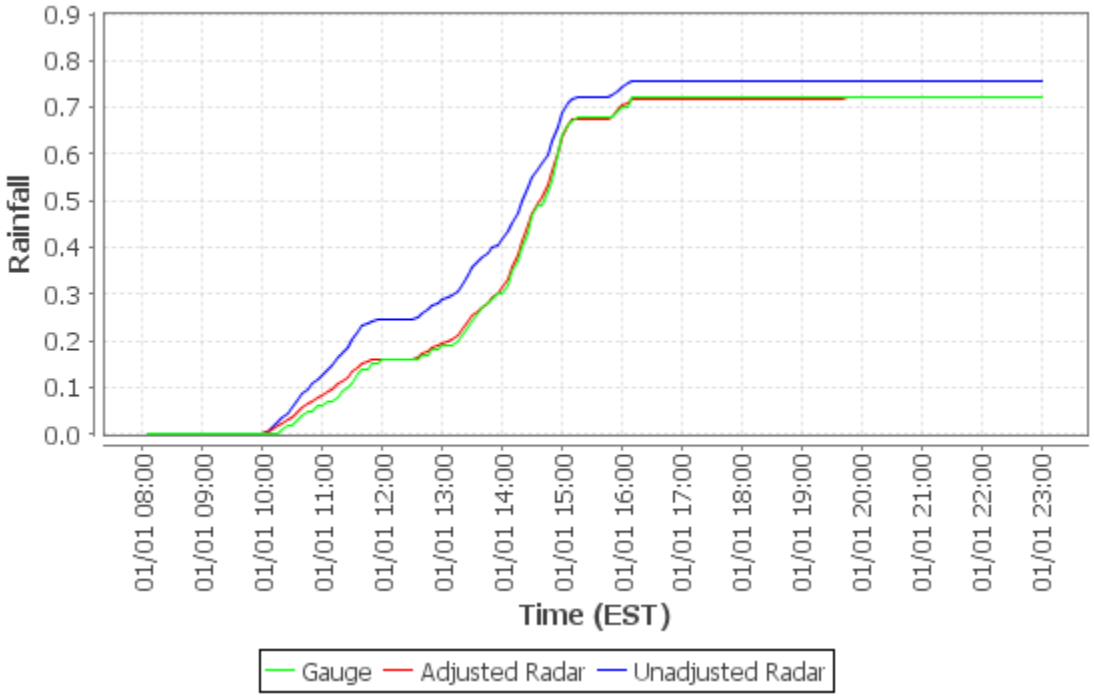
Cumulative Distribution Plot - Moon TWP (Loc21)



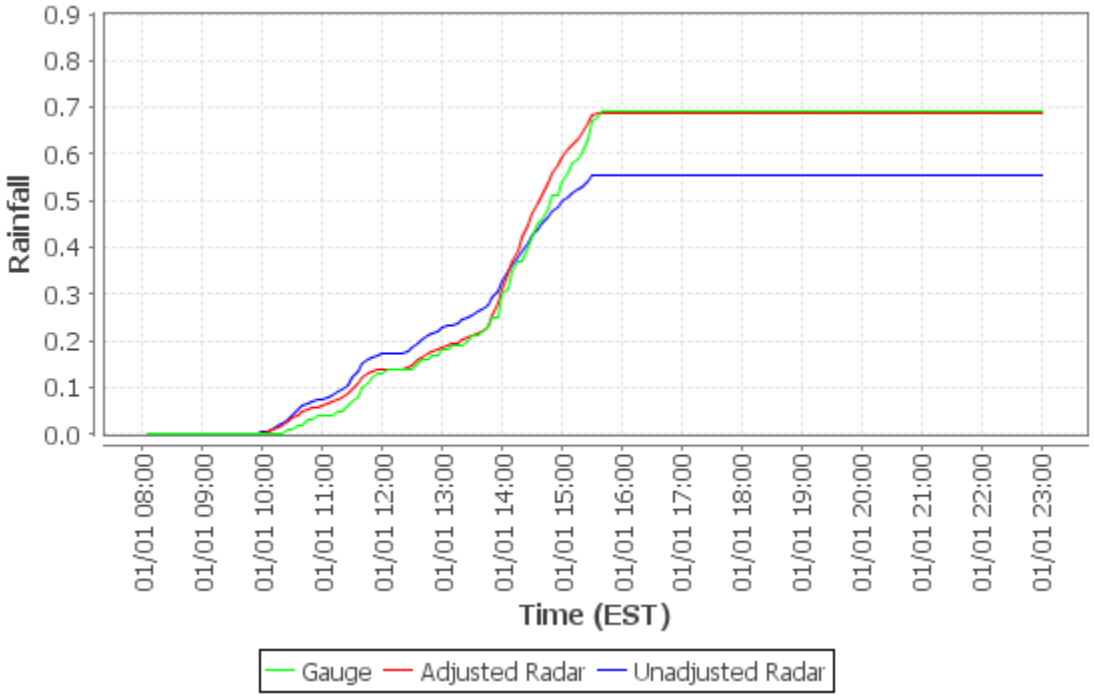
Cumulative Distribution Plot - North Fayette TWP (Loc22)



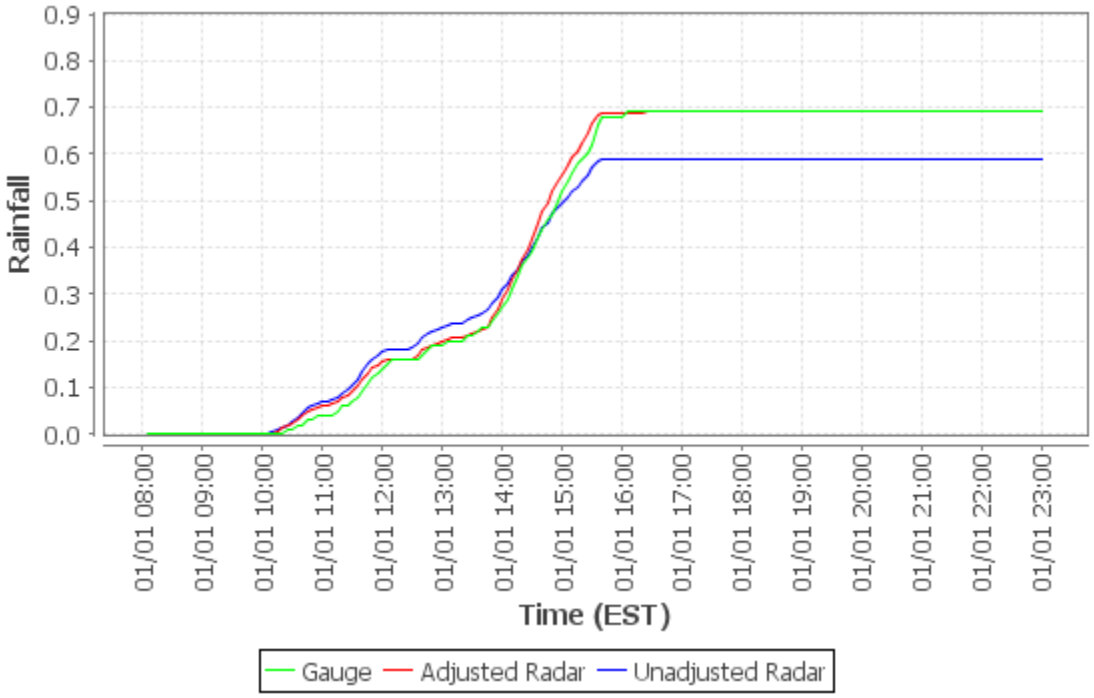
Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



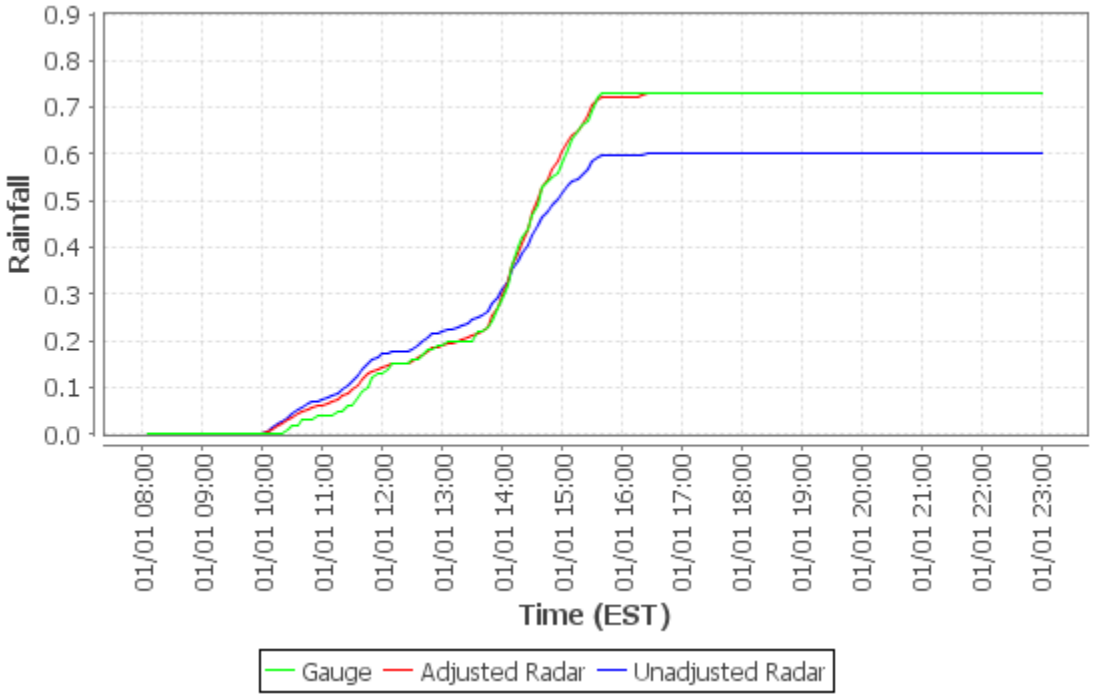
Cumulative Distribution Plot - Jefferson Hills (Loc24)



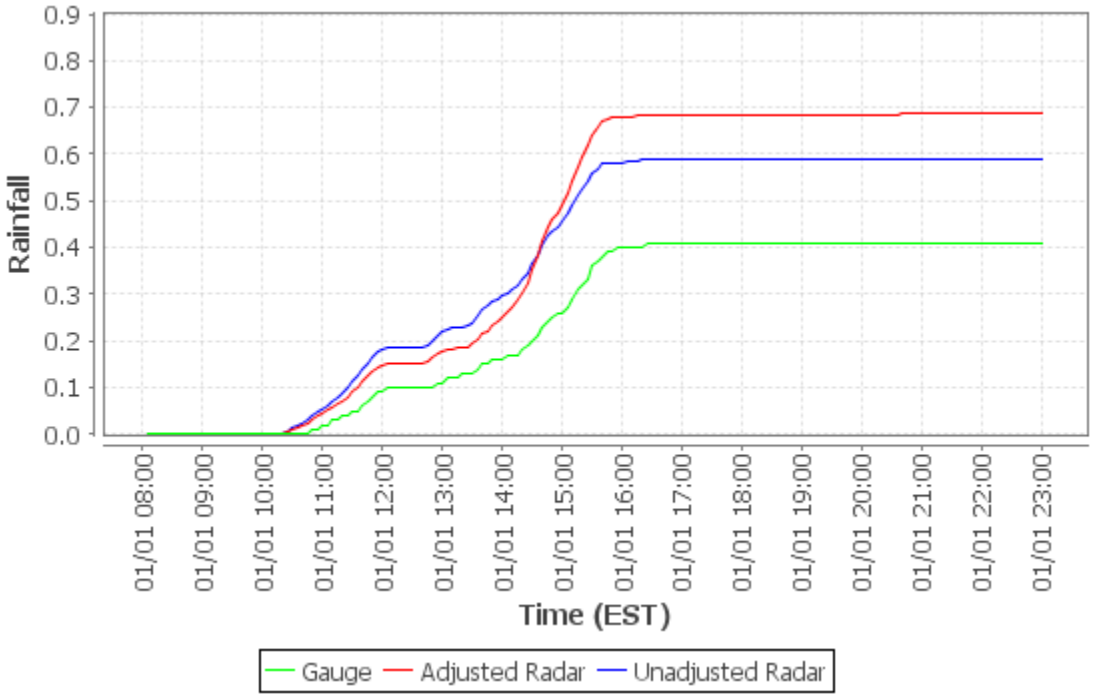
Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



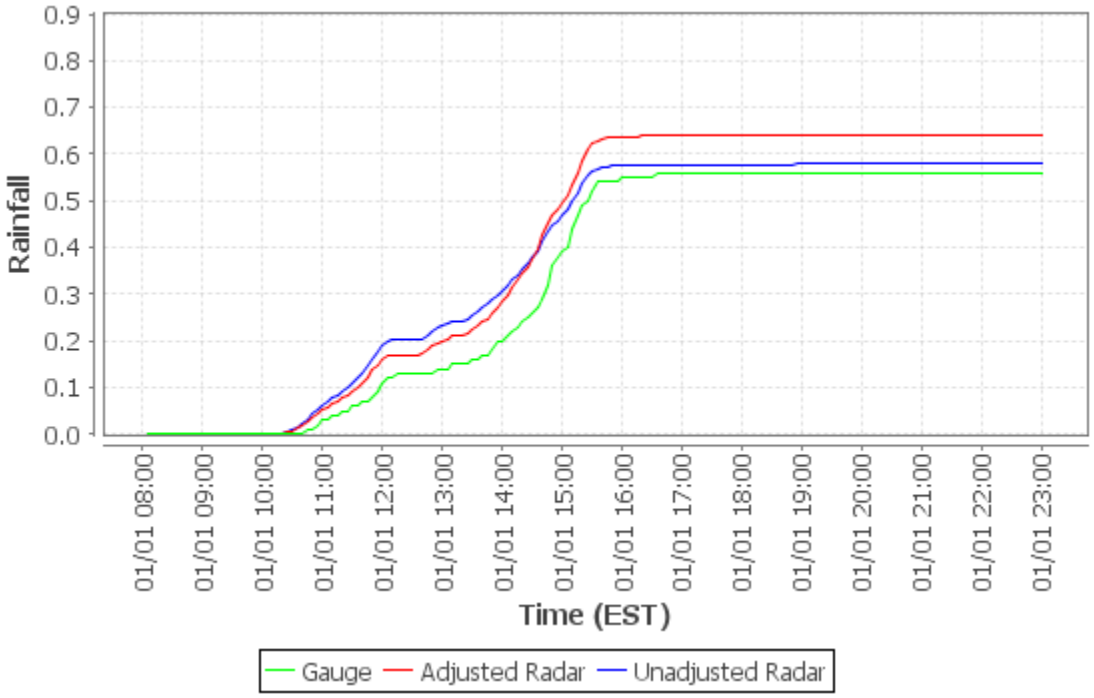
Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



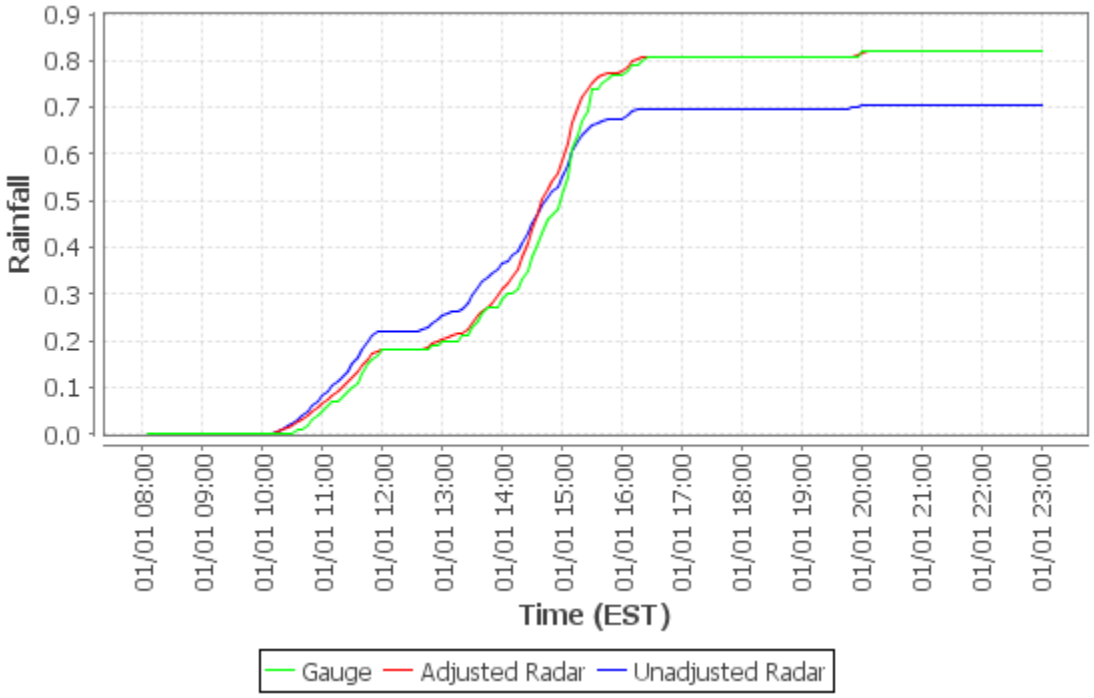
Cumulative Distribution Plot - Marshall TWP (Loc27)



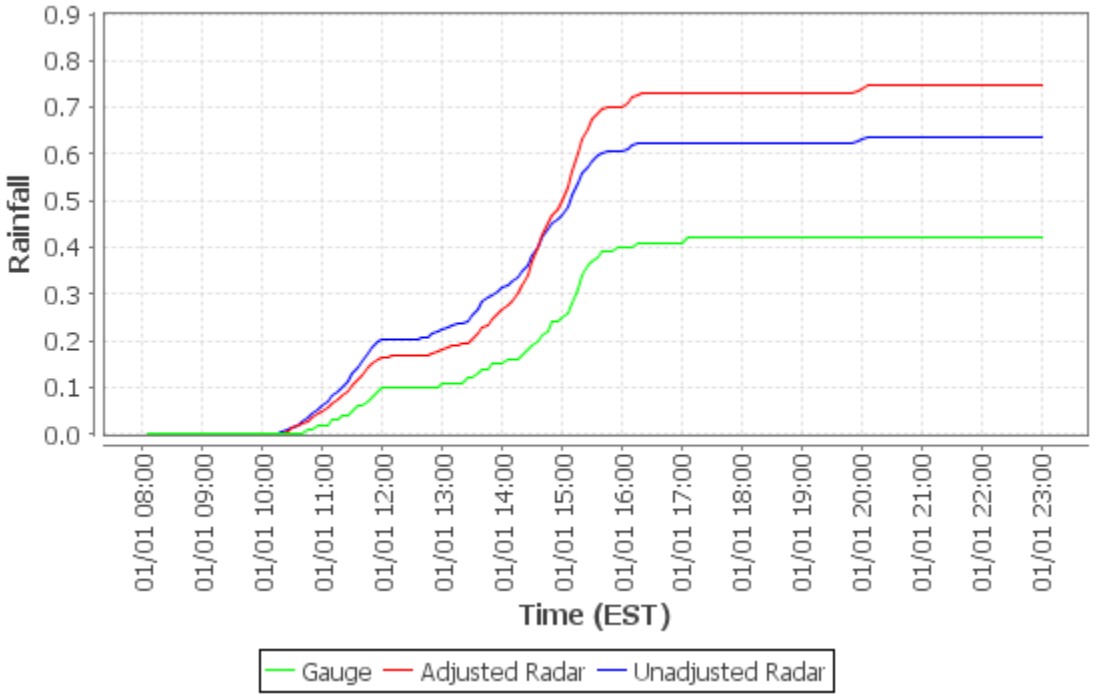
Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



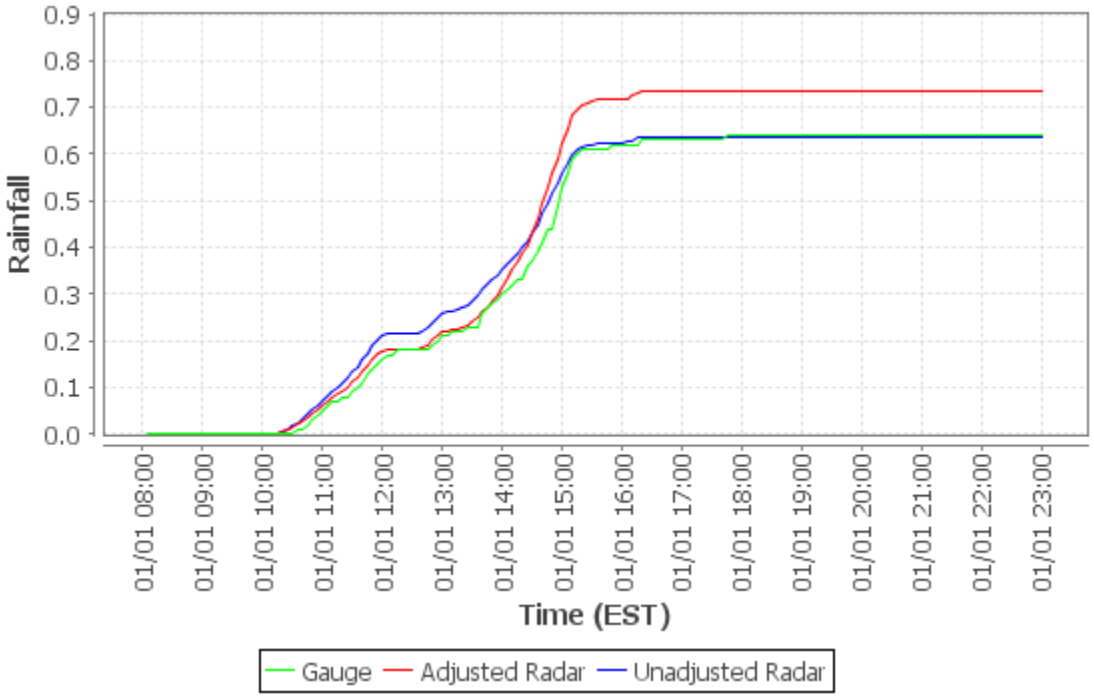
Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



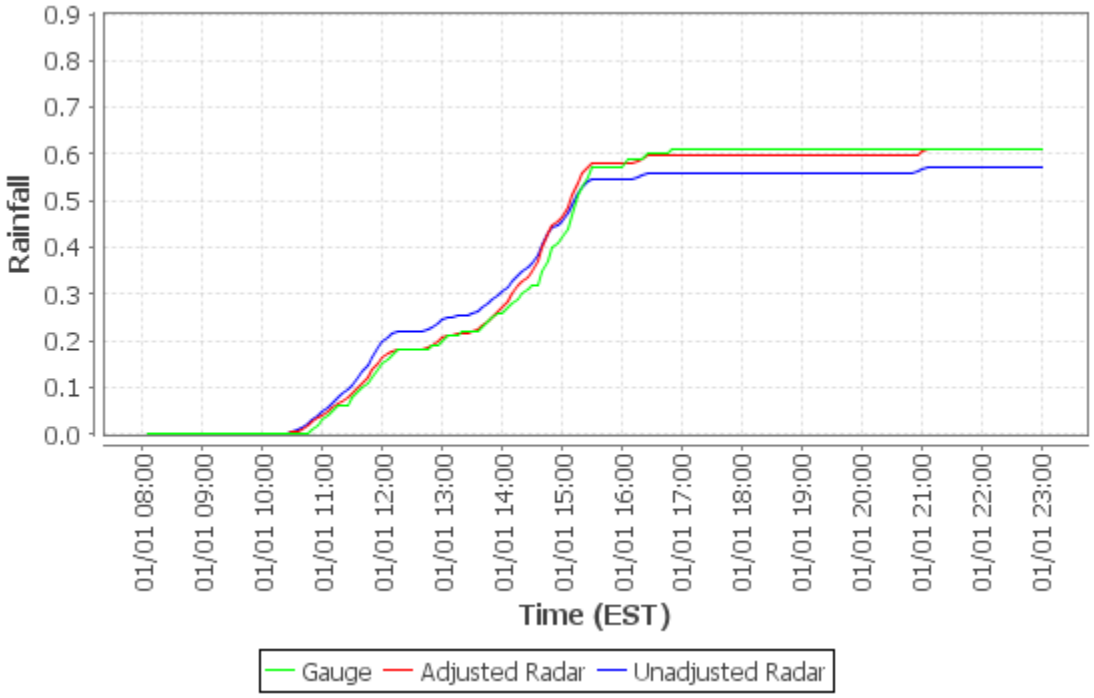
Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



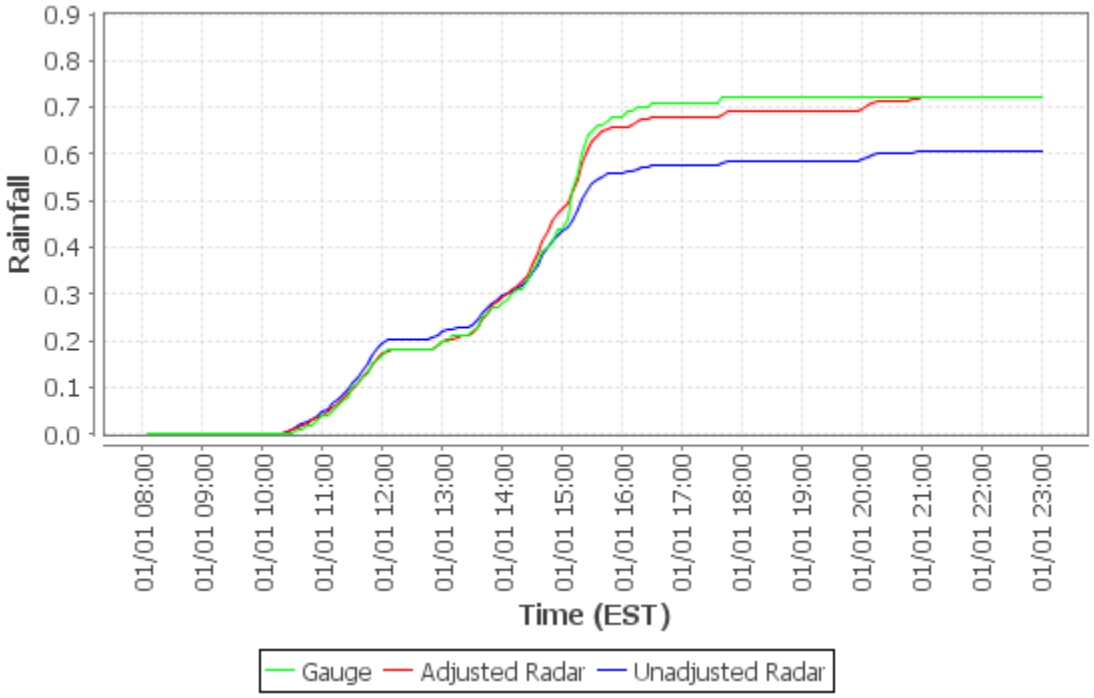
Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



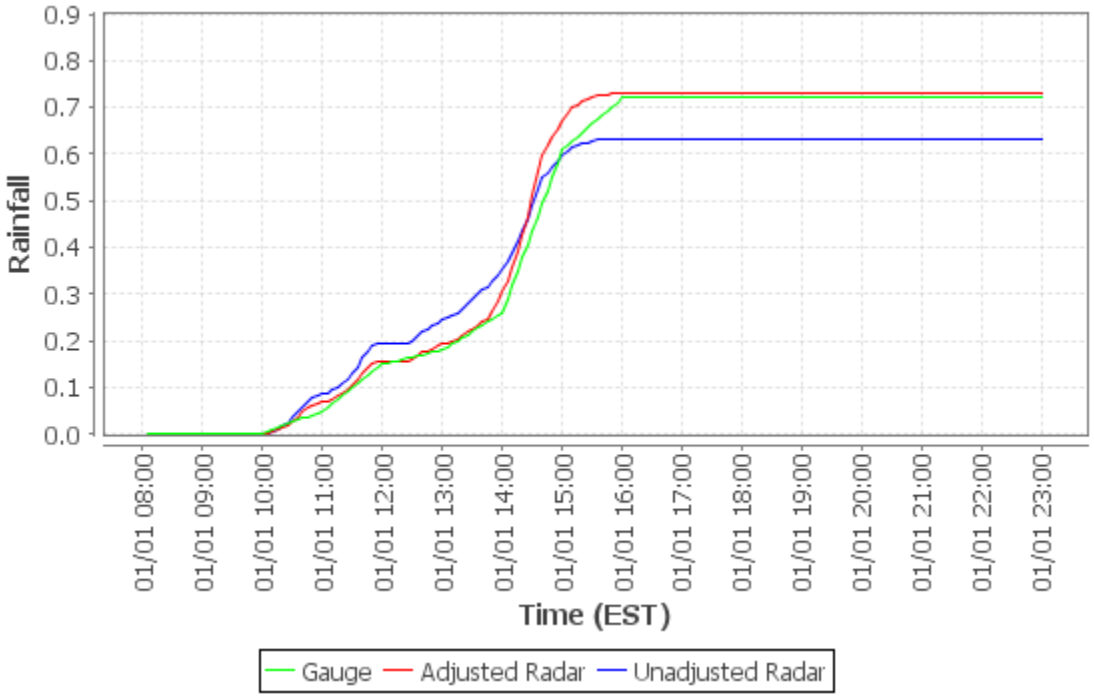
Cumulative Distribution Plot - Arnold (Loc32)



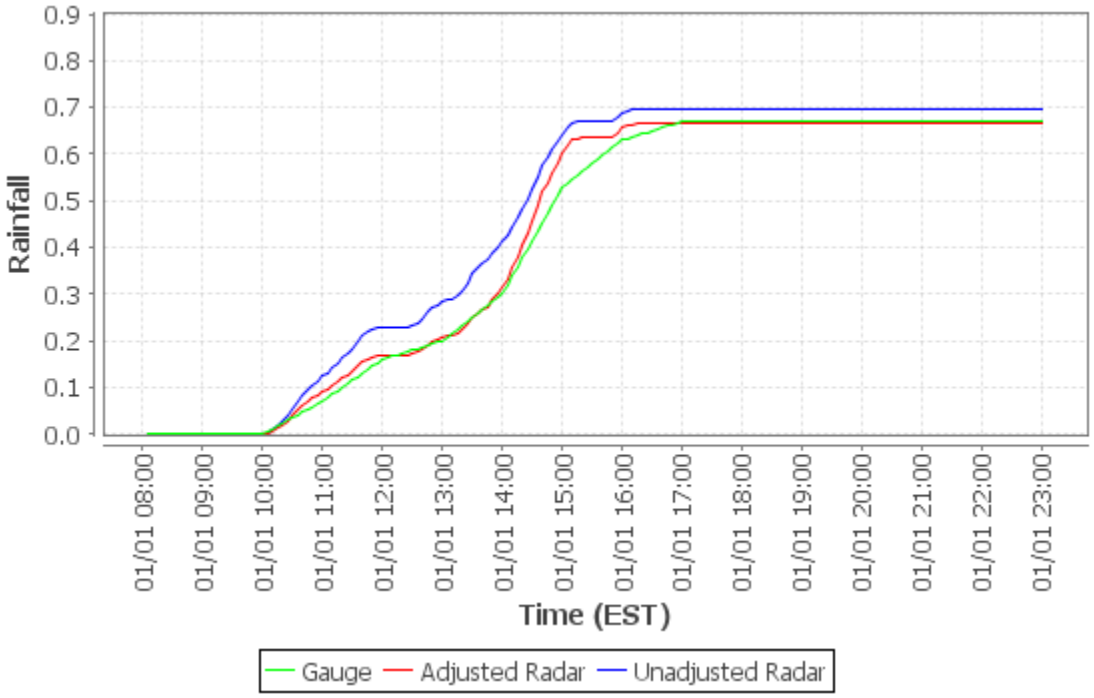
Cumulative Distribution Plot - Richland TWP (Loc33)



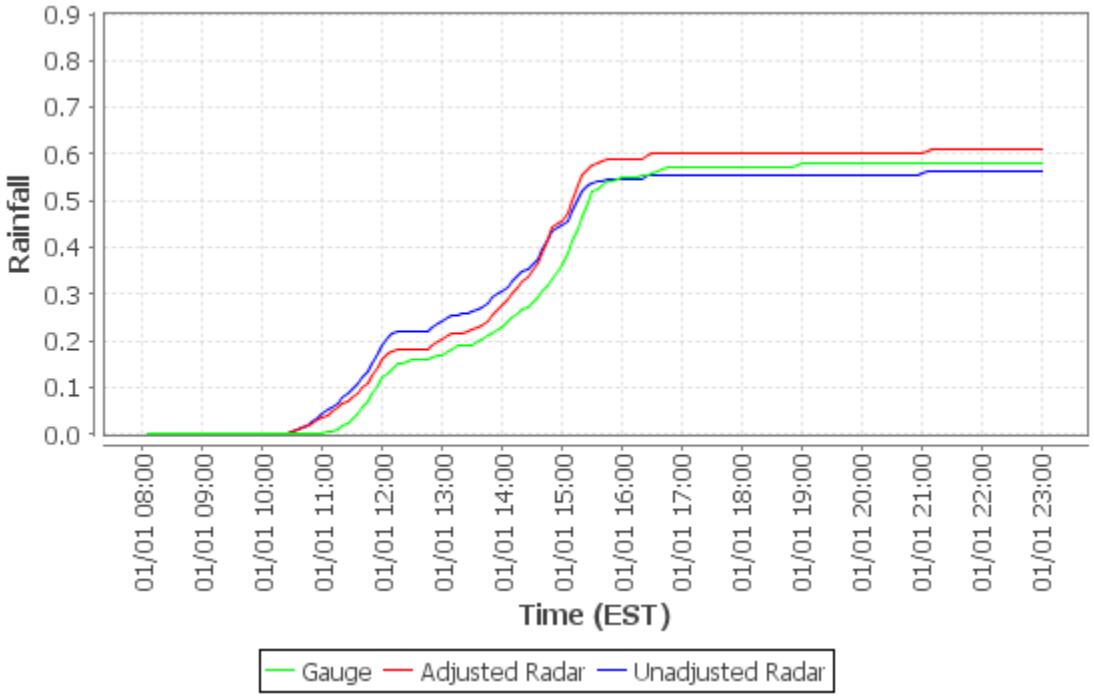
Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



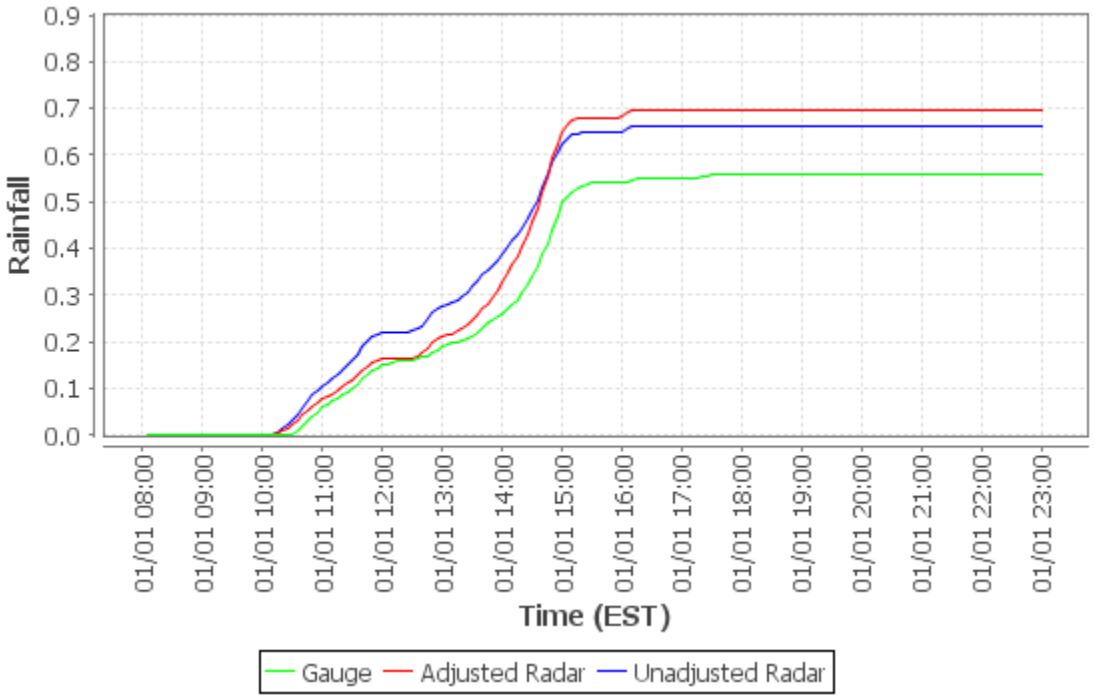
Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



Cumulative Distribution Plot - Allegheny River at Natrona (03049500)

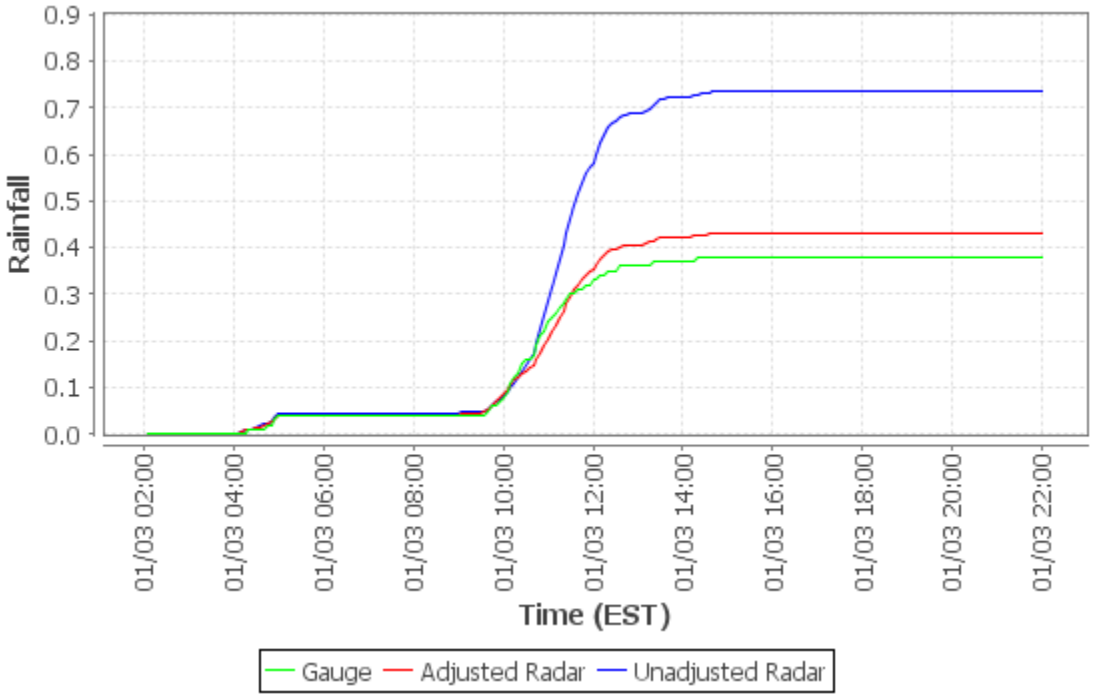


Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

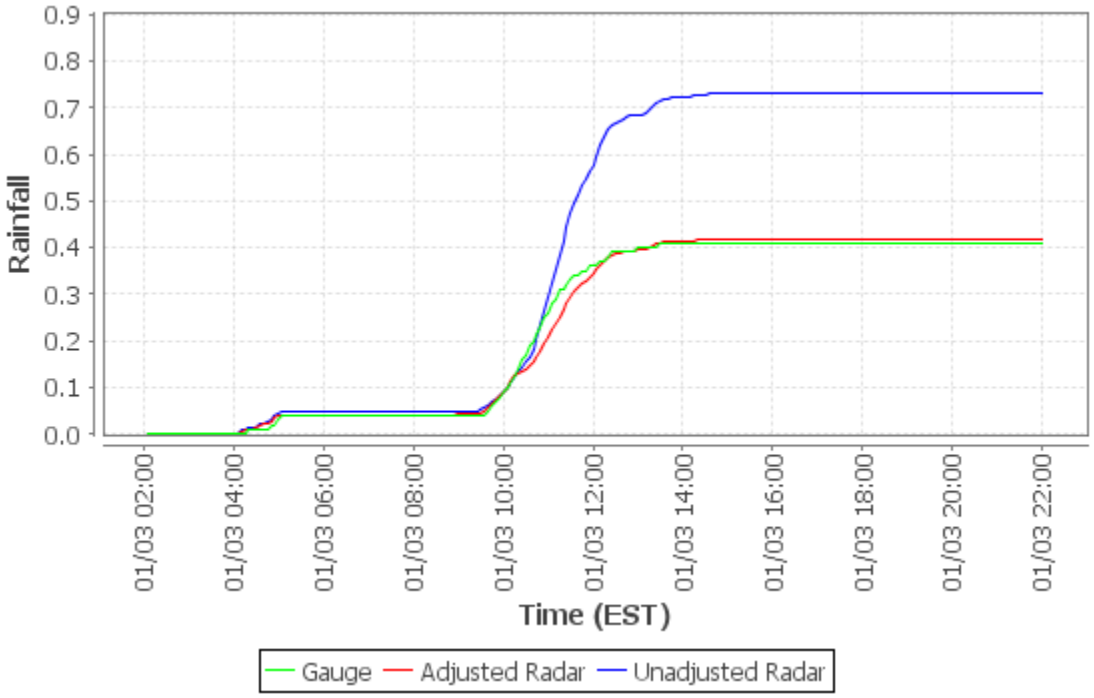


Appendix D - Event 2 (2021-01-03) CDPs

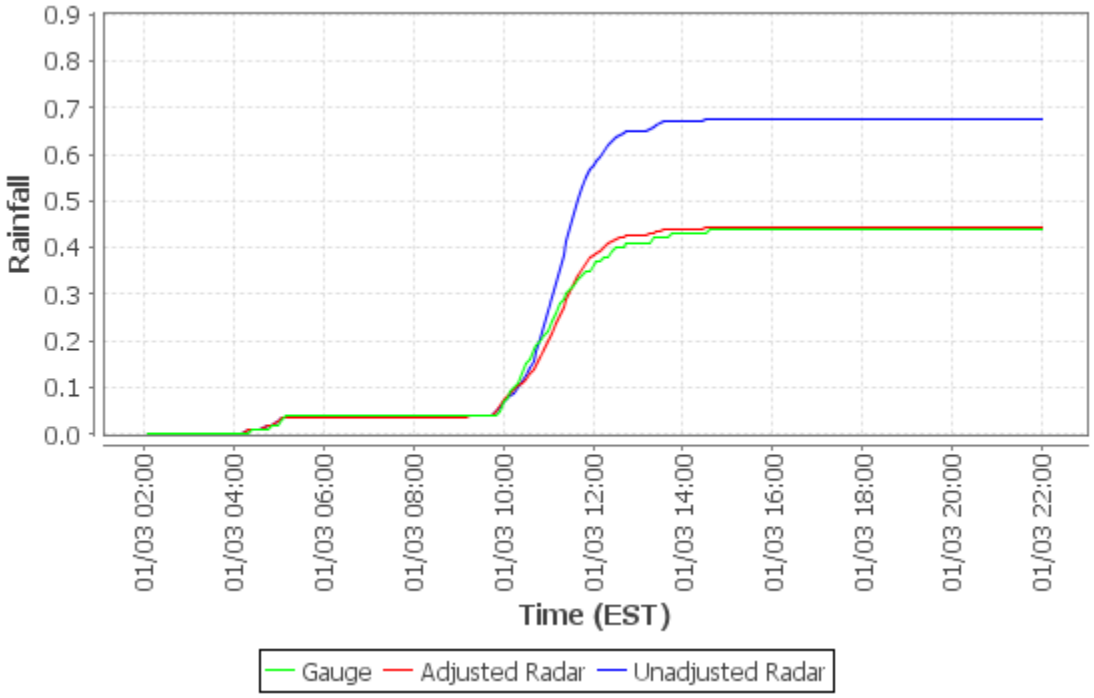
Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



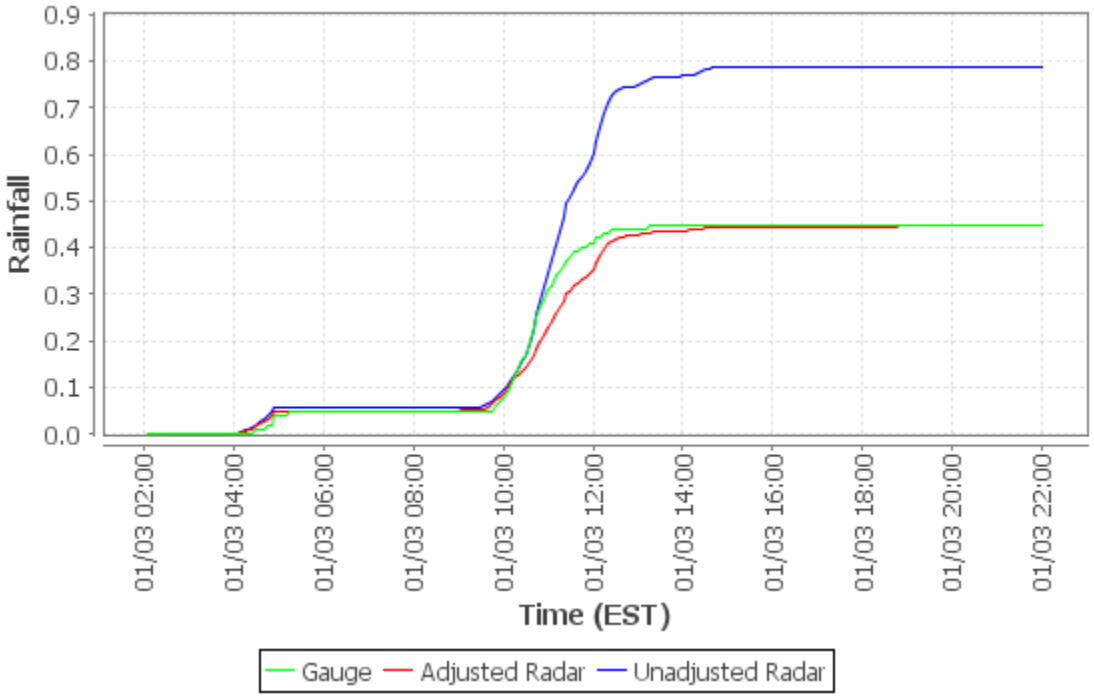
Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



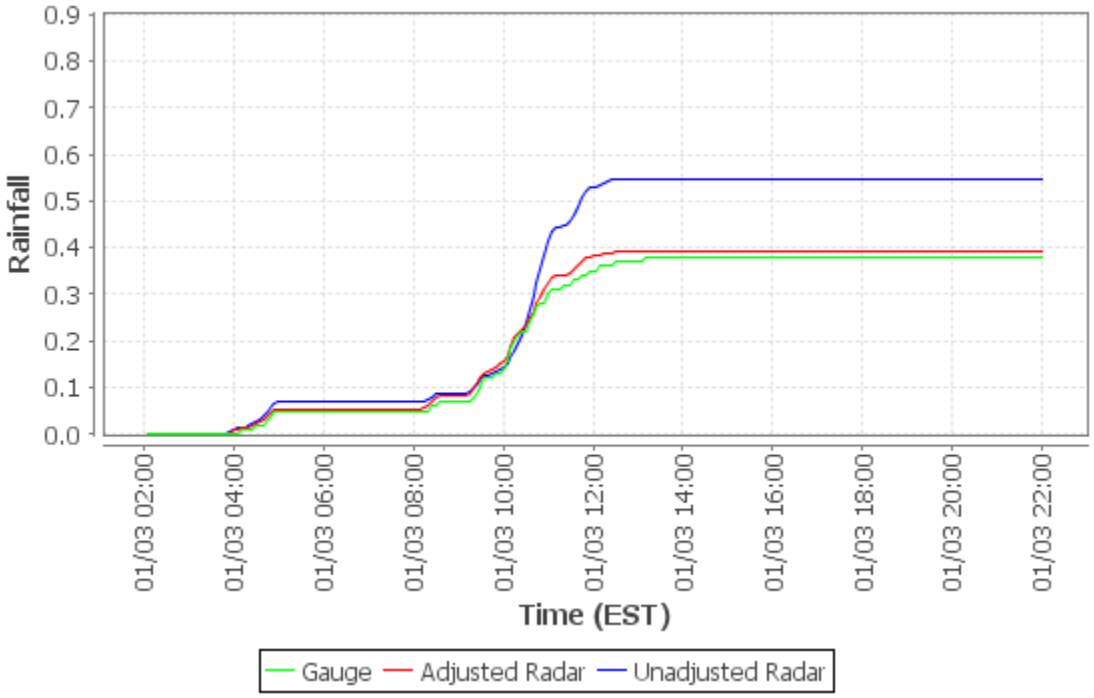
Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



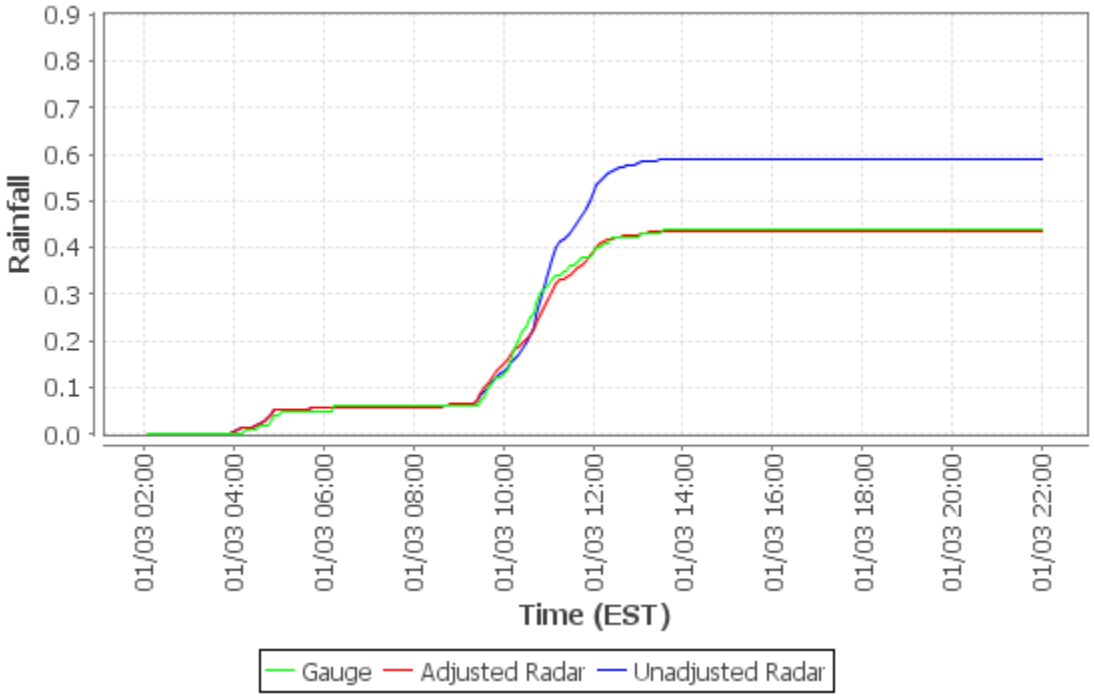
Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



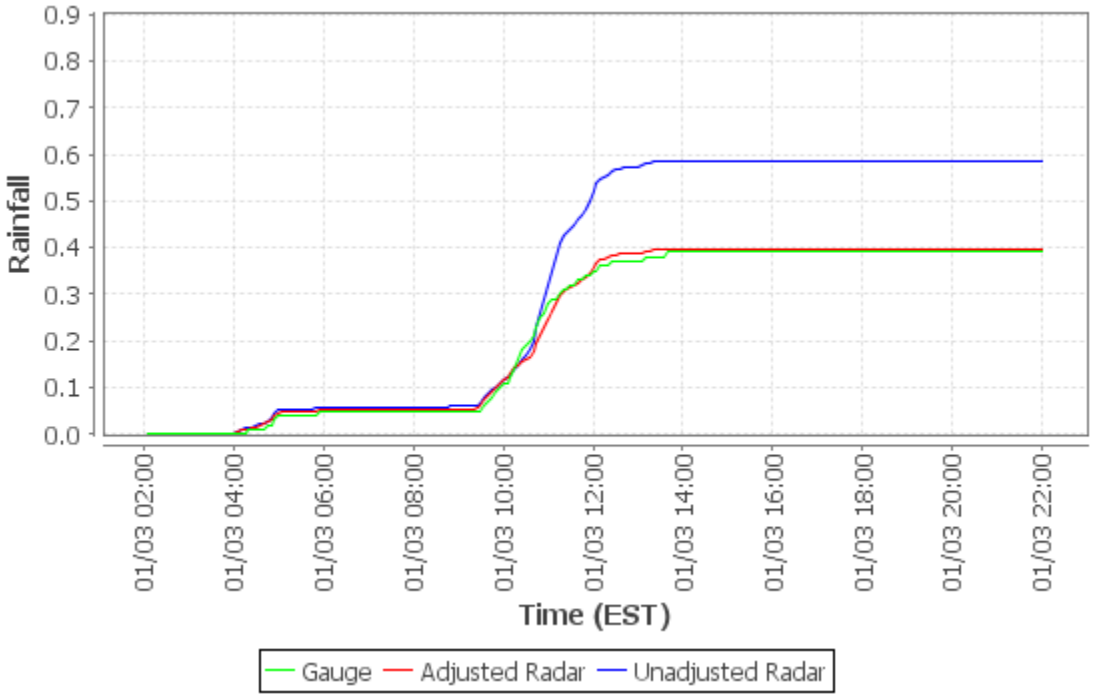
Cumulative Distribution Plot - Upper St. Clair (Loc05)



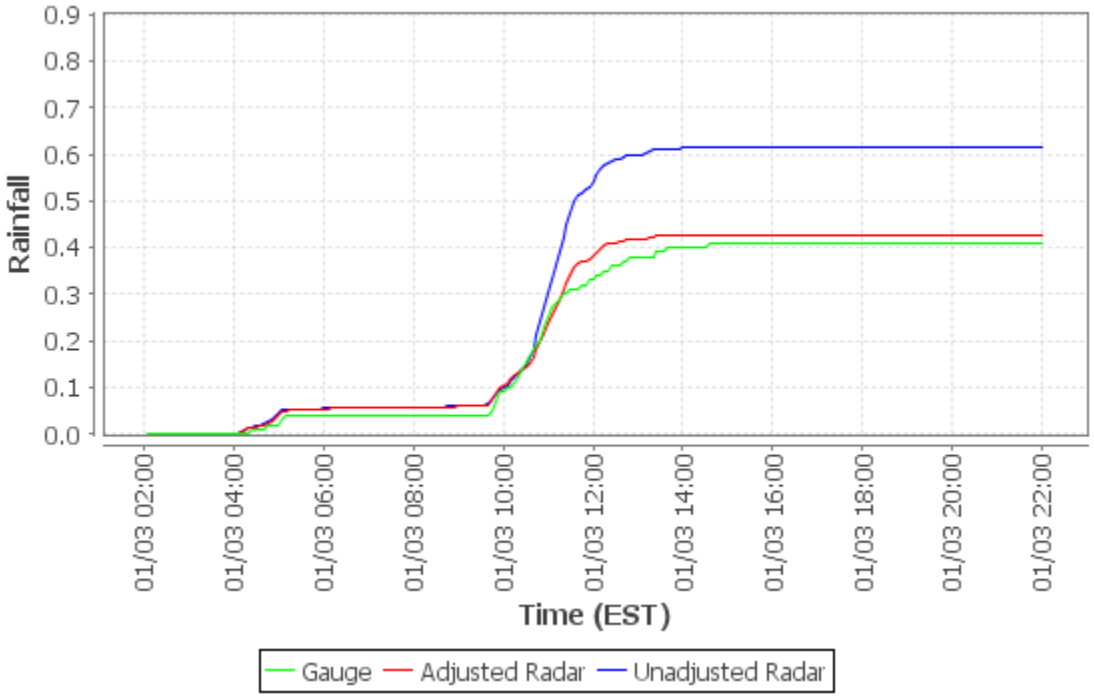
Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



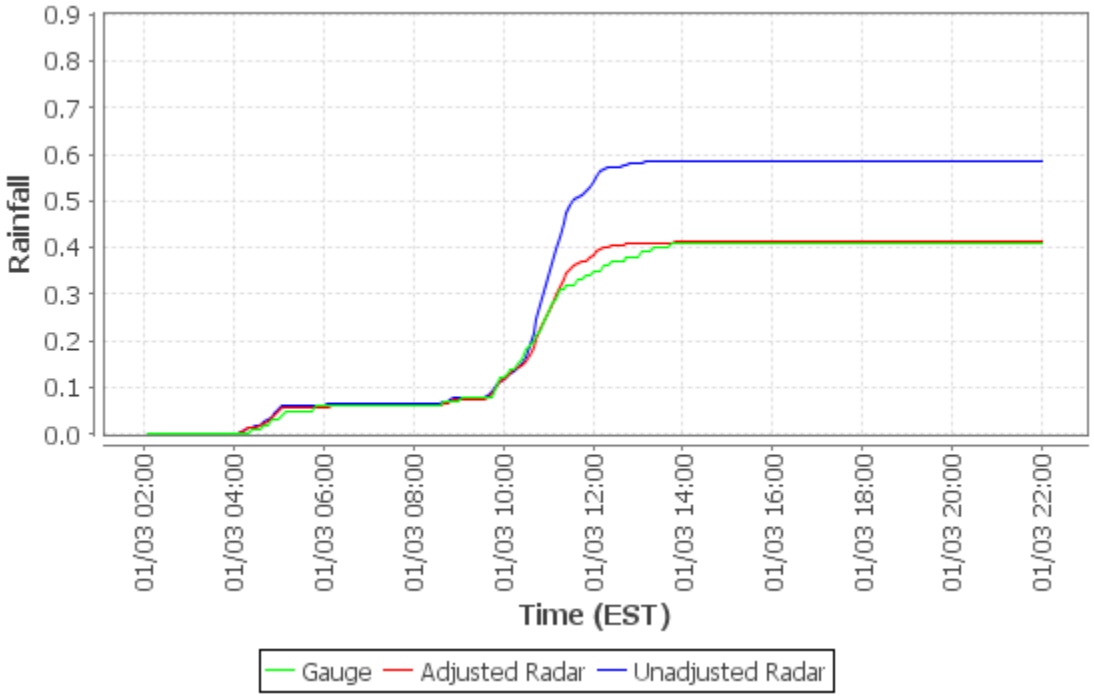
Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



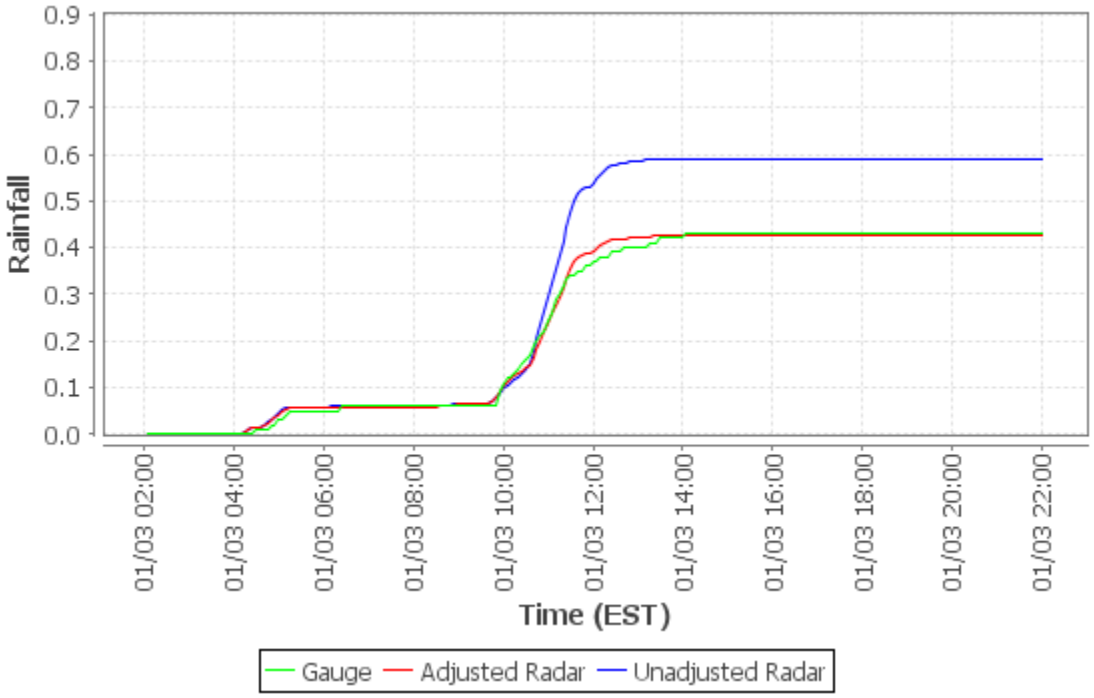
Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



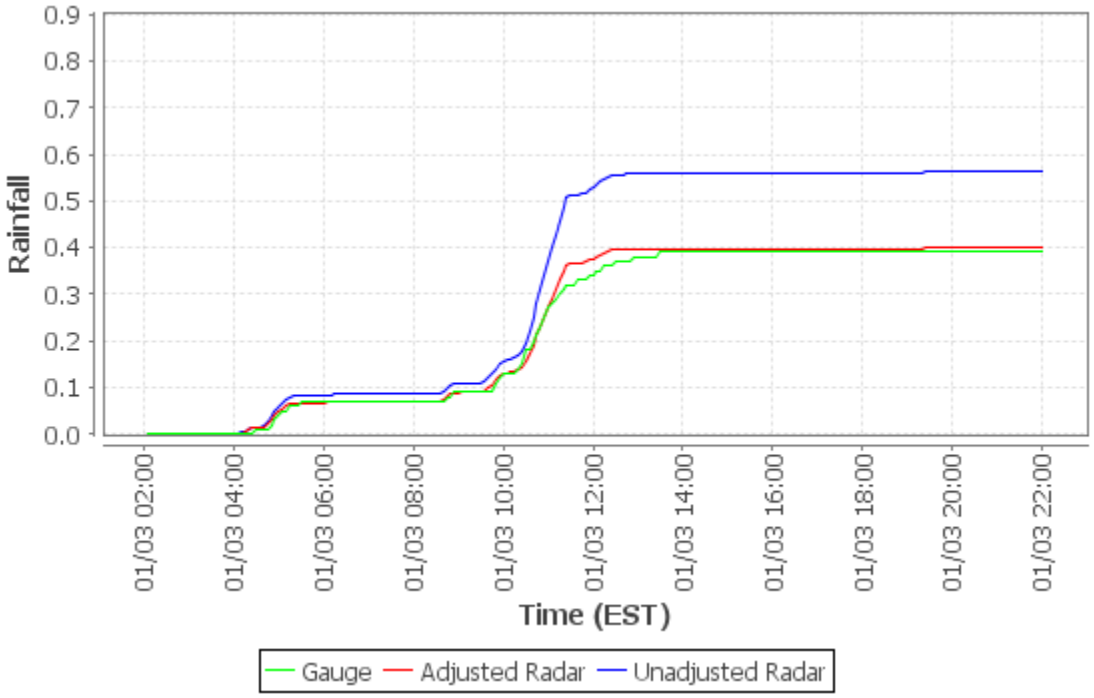
Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



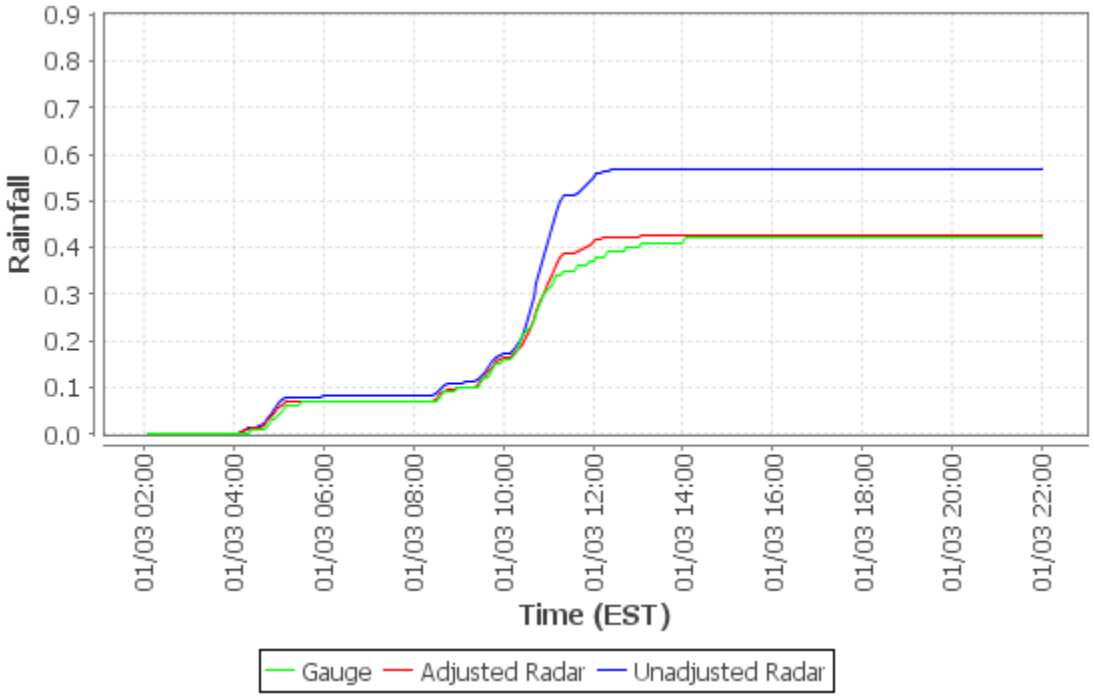
Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



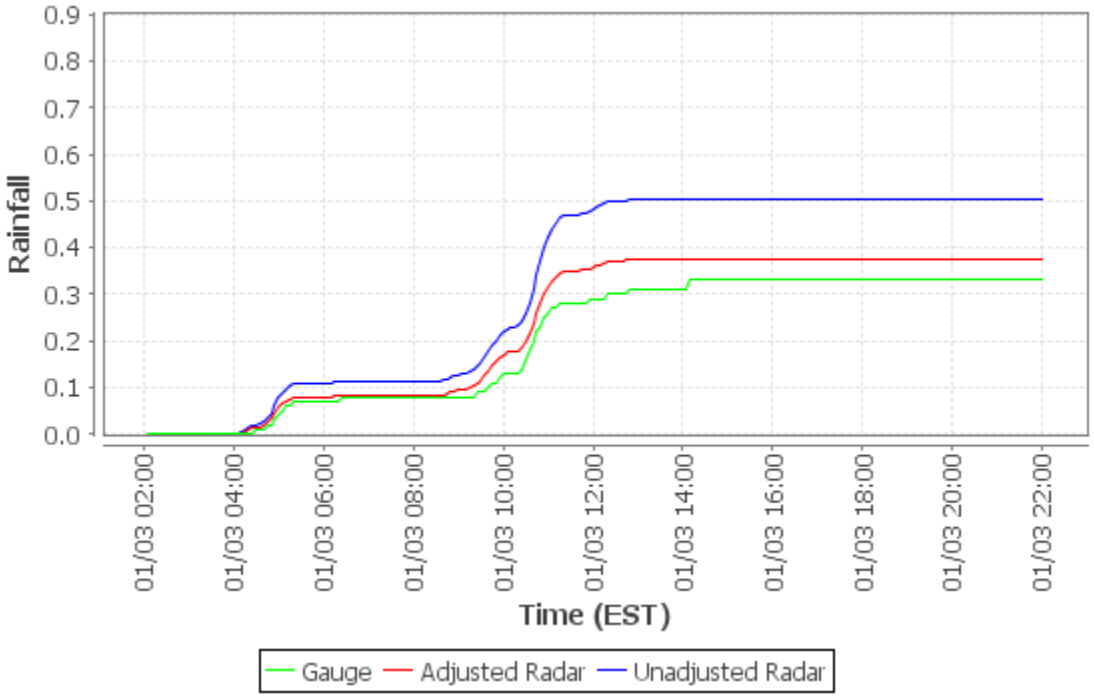
Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



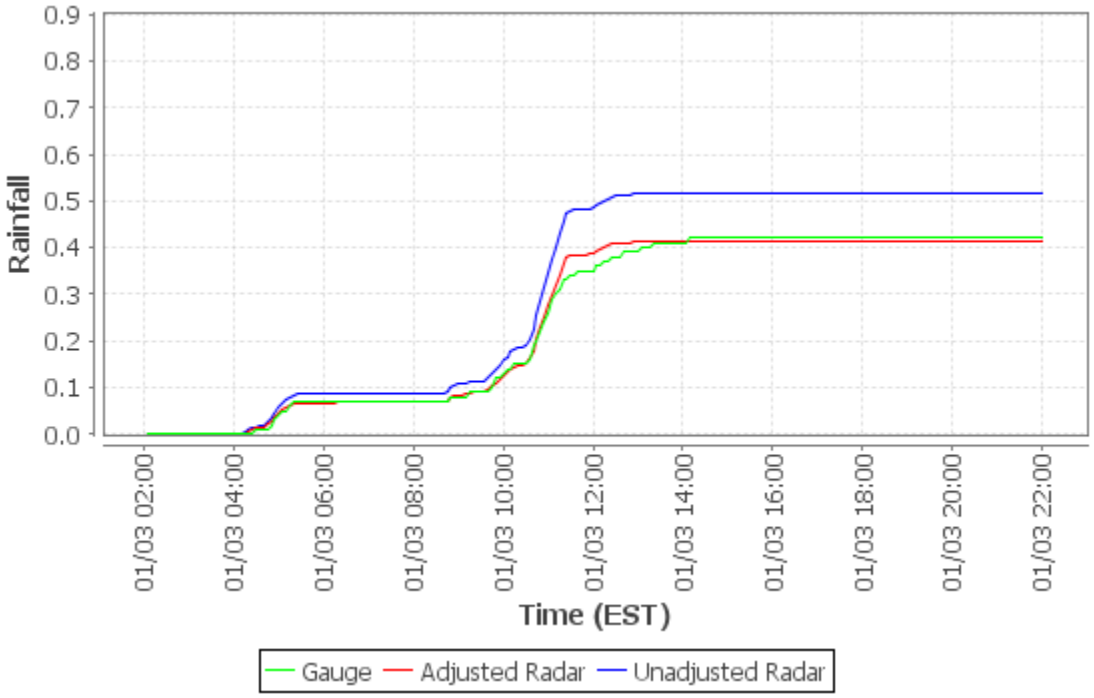
Cumulative Distribution Plot - Baldwin (Loc12)



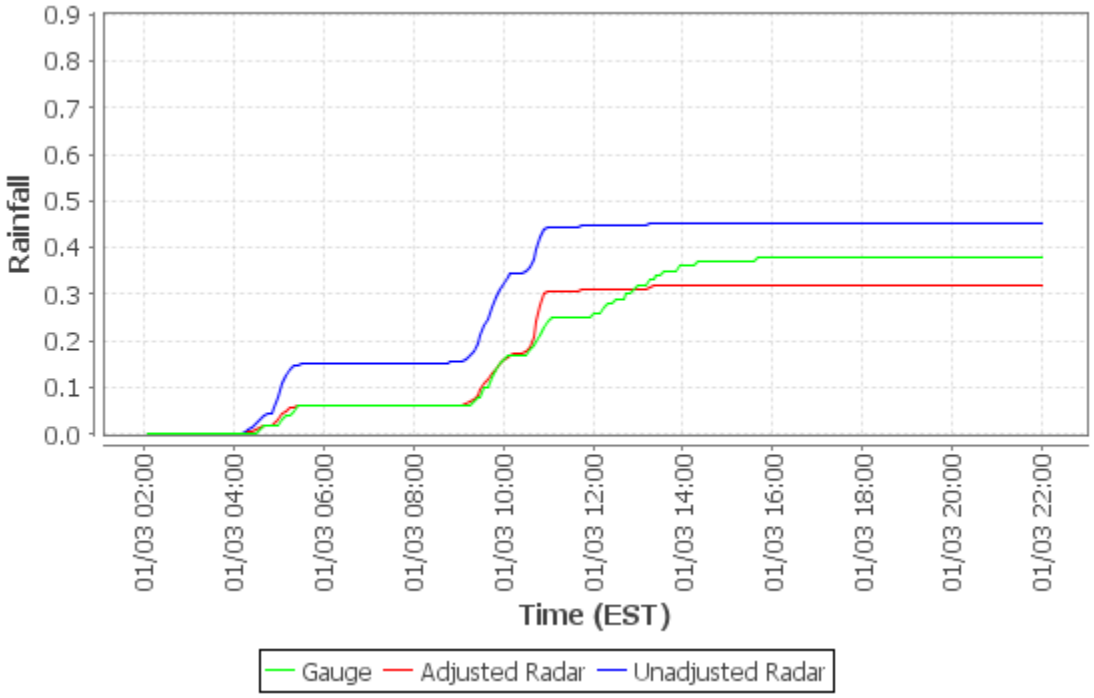
Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



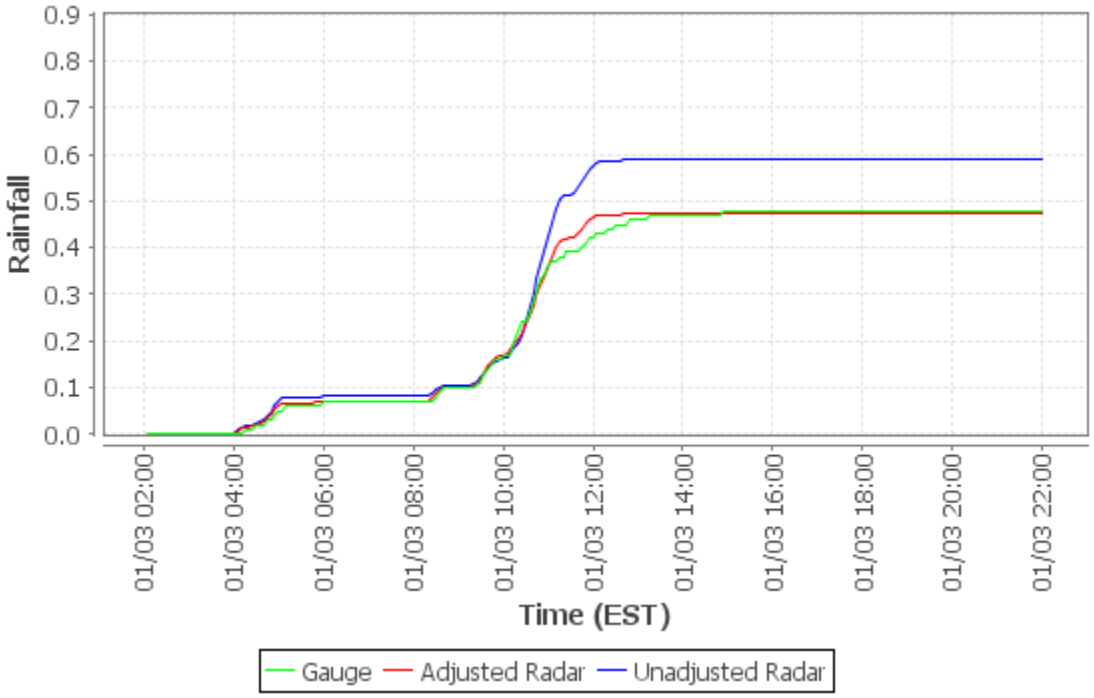
Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



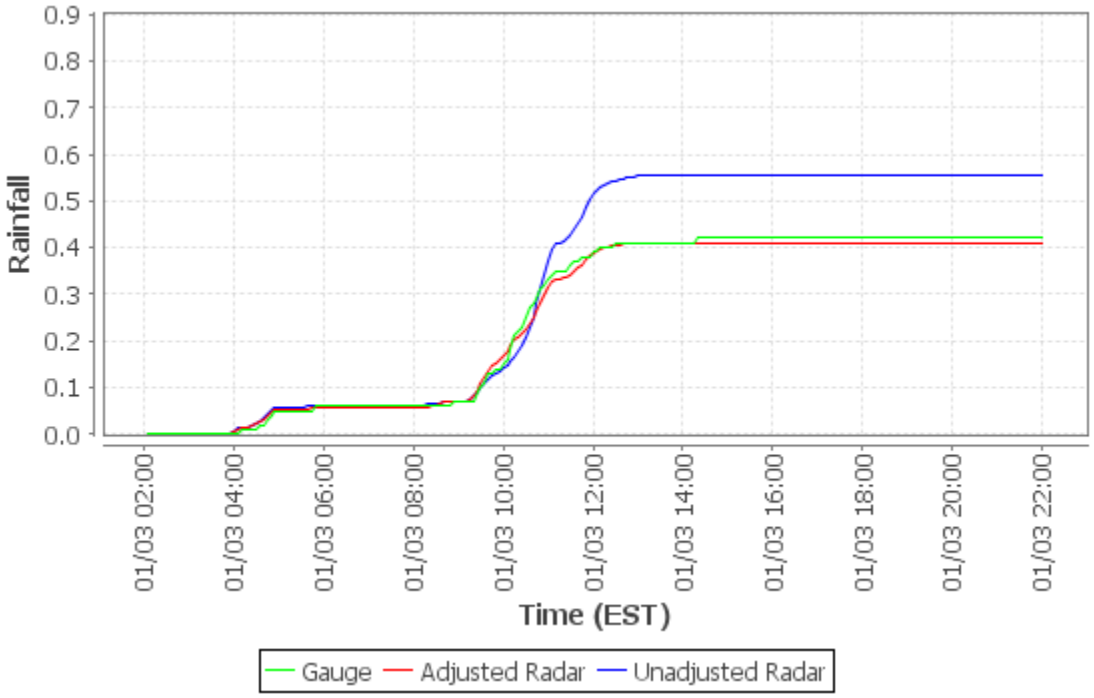
Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



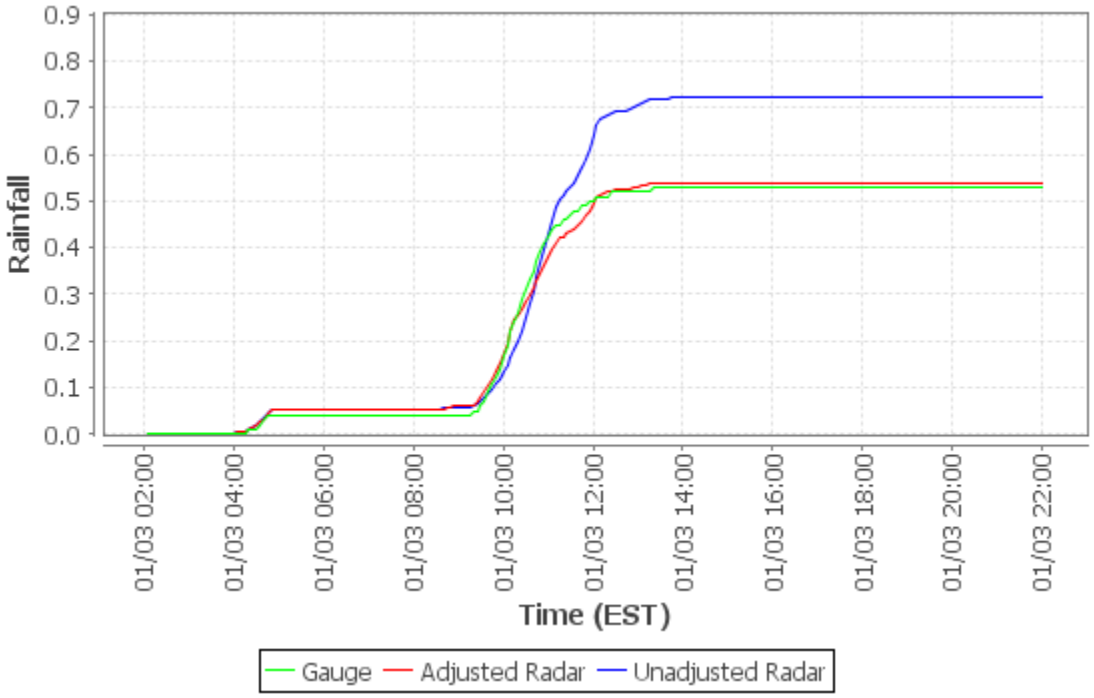
Cumulative Distribution Plot - Castle Shannon (Loc16)



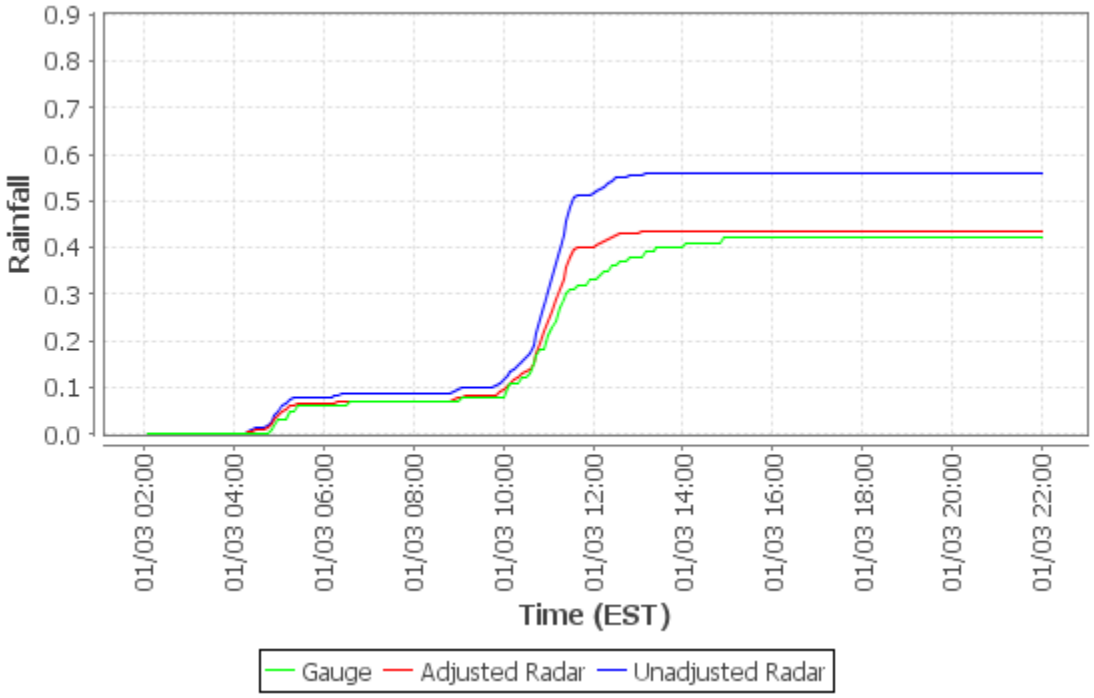
Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



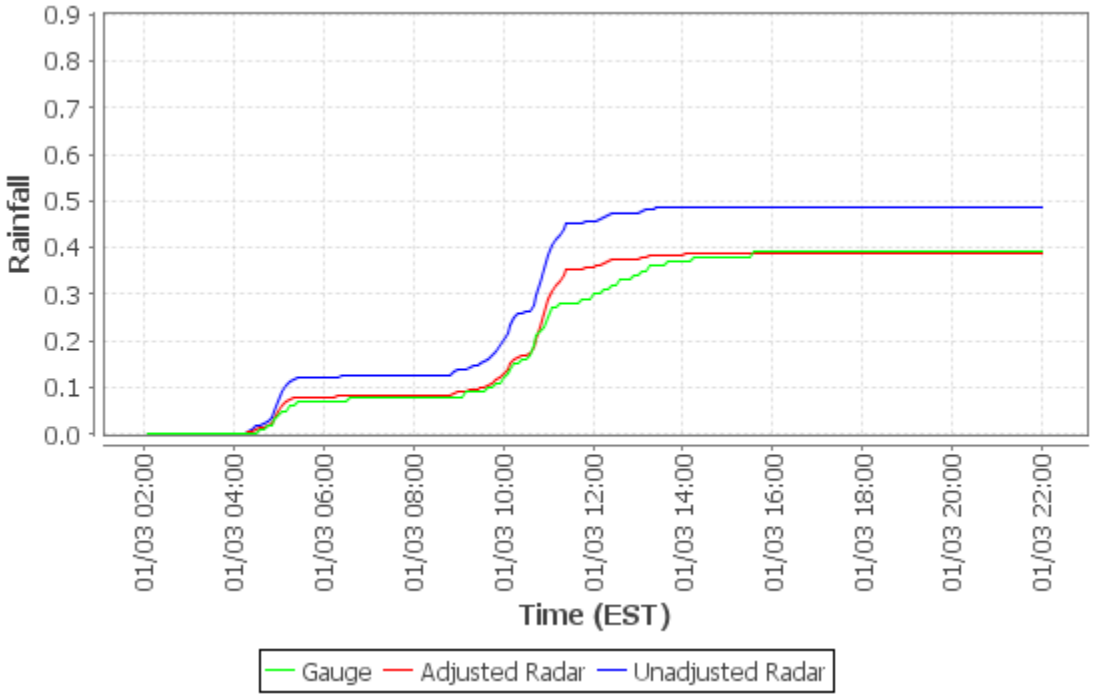
Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



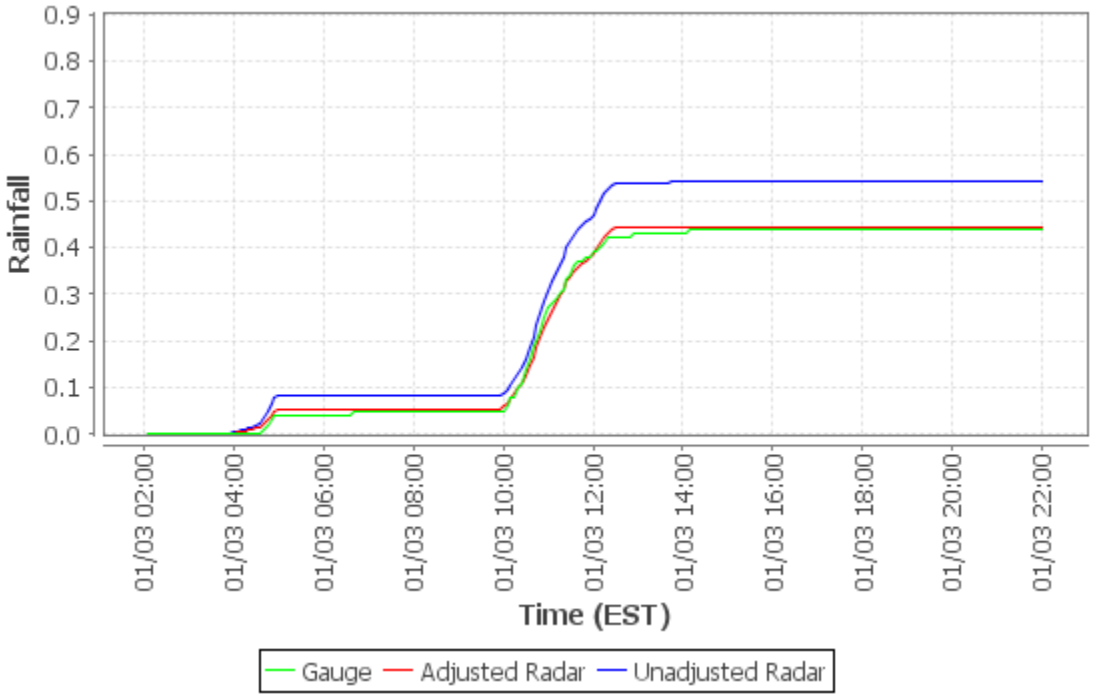
Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



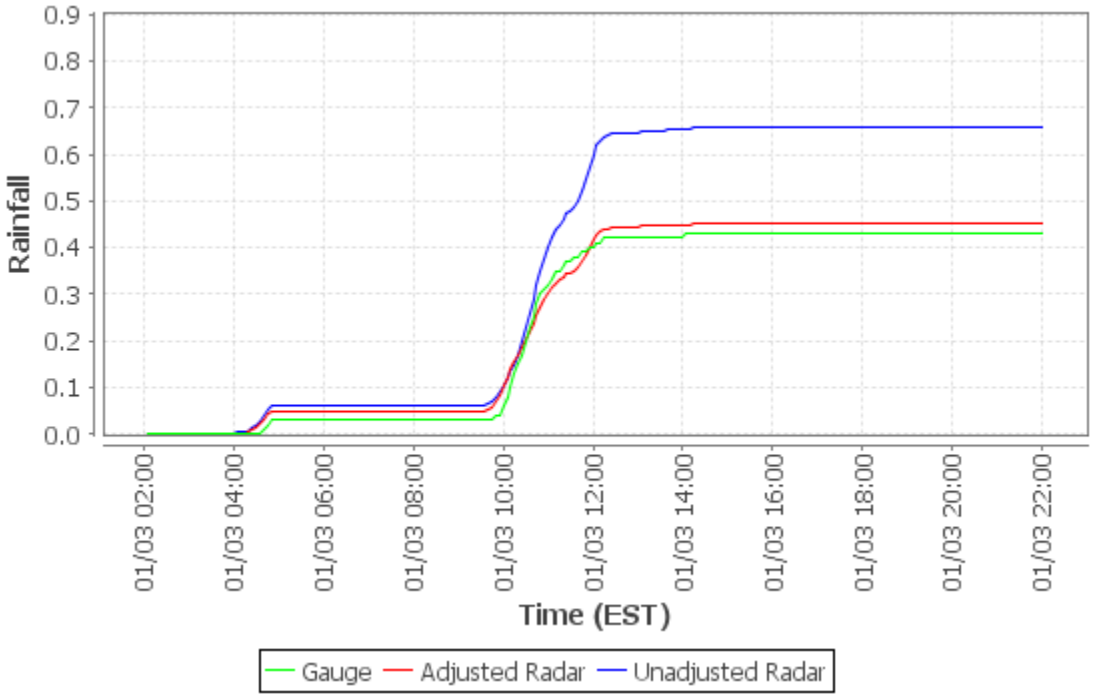
Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



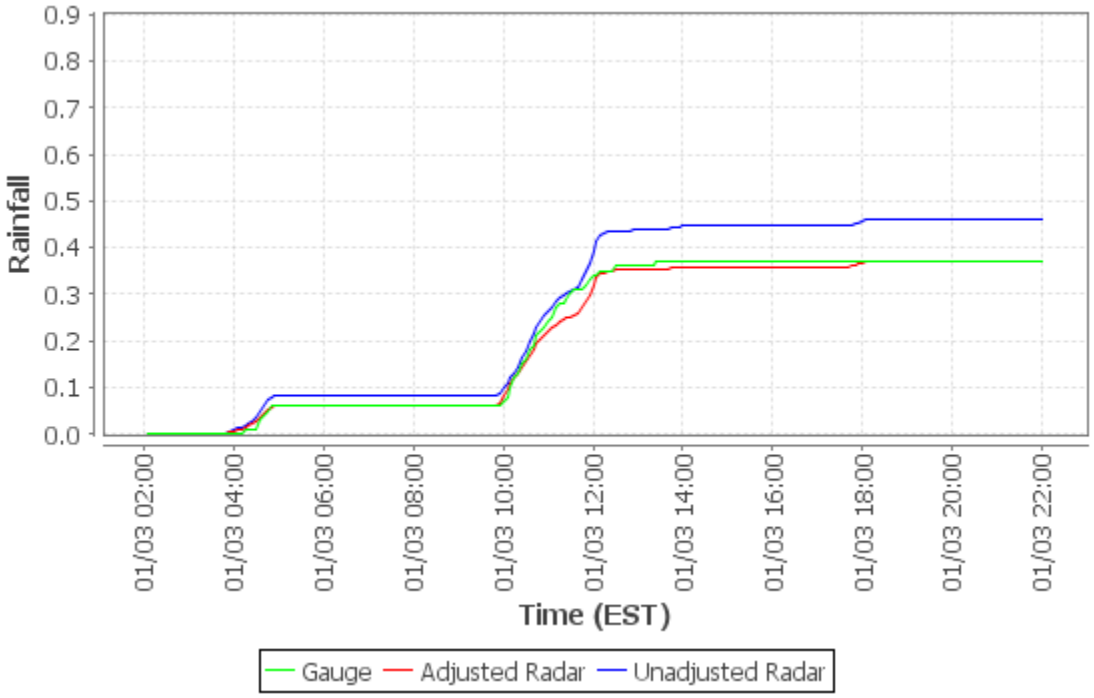
Cumulative Distribution Plot - Moon TWP (Loc21)



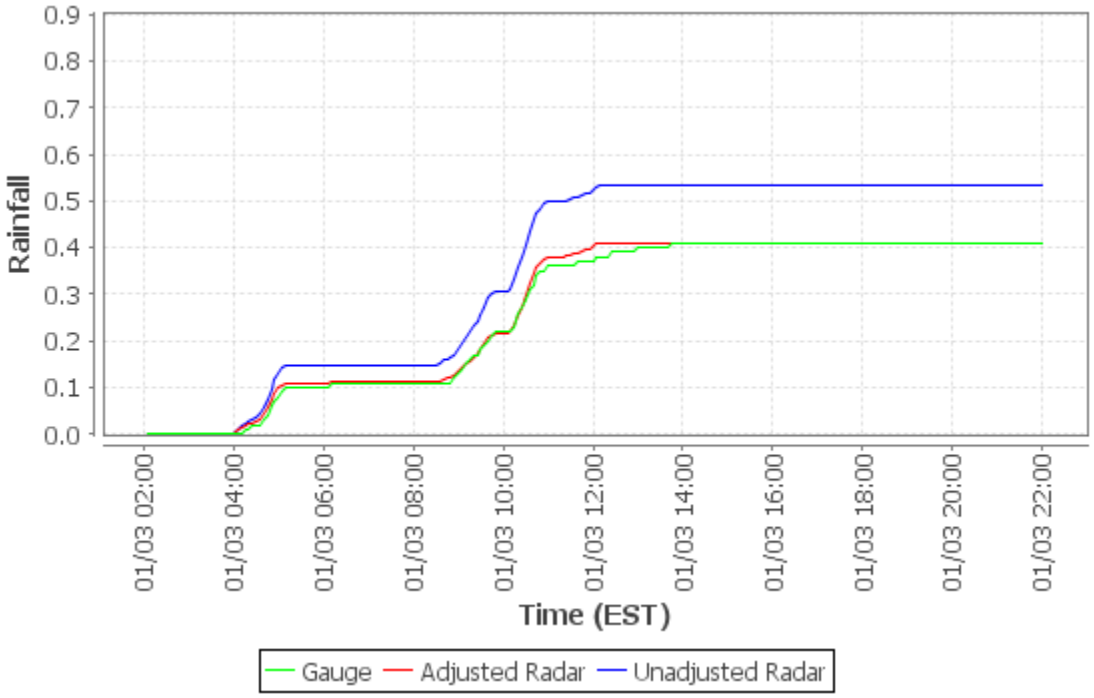
Cumulative Distribution Plot - North Fayette TWP (Loc22)



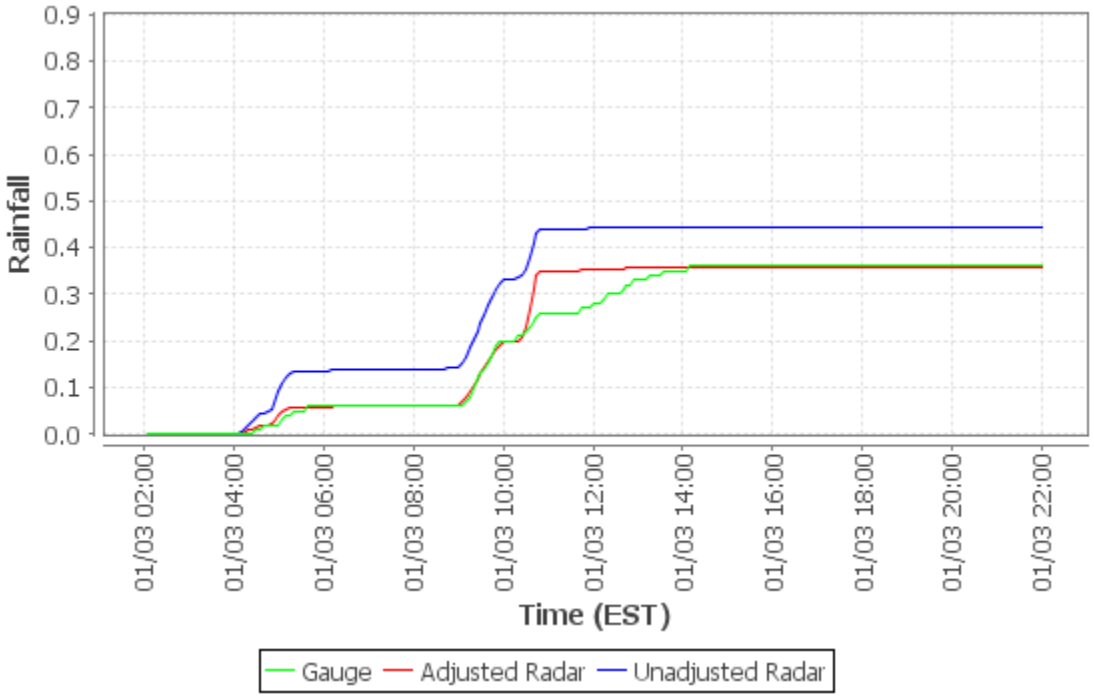
Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



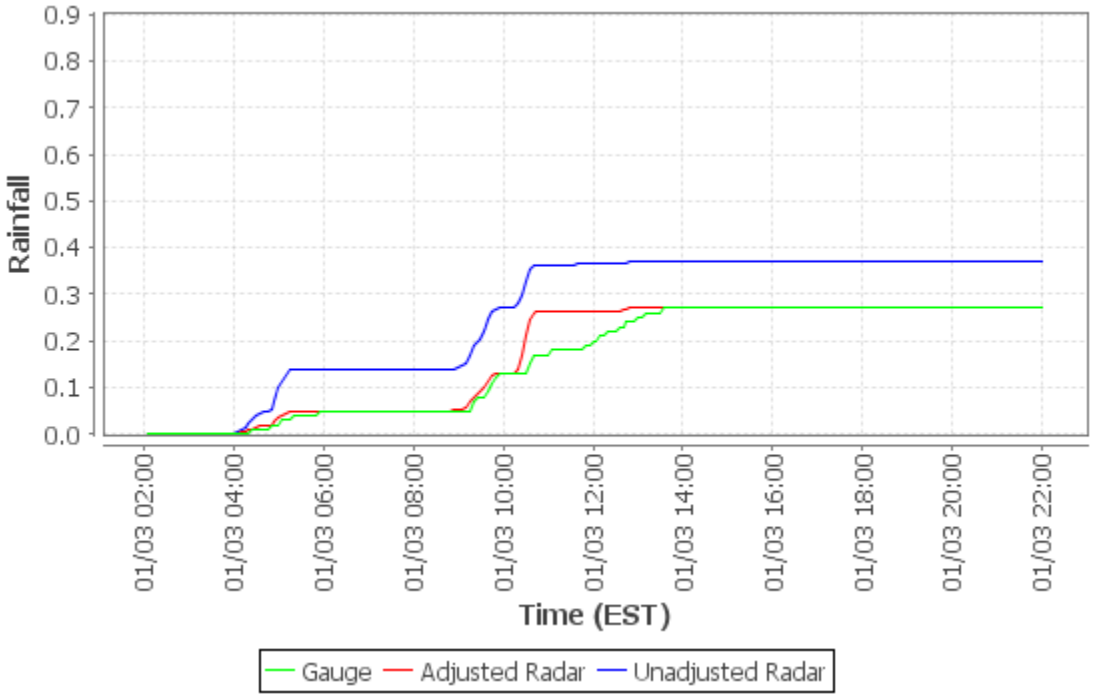
Cumulative Distribution Plot - Jefferson Hills (Loc24)



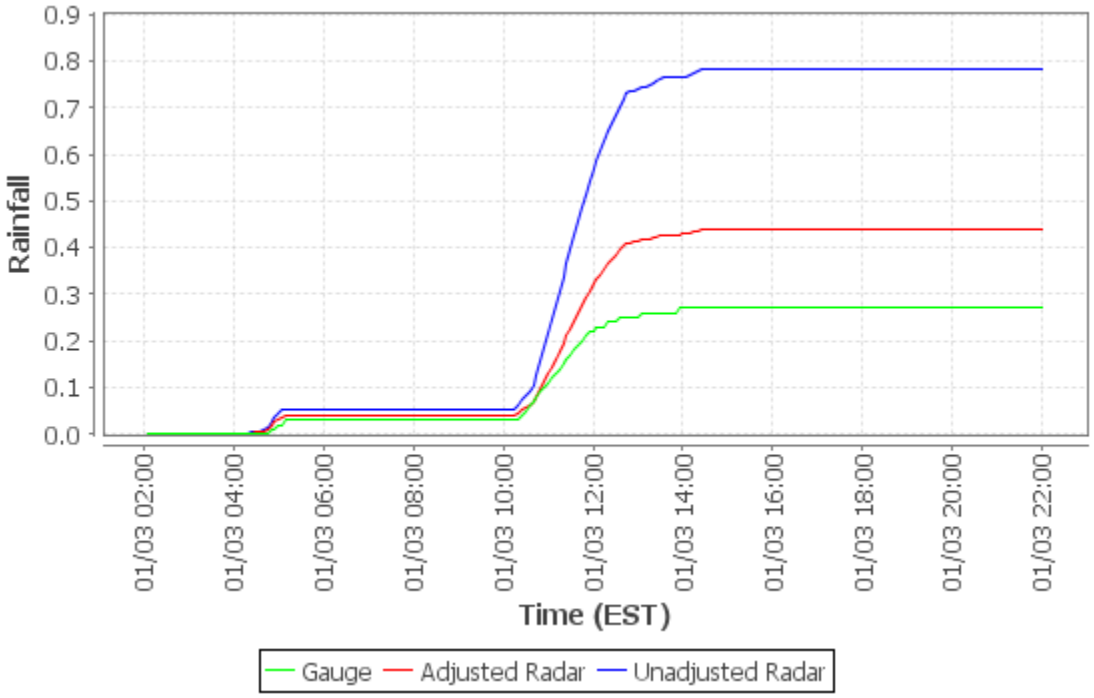
Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



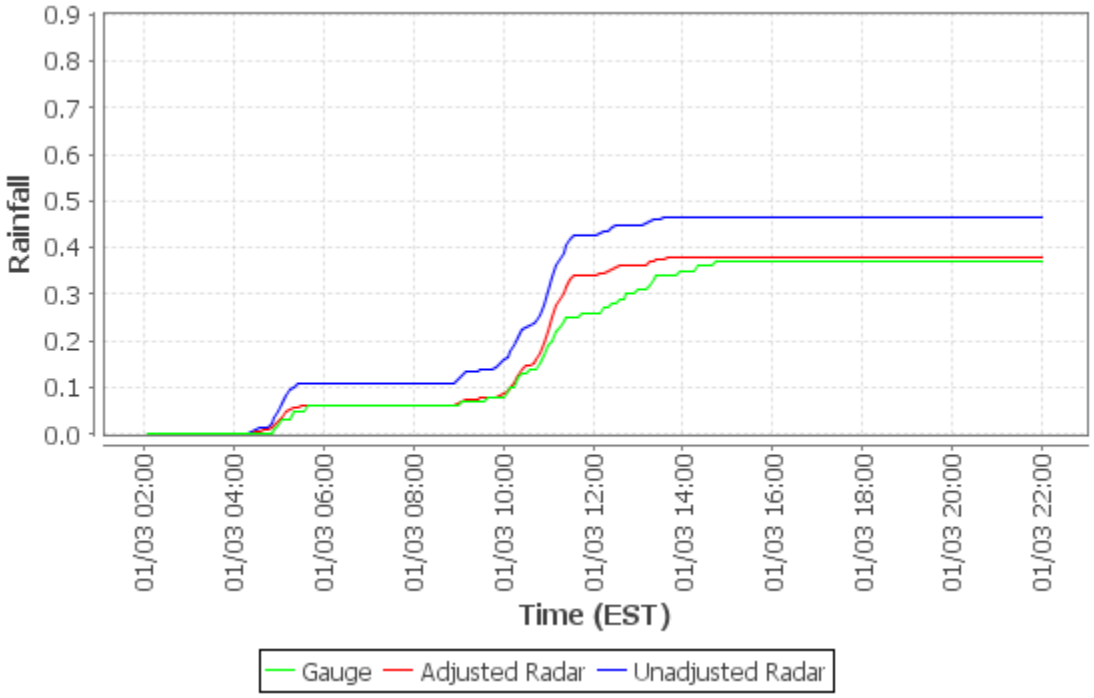
Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



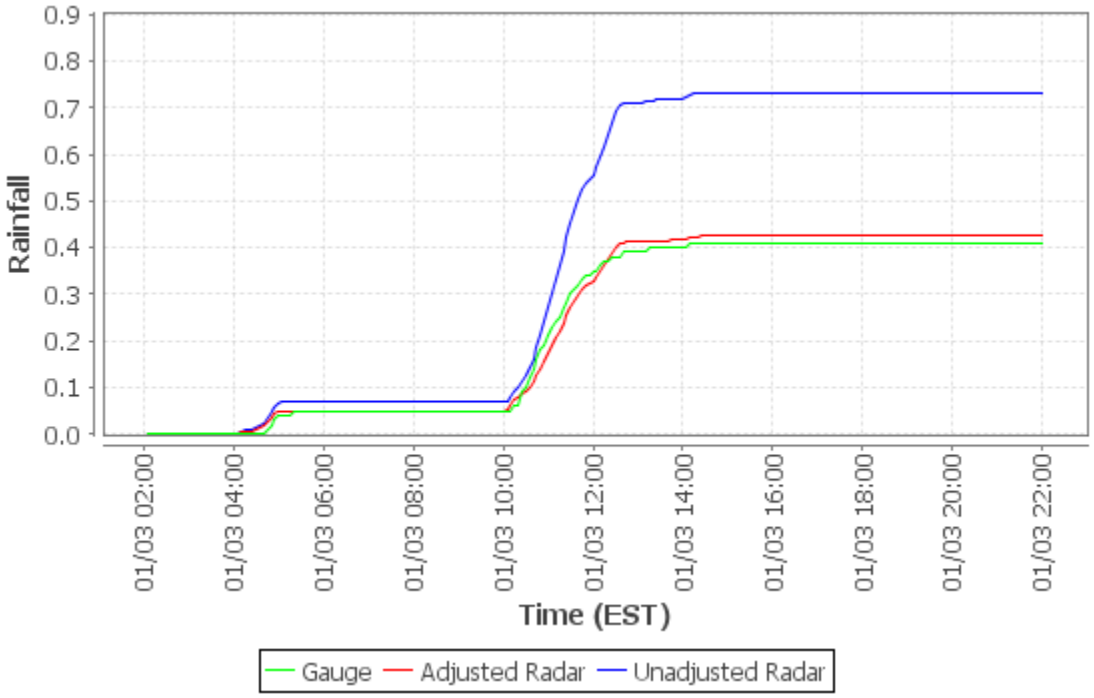
Cumulative Distribution Plot - Marshall TWP (Loc27)



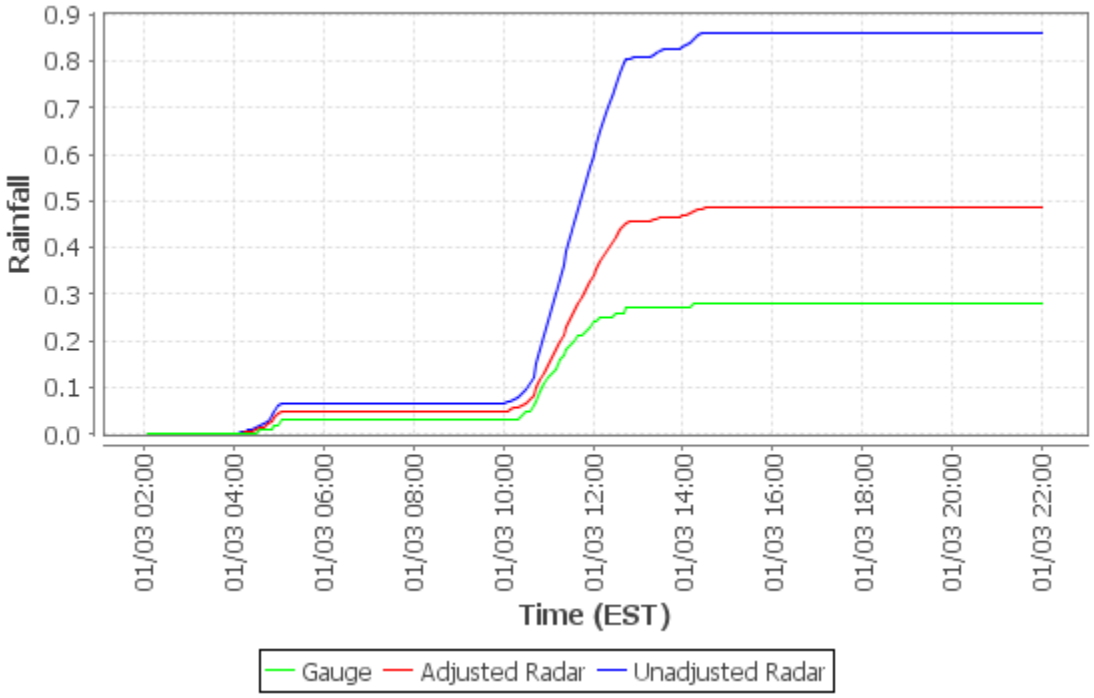
Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



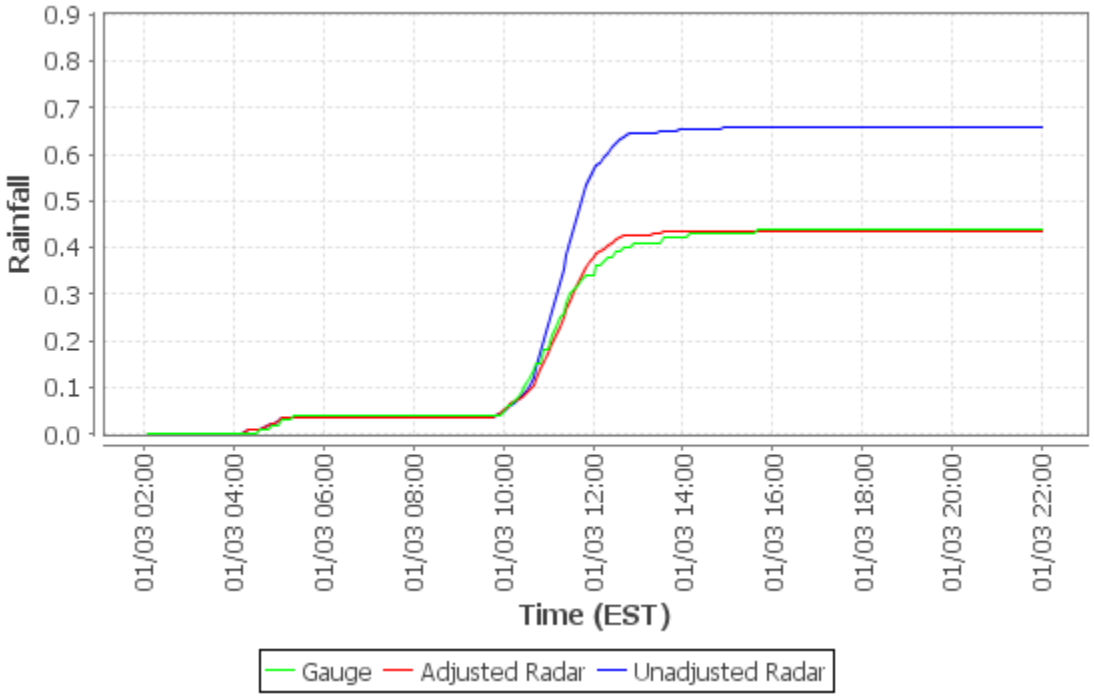
Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



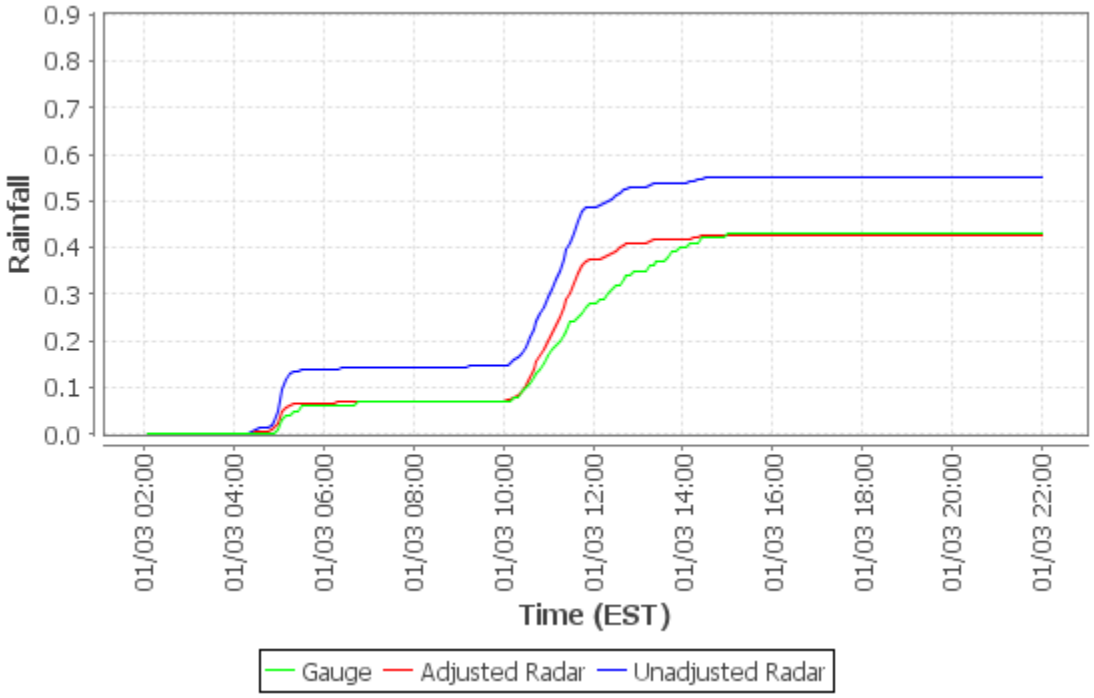
Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



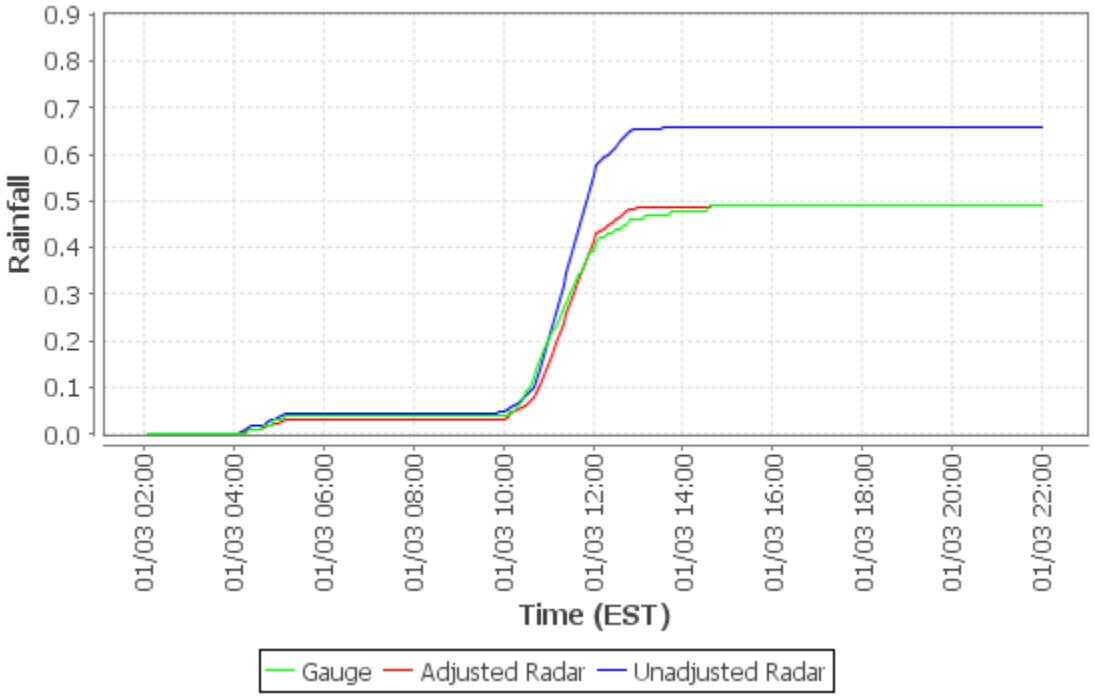
Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



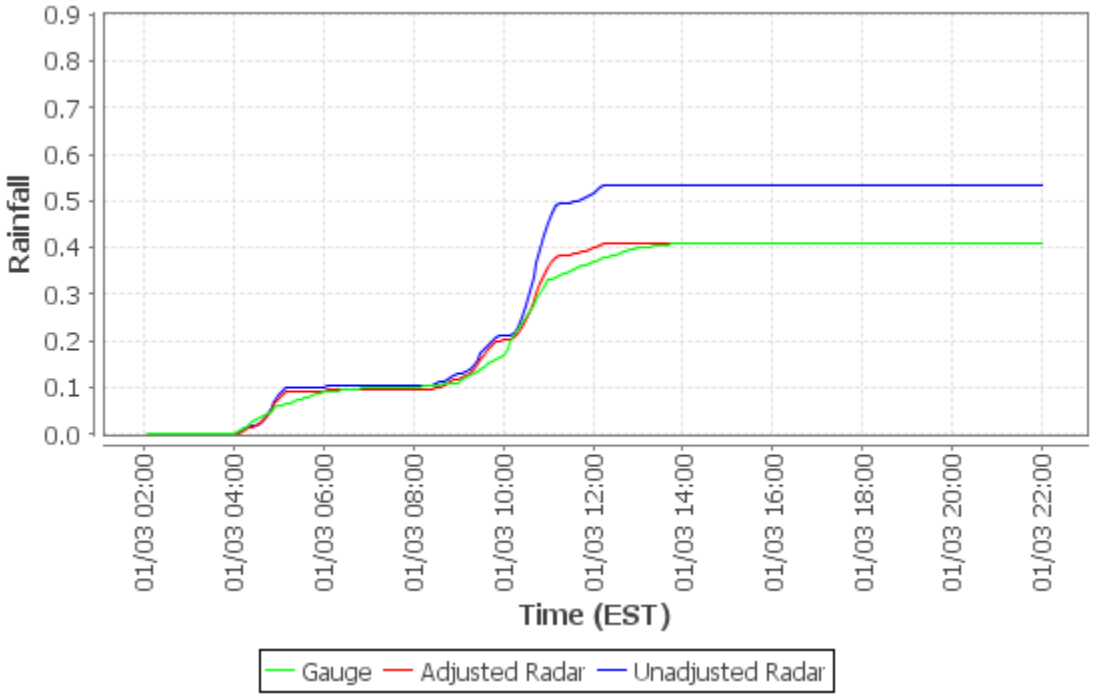
Cumulative Distribution Plot - Arnold (Loc32)



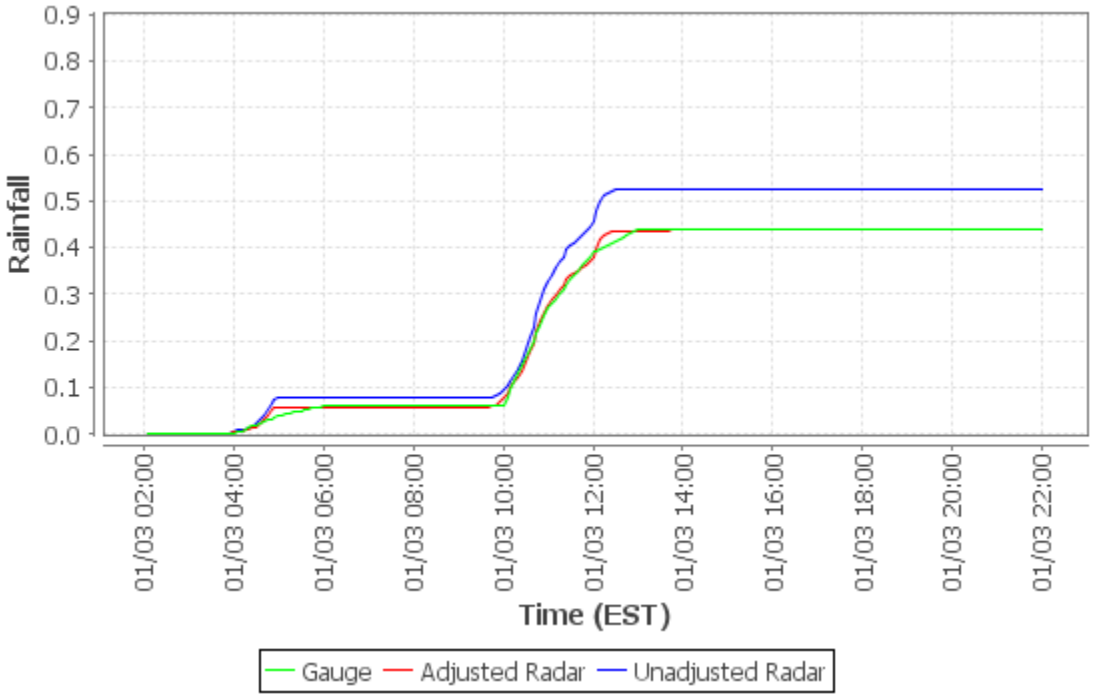
Cumulative Distribution Plot - Richland TWP (Loc33)



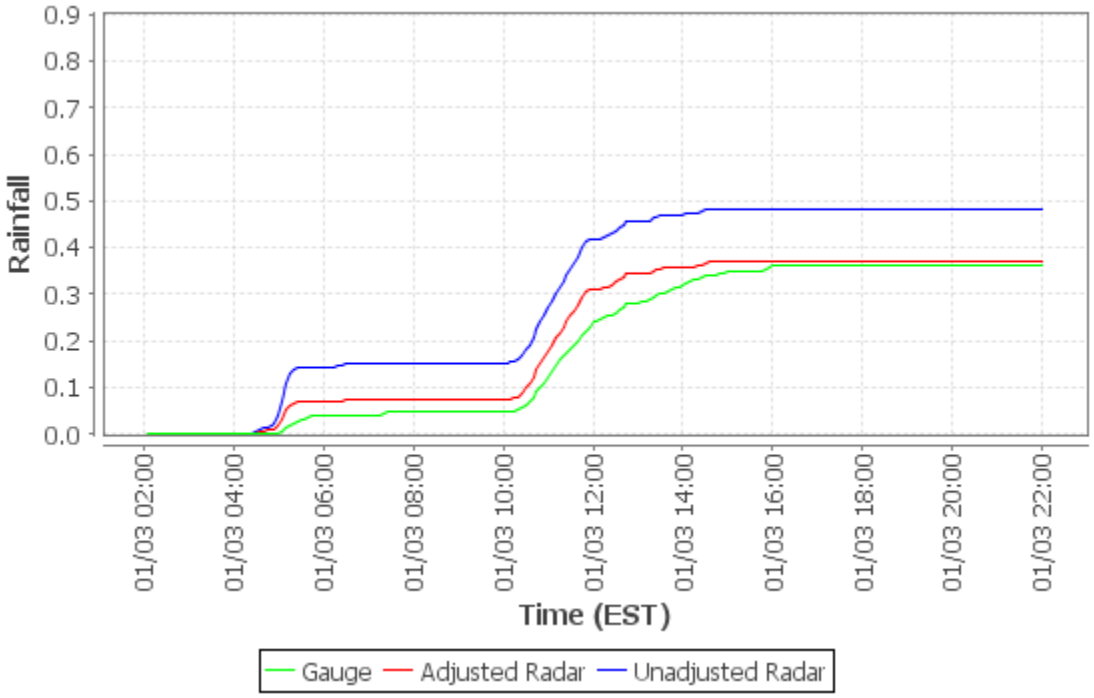
Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



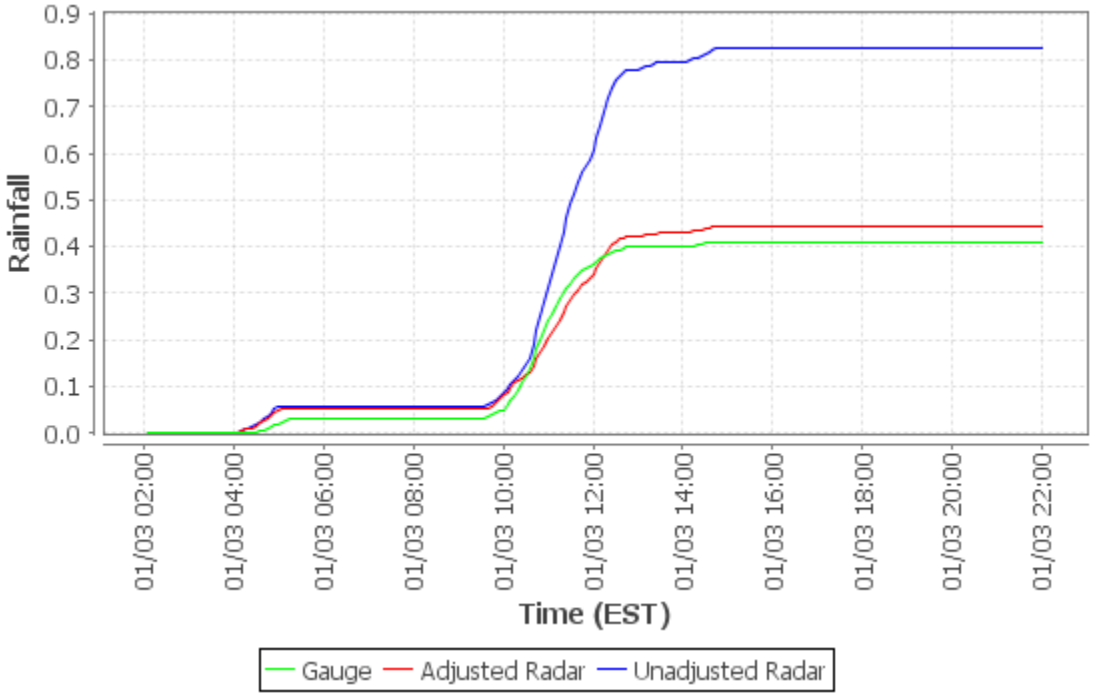
Cumulative Distribution Plot - Greater Pittsburgh Int'l (KPIT)



Cumulative Distribution Plot - Allegheny River at Natrona (03049500)

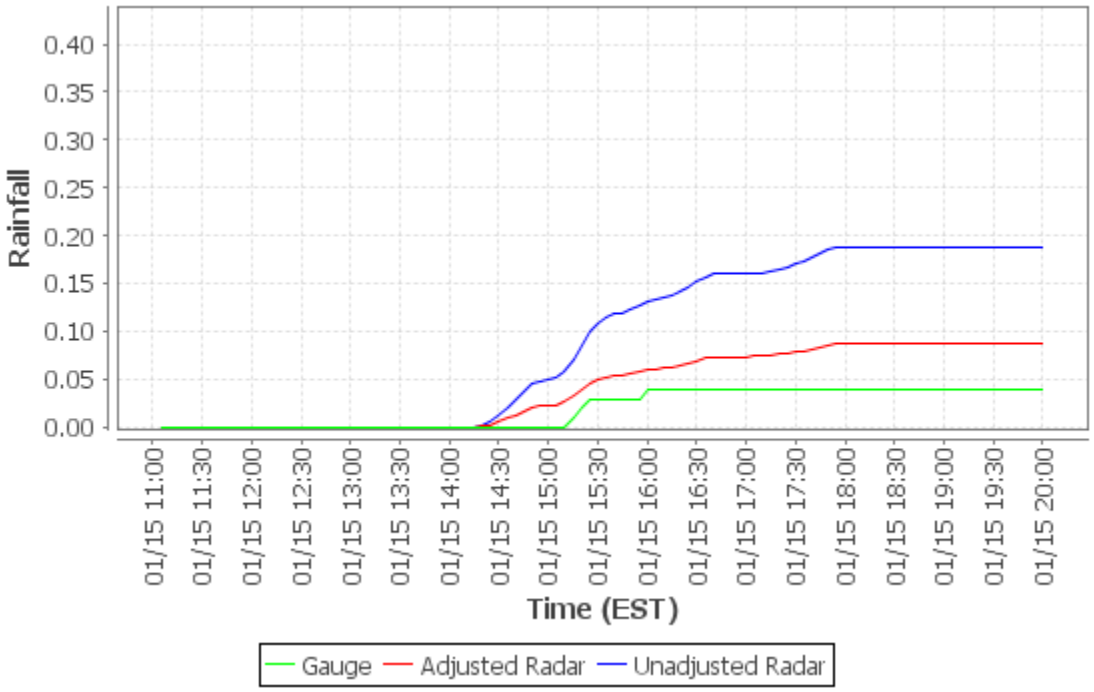


Cumulative Distribution Plot - Ohio River at Emsworth Dam Lower Pool at Emsworth (03085734)

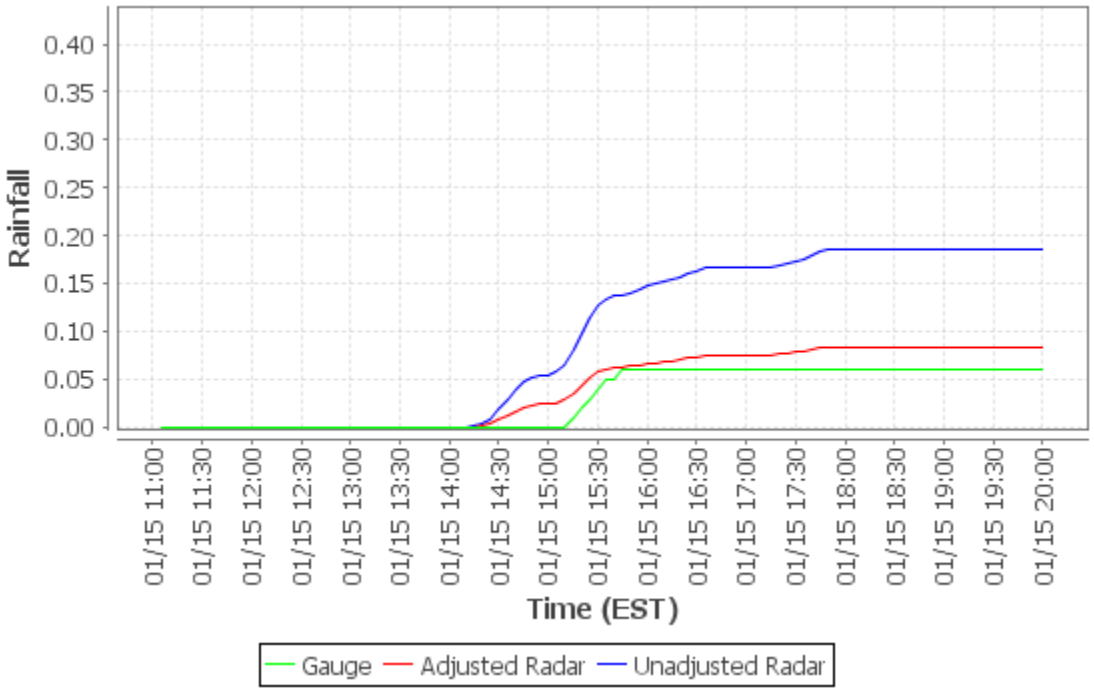


Appendix E - Event 3 (2021-01-15) CDPs

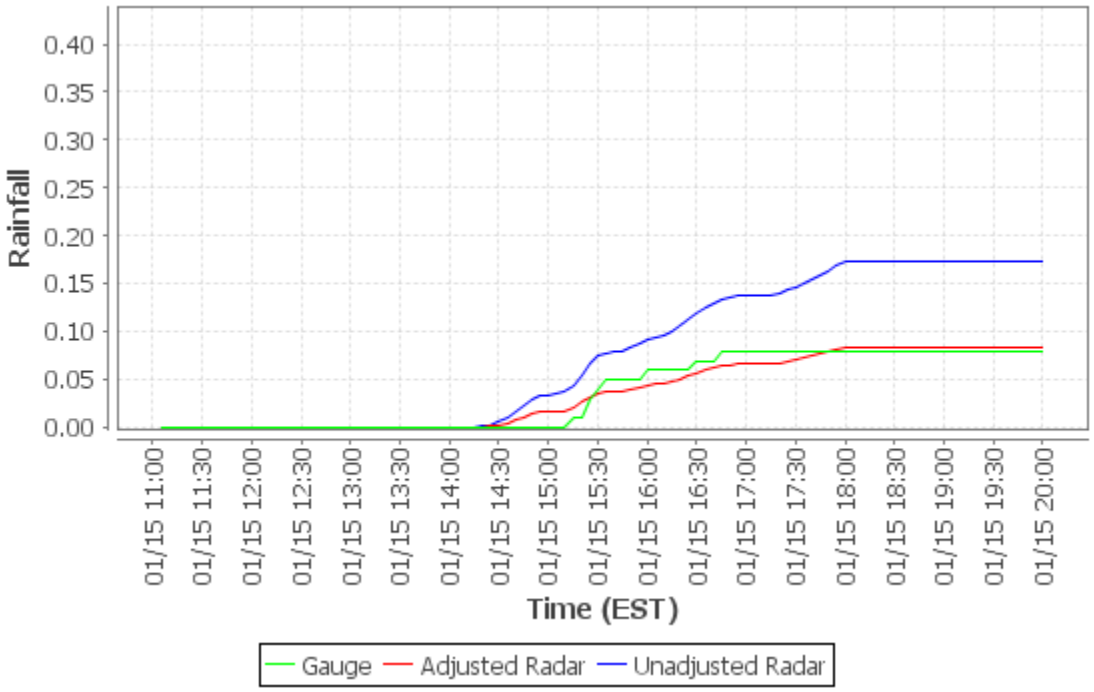
Cumulative Distribution Plot - PWSA-Montana St. (Loc01)



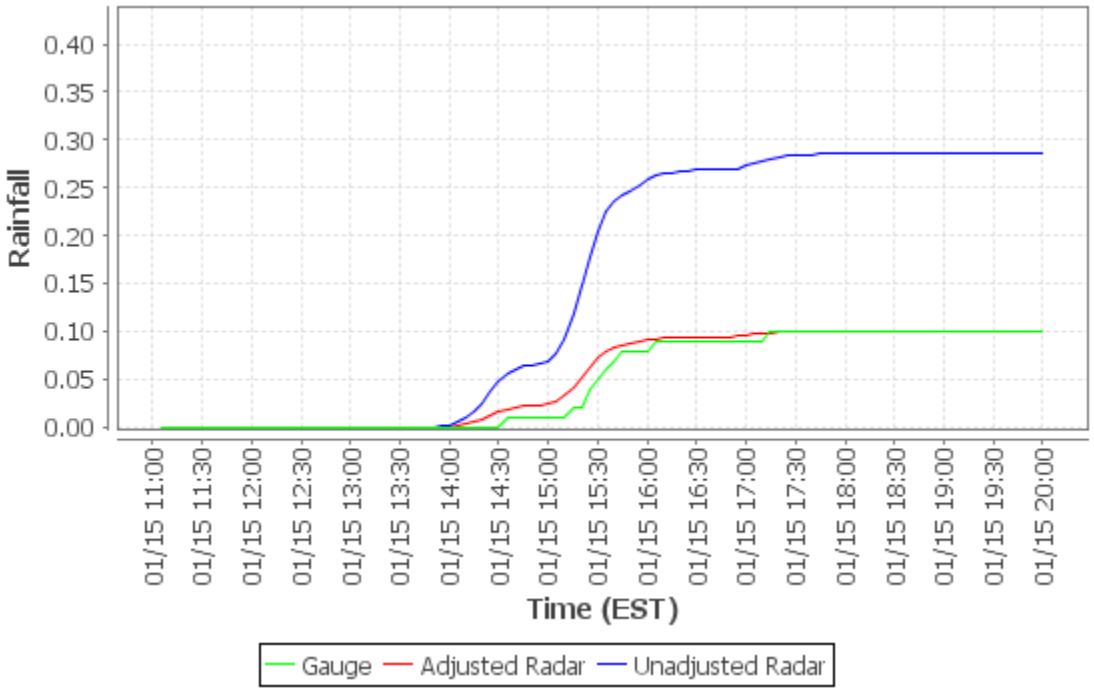
Cumulative Distribution Plot - ALCOSAN WWTP Lab (Loc02)



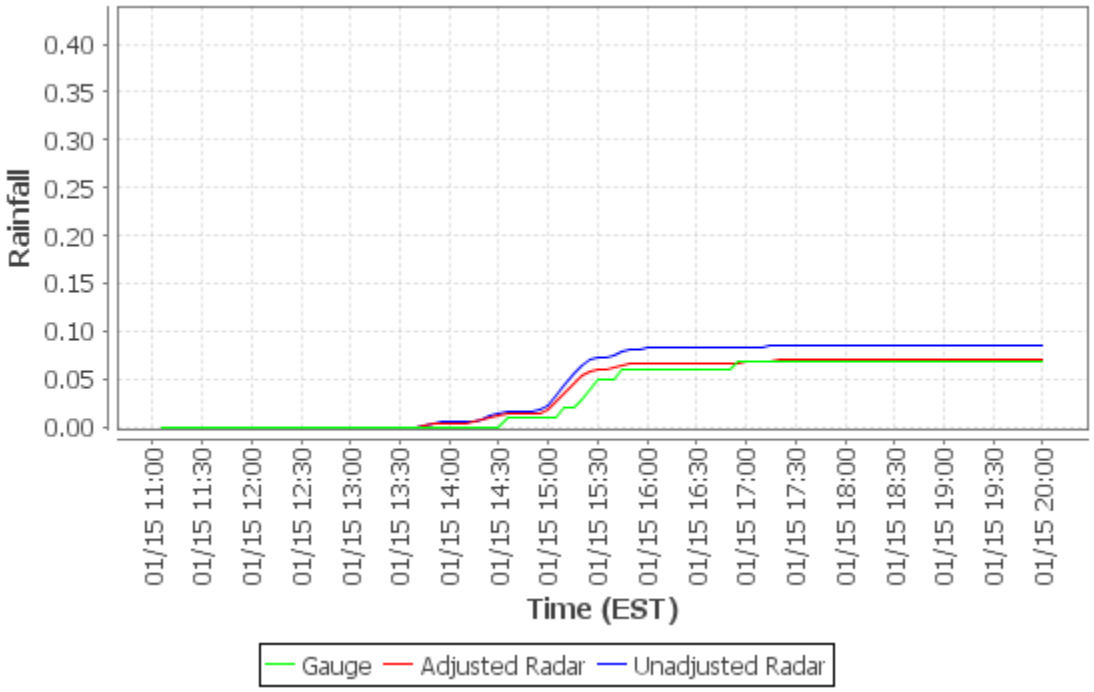
Cumulative Distribution Plot - Shaler Munic Bldg (Loc03)



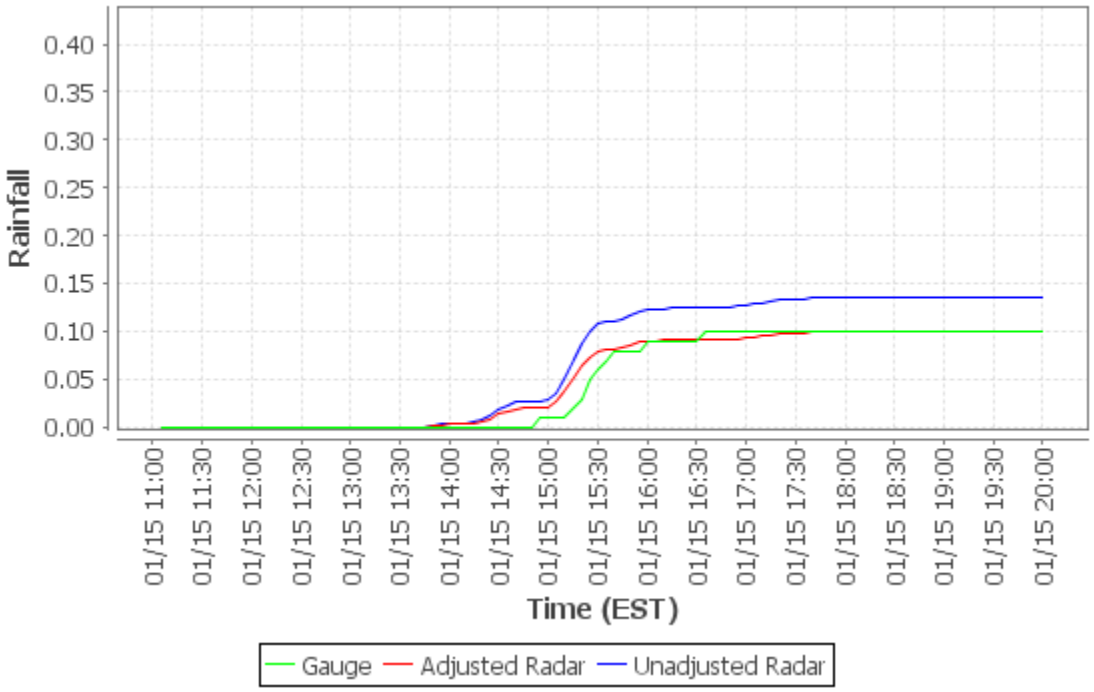
Cumulative Distribution Plot - Kennedy Twp PS (Loc04)



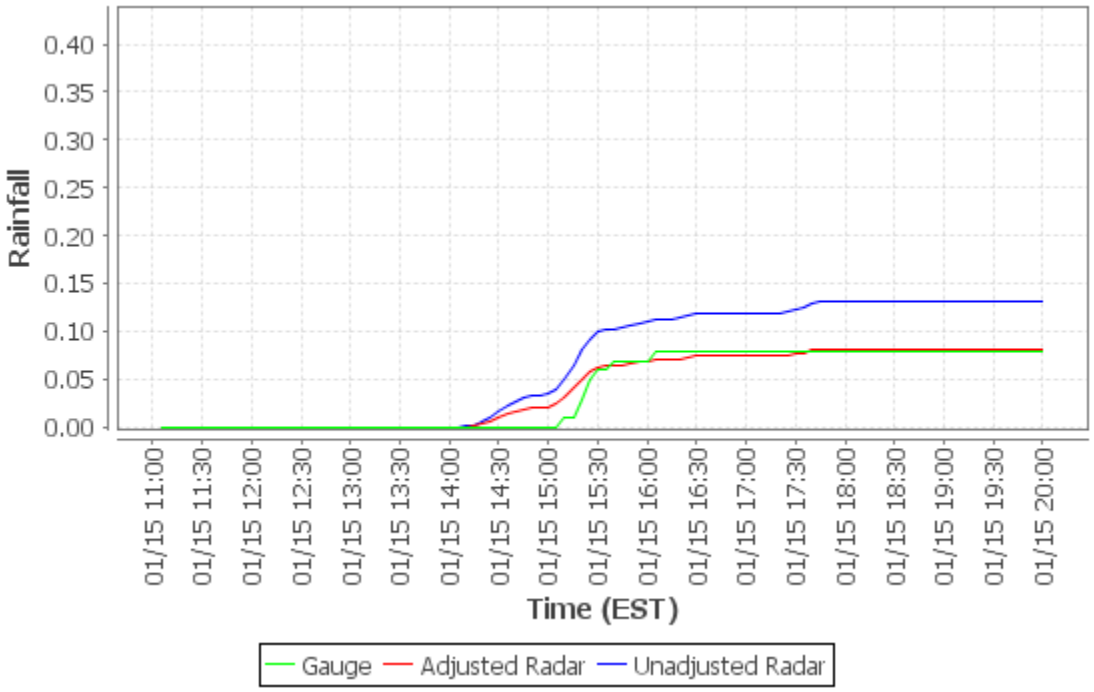
Cumulative Distribution Plot - Upper St. Clair (Loc05)



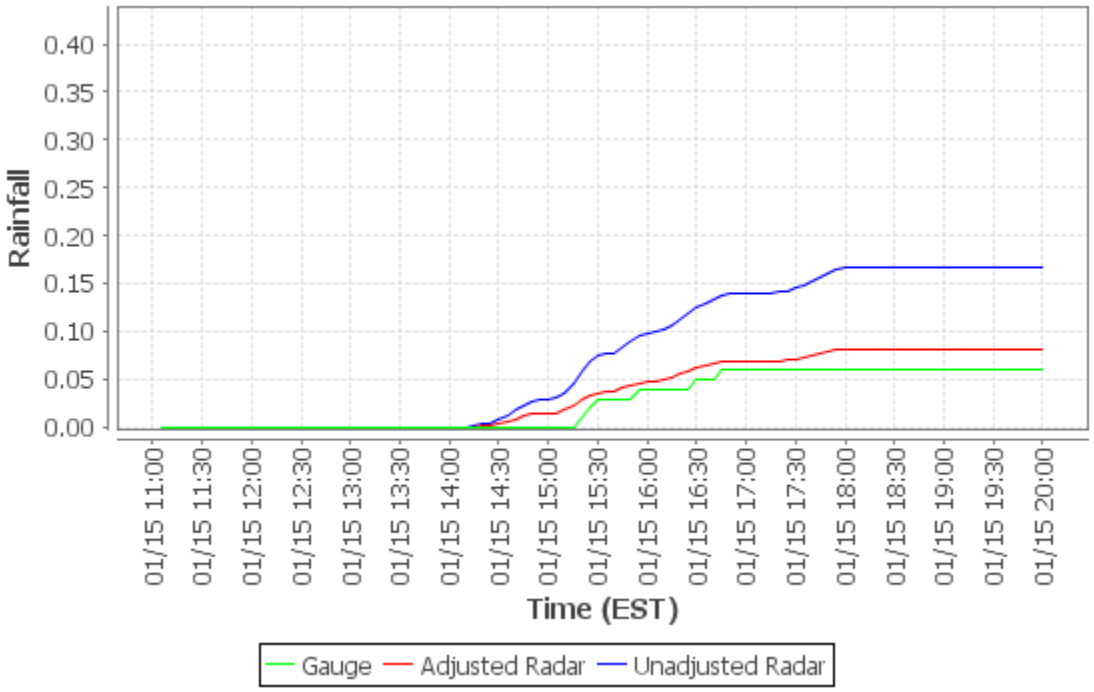
Cumulative Distribution Plot - Carnegie Transit Time (Loc06)



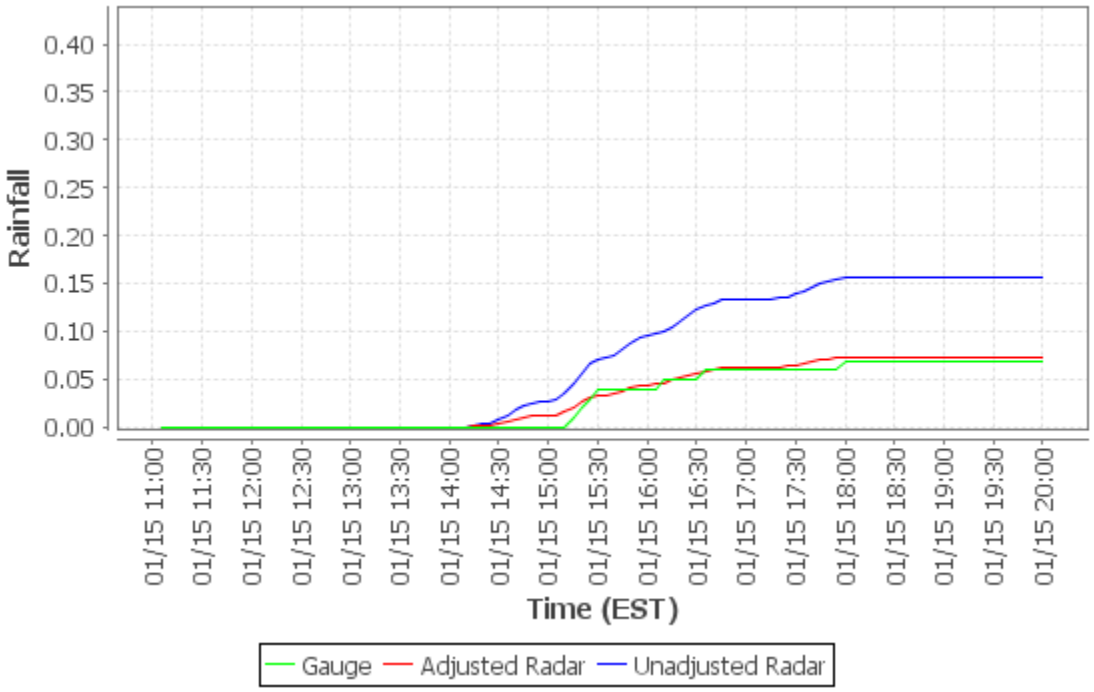
Cumulative Distribution Plot - Greentree Munic Bldg (Loc07)



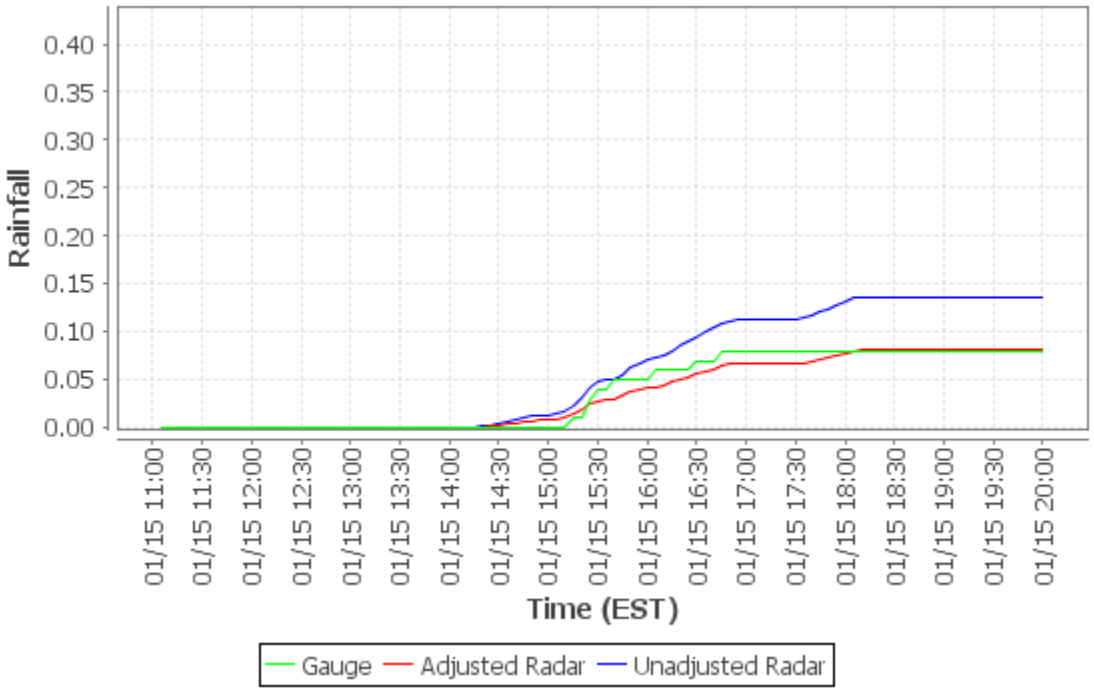
Cumulative Distribution Plot - AC Health Dept Bldg (Loc08)



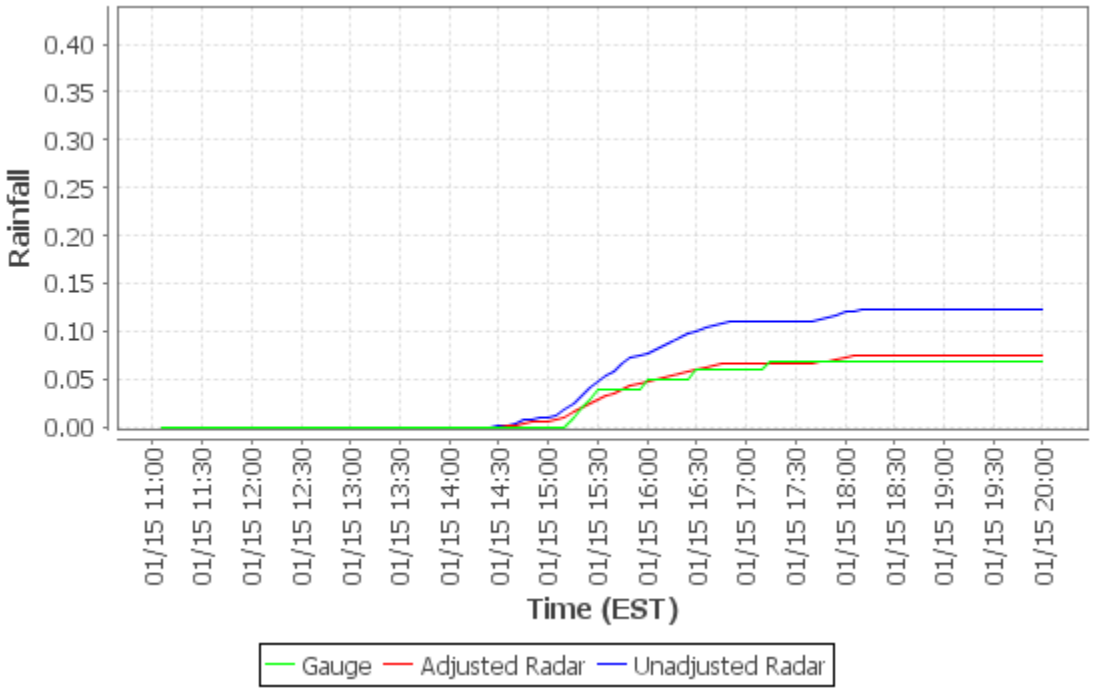
Cumulative Distribution Plot - Univ of Pittsburgh (Loc09)



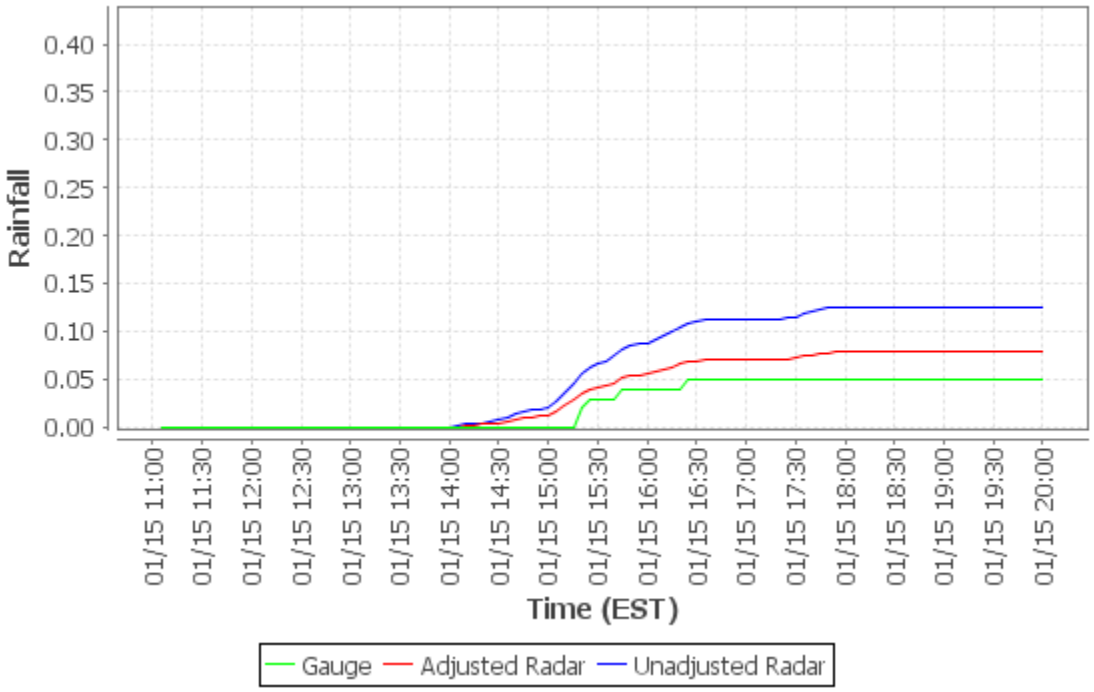
Cumulative Distribution Plot - PWSA-Highland Park (Loc10)



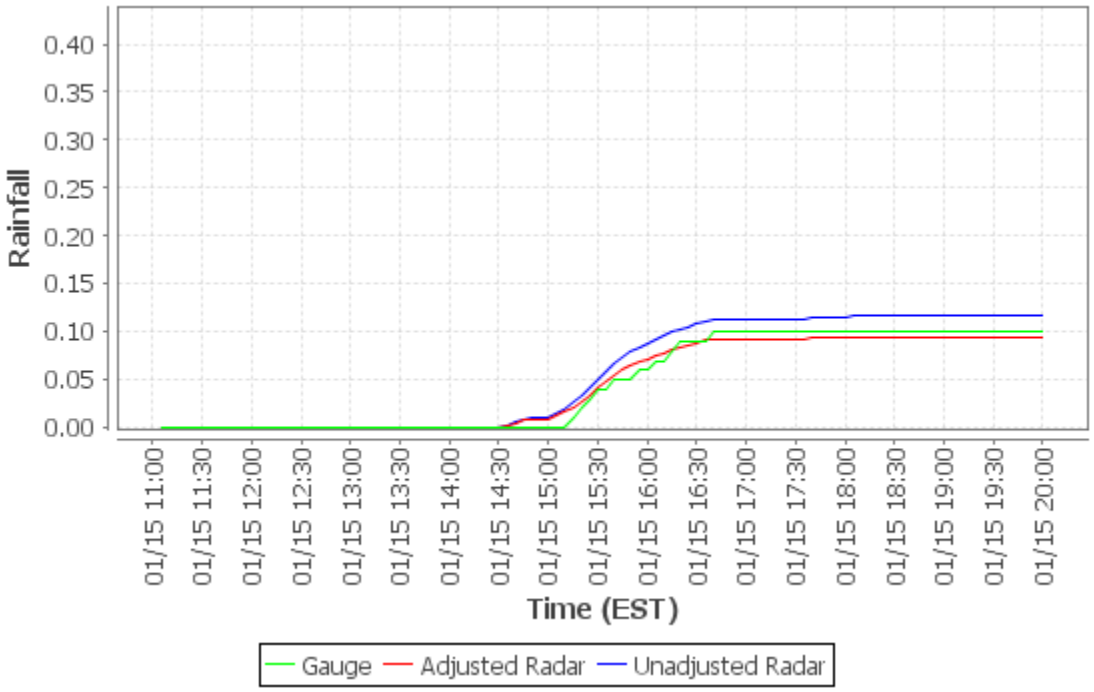
Cumulative Distribution Plot - M-46 Access Shaft (Loc11)



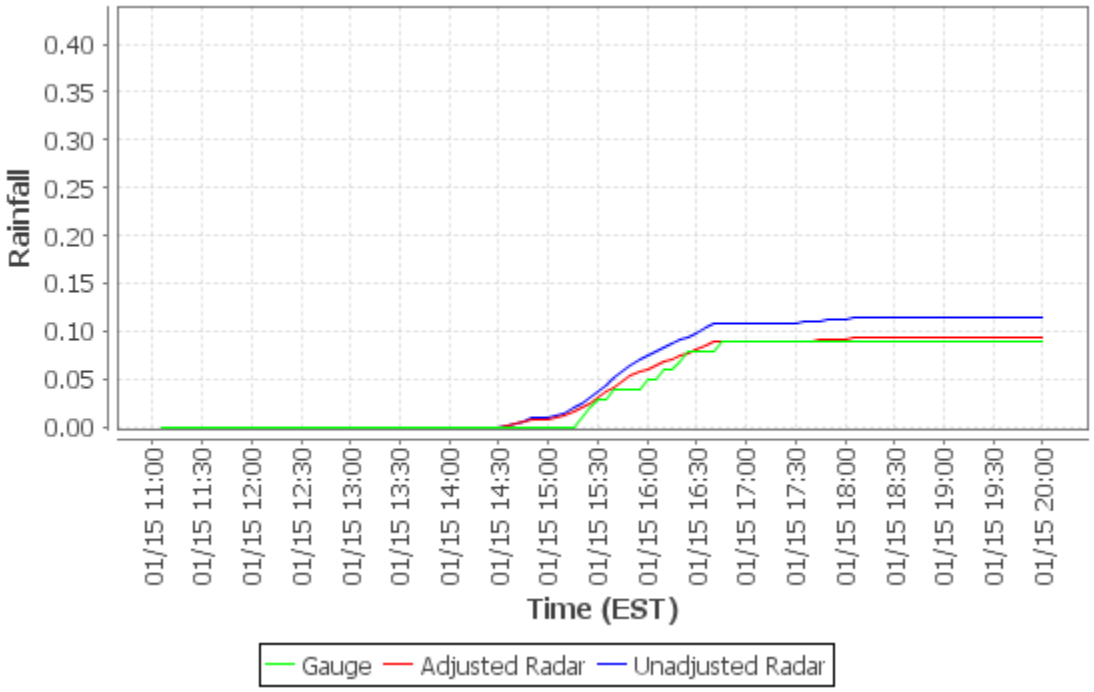
Cumulative Distribution Plot - Baldwin (Loc12)



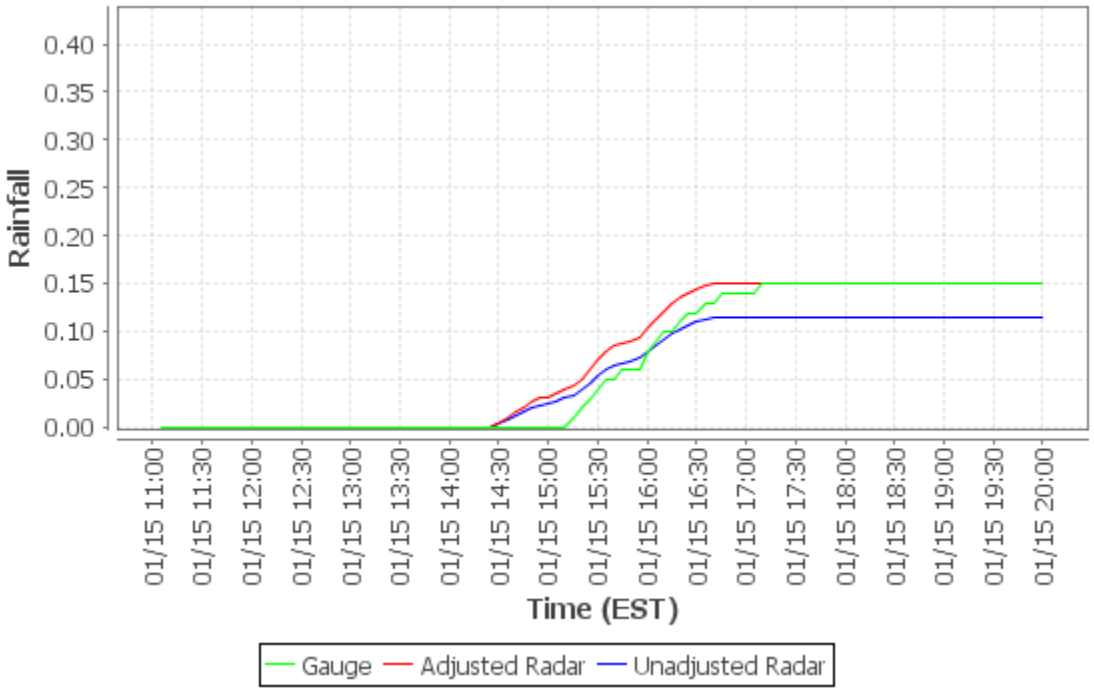
Cumulative Distribution Plot - M-59 Access Shaft (Loc13)



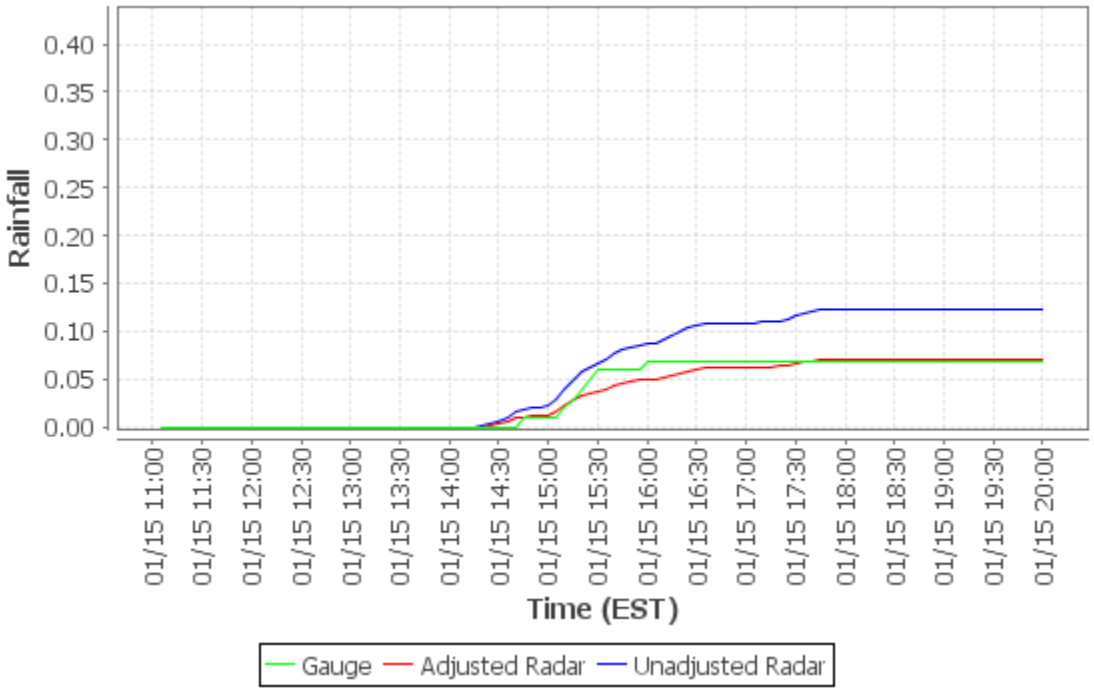
Cumulative Distribution Plot - Churchill Munic Bldg (Loc14)



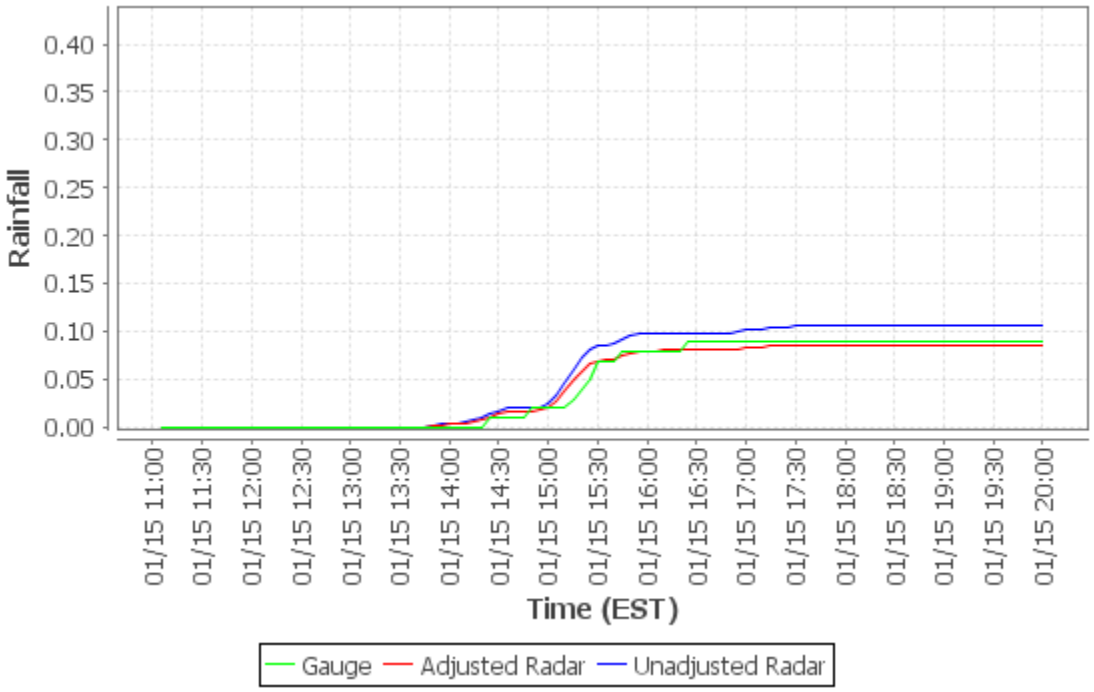
Cumulative Distribution Plot - Trafford Maint Bldg (Loc15)



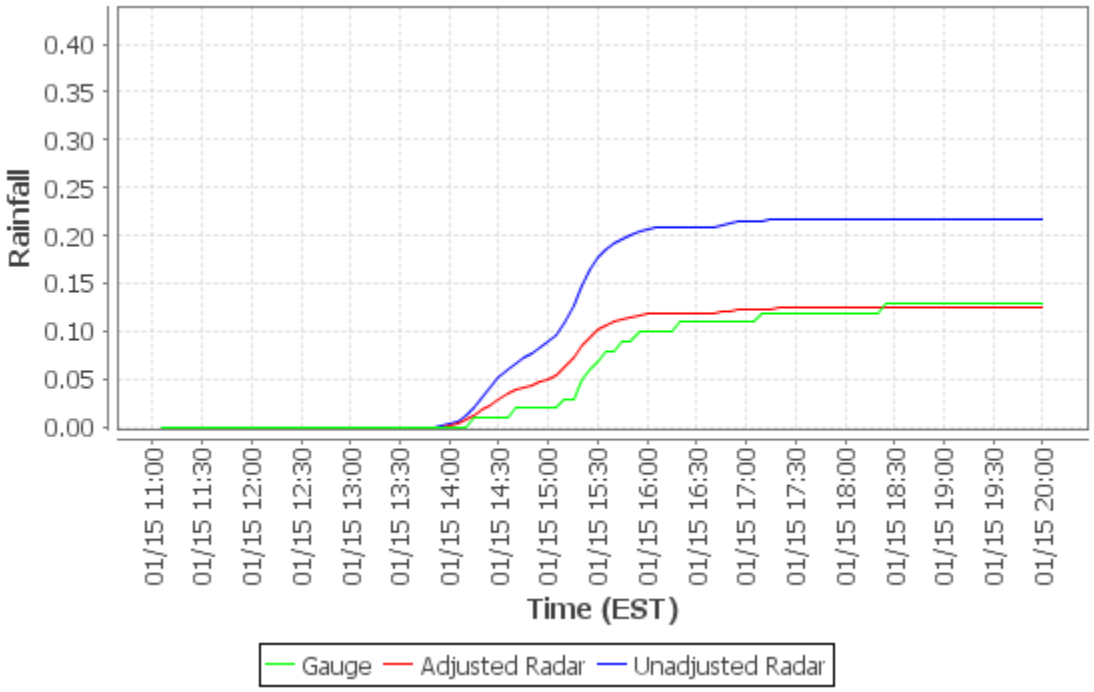
Cumulative Distribution Plot - Castle Shannon (Loc16)



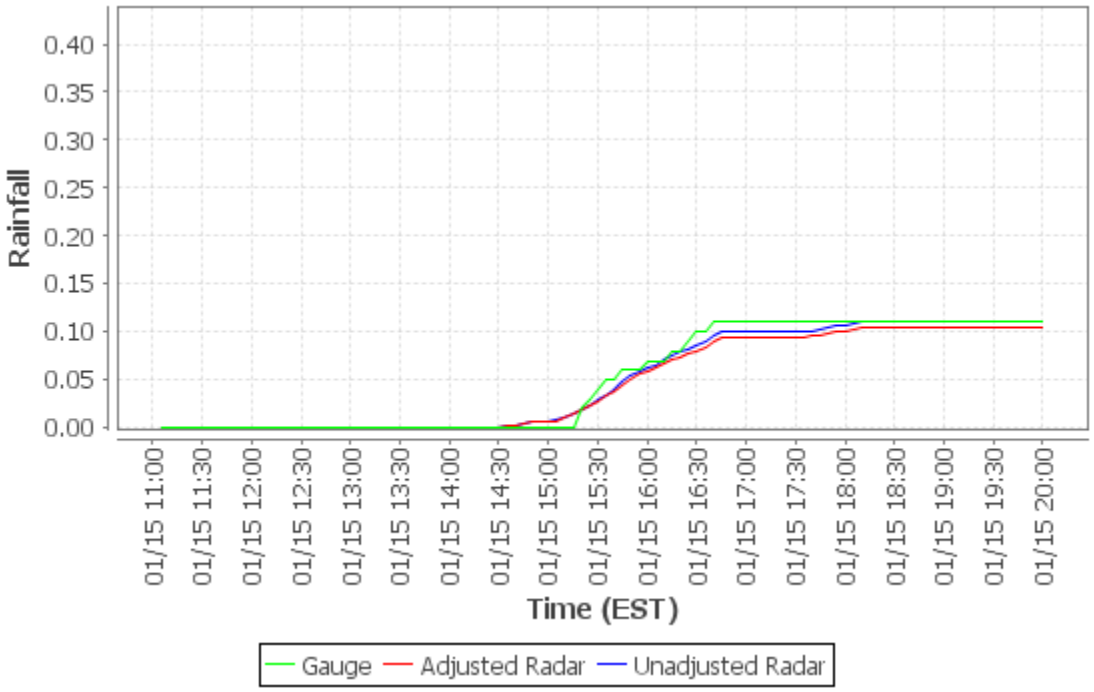
Cumulative Distribution Plot - Chartiers Pump Station (Loc17)



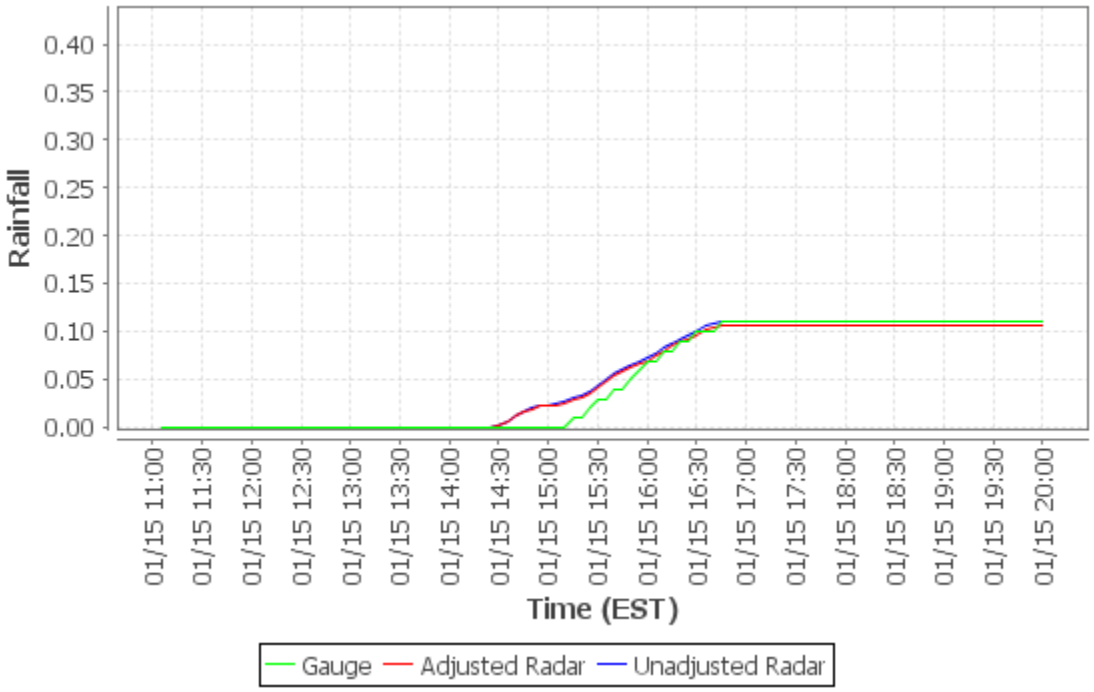
Cumulative Distribution Plot - Oakdale Pump Station (Loc18)



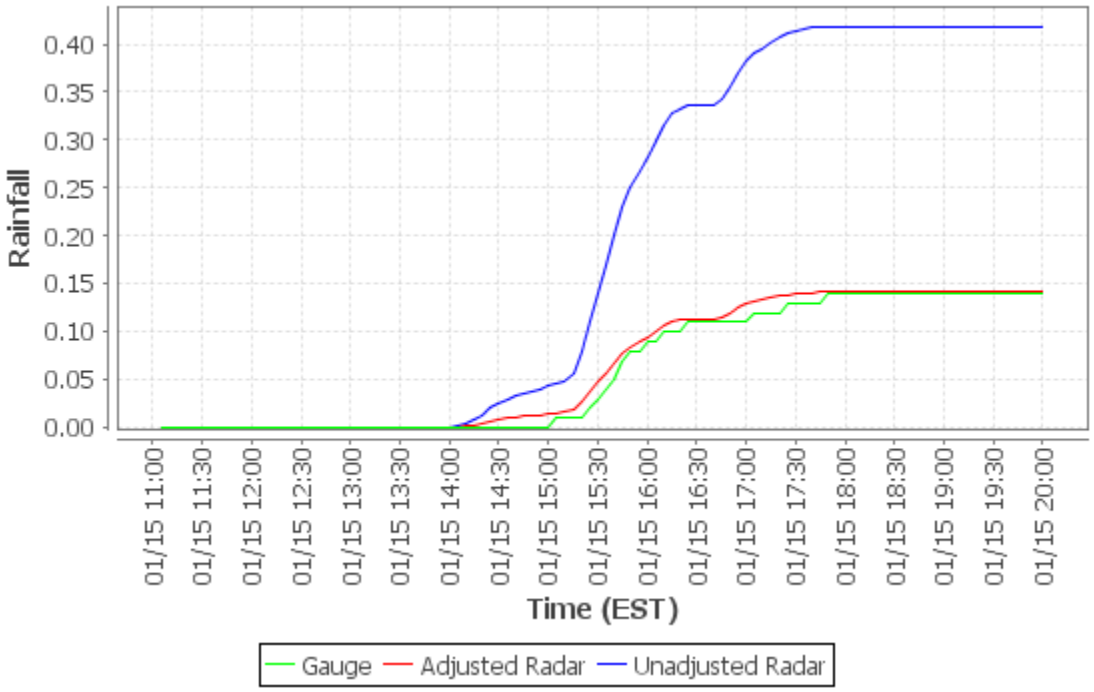
Cumulative Distribution Plot - Sandy Creek Eq Facility (Loc19)



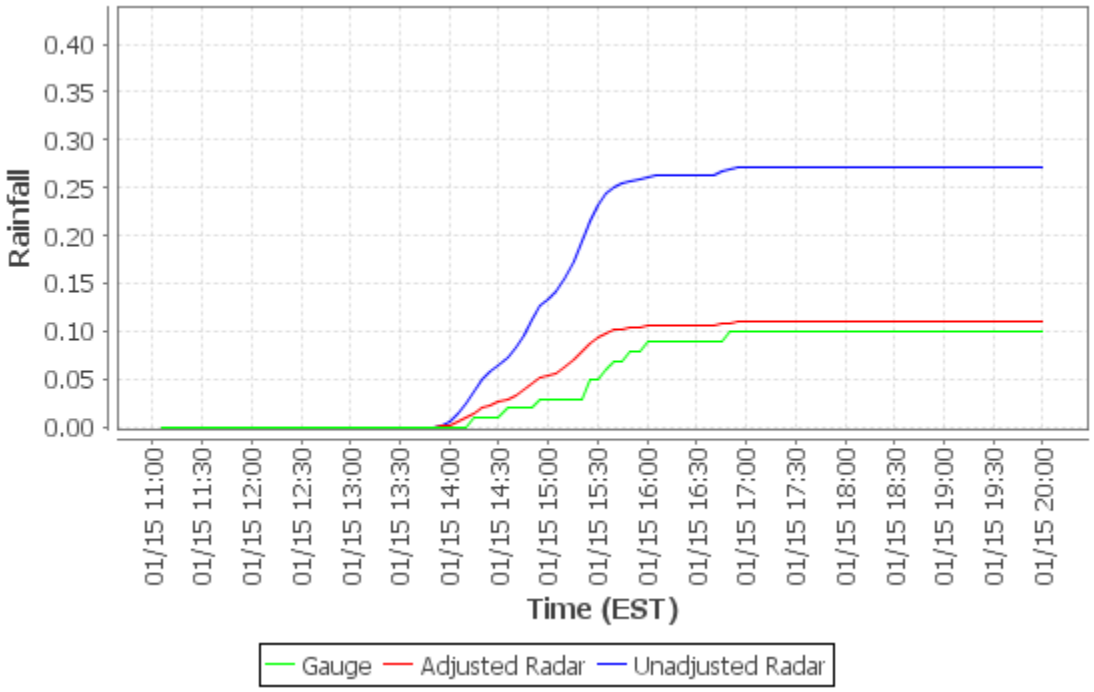
Cumulative Distribution Plot - Gascola Eq Facility (Loc20)



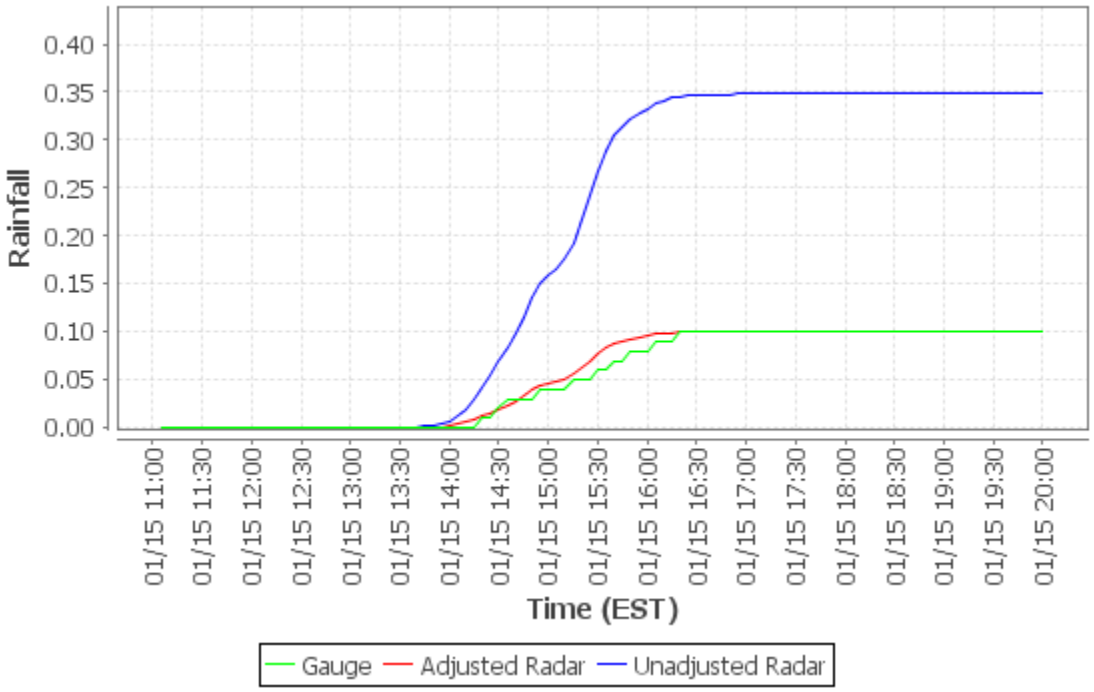
Cumulative Distribution Plot - Moon TWP (Loc21)



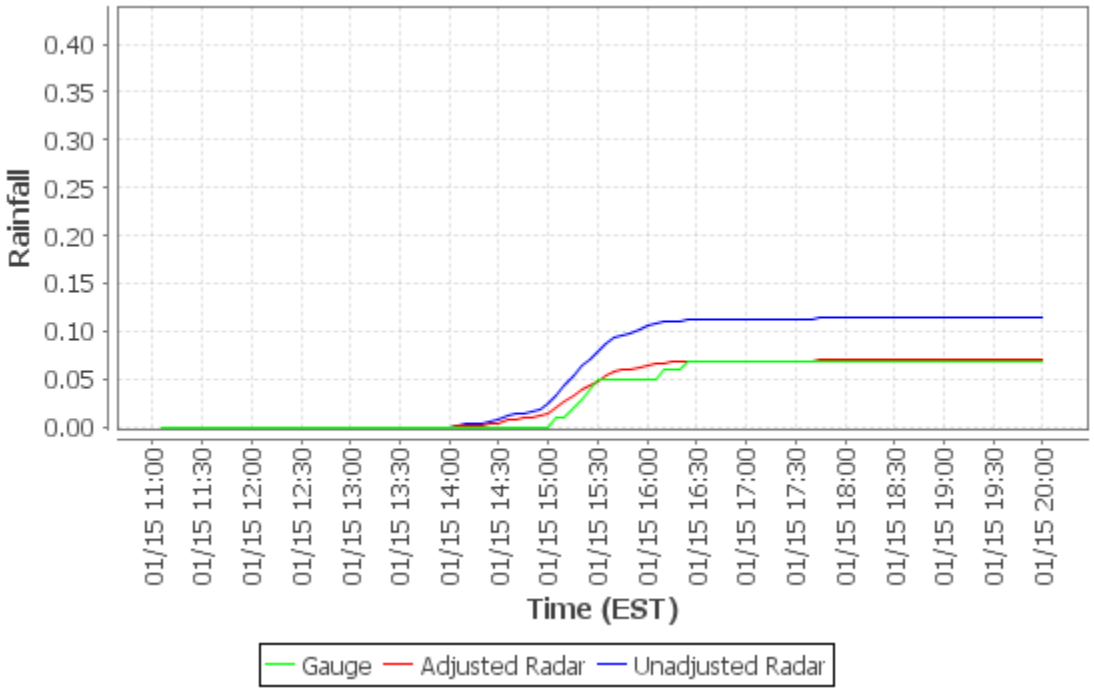
Cumulative Distribution Plot - North Fayette TWP (Loc22)



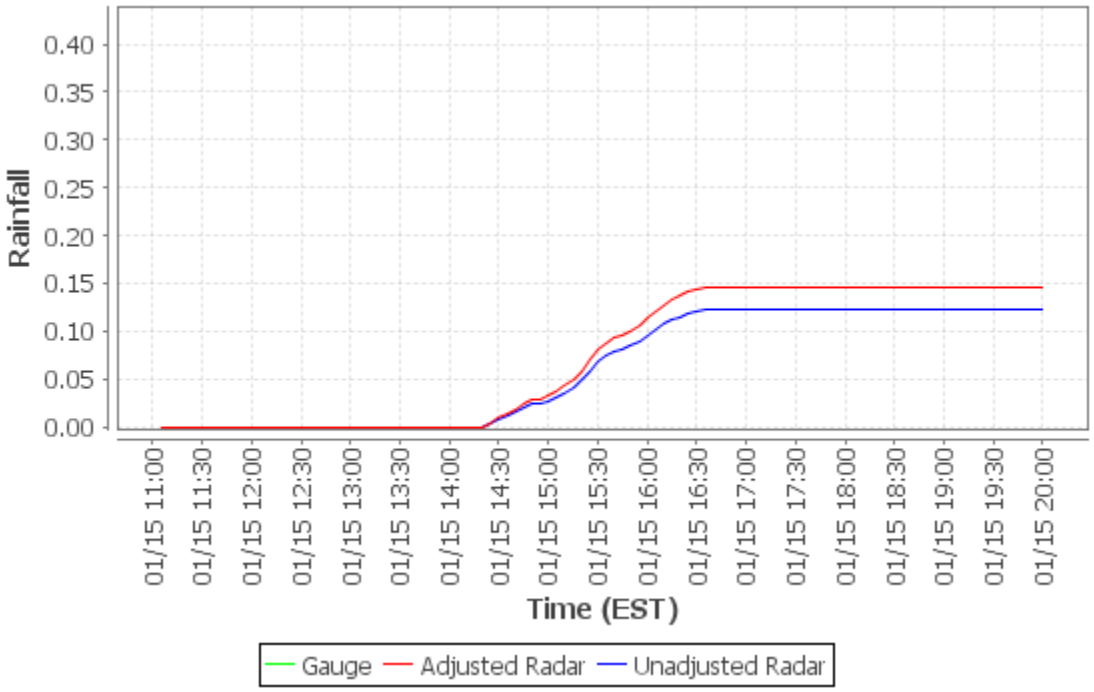
Cumulative Distribution Plot - Clinton Munic Bldg (Loc23)



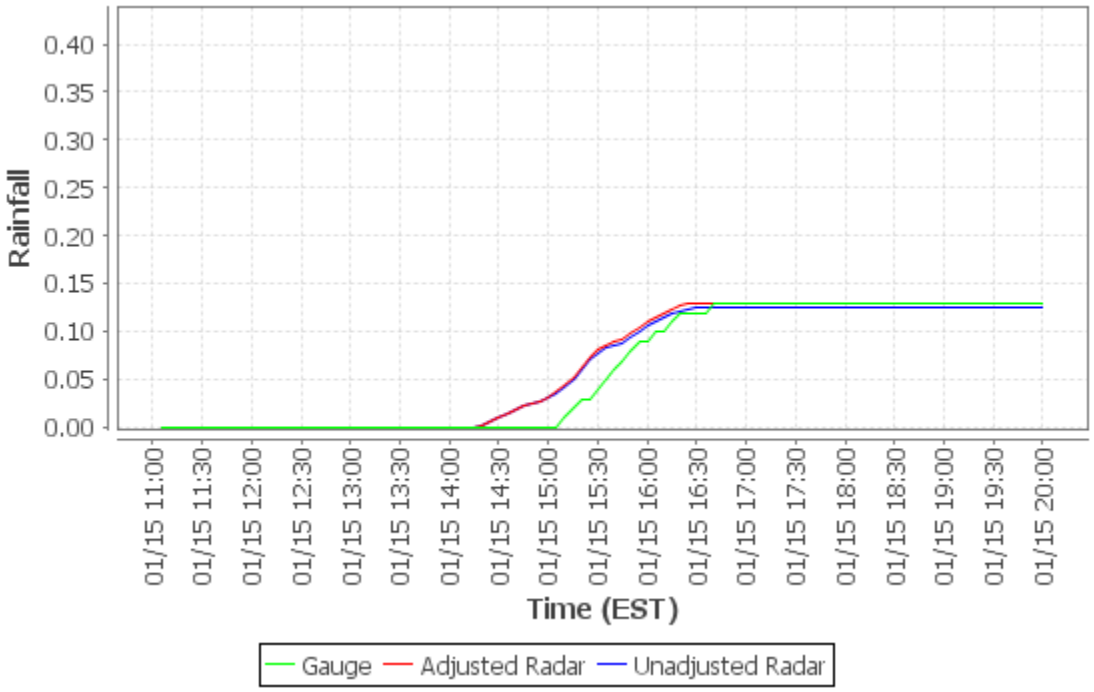
Cumulative Distribution Plot - Jefferson Hills (Loc24)



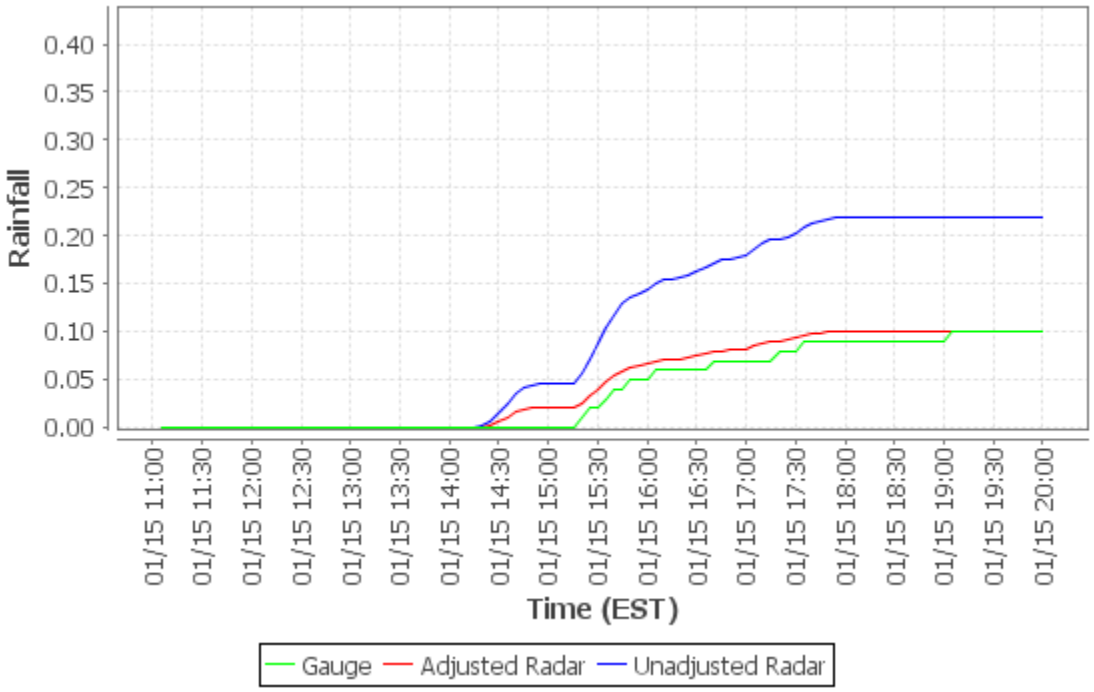
Cumulative Distribution Plot - White Oak Public Works Bldg (Loc25)



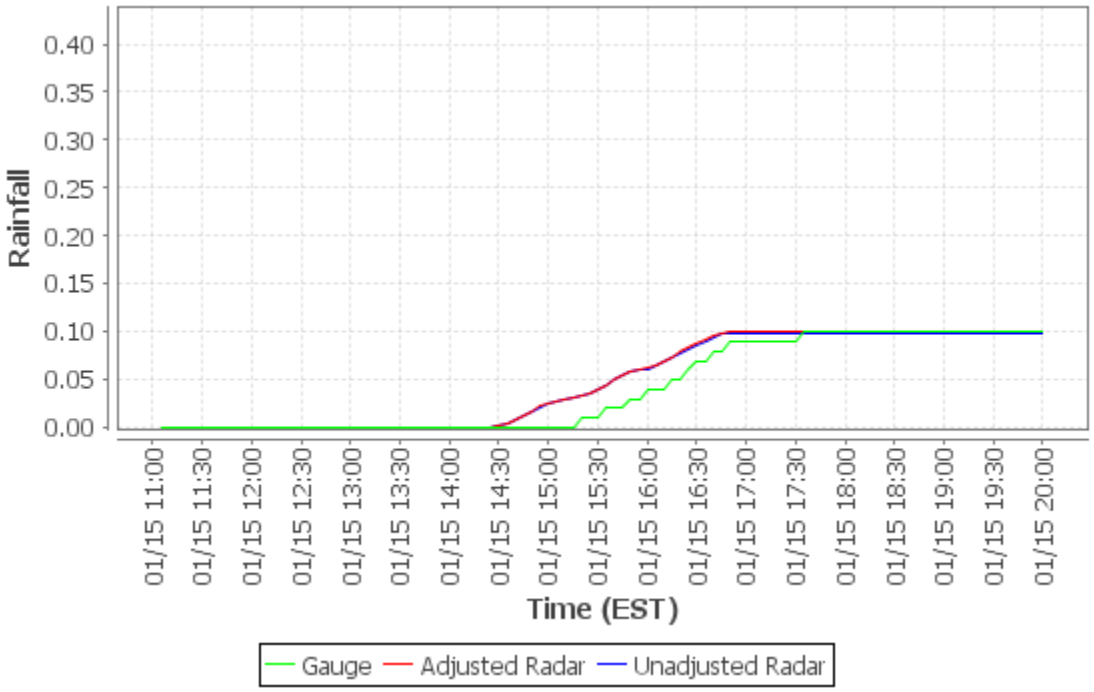
Cumulative Distribution Plot - Elizabeth TWP Municipal Bldg (Loc26)



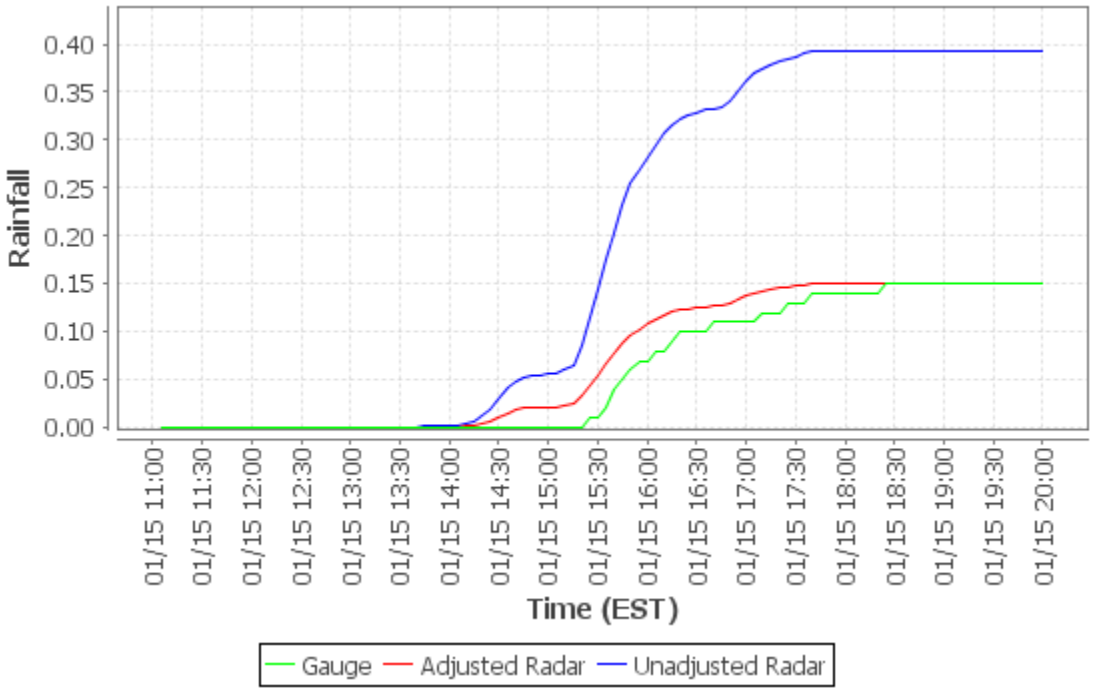
Cumulative Distribution Plot - Marshall TWP (Loc27)



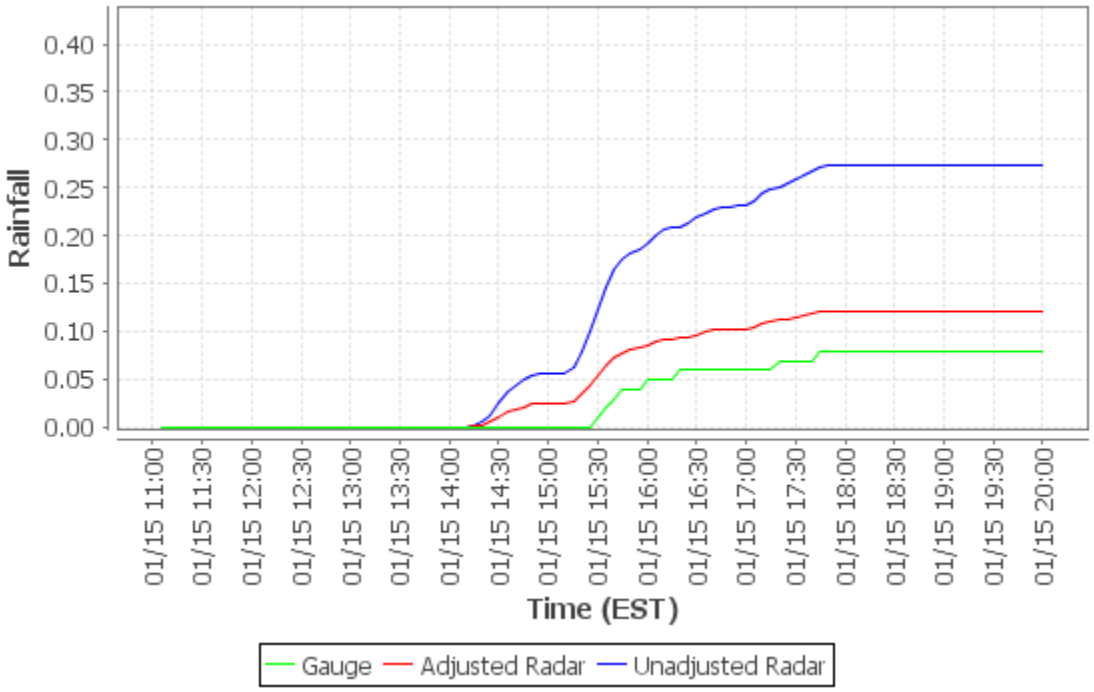
Cumulative Distribution Plot - Plum Municipal Bldg (Loc28)



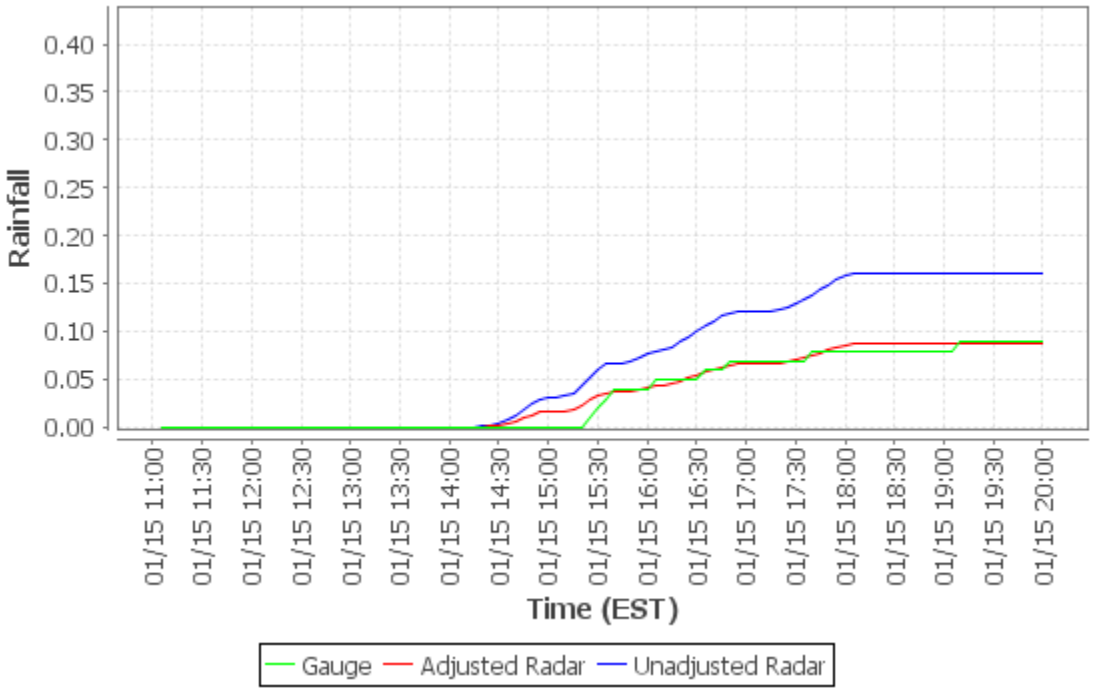
Cumulative Distribution Plot - Bell Acres Munic Bldg (Loc29)



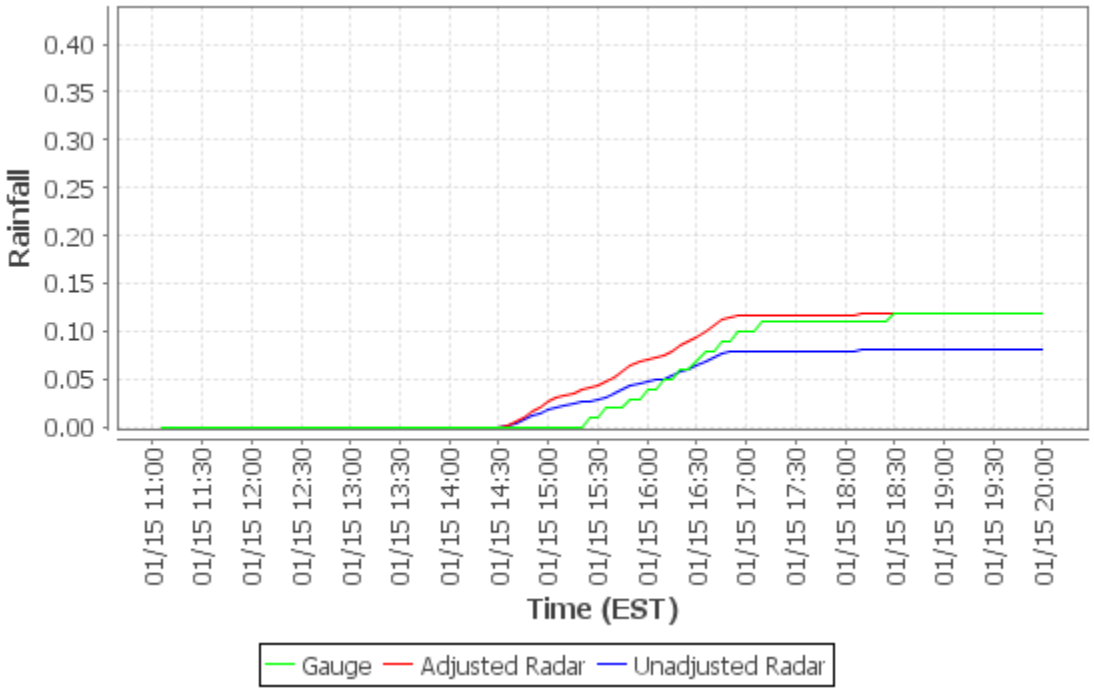
Cumulative Distribution Plot - McCandless Twn Hall (Loc30)



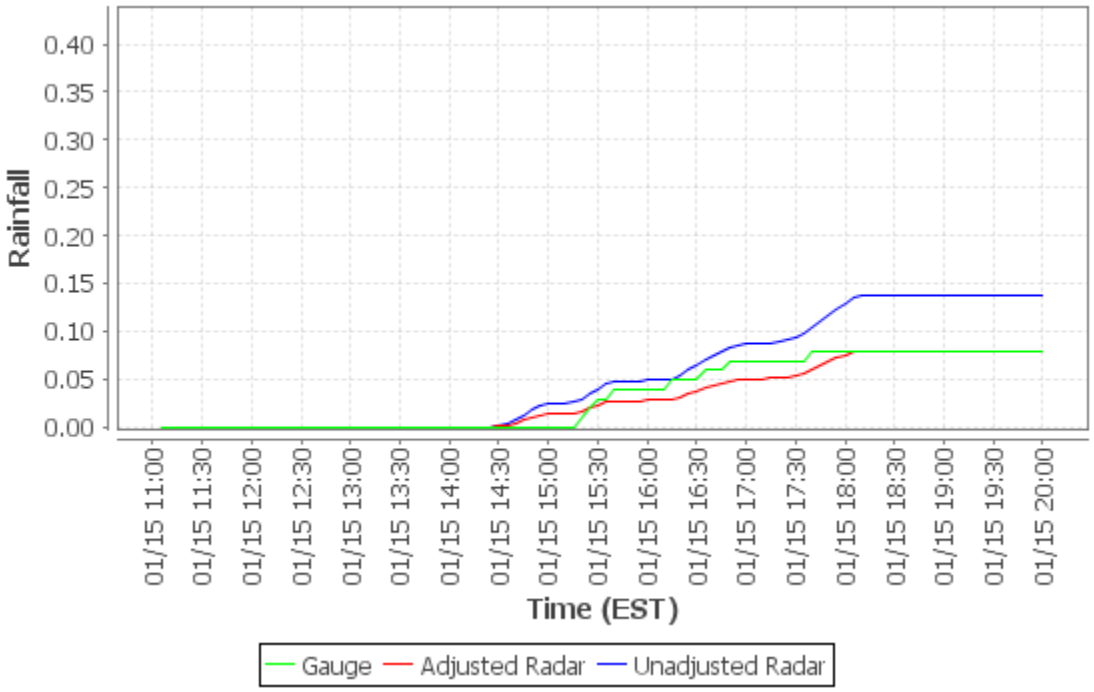
Cumulative Distribution Plot - Hampton Municipal Bldg (Loc31)



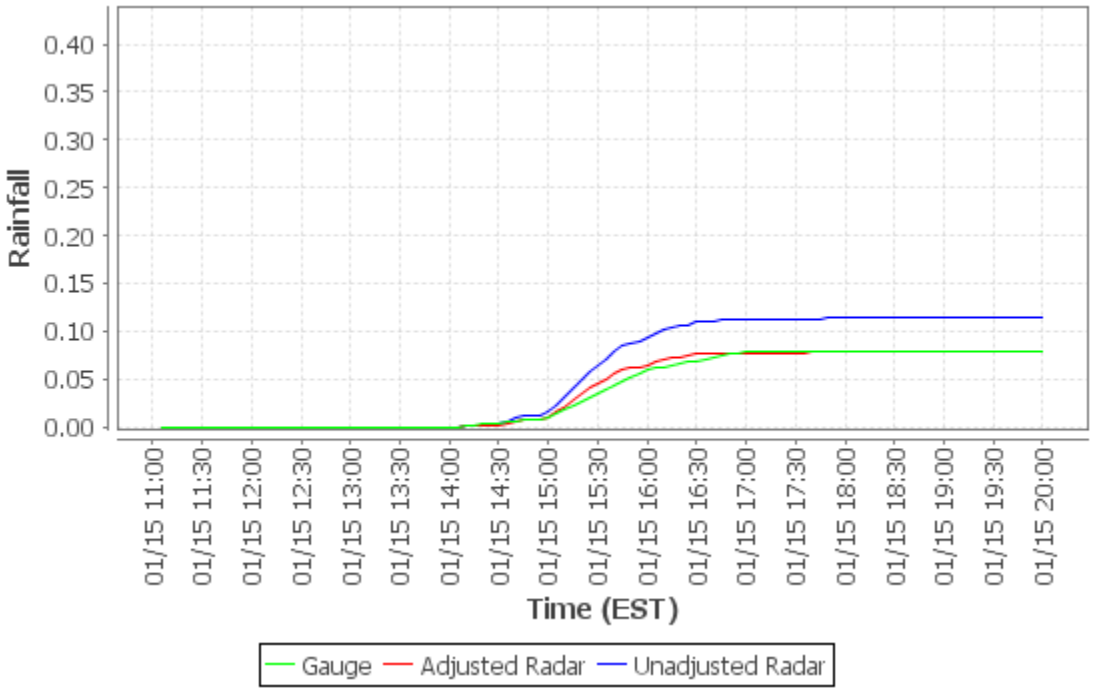
Cumulative Distribution Plot - Arnold (Loc32)



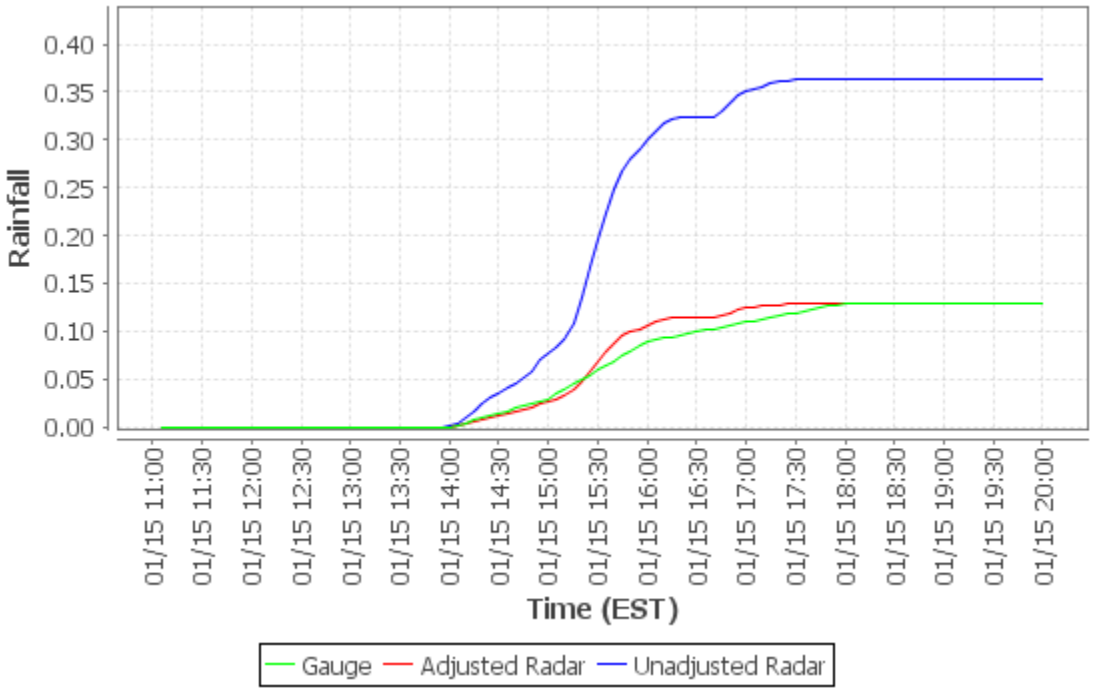
Cumulative Distribution Plot - Richland TWP (Loc33)



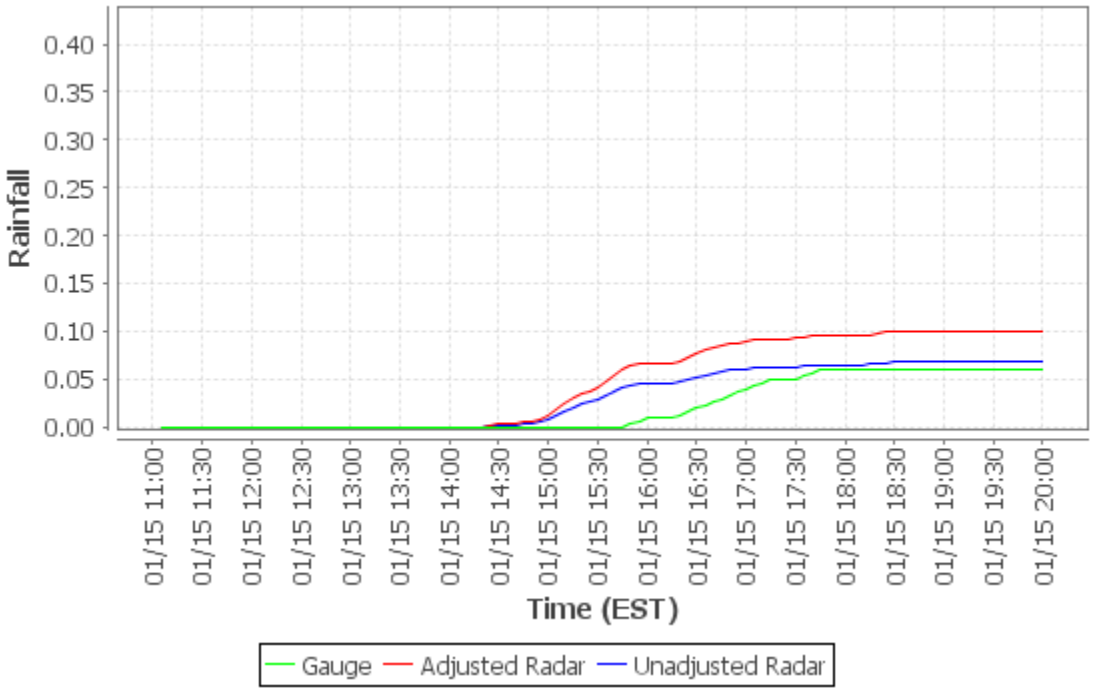
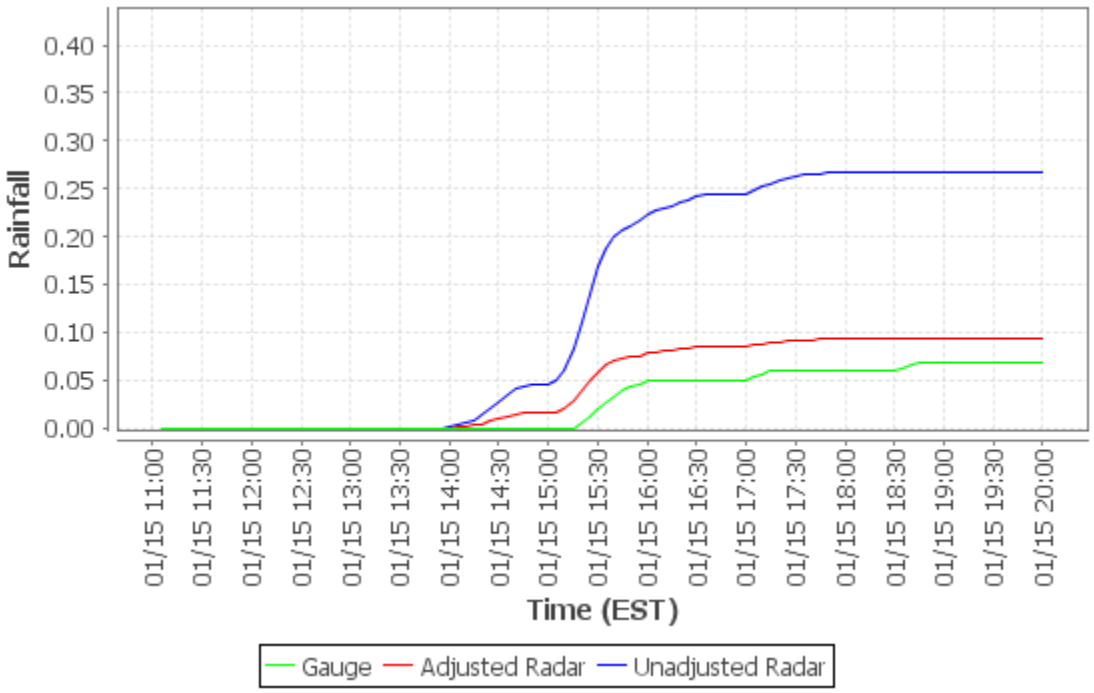
Cumulative Distribution Plot - Pittsburgh Allegheny Cty (KAGC)



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



Cumulative Distribution Plot - Allegheny River at Natrona (03049500)



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