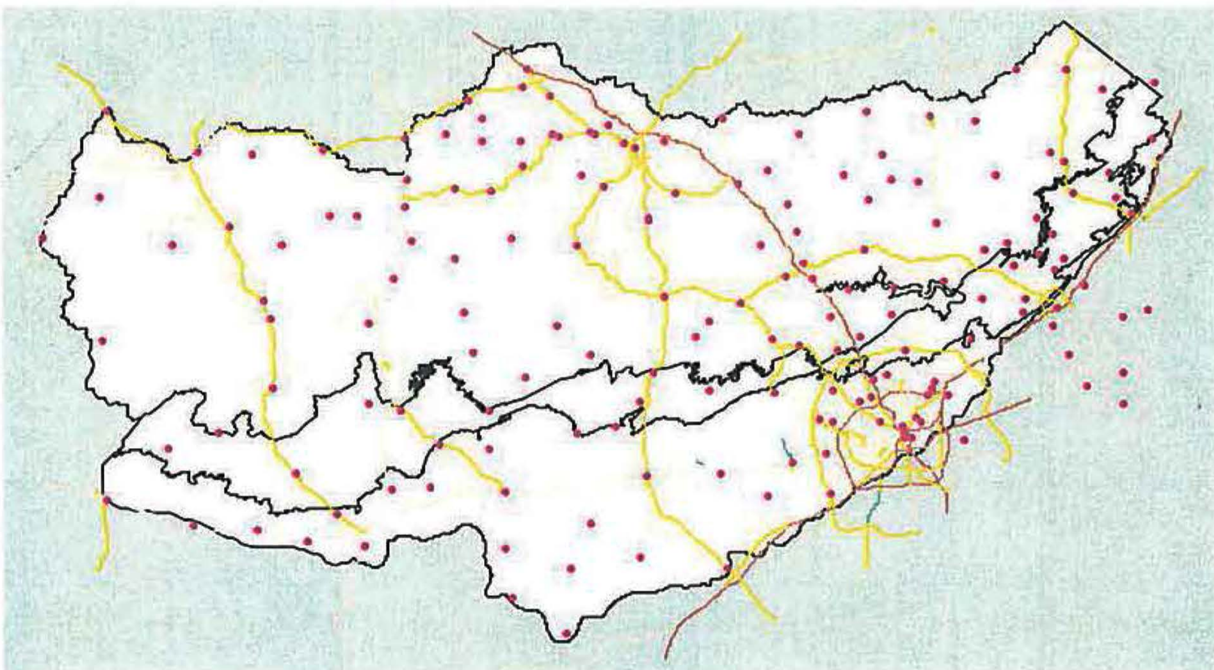
Edwards Aquifer Authority

Rain Gauge Analysis Study Report



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Executive Summary

The purpose of this report is to identify improvements to the rain gauge network that will increase the usefulness and accuracy of rainfall monitoring over the Edwards Aquifer Area (EAA). The proposed rain gauge networks are intended to provide more evenly distributed coverage over the aquifer area and for use in radar calibration. The existing gauge network of 61 EAA gauges in combination with the 41 gauges in the Guadeloupe-Blanco River Authority (GBRA) network provides an average density of one gauge per 87 mi^2 and a mean inter-gauge spacing that varies from 7 to15 mi depending on the zone. Some zones, such as the Artesian Zone, have fewer gauges than other zones. Proposed new gauge locations are confined to easily accessible roadway locations to reduce access and operations costs.

The proposed rain gauge network achieves a density of one gauge per 66 mi^2 with a uniform inter-gauge spacing of 8 mi. An Alternative Configuration that relies on a private network of gauges achieves an improved density of one gauge per 55 mi^2 with higher densities in and around San Antonio. Using the private network requires fewer new gauges to be installed. With the proposed additional gauges, more uniform coverage among zones, increased gauge density, and reduced inter-gauge spacing is achieved. With the addition of gauges, improvement in radar rainfall accuracy will be greatest in areas where few gauges existed. Analysis of the historical rain gauge performance revealed which gauges could be improved through maintenance actions. Correcting the twenty-one gauges rated as *Suspect* or *Poor* would help improve one-third of the existing gauges in the rain gauge network (RGN). The recommended maintenance actions and adjustments to the gauge network configuration will improve the quality and usefulness of the rain gauge data and benefit the accuracy of radar rainfall.

Introduction

The purpose of this report is to identify locations within the aquifer that can provide sites for rain gauges that will improve rainfall monitoring. The proposed rain gauge network is intended to provide evenly distributed coverage over the aquifer area, and to provide point observations useful for enhancing the accuracy of radar rainfall.

The Edwards Aquifer covers approximately 8900 square miles. The average annual rainfall total for Edwards Aquifer ranges from 18 inches in the west to 34 inches in the east (30-year average from 1971-2000) with May and June being the wettest months. Currently, the aquifer is monitored with 62 rain gauges operated by the Edwards Aquifer Authority (EAA), and 50 gauges from the GBRA network. The aquifer consists of three major zones:

1) Drainage zone, area = 5528 mi^2;
2) Recharge zone, area = 1253 mi^2; and
3) Artesian zone, area = 2125 mi^2.

A map of the zones is shown in Figure 1. Of the above mentioned existing gauges, one of the 62 EAA and 9 of the 50 GBRA rain gauges are not located in the Edwards Aquifer boundary and are not included in the gauge count, but are shown in the figures.

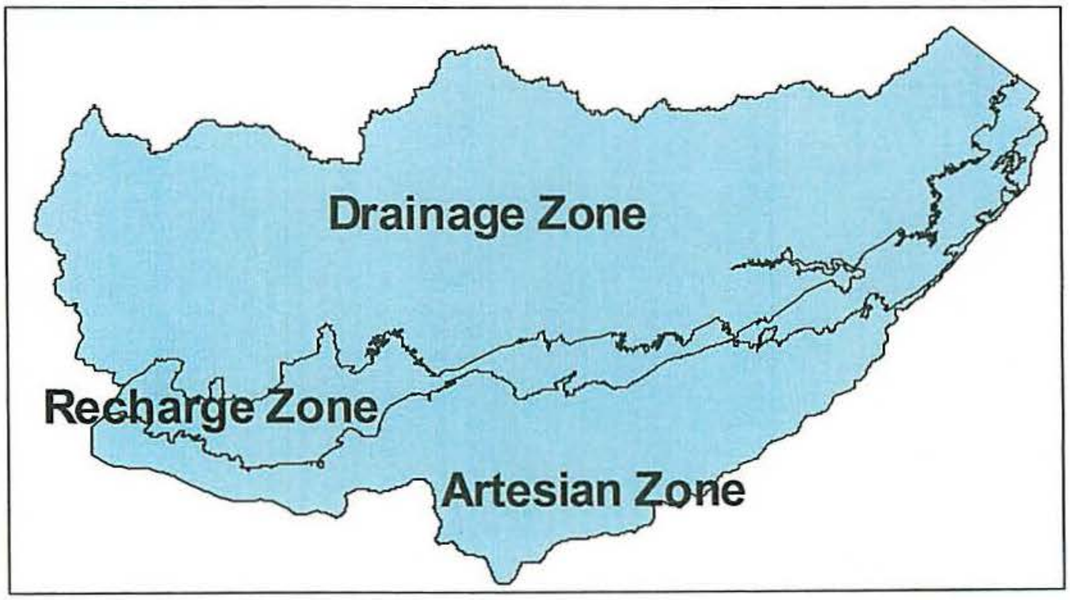

Figure 1: Map showing zones of the Edwards Aquifer

The existing configuration of the rain gauge network in the aquifer has an average density of approximately 1 gauge per 87 mi^2. This value differs for each zone in the aquifer and is presented in Table 1. The average density and distance between gauges is not equally distributed in all zones. When considering both EAA and GBRA gauges for the entire EAA area, the average density is one gauge per 87 mi^2 with a mean distance of 9 miles. Within the Drainage Zone, the density is 80.1 mi^2 also with a mean distance of 9 miles, whereas, in the Artesian Zone, the gauge density is one per 236 mi^2 with a mean inter-gauge distance of 15 miles. The Recharge Zone has the gauge density of one per 52.2 mi^2 with a mean distance of 7 miles. The Transition Zone is only 4 mi^2 and has no specific gauge associated with this area.

Table 1: Average density of existing rain gauge network

ZONE	AREA (mi^2)	Gauge Count		Sum all gages	Density (mi^2)	Average Distance (mi)
		EAA	GBRA			
Drainage Zone	5528	35	34	69	80.1	9
Recharge Zone	1253	17	7	24	52.2	7
Artesian Zone	2125	9	0	9	236.1	15
Transition Zone	4	0	0	0		
Total	8910	61	41	102	87	9

The list of existing EAA rain gauges updated on 06-10-05 by EAA is used to identify gauge locations in latitude/longitude coordinates (see Appendix 1). The configuration of the existing EAA rain gauge network, along with the GBRA rain gauges, is shown in Figure 2. There are fewer gauges in the Artesian Zone due to historical monitoring that has focused on the Drainage Area Zone. In the western area of the Drainage Area Zone, there are comparatively few gauges. However, on a climatological basis, the rainfall totals are much lower in this area.

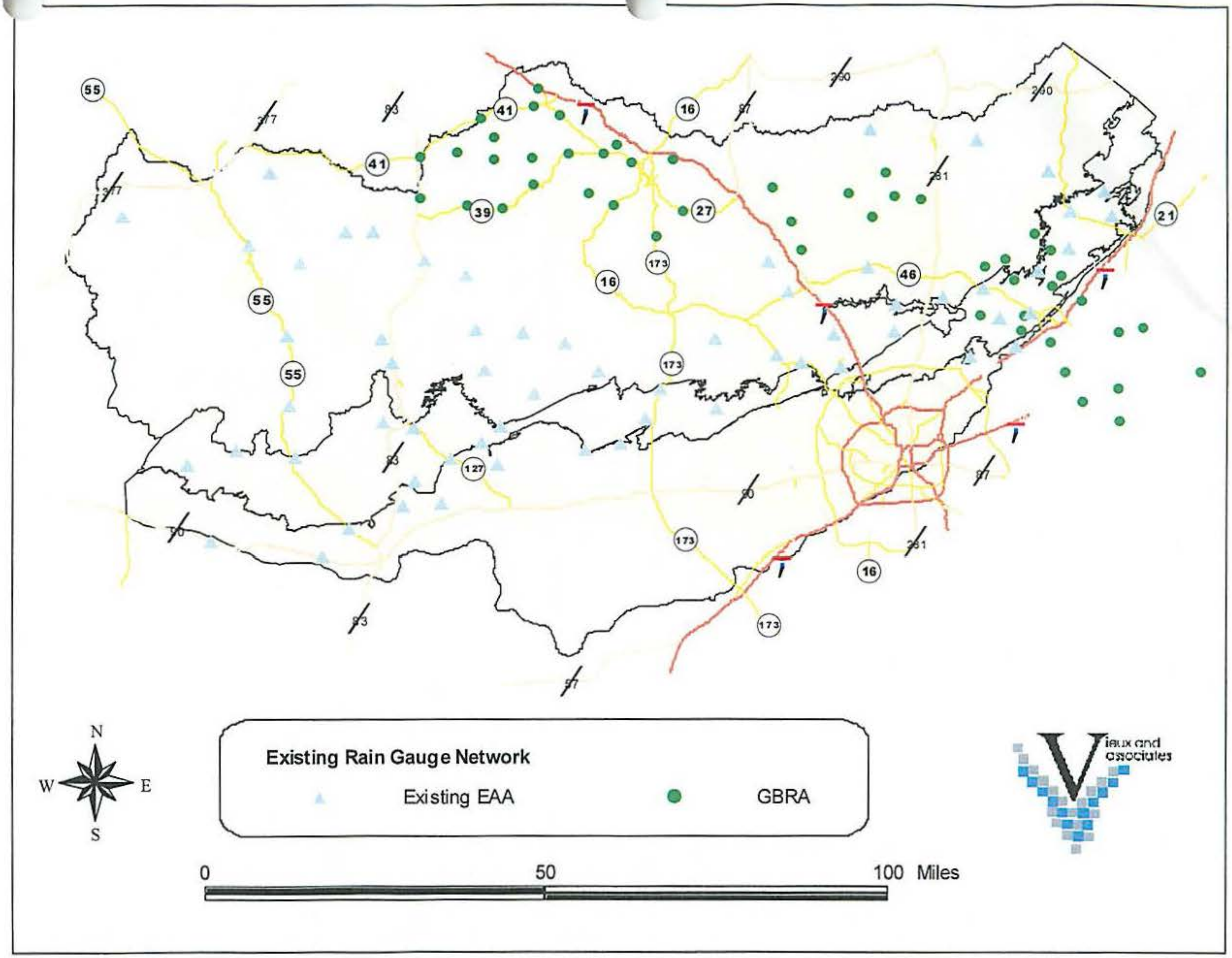

Figure 2: Existing EAA rain gauge network, along with the GBRA rain gauges

Methodology

Given the existing rain gauge network and the gaps in the coverage over the area, new gauge locations are proposed. The proposed gauge locations are intended to fill in the gaps of the existing rain gauge to complete the coverage of the network by itself and in combination with radar for enhanced rainfall accuracy. In some locations, the existing EAA gauges are more densely populated than others, indicating that some of those gauges may be removed. Removal or relocation of existing gauges is intended to improve the gauge network, which can also help reduce the net cost of the network. Historical gauge performance is also evaluated as described below.

The network improvements are made based on the average density and mean gauge distance. These measures are used to recommend: 1) addition of gauges in areas of insufficient coverage, and 2) removal of gauges in areas of excess coverage. The goal of the gauge network adjustment is to create gauge network coverage that is essentially uniform across all zones of the aquifer. Locations are confined to roads for ease of access. A geographic information system was used to identify locations of insufficient coverage and roadways. The resulting network created under this constraint will have more uniform coverage in terms of density and inter-gauge spacing, and be easily accessible.

A double mass analysis is performed in order to evaluate the historical performance of the Edwards Aquifer rain gauge network (RGN) over a two and a half year period, and to make recommendations for gauge maintenance actions. Identifying and correcting gauges that show inconsistent performance helps to improve both rain gauge and radar rainfall measurements. Consistency of historical performance is evaluated using a double mass analysis, which was performed on 63 tipping bucket rain gauges. Several important trends and performance characteristics were observed. Depending on performance consistency over the historical period analyzed, a performance rating of *Good, Suspect,* and *Poor* is assigned.

The existing gauge network shows consistent performance during monthly comparison radar-gauge comparisons. Evaluation of gauges that consistently show performance problems should be addressed through maintenance actions. Under normal conditions gauges can experience a drift in historical record due to instrumentation error, a change in location, or a modification in the local environment surrounding the gauge. Double mass analysis is used to identify long-term biases or abrupt changes in the rainfall data by comparing each gauge to a standard or "trusted" gauge. In this case, eight National Weather Service (NWS) Automated Surface Observing System (ASOS) gauges were chosen as the trusted gauges for double mass analysis because of the high quality and maintenance of these instruments. The NWS ASOS gauges used in this analysis are located within 35 miles of the study region.

Results

The analysis of gauge requirements for each zone to achieve uniform coverage results in a proposed configuration that takes into account both areas of insufficient and excess coverage. Efficiency in achieving the recommended density is improved by removing gauges of excess coverage. The recommendations for the gauge network is organized in two parts, one that considers just adding or removing gauges, and an alternative network configuration that considers a private rain gauge network. The proposed gauge network configuration includes both 1) additional gauges needed, and 2) gauges to be removed. The alternative configuration relies on gauges from a private network that increases the coverage and density near urban areas such as San Antonio. Resulting gauge locations have been checked for accessibility using roads and digital aerial photography. An example of an existing and proposed gauge location is shown in Figure 3. The exact location of the proposed locations can be changed depending on land right acquisition and accessibility.

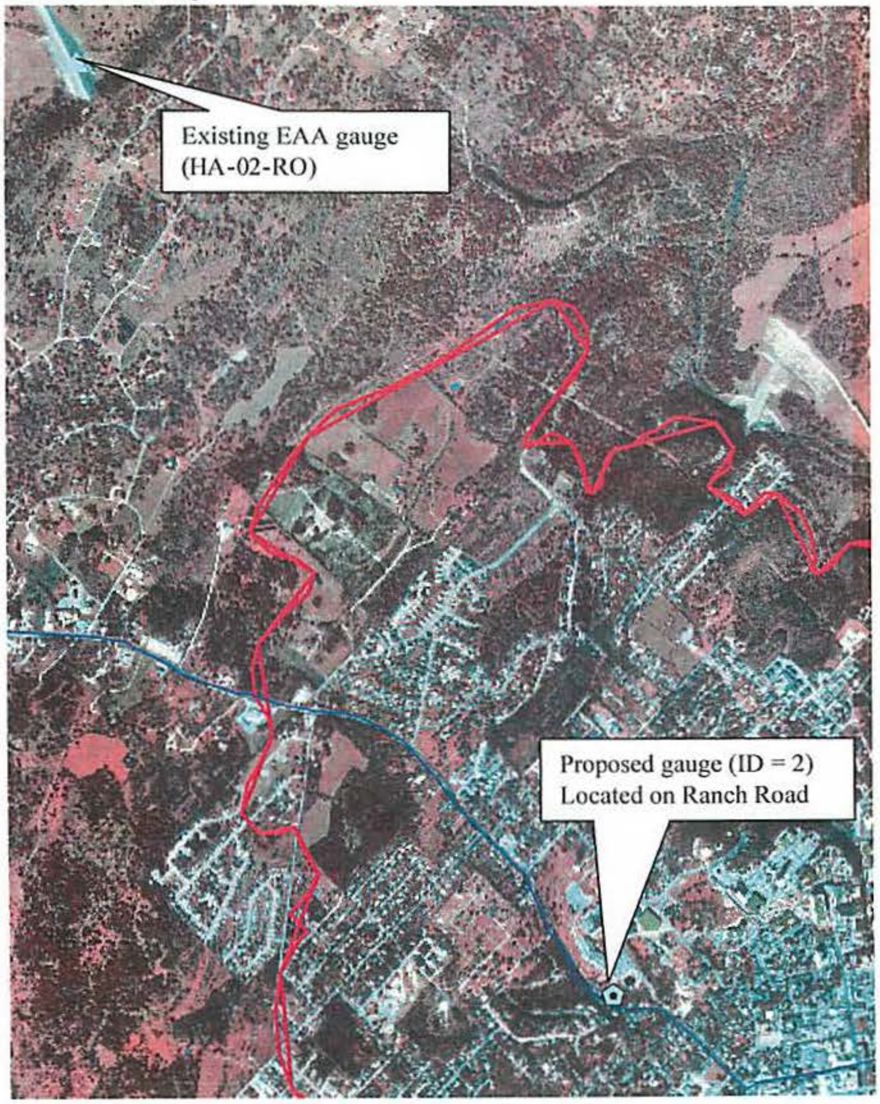

Figure 3 Aerial photography and road network used to identify accessible gauge locations.

Proposed Configuration

The proposed network configuration that will achieve more uniform gauge density is shown in Figure 4. The corresponding list of new proposed gauge locations is presented in Table 2. The resulting configuration shown in Figure 5 depicts each EAA and GBRA gauge with the same symbol for easier visual inspection of the network density and coverage area.

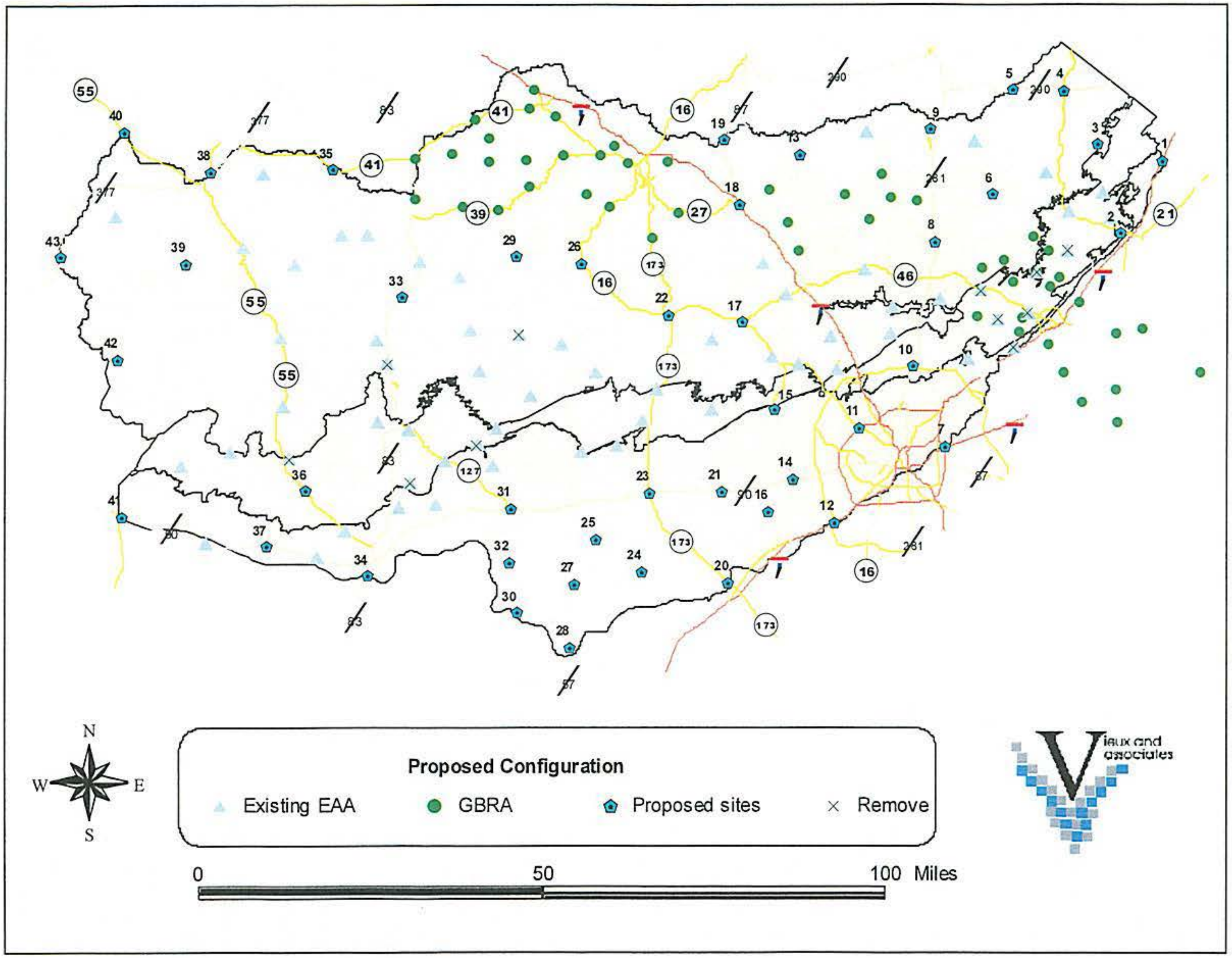

Figure 4: Proposed network configuration

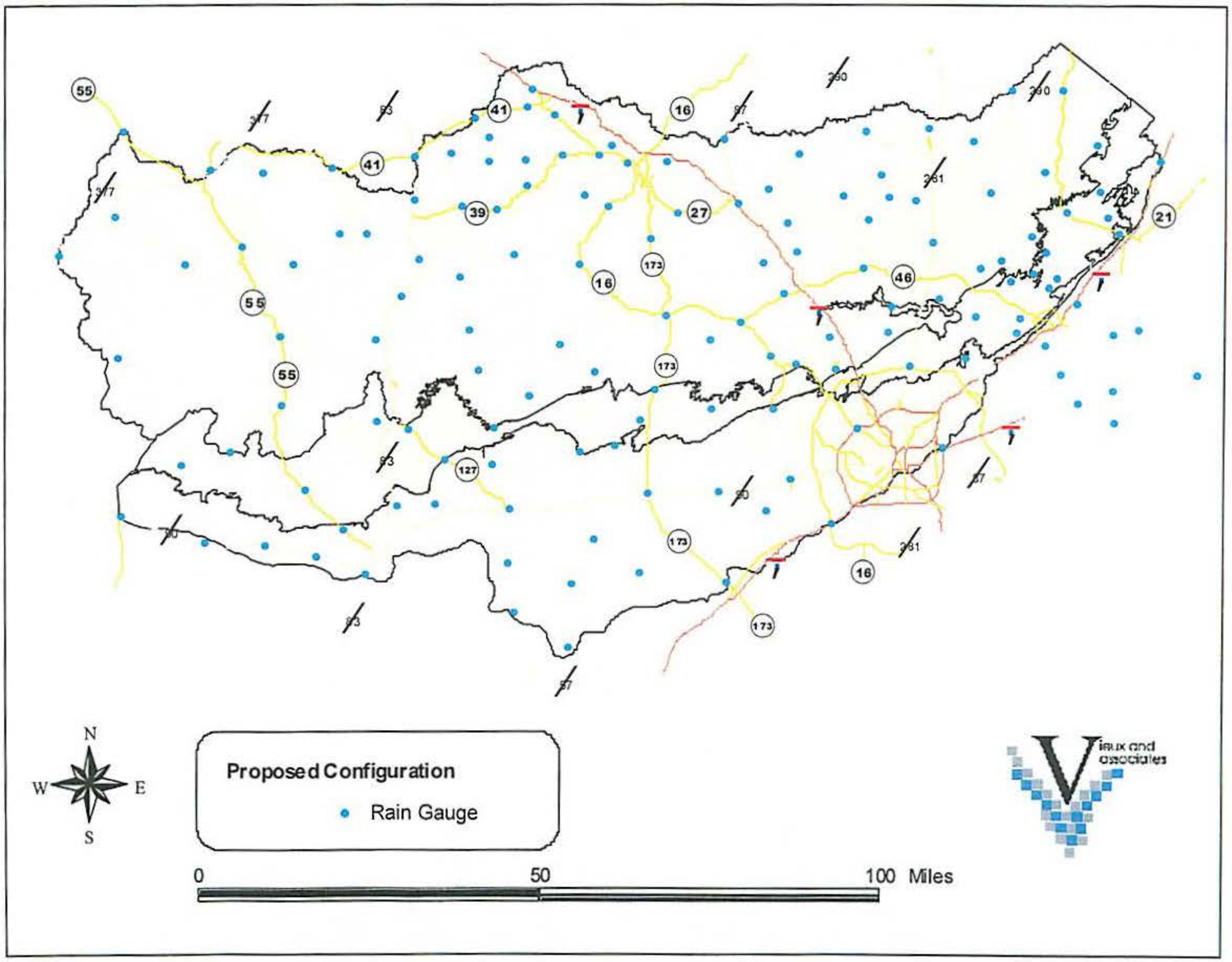

Figure 5: Gauge network showing proposed configuration with uniform symbols

Table 2: List of new proposed gauge locations

Gauge ID	Approximate Location	Latitude	Longitude	County	Quad Name	
1	I-35, south of S Loop 4	30° 2' 21"	-97° 50' 38"	Hays	Buda	SW
2	Ranch Road 12 and Smith Avenue	29° 53' 8"	-97° 57' 6"	Hays	San Marcos North	SE
3	Farm-to-Market Road 150 and Grande Street	30° 4' 37"	-98° 0' 9"	Hays	Driftwood	NE
4	US Hwy 290 and Ranch Road 12	30° 11' 30"	-98° 5' 4"	Hays	Shingle Hills	SW
5	US Hwy 290, between Henly Loop and Old Red Ranch Road	30° 11' 41"	-98° 12' 37"	Hays	Henly	NW
6	Farm-to-Market Road 32 and Farm-to-Market Road 484	29° 58' 30"	-98° 15' 50"	Comal	Fischer	NE
7	I-410, between I-10 and Dietrich Road	29° 26' 18"	-98° 23' 30"	Bexar	San Antonio East	NE
8	US Hwy 281 and Farm-to-Market Road 311	29° 52' 29"	-98° 24' 32"	Comal	Anhalt	NE
9	US 281, north of Haller Dr.	30° 6' 59"	-98° 24' 52"	Blanco	Blanco	NE
10	US Hwy 281 and Loop 1604	29° 36' 42"	-98° 28' 5"	Bexar	Longhorn	NW
11	I-410 and Bandera Rd	29° 28' 55"	-98° 36' 4"	Bexar	San Antonio West	NW
12	I-35 and Loop 1604	29° 16' 45"	-98° 39' 56"	Bexar	MacDona	SE
13	Ranch Road 1376 and Platten Creek Road	30° 3' 53"	-98° 44' 19"	Kendall	Whitworth Ranch	NW
14	State Hwy 16 and State Hwy 46	29° 22' 30"	-98° 45' 53"	Bexar	La Coste	NE
15	State Hwy 211 and Farm-to-Market Road 471	29° 31' 22"	-98° 48' 20"	Bexar	San Geronimo	SE
16	Farm-to-Market Road 471 and County Road 583	29° 18' 19"	-98° 49' 38"	Medina	La Coste	SW
17	State Hwy 16 and State Hwy 46	29° 42' 38"	-98° 53' 8"	Bandera	Pipe Creek	NE
18	I-10 and US Hwy 87	29° 57' 40"	-98° 53' 21"	Kendall	Comfort	NE
19	US Hwy 87, north of I-10	30° 5' 58"	-98° 55' 17"	Kendall	Cypress Creek	NE
20	State Hwy 173 and County Road 5710	29° 9' 15"	-98° 55' 28"	Medina	Devine	SE
21	US Hwy 90, between County Road 4614 and County Road 4612	29° 20' 56"	-98° 56' 22"	Medina	Castroville	NW
22	Stat Hwy 16 and 15th St	29° 43' 39"	-99° 4' 1"	Bandera	Bandera	NW
23	US Hwy 90 and State Hwy 173	29° 20' 54"	-99° 7' 3"	Medina	Murphy School	NW
24	Farm-to-Market Road 462 and County Road 642	29° 10' 41"	-99° 8' 14"	Medina	Yancey	SE
25	Farm-to-Market Road 2200	29° 15' 3"	-99° 15' 7"	Medina	D'Hanis	SE
26	State Hwy 16 and Farm-to-Market Road 2107	29° 50' 18"	-99° 16' 52"	Bandera	A Bar A Ranch	NE
27	Deer Creek Road and County Road 621	29° 9' 14"	-99° 18' 13"	Medina	Frio Town NE	SE
28	Farm-to-Market Road 140 and Vanco Ranch Road	29° 1' 8"	-99° 18' 58"	Frio	Frio Town	SW
29	Farm-to-Market Road 2107and North Prong	29° 51' 20"	-99° 26' 22"	Bandera	Love Creek	NW
30	Ranch Road 187, north of Ranch Road 140	29° 5' 37"	-99° 26' 37"	Uvalde	Gross Tank	NW
31	US Hwy90 and Center St	29° 19' 3"	-99° 27' 27"	Uvalde	Sabinal	NW
32	Ranch Road 187 and Nuley Lane	29° 11' 58"	-99° 27' 42"	Uvalde	Irishman Hill	NW
33	US Hwy 83 and Chalk Creek Rd.	29° 46' 11"	-99° 43' 14"	Real	Circle Bluff	SW

34	Crystal City Hwy and Usmf St	29° 10' 33"	-99° 48' 25"	Uvalde	Uvalde	SE
35	State Hwy 41 and Fairview Rd.	30° 2' 36"	-99° 53' 27"	Real	EarWood Creek SW	SE
36	State Hwy 55, between Ranch Road 334 and Louis Ln	29° 21' 25"	-99° 57' 22"	Uvalde	Chalk Bluff	NW
37	US Hwy 90, west of Ranch Road 1022	29° 14' 19"	-100° 3' 9"	Uvalde	Cline	NE
38	US Hwy 377 and State Hwy 2630	30° 2' 25"	-100° 11' 29"	Edwards	Rock Springs	SW
39	Cedar Creek and County Road 16	29° 50' 31"	-100° 15' 7"	Edwards	Cutting Pen Draw	NE
40	State Hwy 55, south of County Road 101	30° 7' 28"	-100° 24' 19"	Edwards	Ray Lake SW	NE
41	US Hwy 90 and State Loop 166	29° 18' 18"	-100° 24' 26"	Kinney	Bracket Ville	SE
42	Ranch Road 674	29° 38' 29"	-100° 25' 6"	Edwards	Wiley Waterhole	SE
43	US Hwy 377, north of County Road 22	29° 51' 29"	-100° 33' 37"	Edwards	Carta Valley SE	NE

The proposed gauge network configuration achieves an average density of 1 gauge per 66 mi^2, as opposed to the existing 1 gauge per 87 mi^2. This proposed configuration also improves the average distance to 8 mi between gauges, which is more uniform than the existing network that varies in terms of mean inter-gauge distance among zones. The proposed configuration also results in nearly uniform average distance between gauges in all zones. The greatest improvement is in the spacing between gauges in the Artesian Zone, which decreases from 15 to 9 miles. The resulting number of proposed gauges to be added or removed in each zone and in total is presented in Table 3.

Table 3: Average density of proposed configuration

ZONE	AREA (mi^2)	Gauge Count				Gauge Number	Density (mi^2)	Average Distance (mi)
		EAA	GBRA	Proposed	Removed			
Drainage	5528	35	34	20	-4	85	65.0	8
Recharge	1253	17	7	2	-6	20	62.7	8
Artesian	2125	9	0	21	-1	29	73.3	9
Transition	4	0	0	0	0	0	0	0
Total =	**8910**	**61**	**41**	**43**	**-11**	**134**	**66**	**8**

Alternative Configuration

An alternative configuration is proposed that utilizes a private network of rain gauges operated by AWS/WeatherBug, Inc. This network offers technical rain gauge monitoring that is subject to more rigorous QA/QC and enhanced reliability than is generally available to the public. The WeatherBug network of rain gauges located in the EAA area is shown in Figure 6 as a map that represents the existing configuration of this network. When considering the use of the existing Weather Bug network, the number of additional rain gauges is 33 as opposed to 43 in the proposed configuration. The alternative configuration is mapped in Figure 7. A list of the alternative proposed gauges to be added is shown in Table 4. This list follows the same numbering as in Table 2 above. The gauges with the same ID have the same locations in both the proposed and alternative configuration. In locations where a proposed gauge was nearby a WeatherBug gauge, it is removed from the alternative proposal. For easier comparison between proposed configurations, the omitted gauges IDs are gray and have blank information, as shown in Table 4. For purposes of visual inspection, the alternative configuration with uniform map symbols is shown in Figure 8.

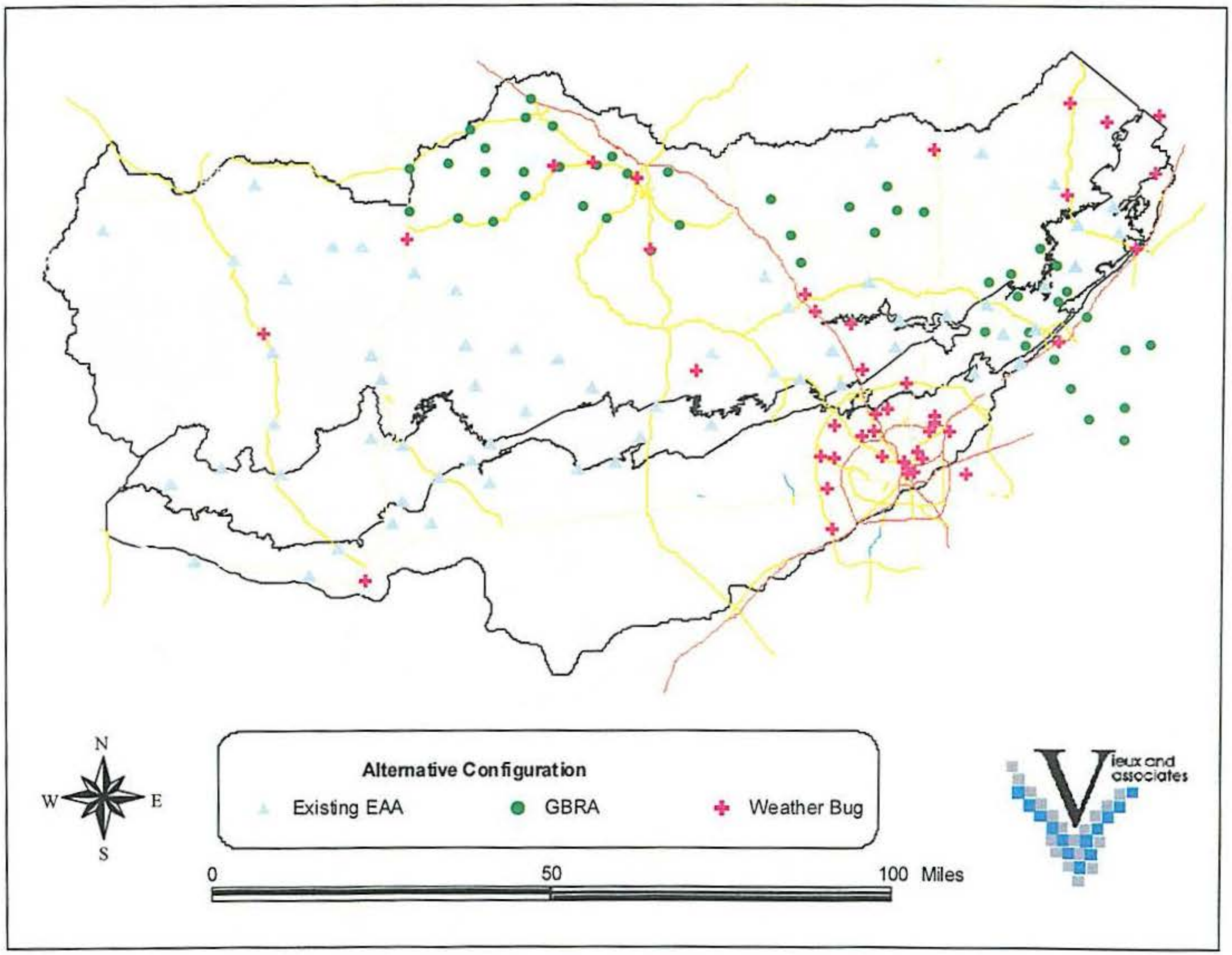

Figure 6: Weather Bug rain gauge network

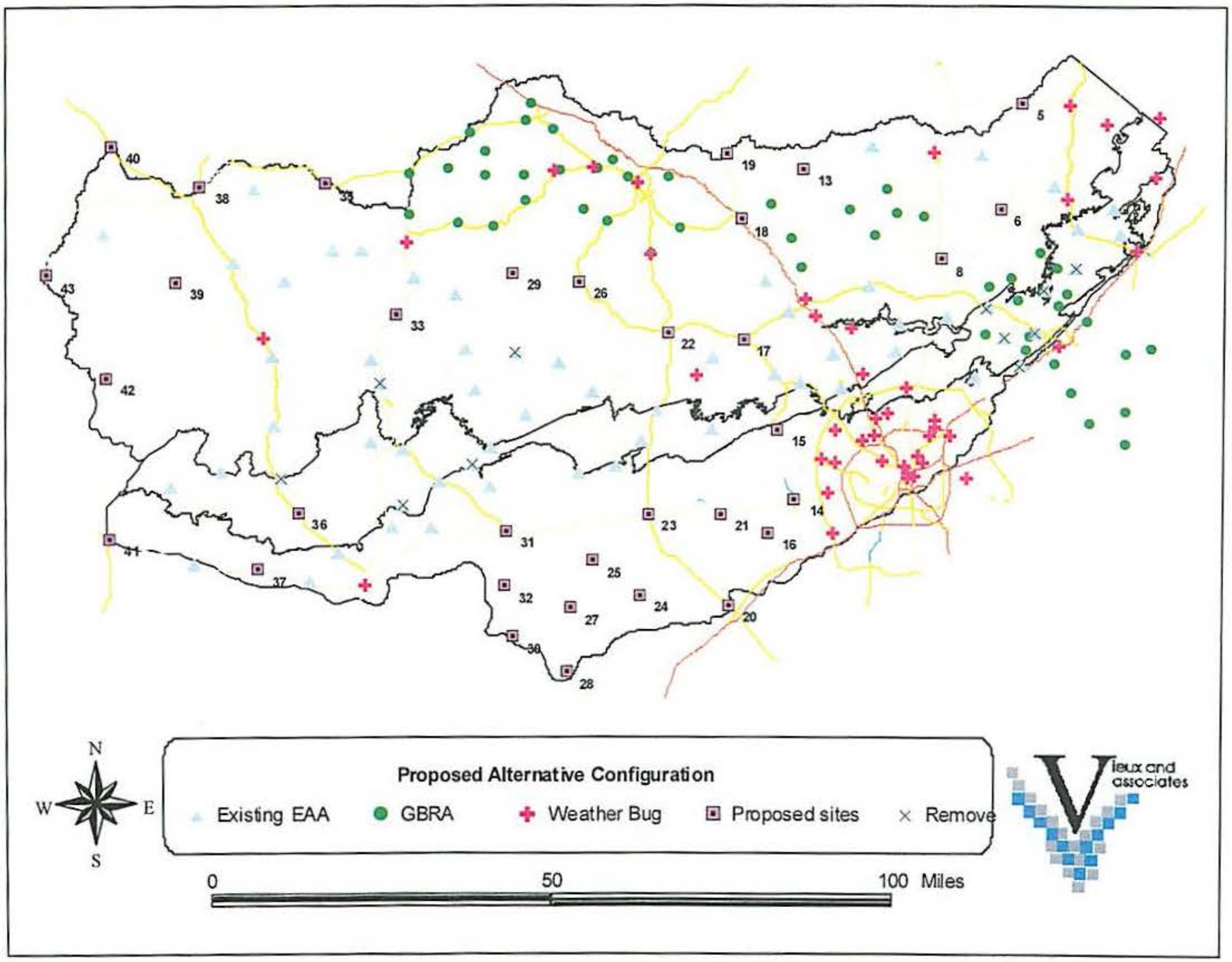

Figure 7: Proposed alternative rain gauge network

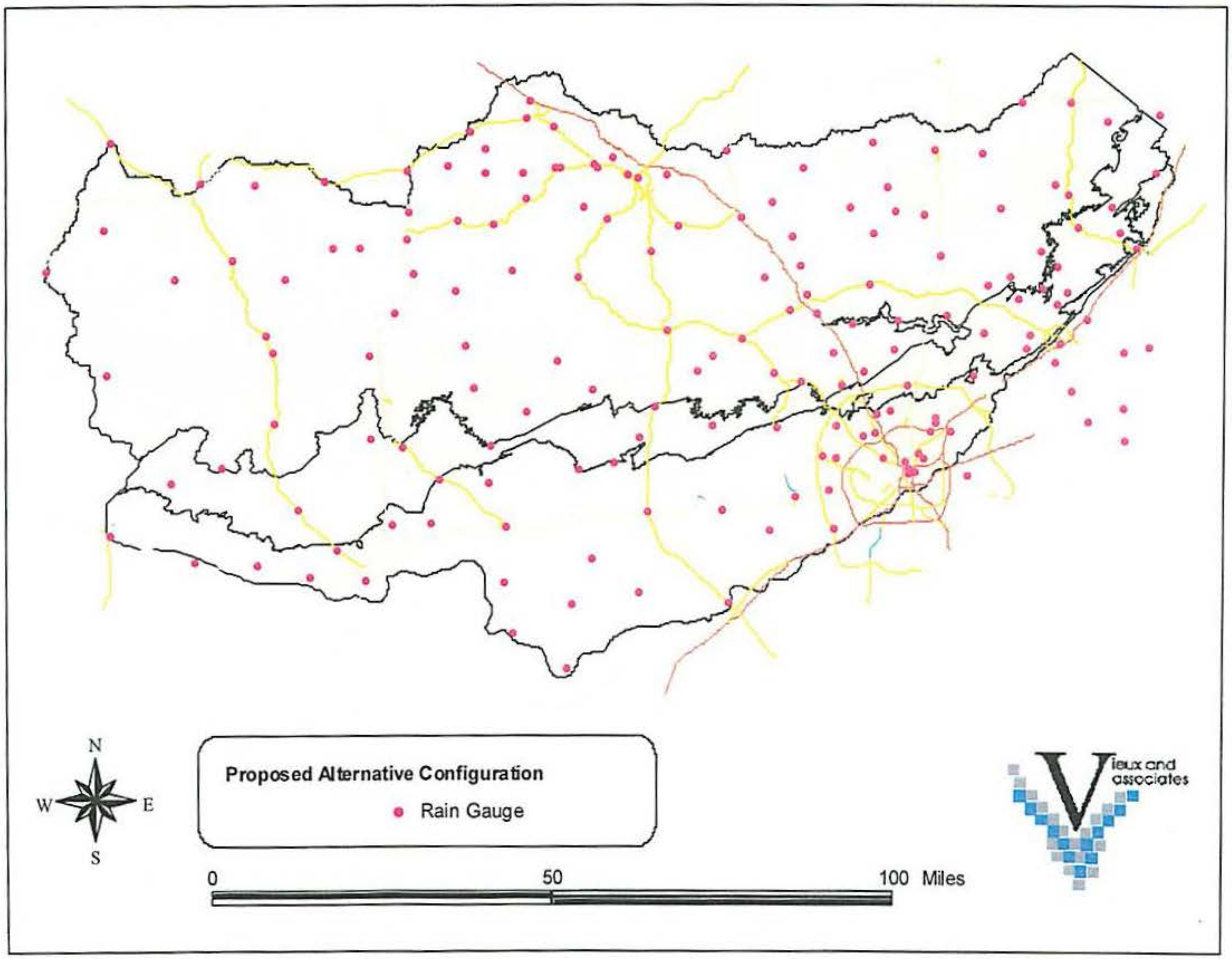

Figure 8: Gauge network showing proposed alternative configuration with uniform symbols

Table 4: Alternatively proposed rain gauges to be installed

Gauge ID	Approximate Location	Latitude	Longitude	County	Quad Name	
1						
2						
3						
4						
5	US Hwy 290, between Henly Loop and Old Red Ranch Road	30° 11' 41"	-98° 12' 37"	Hays	Henly	NW
6	Farm-to-Market Road 32 and Farm-to-Market Road 484	29° 58' 30"	-98° 15' 50"	Comal	Fischer	NE
7						
8	US Hwy 281 and Farm-to-Market Road 311	29° 52' 29"	-98° 24' 32"	Comal	Anhalt	NE
9						
10						
11						
12						
13	Ranch Road 1376 and Platten Creek Road	30° 3' 53"	-98° 44' 19"	Kendall	Whitworth Ranch	NW
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15	State Hwy 211 and Farm-to-Market Road 471	29° 31' 22"	-98° 48' 20"	Bexar	San Geronimo	SE
16	Farm-to-Market Road 471 and County Road 583	29° 18' 19"	-98° 49' 38"	Medina	La Coste	SW
17	State Hwy 16 and State Hwy 46	29° 42' 38"	-98° 53' 8"	Bandera	Pipe Creek	NE
18	I-10 and US Hwy 87	29° 57' 40"	-98° 53' 21"	Kendall	Comfort	NE
19	US Hwy 87, north of I-10	30° 5' 58"	-98° 55' 17"	Kendall	Cypress Creek	NE
20	State Hwy 173 and County Road 5710	29° 9' 15"	-98° 55' 28"	Medina	Devine	SE
21	US Hwy 90, between County Road 4614 and County Road 4612	29° 20' 56"	-98° 56' 22"	Medina	Castroville	NW
22	Stat Hwy 16 and 15th St	29° 43' 39"	-99° 4' 1"	Bandera	Bandera	NW
23	US Hwy 90 and State Hwy 173	29° 20' 54"	-99° 7' 3"	Medina	Murphy School	NW
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26	State Hwy 16 and Farm-to-Market Road 2107	29° 50' 18"	-99° 16' 52"	Bandera	A Bar A Ranch	NE
27	Deer Creek Road and County Road 621	29° 9' 14"	-99° 18' 13"	Medina	Frio Town NE	SE
28	Farm-to-Market Road 140 and Vanco Ranch Road	29° 1' 8"	-99° 18' 58"	Frio	Frio Town	SW
29	Farm-to-Market Road 2107and North Prong	29° 51' 20"	-99° 26' 22"	Bandera	Love Creek	NW
30	Ranch Road 187, north of Ranch Road 140	29° 5' 37"	-99° 26' 37"	Uvalde	Gross Tank	NW

31	US Hwy90 and Center St	29° 19' 3"	-99° 27' 27"	Uvalde	Sabinal	NW
32	Ranch Road 187 and Nuley Lane	29° 11' 58"	-99° 27' 42"	Uvalde	Irishman Hill	NW
33	US Hwy 83 and Chalk Creek Rd.	29° 46' 11"	-99° 43' 14"	Real	Circle Bluff	SW
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35	State Hwy 41 and Fairview Rd.	30° 2' 36"	-99° 53' 27"	Real	EarWood Creek SW	SE
36	State Hwy 55, between Ranch Road 334 and Louis Ln	29° 21' 25"	-99° 57' 22"	Uvalde	Chalk Bluff	NW
37	US Hwy 90, west of Ranch Road 1022	29° 14' 19"	-100° 3' 9"	Uvalde	Cline	NE
38	US Hwy 377 and State Hwy 2630	30° 2' 25"	-100° 11' 29"	Edwards	Rock Springs	SW
39	Cedar Creek and County Road 16	29° 50' 31"	-100° 15' 7"	Edwards	Cutting Pen Draw	NE
40	State Hwy 55, south of County Road 101	30° 7' 28"	-100° 24' 19"	Edwards	Ray Lake SW	NE
41	US Hwy 90 and State Loop 166	29° 18' 18"	-100° 24' 26"	Kinney	Bracket Ville	SE
42	Ranch Road 674	29° 38' 29"	-100° 25' 6"	Edwards	Wiley Waterhole	SE
43	US Hwy 377, north of County Road 22	29° 51' 29"	-100° 33' 37"	Edwards	Carta Valley SE	NE

The analysis for the average density of the alternative configuration in Table 5 shows an improvement in the density to 1 gauge per 55 mi^2 from the existing 1 gauge per 87 mi^2, or the proposed 1 gauge per 66 mi^2. The alternative proposal also results in nearly uniform average distance between gauges in all zones. The alternative proposal especially decreases the spacing between gauges in the artesian zone to 7 miles. The number of alternatively proposed gauges to be added and/or removed in each zone and in total for the whole aquifer is shown in Table 5. While the proposed number of rain gauges to be removed remains the same in both the proposed and alternative configurations, improved gauge density results from using 39 existing AWS/WeatherBug gauges.

Table 5: Average density of alternative proposed configuration

ZONE	AREA (mi^2)	Gauge Count					Sum all gages	Density (mi^2)	Average Distance (mi)
		EAA	GBRA	Proposed	Removed	Weather Bug			
Drainage Zone	5528	35	34	17	-4	15	97	57.0	8
Recharge Zone	1253	17	7	1	-6	1	20	62.7	8
Artesian Zone	2125	9	0	15	-1	23	46	46.2	7
Transition Zone	4	0	0	0	0	0	0		
Total	8910	61	41	33	-11	39	163	55.0	7

Rainfall accuracy improvement will be the greatest where gauges are installed in areas of low coverage. For the Artesian Zone, the number of gauges increases from 9 to 29 in the proposed configuration. Local improvement to radar rainfall accuracy is achieved with the installation of gauges. With the addition of a gauge at a particular location, the radar rainfall will be more accurate. For rainfall that has a 30 mm standard deviation, the standard error of the mean rainfall improves from 20 to 11 mm with 95.5% confidence when increasing from 9 to 29 gauges based on the standard error of the mean. This hypothetical improvement of 44.5% is estimated by computing the standard error of the mean with the specified confidence limits and an assumed 30 mm standard deviation. Actual accuracy improvements from adding a gauge or set of gauges may differ at any particular location or for any given time period.

Historical Rain Gauge Performance

For this study, gauge data for 63 tipping bucket stations from 1 January 2003 to 31 May 2005 was provided. The standard value for each Edwards Aquifer gauge was obtained by surfacing the eight NWS ASOS gauge values over the entire Edwards Aquifer RGN using a distance-weighted average interpolation.

For this study, gauges are classified into three performance categories: *Good*, *Suspect*, and *Poor*. For purposes of classification, a *Good* gauge is one that currently (since January 2005) performs at a level consistent with the NWS gauges (within ±20%); a *Suspect* gauge is defined as a gauge that currently performs at a level less consistent with the NWS gauges (between ±20% and ±35%); and a *Poor* gauge is defined as a gauge that consistently performs poorly when compared to the NWS gauges (in excess of ±35%).

Double mass analysis is performed by plotting the cumulative rainfall from each gauge versus the cumulative rainfall of the standard gauge. Over a significant length of time, the trend should follow approximately a 1:1 line. In other words, for each inch of rainfall observed at the NWS stations, approximately an inch should be observed at the gauge location. A trend is identified by analyzing graphs of double mass data. Trends that indicate a performance problem are: 1) where a deviation from the 1:1 line caused by consistent over/under-reporting, 2) significant long-term change in slope, or 3) a smooth, long-term departure from the expected seasonal variation of rainfall distribution. Spatial-temporal variability of rainfall, often present in relatively short durations (daily or hourly), is smoothed out when examined over a relatively longer period (monthly or yearly). Natural spatial variability of rainfall does occur that can account for short duration deviations from the 1:1 line, but not over a prolonged period. Climatological trends also exist across the EAA area from west to east. By surfacing the NWS ASOS gauge accumulations for comparative purposes, the climatological and short-term deviations are partially accounted for. Figure 9 shows the locations of both the NWS ASOS network and the Edwards Aquifer RGN. The rating for each gauge described below is also shown here with different map symbols.

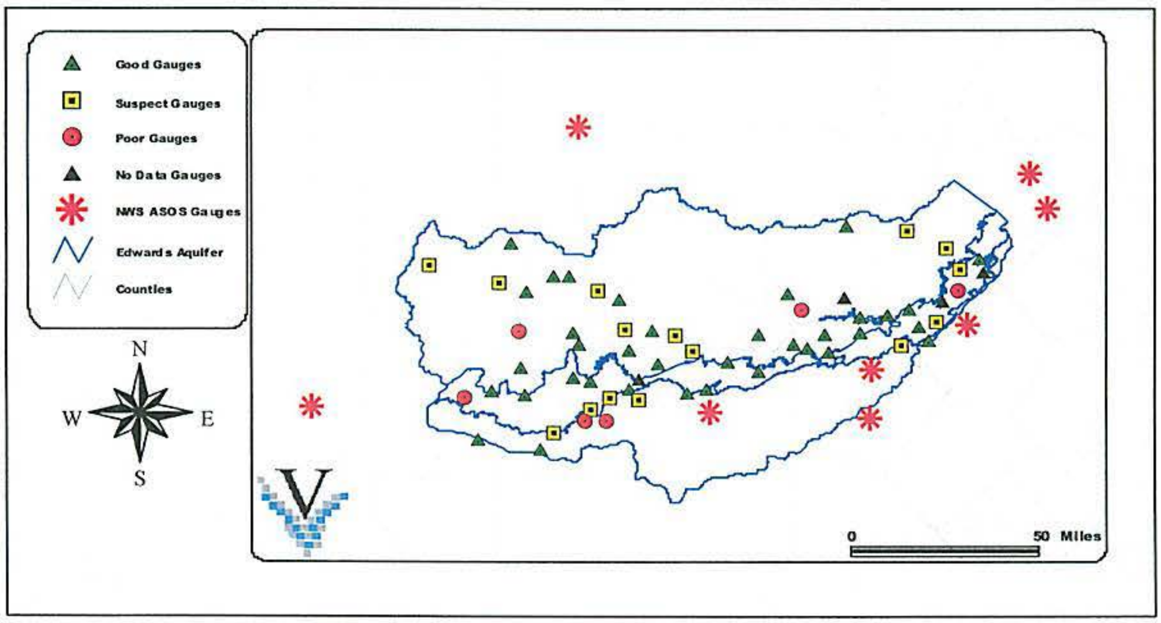


Figure 9: Gauge location in the Edwards Aquifer RGN and the NWS ASOS gauges

Individual charts showing the double mass analysis for each gauge were examined (see Appendix 5). Trends in gauge accumulation in relation to the NWS gauges were observed from the double mass analysis. Several gauges appeared to have missing data for an extended amount of time throughout the study period. These occurrences were observed when the gauge being analyzed reported no rainfall, yet the NWS gauges reported rainfall resulting in a series of horizontal points on the double mass plot along the x-axis. In order to objectively compare the NWS and Edwards Aquifer gauge accumulations, periods where an Edwards Aquifer gauge appeared to have missing data were removed from the NWS gauge accumulations. This adjustment facilitates trend identification because the data is more comparable without missing data periods. Figure 10 depicts the percentage departure of each gauge versus the NWS gauges for the period of 1 January 2003 to 31 May 2005. Figure 11 depicts the percentage departure of each gauge versus the NWS gauges for the period of 1 January 2005 to 31 May 2005 from which the gauges were rated. The color of the bars represent the performance of each gauge where green is *Good*, yellow is *Suspect*, and Red is *Poor*. Appendix 4 summarizes numerical percentages and ratings for each gauge contained in Figures 10 and 11. Appendix 5 contains the double-mass plots for all gauges considered in the historical analysis.

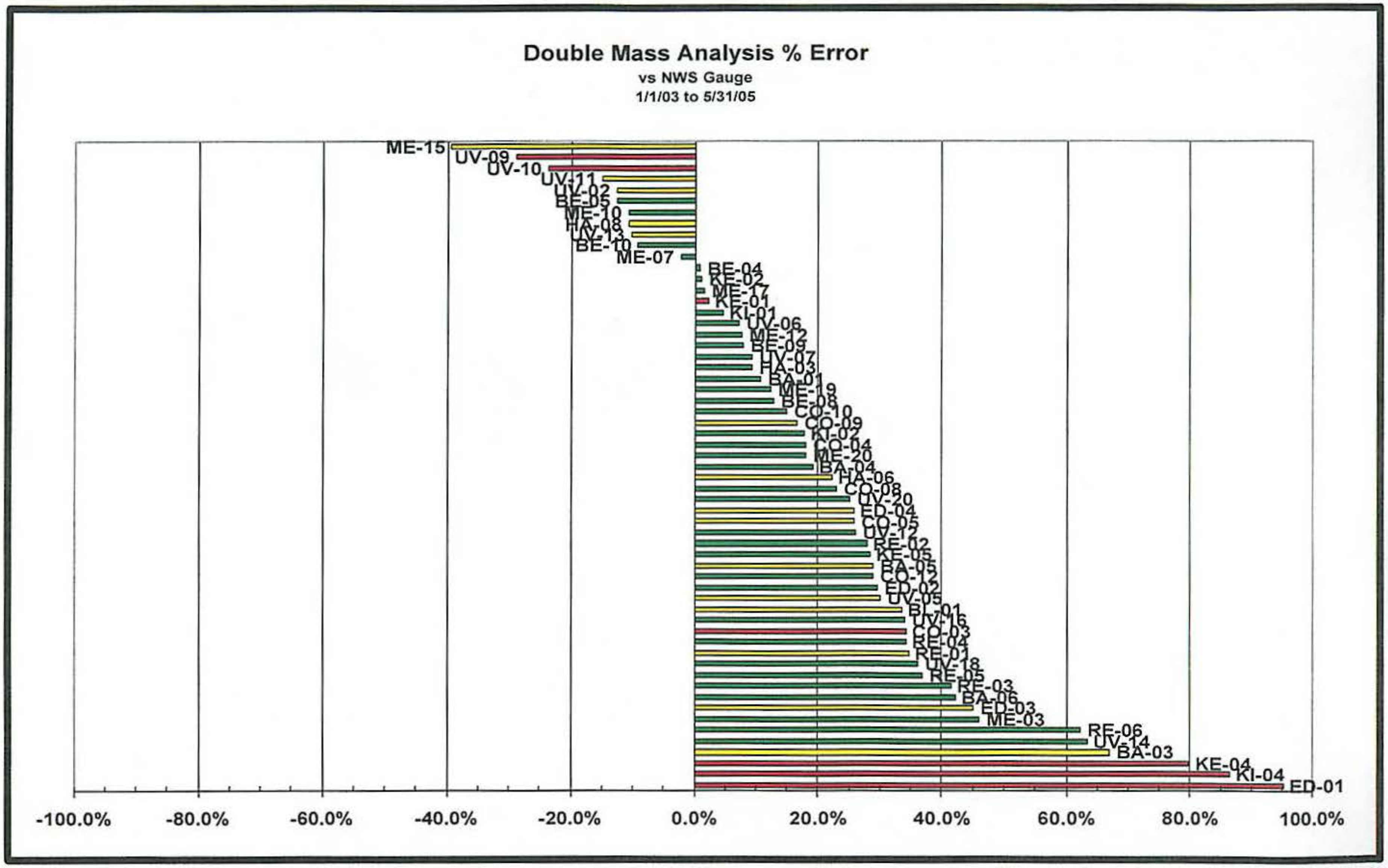


Figure 10: Summary of double mass analysis as departures from the NWS gauges for entire study period

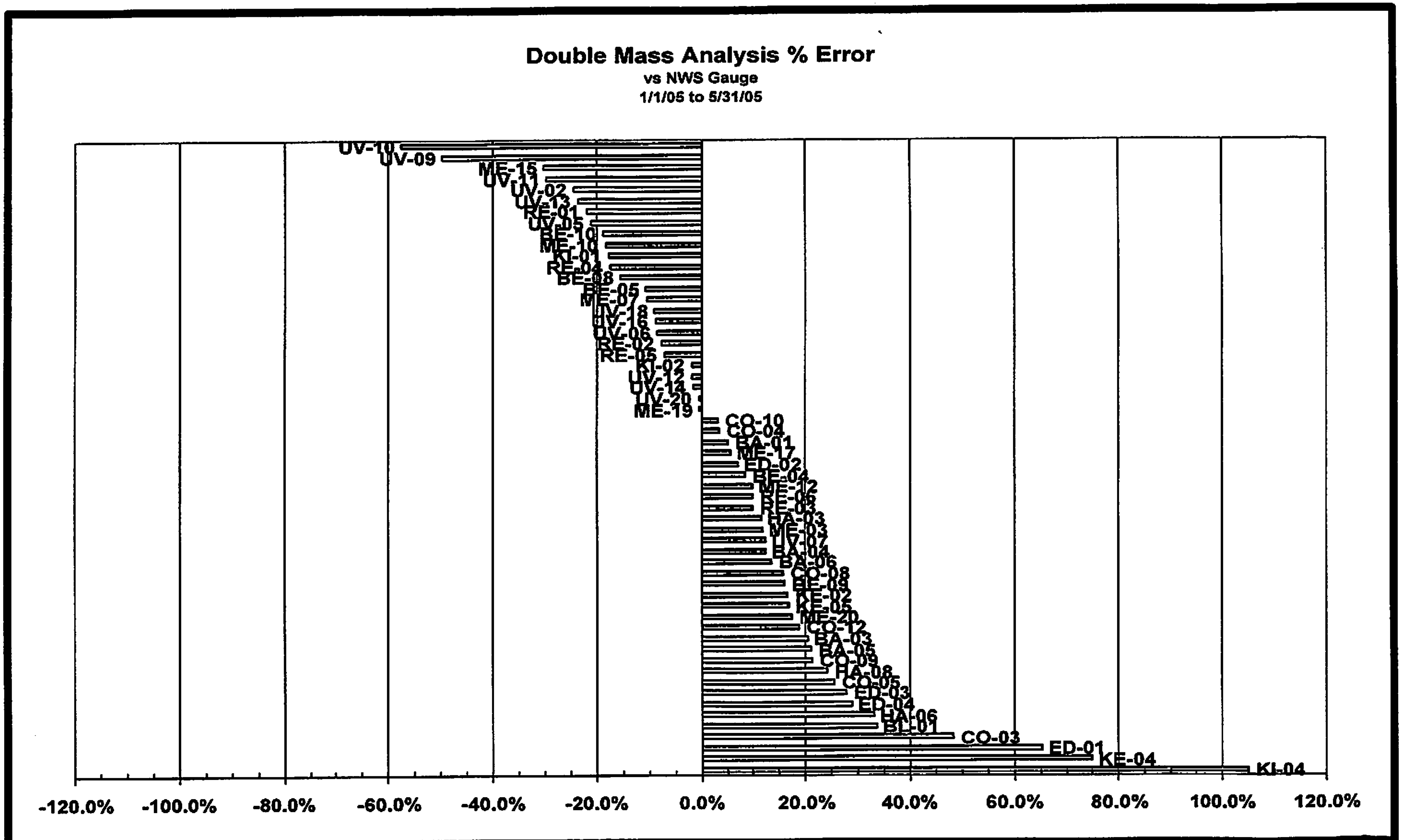


Figure 11: Summary of double mass departures from the NWS gauges since January 2005

Summary

This report presents the evaluation of the existing network in terms of historical performance, and recommendations for improved gauge network coverage and density. The existing gauge network in combination with the GBRA network has an average density of one gauge per 87 mi^2 and a mean inter-gauge spacing that is variable from 7 to15 mi depending on the zone. Recommended gauge network improvements identify additional gauges and gauges that could be removed to achieve a more uniform gauge density and coverage of the Drainage, Recharge, and Artesian Zones of the Edwards Aquifer. Two network configurations are recommended: 1) Proposed Configuration, and 2) Alternative Configuration. Both recommended network configurations rely on the existing EAA network and two other networks. The GBRA supplements the EAA network in both configurations. A private network operated by AWS/WeatherBug and requiring upgrade and service fees supplements the Alternative Configuration. The net number of gauges (existing, plus addition minus removal) in the Proposed Configuration is 134. The net number of gauges in the Alternative Configuration is 163 gauges.

With the additional gauges proposed, more uniform coverage among zones, increased gauge density, and reduced inter-gauge spacing is achieved. The proposed configuration achieves a density of one gauge per 66 mi^2 and a uniform inter-gauge spacing of 8 mi. The Alternative Configuration achieves a density of one gauge per 55 mi^2 with higher densities in and around San Antonio. The proposed rain gauge network provides a more evenly distributed coverage over each zone of the aquifer, and point observations useful for enhancing the accuracy of radar rainfall. With the addition of gauges, improvements in accuracy will be greatest in areas of insufficient coverage, i.e., where few gauges exist. The greatest improvement in accuracy is expected in the Artesian Zone with the additional gauges in areas where there were few gauges.

Results of the rain gauge network assessment revealed maintenance actions and monitoring that could improve gauge performance and reliability. It is recommended that in addition to scheduled maintenance, specific actions be taken for gauges BA-03, BA-05, BL-01, CO-03, CO-05, CO-09, ED-01, ED-03, ED-04, HA-06, HA-08, KE-04, KI-04, ME-15, RE-01, UV-02, UV-05, UV-09, UV-10, UV-11, and UV-13. If field calibration tests were performed and corrected actions taken, these gauges and the entire rain gauge network would be improved. Once maintenance actions have been completed, and a sufficient time has elapsed, e.g., one season or year, another double mass analysis of the RGN should be performed. Improvements in the reliability of the rain gauge network will improve the gauge measurements and likely increase the percentage of gauges used each month to adjust radar rainfall products. Correcting the twenty-one gauges rated as *Suspect* or *Poor* would help improve one-third of the gauges in the rain gauge network. Maintenance actions will improve gauges that are in error by as much as 35%. The recommended maintenance actions and the proposed additional gauges will improve the quality and usefulness of the rain gauge data and benefit the accuracy of radar rainfall.

Appendices

Appendix 1: Existing EAA gauges (06-10-05)

Gauge ID	Latitude	Longitude
ED-01-RO	29-41-06.6	100-01-6.2
ED-02-RO	30-02-6.33	100-03-37.15
ED-03-RO	29-52-46.49	100-6-40.47
ED-04-RO	29-56-33.4	100-25-22.16
RE-01-RO	29-50-53.9	99-40-39.27
RE-02-RO	29-37-50.8	099-45-24.2
RE-03-RO	29-40-44.4	99-46-55.4
RE-04-RO	29-54-22	99-52-24
RE-05-RO	29-54-23.2	099-48-19.9
RE-06-RO	29-50-29.16	99-59-15.58
BA-01-RO	29-40-24.34	98-57-37.65
BA-03-RO	29-40-2.13	99-19-51.56
BA-04-RO	29-41-26.15	99-25-58.23
BA-05-RO	29-41-54.10	99-33-6.87
BA-06-RO	29-48-45.8	099-34-35
BE-04-RO	29-40-57.98	98-31-18.02
BE-05-RO	29-44-24.8	098-30-46.1
BE-08-RO	29-37-6.06	98-44-51.39
BE-09-RO	29-36-30.89	098-39-2.87
BE-10-RO	29-40-43.33	98-40-2.4
BL-01-RO	30-05-22.2	098-18-23.0
CO-03-RO	29-51-4.18	98-04-53.93
CO-04-RO	29-38-55.1	98-13-7.29
CO-05-RO	29-43-8.21	98-10-52.72
CO-07-RO	29-48-17.8	098-09-32.0
CO-08-RO	29-42-30.8	098-15-23.0
CO-09-RO	29-37-35.99	98-19-55.64
CO-10-RO	29-46-16.8	98-17-52
CO-12-RO	29-45-9.80	98-23-45.97
KE-01-RO	29-49-9.57	98-34-56.34

KE-02-RO	30-06-41.28	98-34-20.32
KE-04-RO	29-46-11.8	098-46-34.1
KE-05-RO	29-50-9.44	98-49-52.56
KI-01-RO	29-14-53.9	100-12-12.3
KI-02-RO	29-26-36	100-08-30
KI-04-RO	29-24-45.8	100-15-45.3
HA-02-RO	29-55-10.89	97-58-26.79
HA-03-RO	29-58-23.88	97-59-34.31
HA-06-RO	29-55.57.88	098-04-37.98
HA-08-RO	30-01-11.8	098-07-59.03
ME-03-RO	29-38-13.6	98-48-40.96
ME-07-RO	29-31-32	98-57-36
ME-10-RS	29-34-4.35	99-05-49.35
ME-12-RO	29-27-04.8	099-11-40.1
ME-15-RO	29-36-20.8	099-14-53.1
ME-17-RO	29-30-18.07	99-07-57.35
ME-19-RO	29-26-19.8	99-16-59.28
ME-20-RO	29-33-32	99-24-19.38
UV-02-RO	29-24-35.8	099-29-51.2
UV-03-RS	29-29-26.82	99-29-34.02
UV-05-RO	29-25-14.6	99-36-54.32
UV-06-RO	29-27-24.07	99-32-16.14
UV-07-RO	29-36-39.33	99-31-54.07
UV-09-RO	29-19-25	99-43-48
UV-10-RO	29-19-37.8	99-38-17.7
UV-11-RO	29-22-25.08	099-42-12.02
UV-12-RO	29-29-19	99-42-21.4
UV-13-RO	29-16-22.9	099-51-47.2
UV-14-RO	29-30-14.9	099-46-54.5
UV-16-RO	29-12-50.24	99-55-41.41
UV-18-RS	29-25-43.8	099-59-50.39
UV-20-RO	29-32-21.17	100-00-45.13

Appendix 2: Comparison of density and average distance of gauges for the existing and proposed network configurations*

Existing

ZONE	AREA (mi^2)	Gauge Count					Sum all gages	Density (mi^2)	Average Distance (mi)
		EAA	GBRA						
Drainage Zone	5528	35	34				69	80.1	9
Recharge Zone	1253	17	7				24	52.2	7
Artesian Zone	2125	9	0				9	236.1	15
Transition Zone	4	0	0				0		
Total	8910	61	41				102	87	9

Proposed Configuration

ZONE	AREA (mi^2)	Gauge Count					Sum all gages	Density (mi^2)	Average Distance (mi)
		EAA	GBRA	Proposed	Remove				
Drainage Zone	5528	35	34	20	-4		85	65.0	8
Recharge Zone	1253	17	7	2	-6		20	62.7	8
Artesian Zone	2125	9	0	21	-1		29	73.3	9
Transition Zone	4	0	0	0	0		0		
Total	8910	61	41	43	-11		134	66	8

Alternative

ZONE	AREA (mi^2)	Gauge Count					Sum all gages	Density (mi^2)	Average Distance (mi)
		EAA	GBRA	Proposed	Remove	Weather Bug			
Drainage Zone	5528	35	34	17	-4	15	97	57.0	8
Recharge Zone	1253	17	7	1	-6	1	20	62.7	8
Artesian Zone	2125	9	0	15	-1	23	46	46.2	7
Transition Zone	4	0	0	0	0	0	0		
Total	8910	61	41	33	-11	39	163	55	7

* The numbers stated in the above tables are based on the gauges located in the Edwards Aquifer boundary.

Appendix 3: NWS gauge ID and location.

RAIN GAUGE	LOCATION
KATT	Camp Mabry Army National Guard Base
KAUS	Austin-Bergstrom International Airport
KBAZ	New Braunfels Municipal Airport
KDRT	Del Rio International Airport
KHDO	Hondo Municipal Airport
KJCT	Kimble County Airport
KSAT	San Antonio International Airport
KSSF	Stinson Municipal Airport

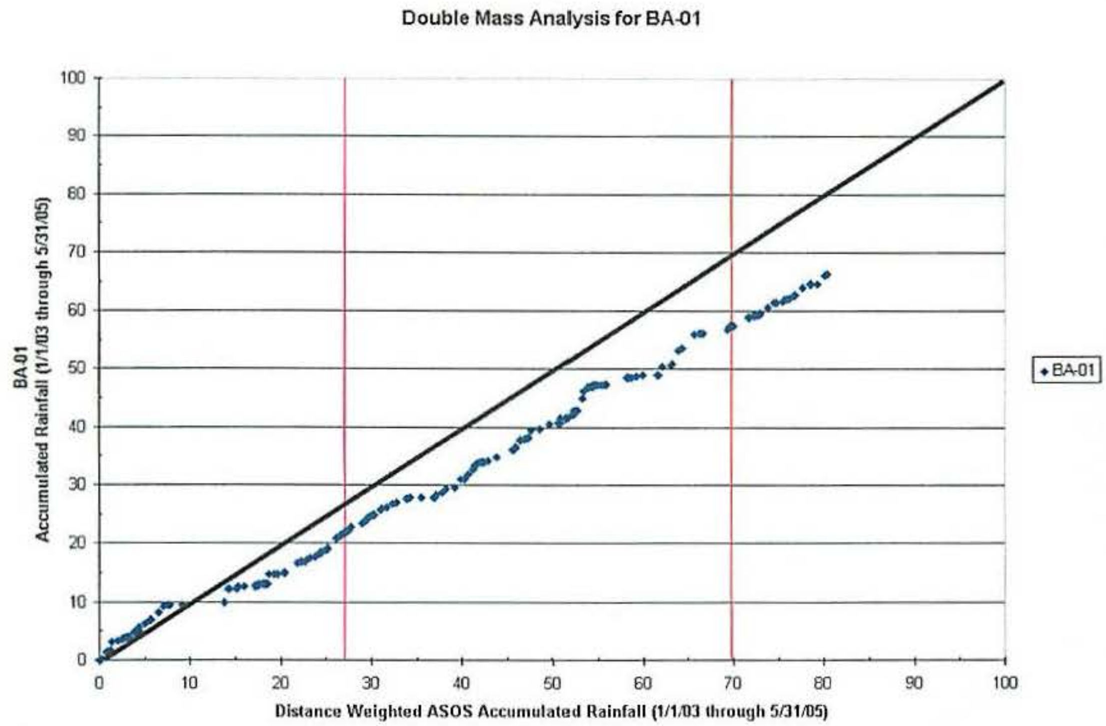
Appendix 4: Double mass analysis and performance rating for each gauge

Gauge ID	% Diff vs NWS 2003-2005	% Diff vs NWS Year 2005	Performance Rating
BE-10	-9.3	-18.7	GOOD
ME-10	-10.8	-18.4	GOOD
KI-01	4.5	-17.7	GOOD
RE-04	34.2	-17.4	GOOD
BE-08	12.9	-15.4	GOOD
BE-05	-12.6	-10.6	GOOD
ME-07	-2.2	-10.6	GOOD
UV-18	36.2	-9.0	GOOD
UV-16	34.0	-8.9	GOOD
UV-06	7.2	-8.5	GOOD
RE-02	27.8	-7.7	GOOD
RE-05	36.8	-7.3	GOOD
KI-02	17.7	-1.9	GOOD
UV-12	26.1	-1.9	GOOD
UV-14	63.3	-1.7	GOOD
UV-20	25.1	-0.6	GOOD
ME-19	12.4	-0.4	GOOD
CO-10	15.0	3.2	GOOD
CO-04	18.1	3.5	GOOD
BA-01	10.8	5.3	GOOD
ME-17	1.1	5.6	GOOD
ED-02	29.6	7.0	GOOD
BE-04	0.8	8.6	GOOD
ME-12	7.7	9.8	GOOD
RE-03	41.1	9.9	GOOD
RE-06	62.2	9.9	GOOD
HA-03	9.4	11.5	GOOD
ME-03	46.0	11.7	GOOD
BA-04	19.1	12.3	GOOD
UV-07	9.3	12.3	GOOD
BA-06	42.2	13.6	GOOD
CO-08	23.0	15.8	GOOD
BE-09	7.9	16.1	GOOD
KE-02	1.1	16.6	GOOD
KE-05	28.3	16.7	GOOD
ME-20	18.1	17.4	GOOD
CO-12	28.9	18.8	GOOD
ME-15	-39.4	-30.2	SUSPECT
UV-11	-14.7	-29.6	SUSPECT
UV-02	-12.7	-24.5	SUSPECT
UV-13	-10.3	-23.7	SUSPECT
RE-01	34.7	-21.9	SUSPECT
UV-05	30.0	-21.2	SUSPECT
BA-03	67.0	20.4	SUSPECT

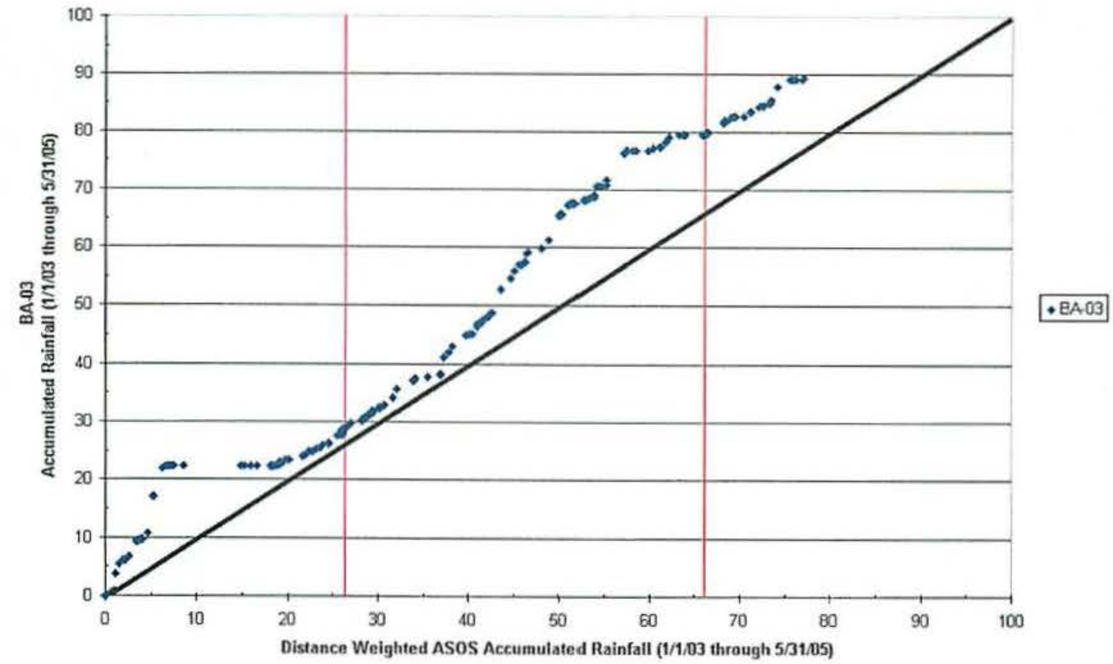
BA-05	28.9	21.1	SUSPECT
CO-09	16.6	21.3	SUSPECT
HA-08	-10.7	24.2	SUSPECT
CO-05	25.9	25.5	SUSPECT
ED-03	45.1	27.8	SUSPECT
ED-04	25.6	28.7	SUSPECT
HA-06	22.2	33.0	SUSPECT
BL-01	33.5	33.5	SUSPECT
UV-10	-23.7	-57.5	POOR
UV-09	-28.8	-49.6	POOR
CO-03	34.2	48.5	POOR
ED-01	95.2	65.3	POOR
KE-04	79.7	74.8	POOR
KI-04	86.4	105.1	POOR
KE-01	2.2	NO DATA	---
CO-07	NO DATA	NO DATA	---
HA-02	NO DATA	NO DATA	---
ME-01	NO DATA	NO DATA	---
UV-03	NO DATA	NO DATA	---

Appendix 5: Double mass analysis plots for each gauge

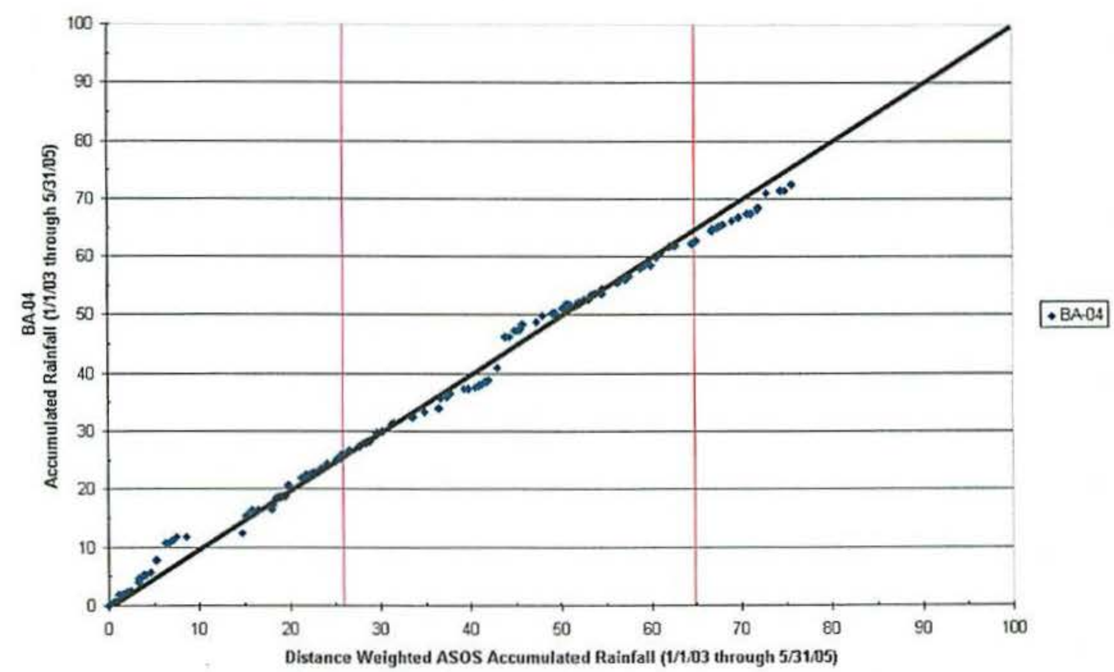
The two vertical lines parallel to the *y*-axis in each double mass plot represent 1 January 2004 (pink) and 1 January 2005 (red), respectively.



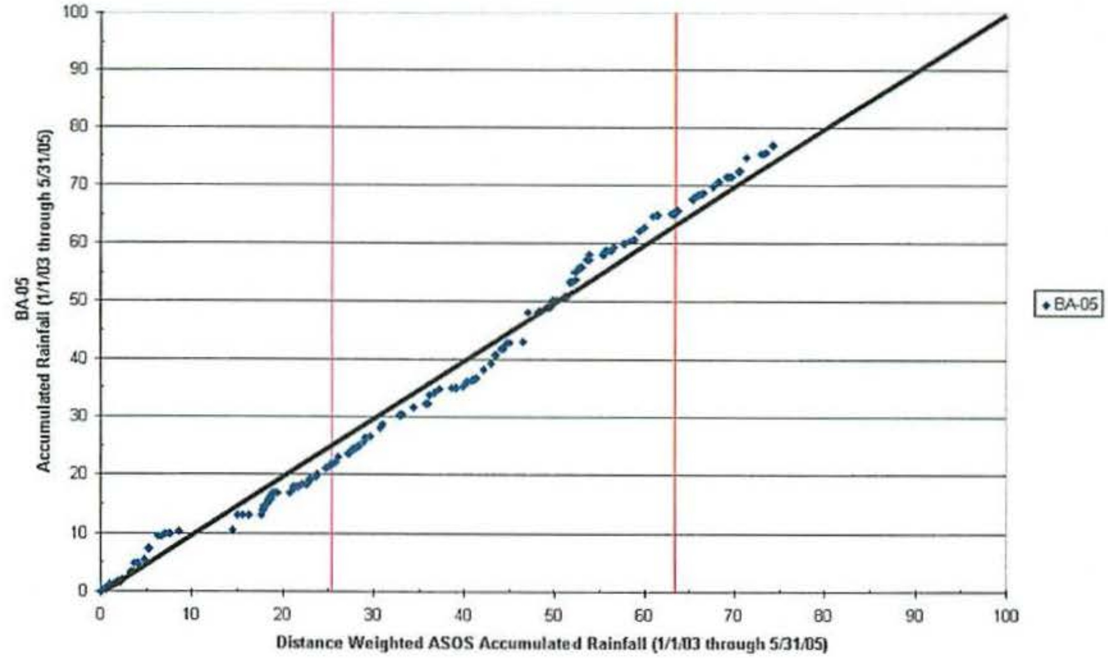
Double Mass Analysis for BA-03



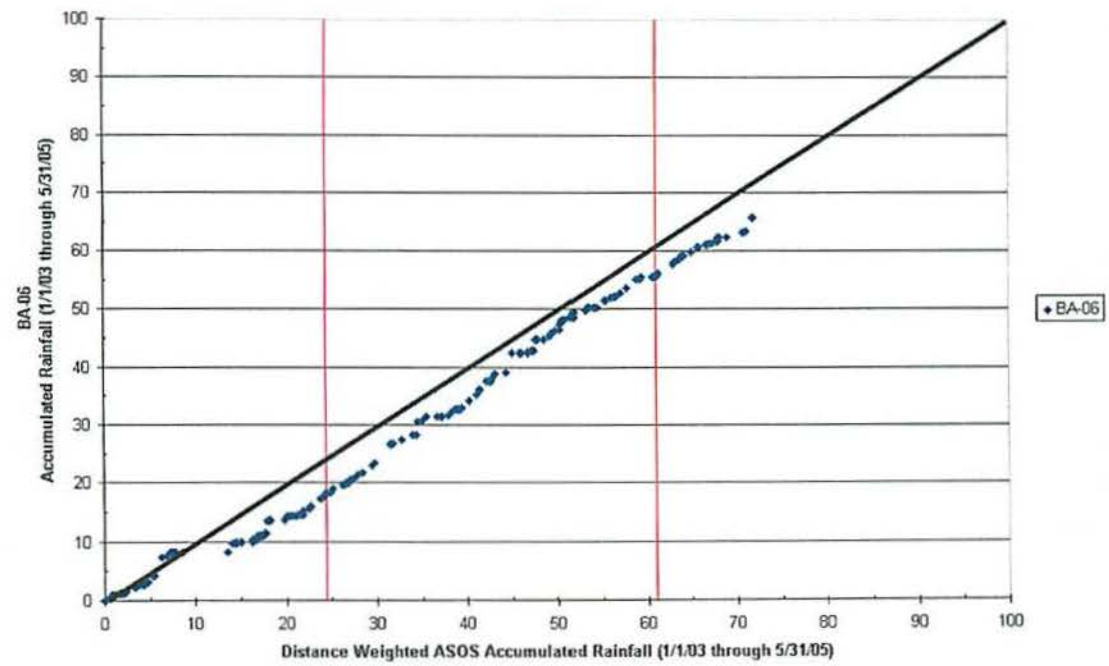
Double Mass Analysis for BA-04

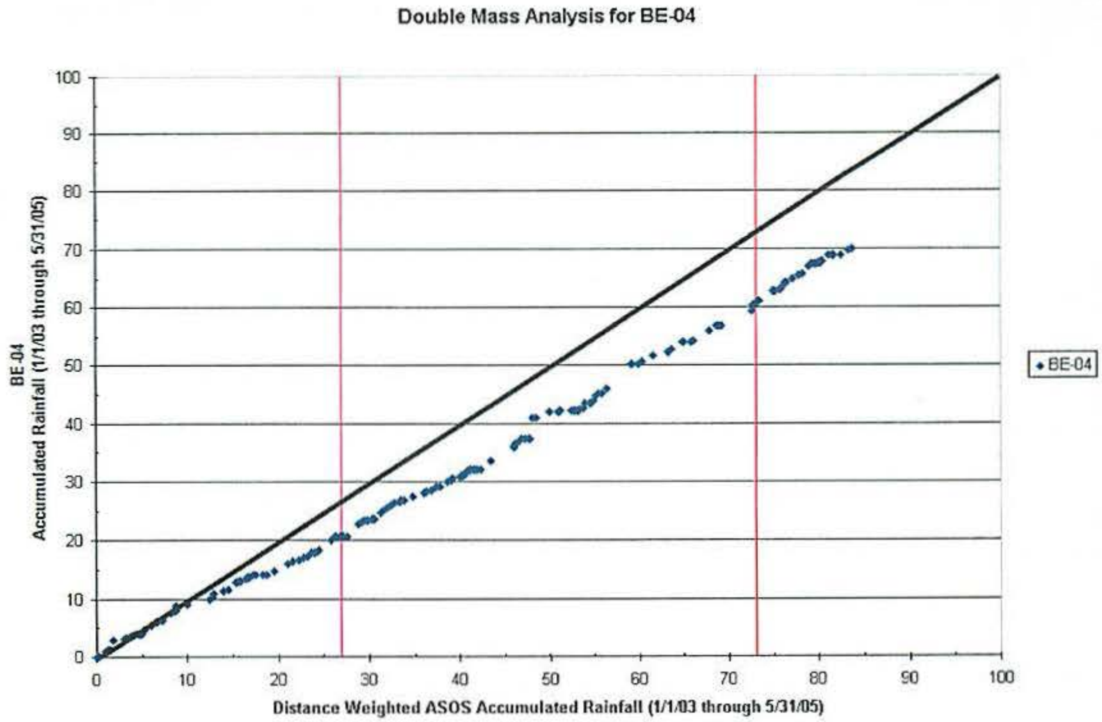


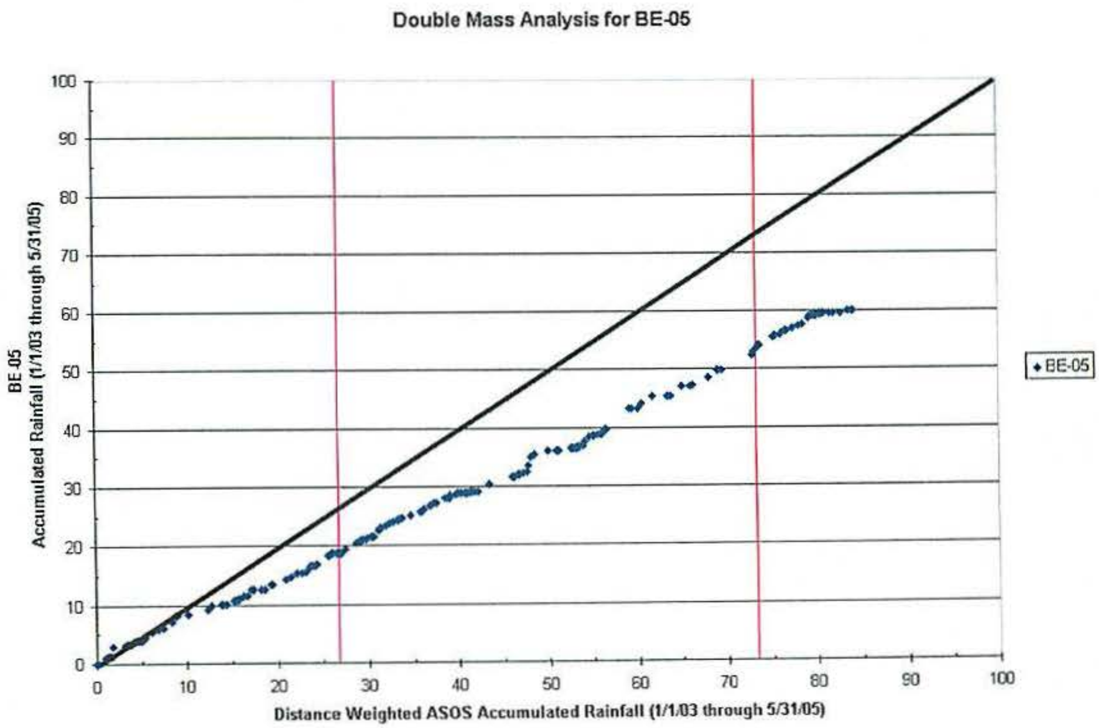
Double Mass Analysis for BA-05



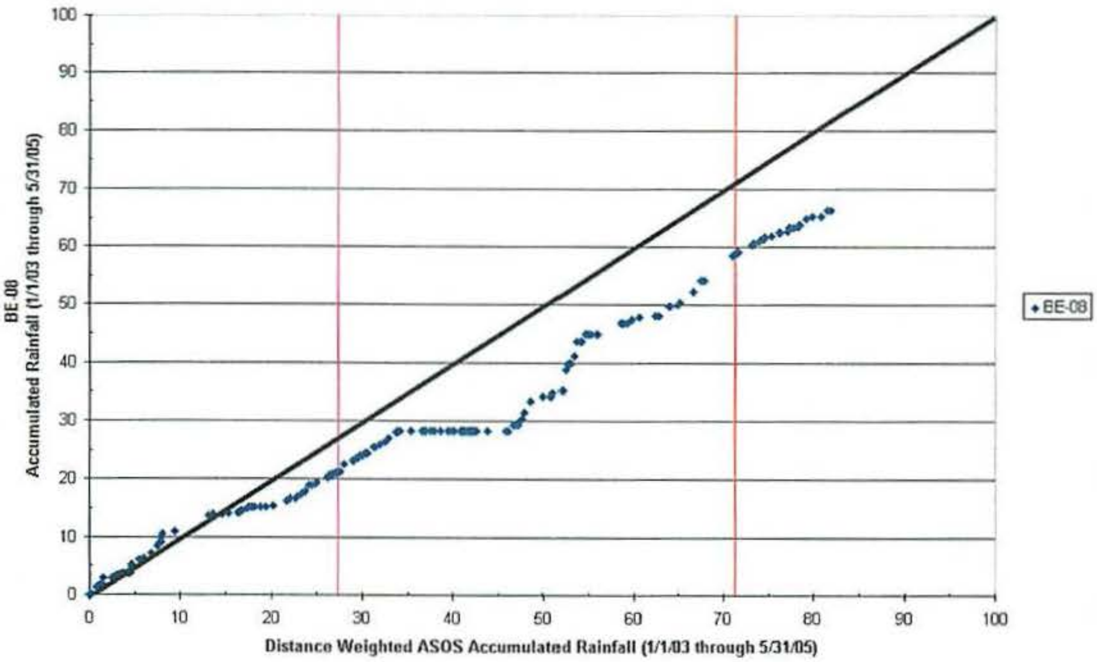
Double Mass Analysis for BA-06



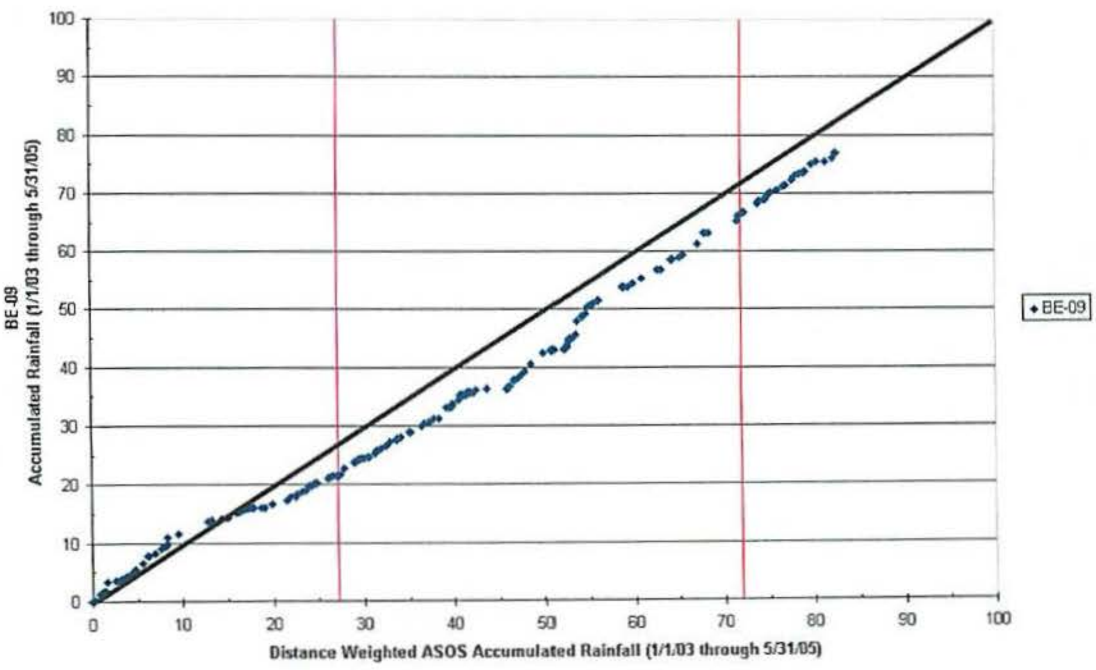

Double Mass Analysis for BE-04
BE-04
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
0
10
20
30
40
50
60
70
80
90
100
BE-04


Double Mass Analysis for BE-05
BE-05
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
0
10
20
30
40
50
60
70
80
90
100
BE-05

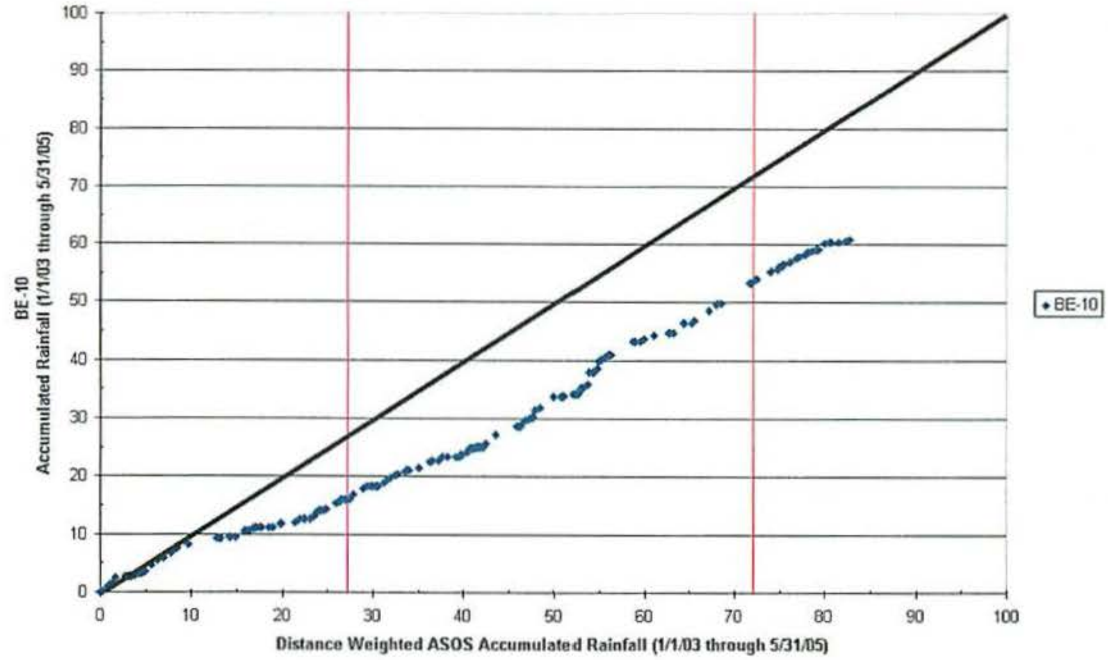
Double Mass Analysis for BE-08



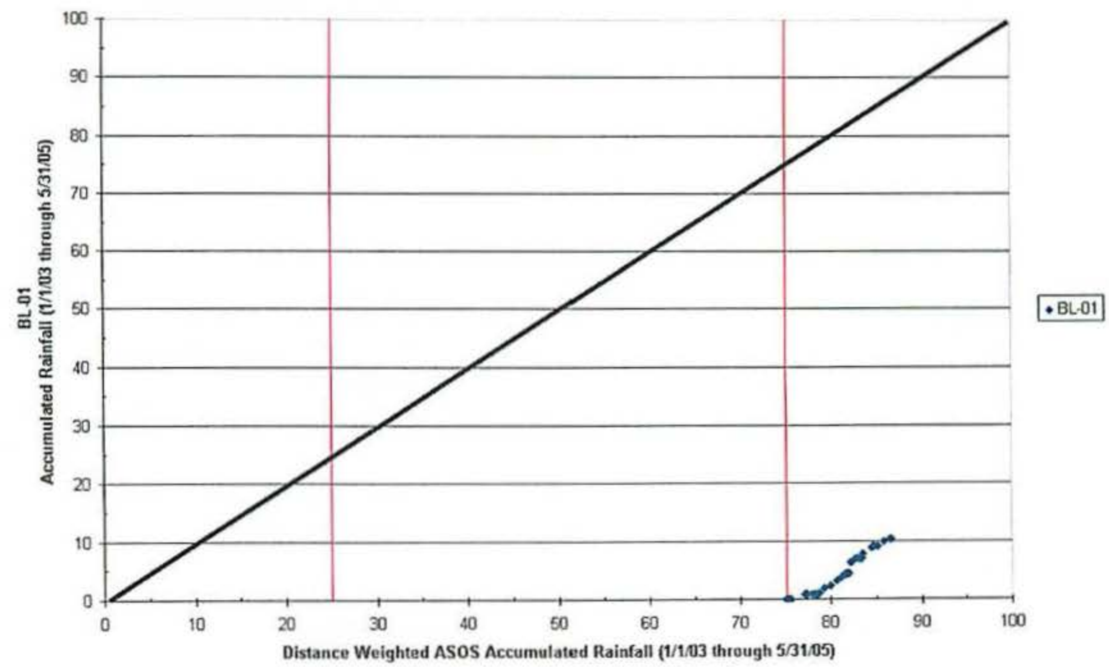
Double Mass Analysis for BE-09



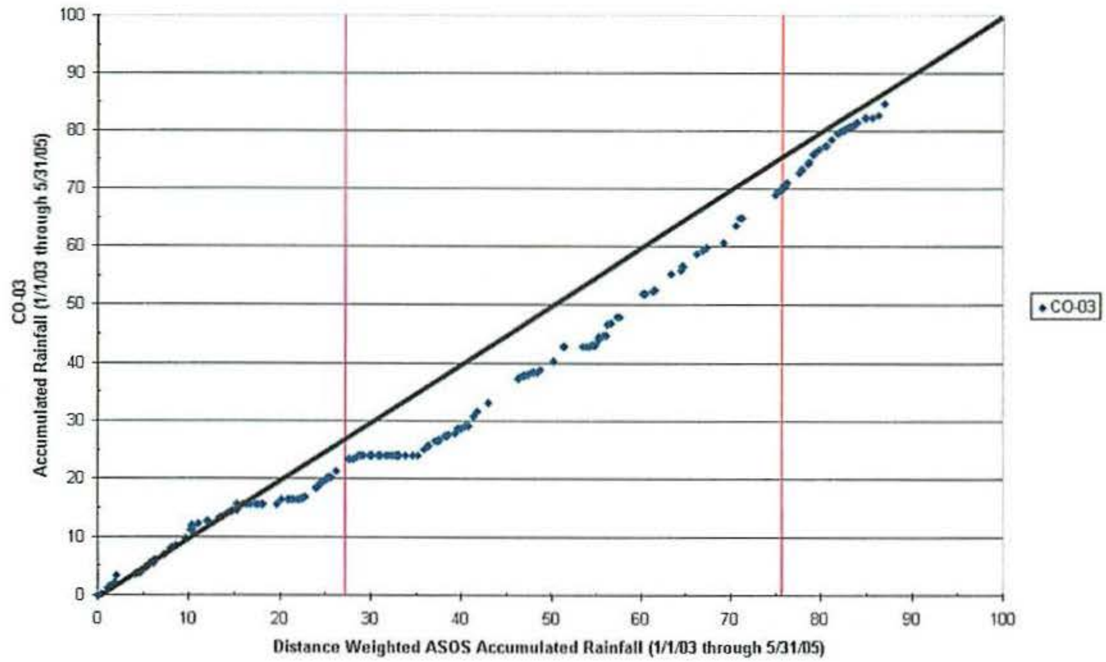
Double Mass Analysis for BE-10



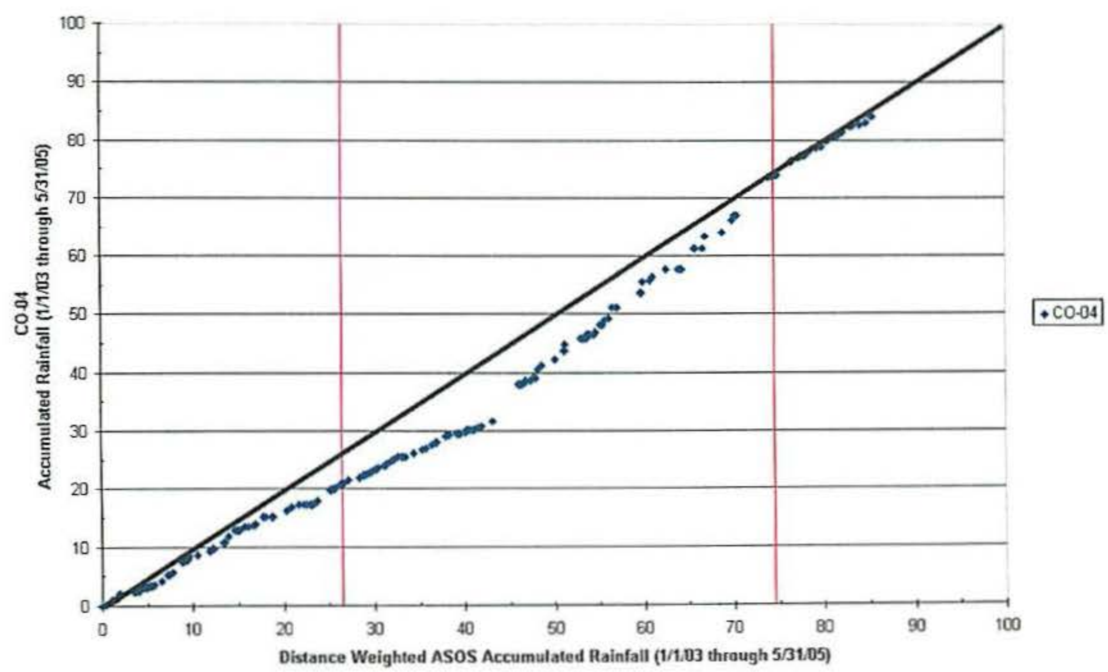
Double Mass Analysis for BL-01



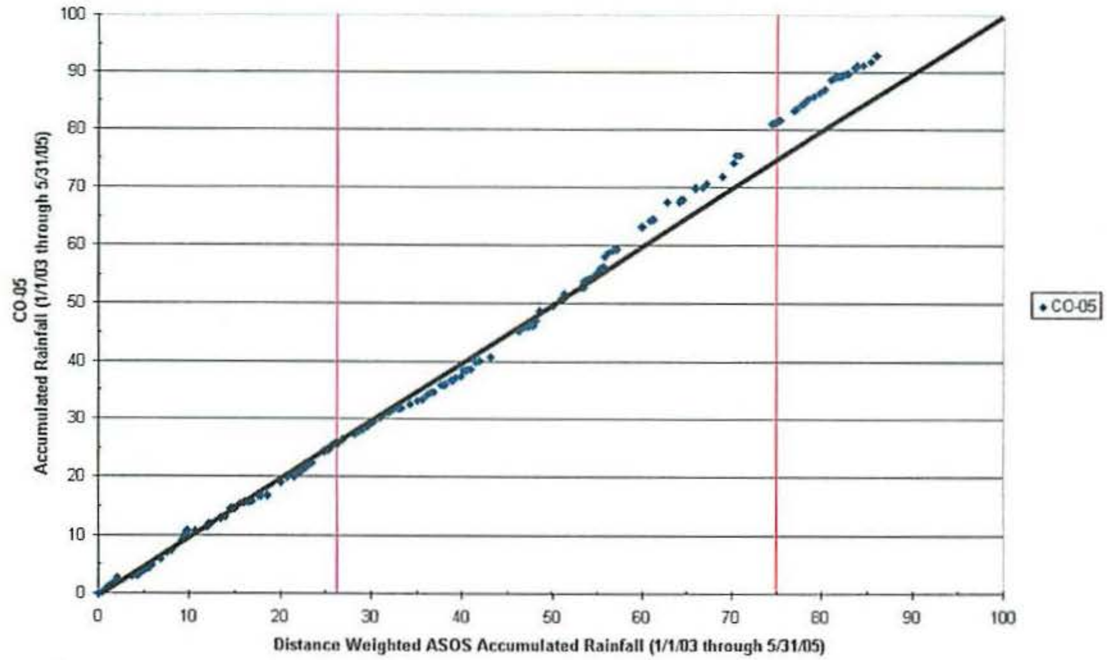
Double Mass Analysis for CO-03



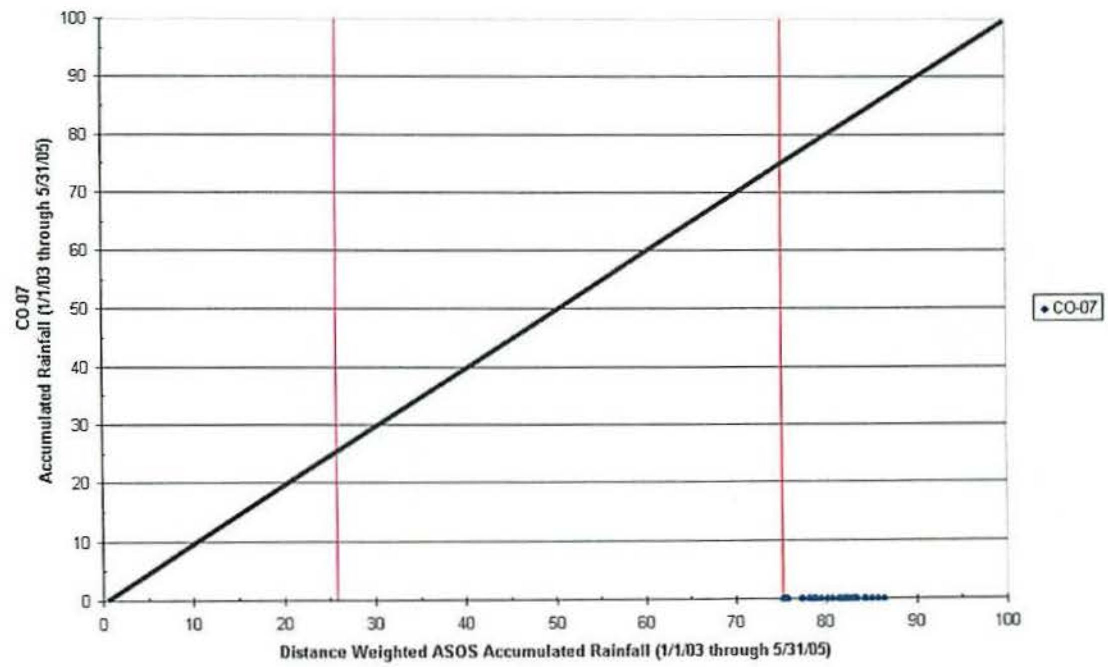
Double Mass Analysis for CO-04



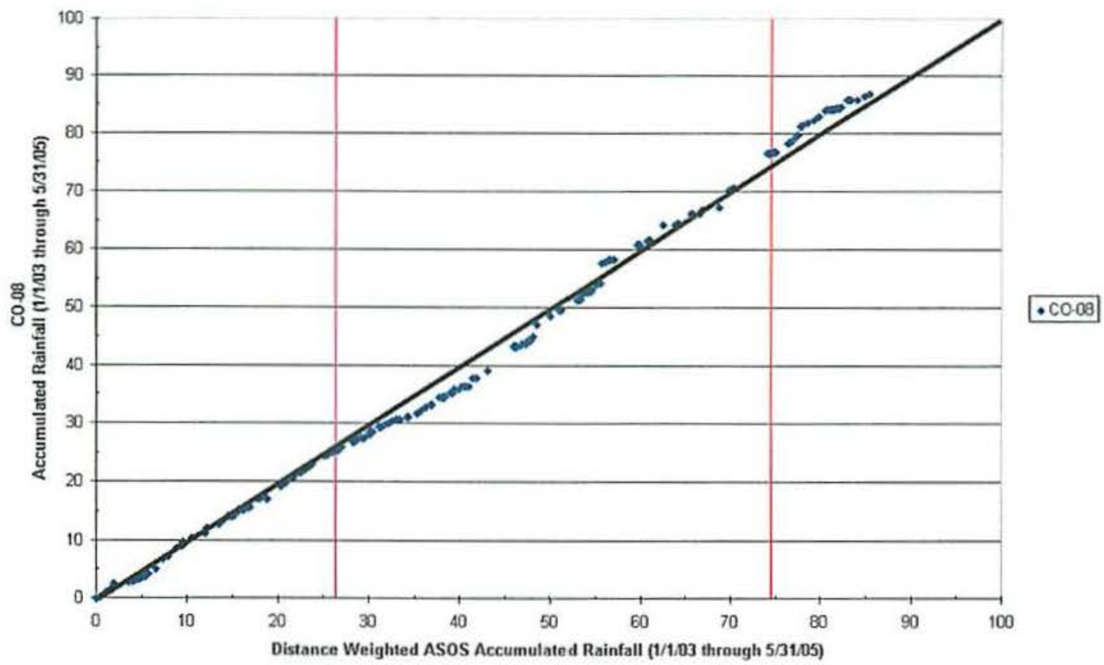
Double Mass Analysis for CO-05



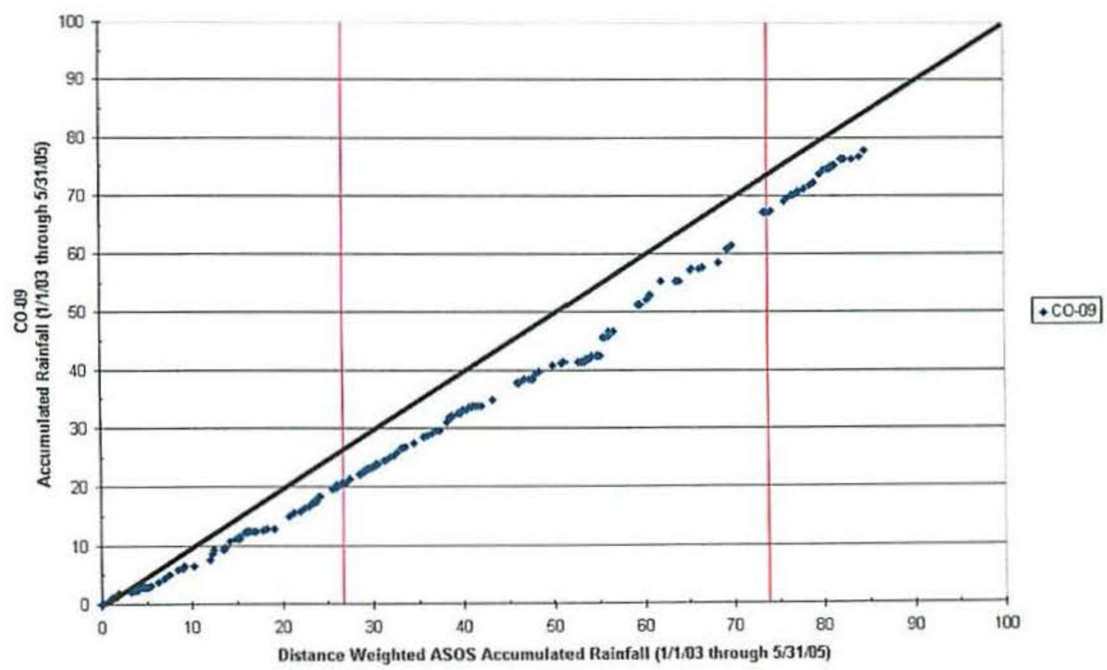
Double Mass Analysis for CO-07



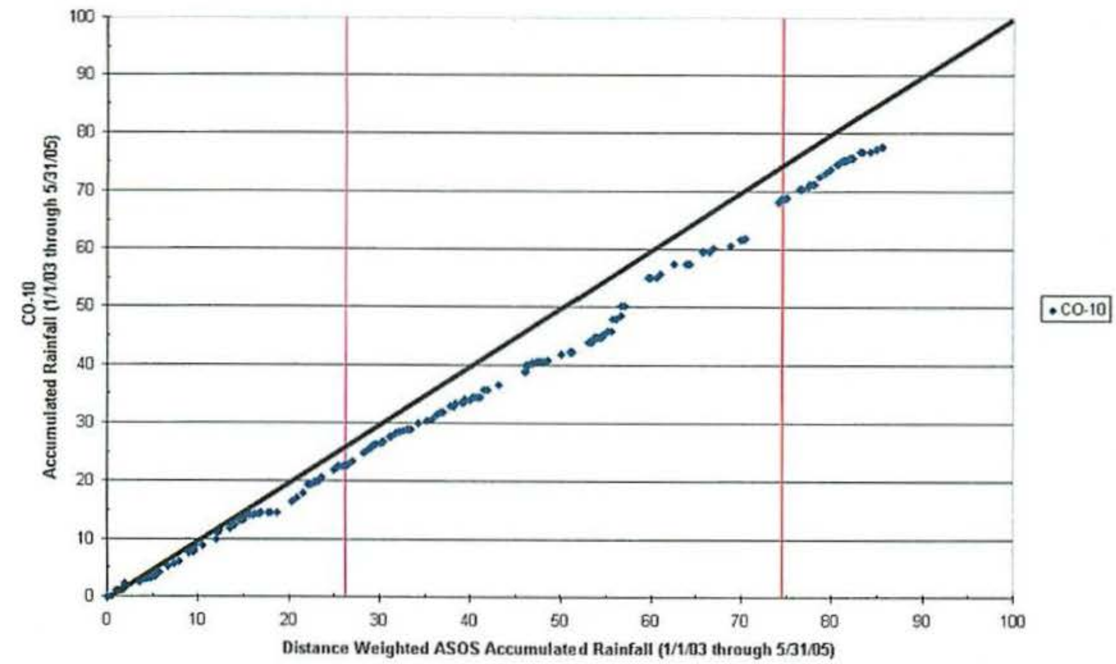
Double Mass Analysis for CO-08



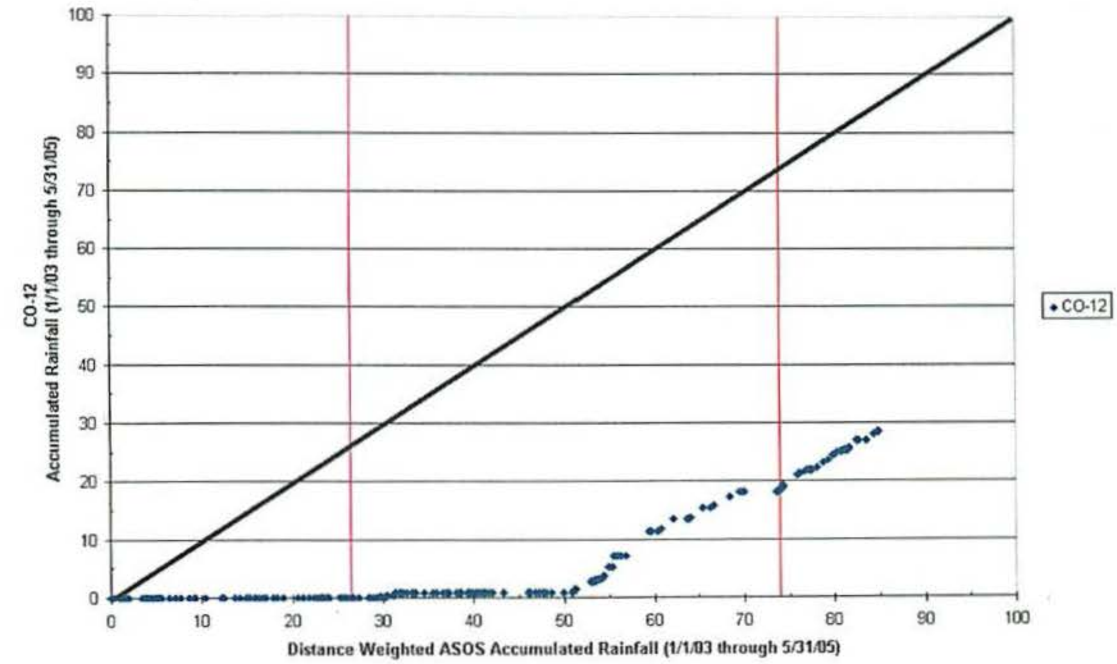
Double Mass Analysis for CO-09



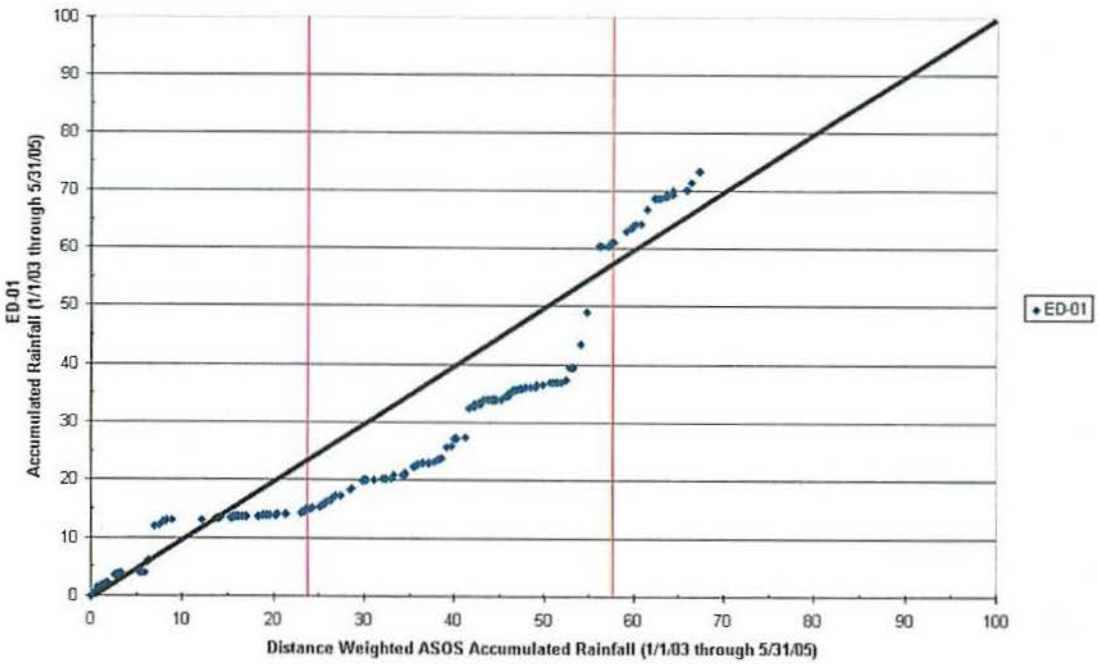
Double Mass Analysis for CO-10



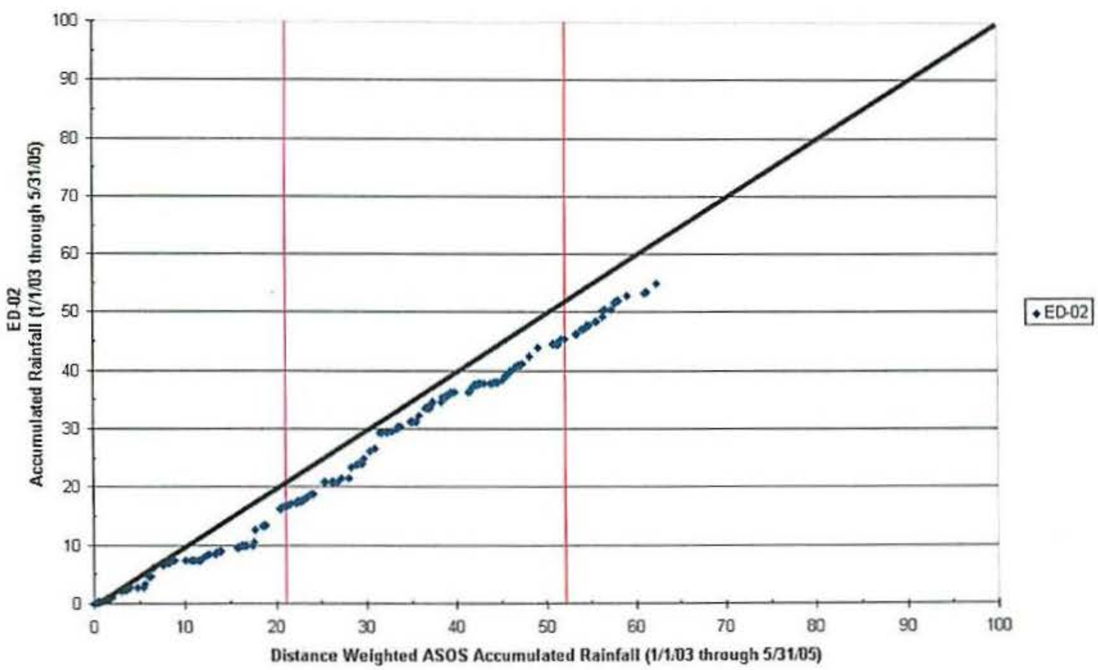
Double Mass Analysis for CO-12



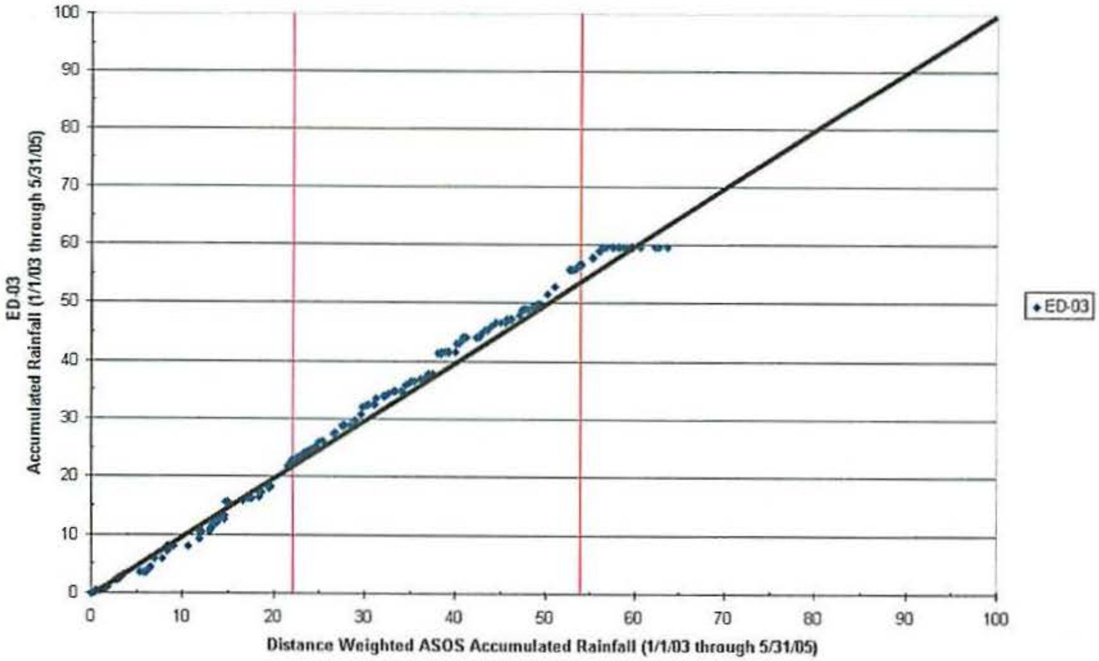
Double Mass Analysis for ED-01



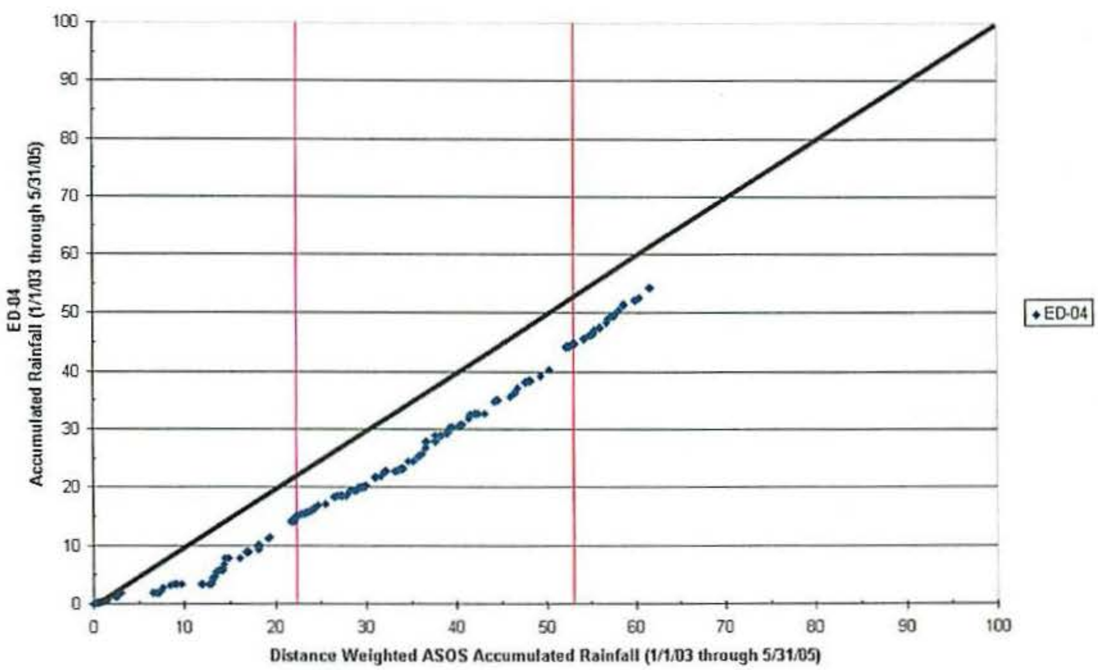
Double Mass Analysis for ED-02



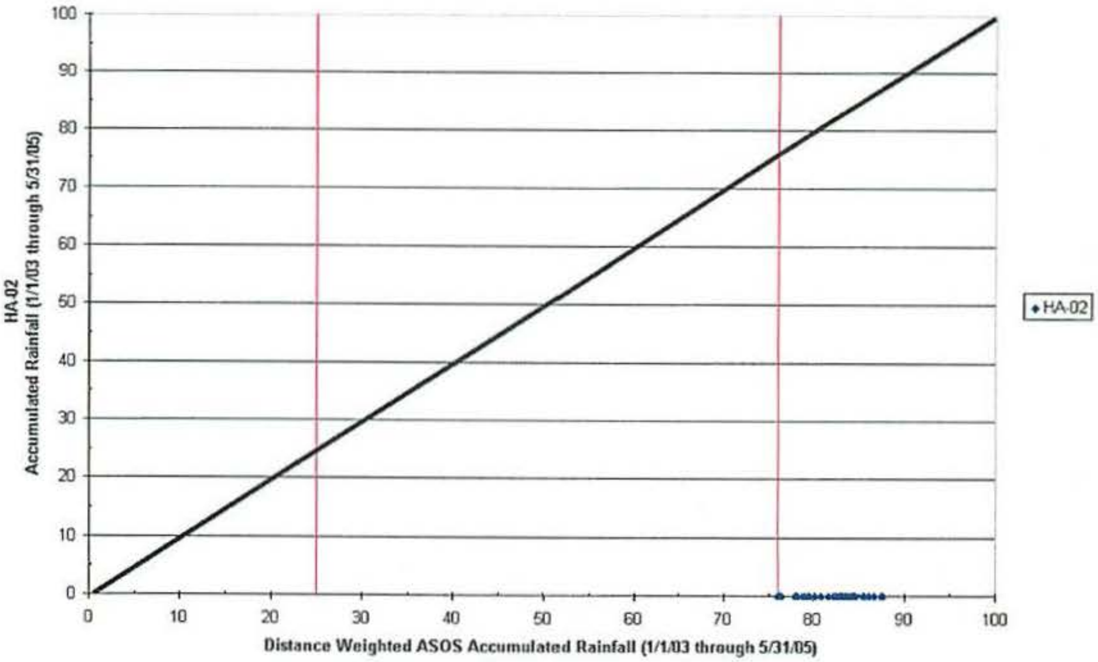
Double Mass Analysis for ED-03



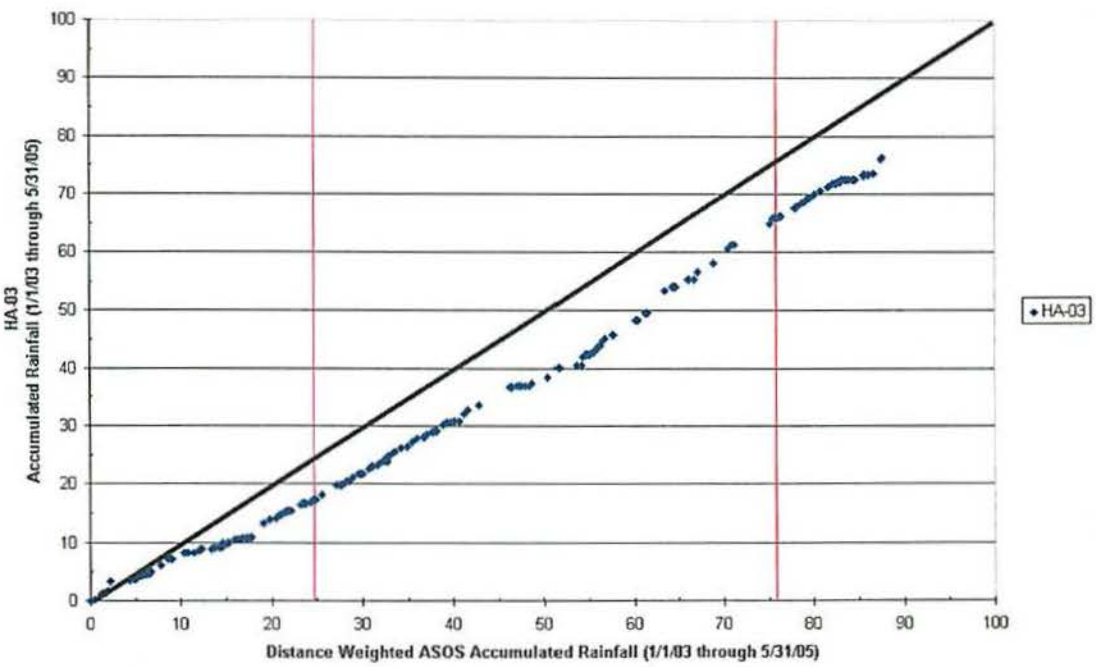
Double Mass Analysis for ED-04



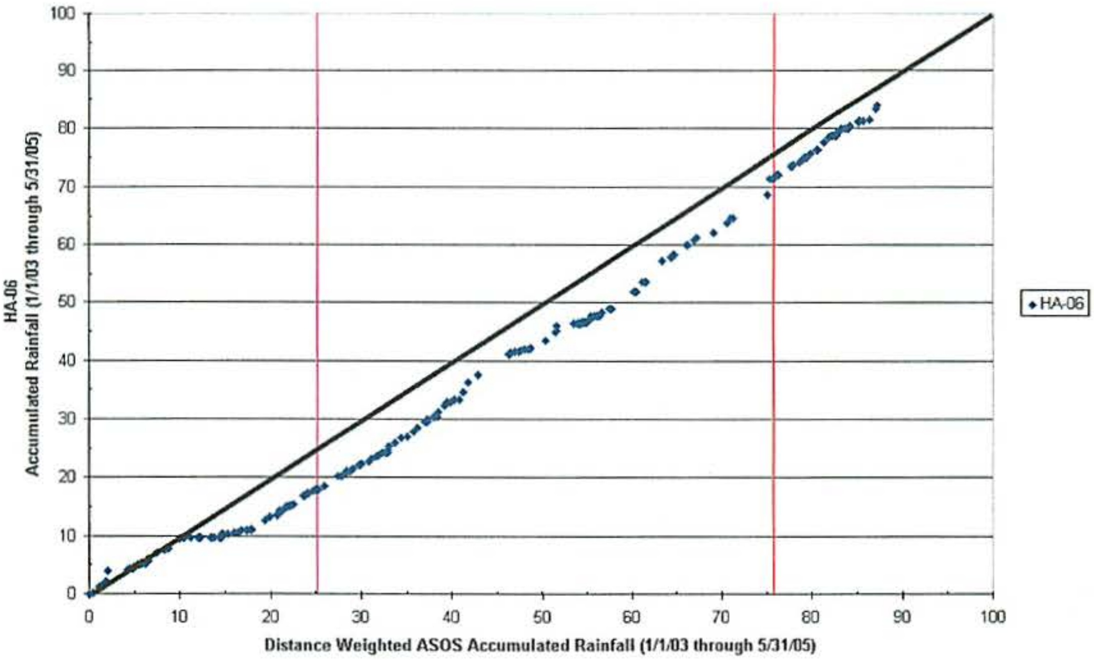
Double Mass Analysis for HA-02



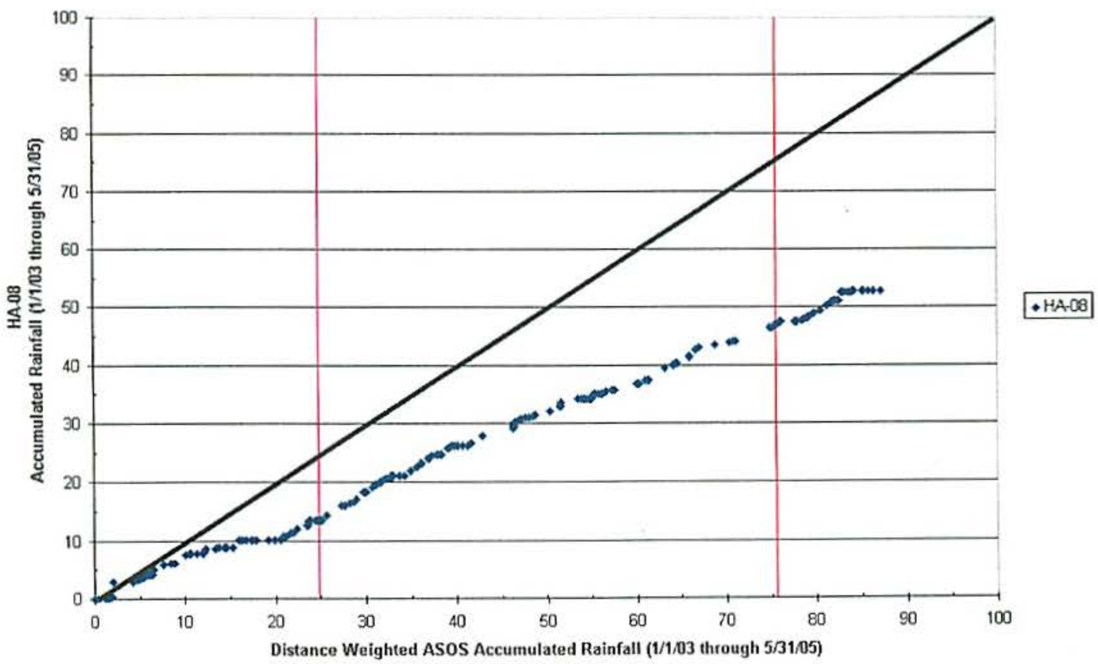
Double Mass Analysis for HA-03



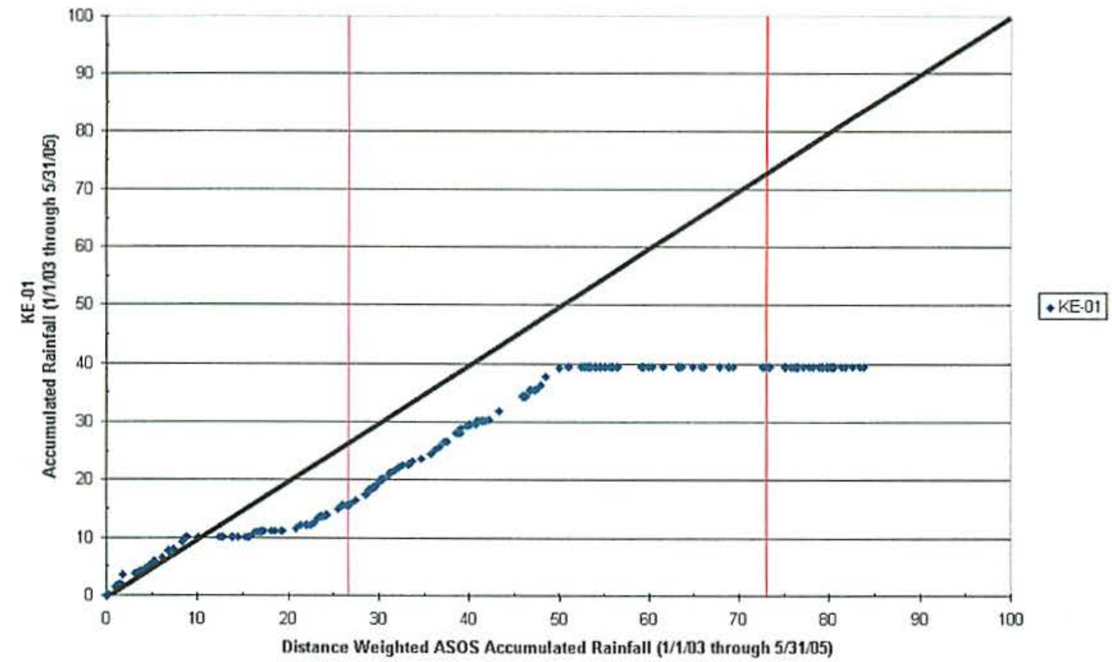
Double Mass Analysis for HA-06



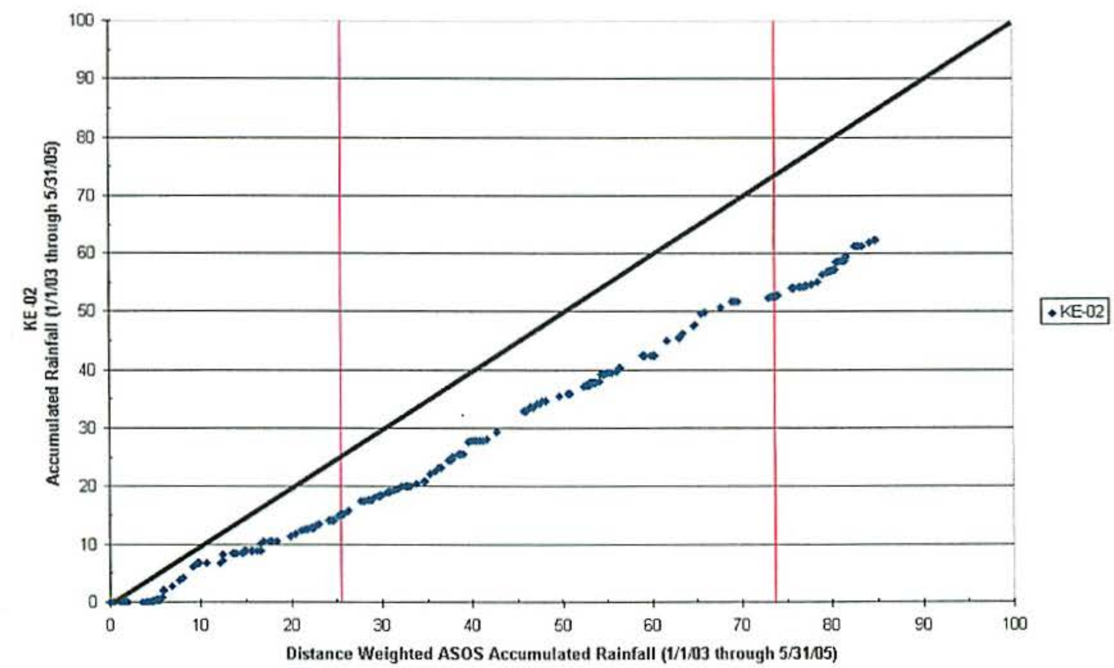
Double Mass Analysis for HA-08



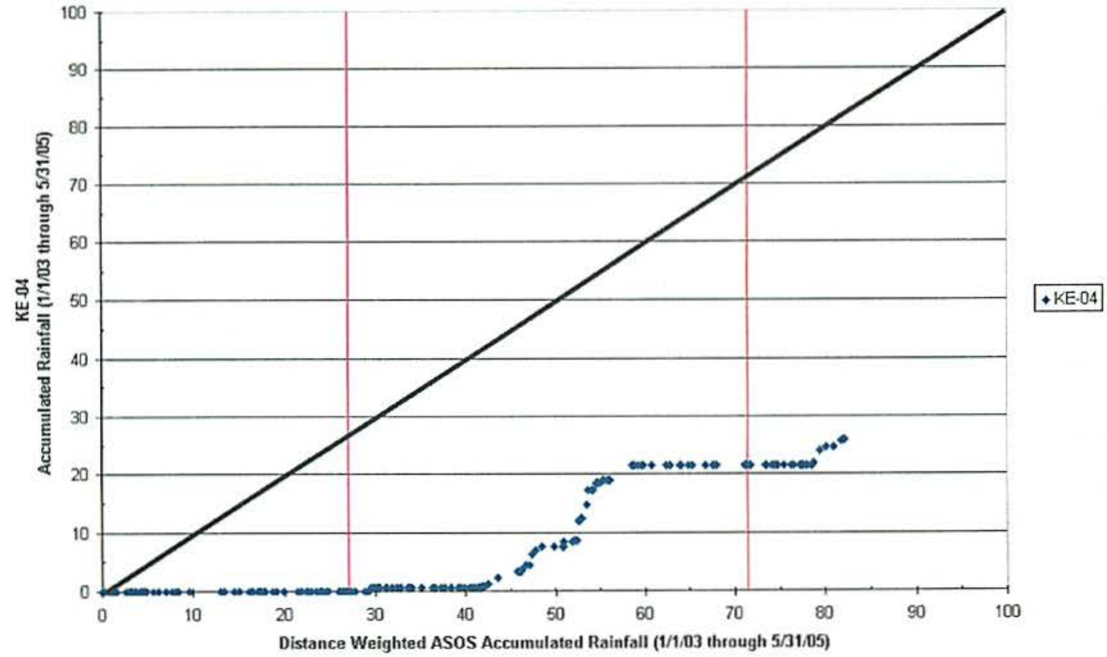
Double Mass Analysis for KE-01



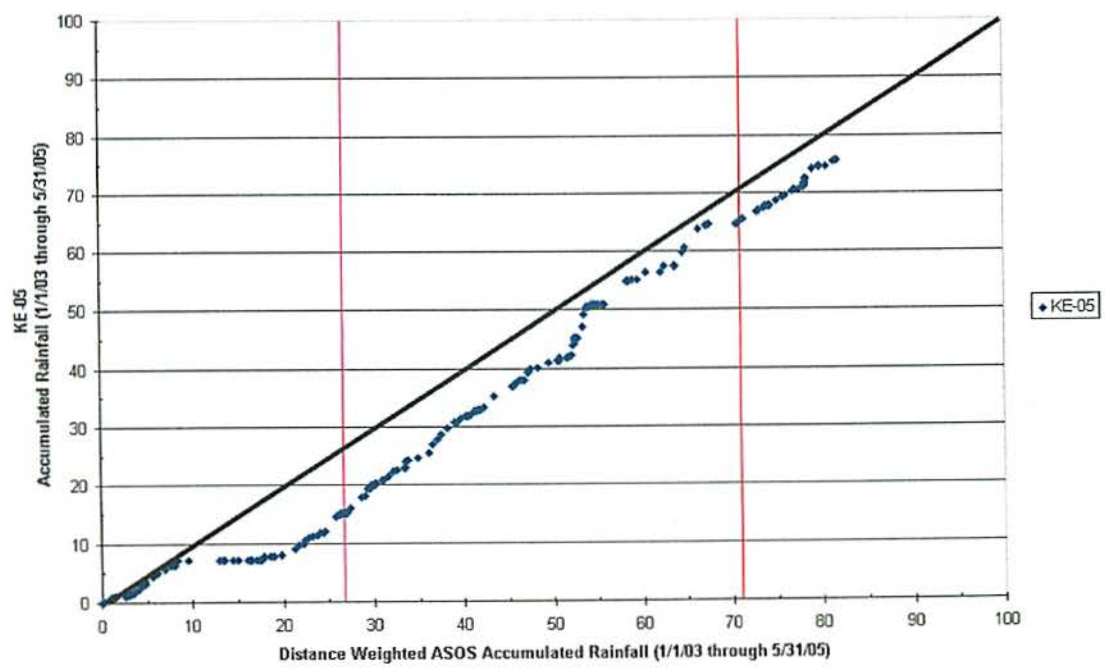
Double Mass Analysis for KE-02



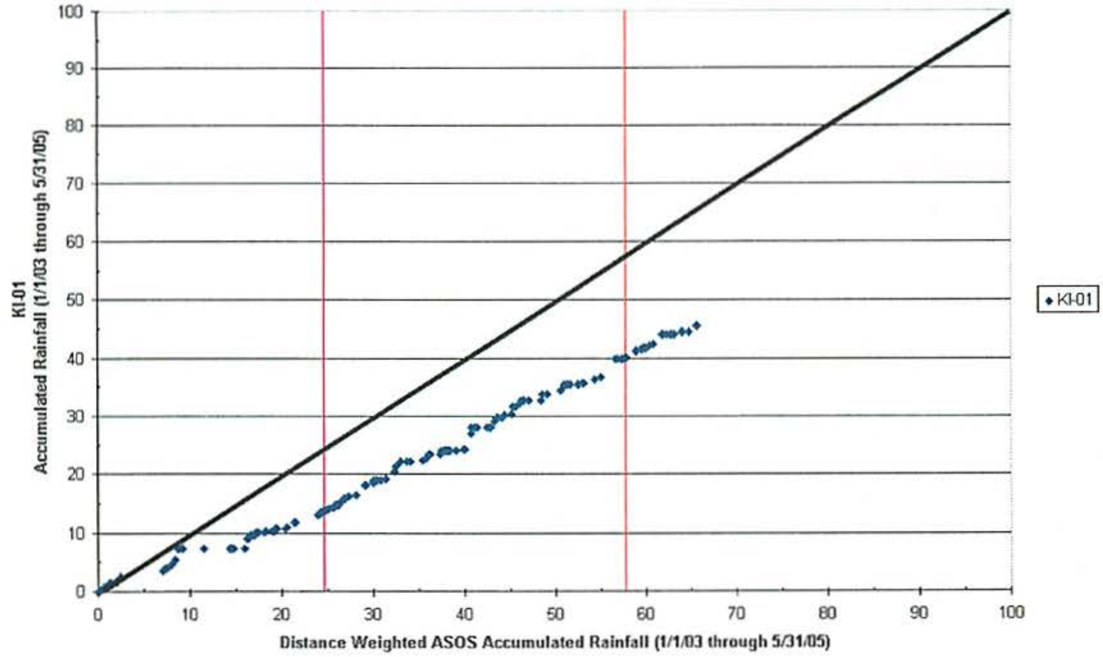
Double Mass Analysis for KE-04



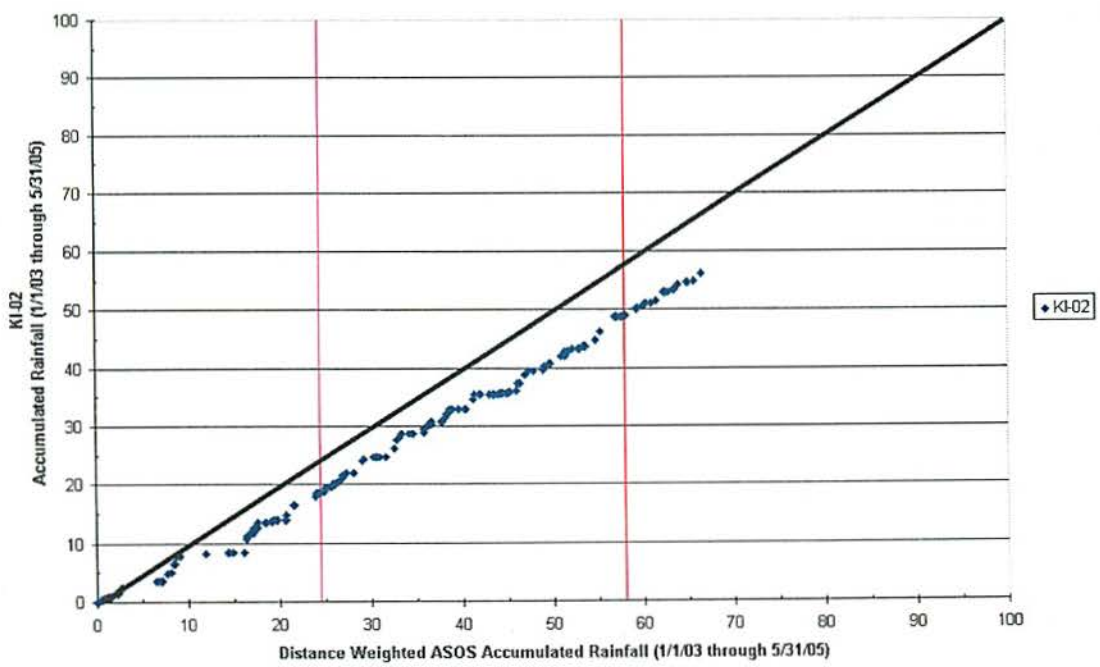
Double Mass Analysis for KE-05



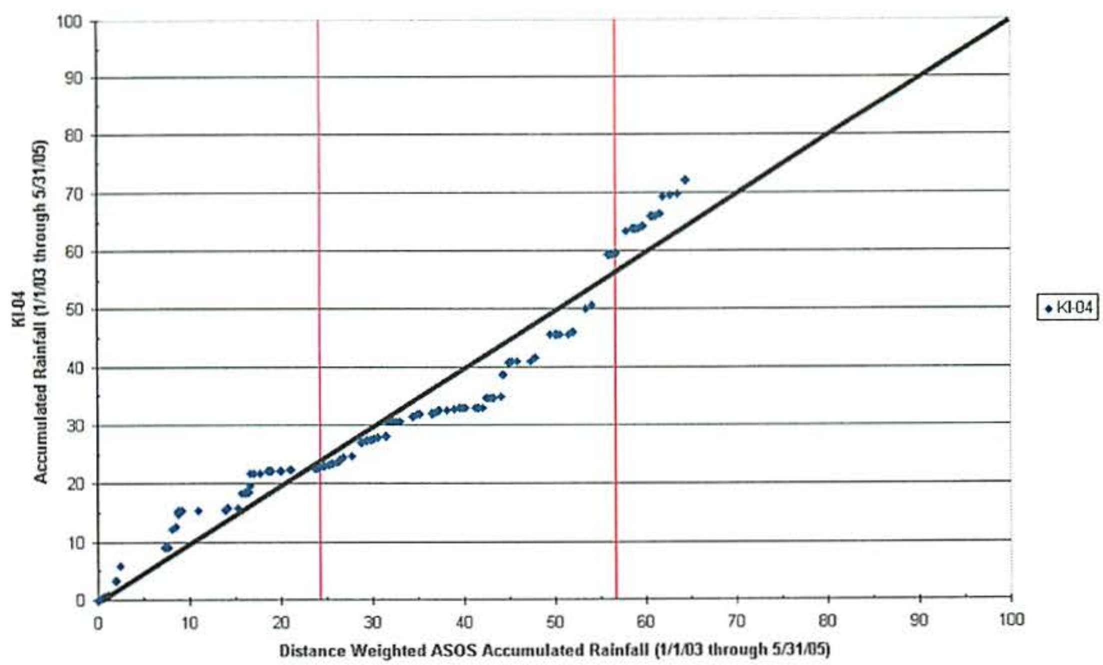
Double Mass Analysis for KI-01



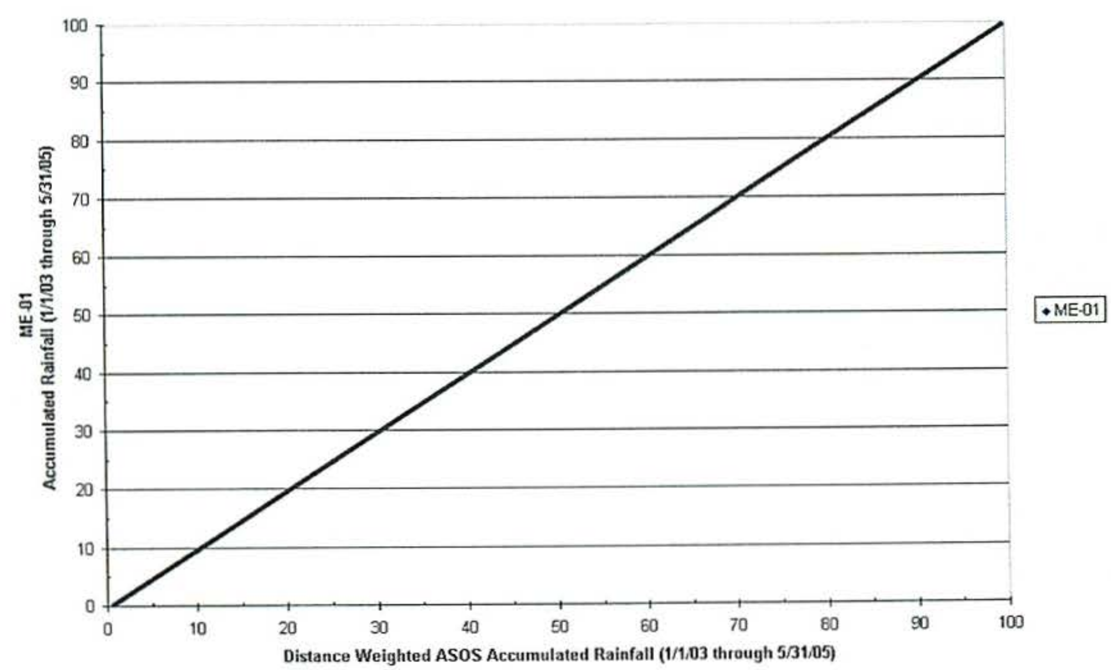
Double Mass Analysis for KI-02



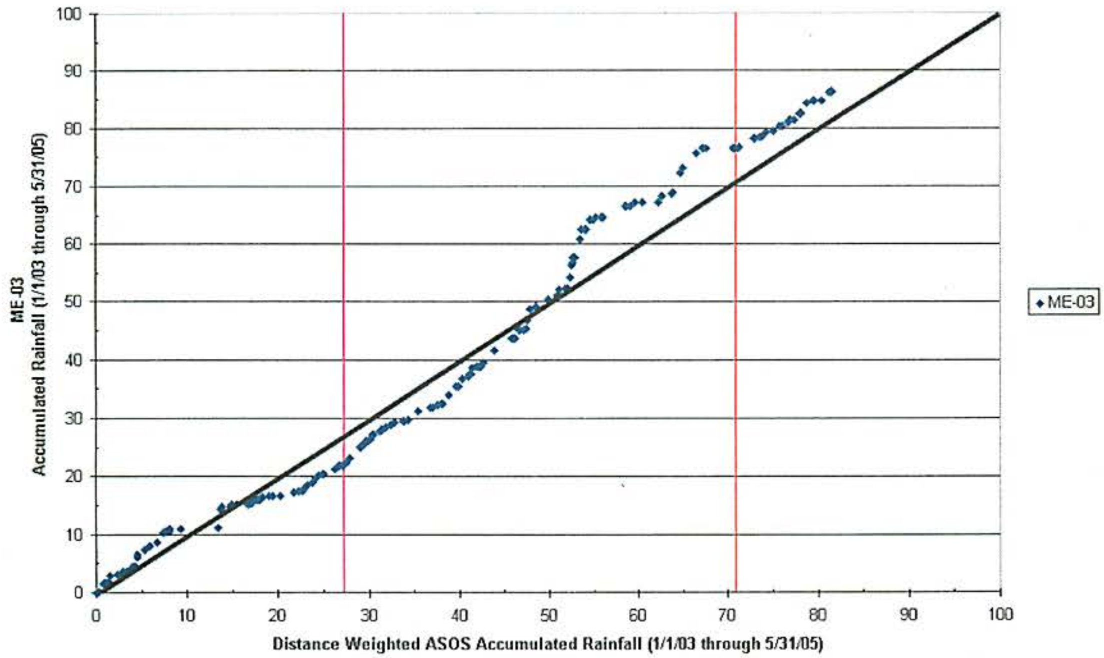
Double Mass Analysis for KI-04



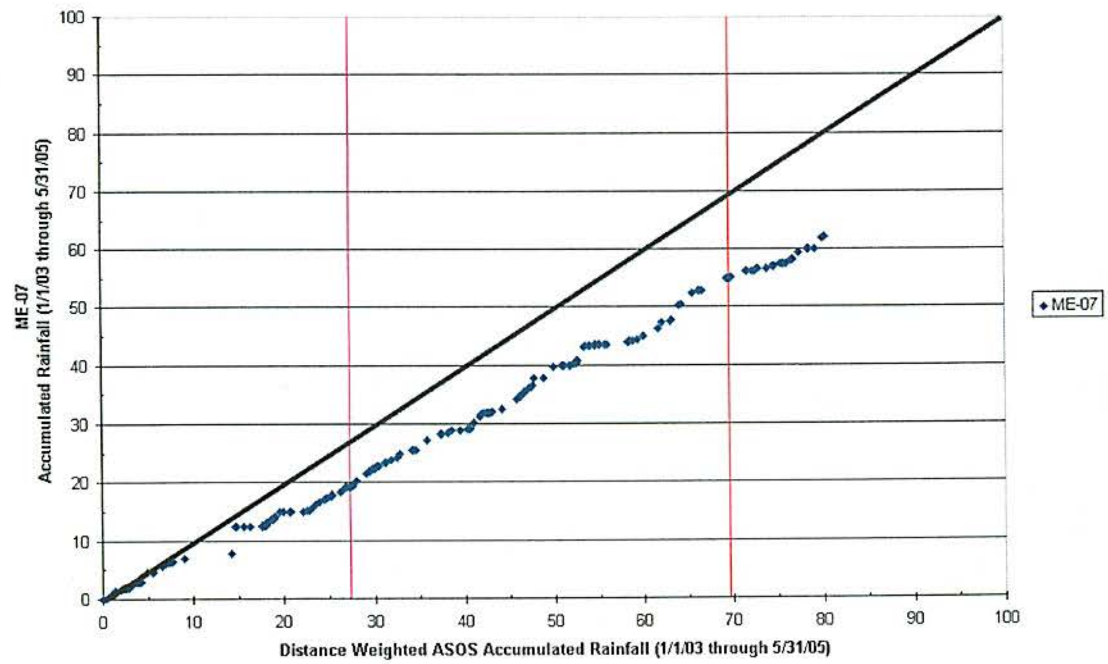
Double Mass Analysis for ME-01



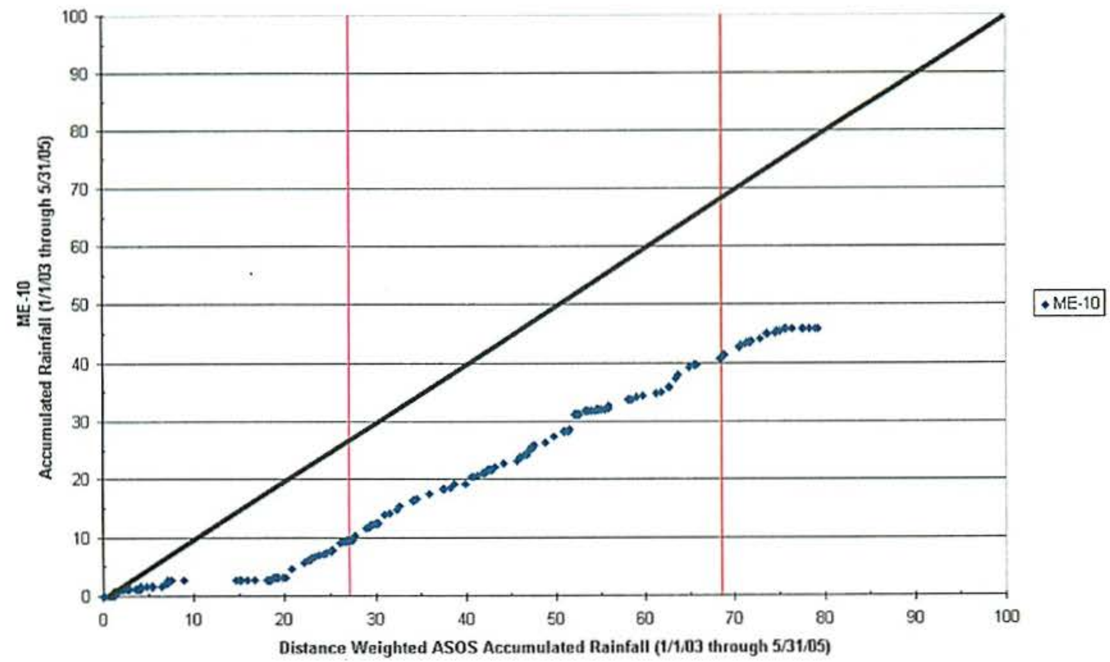
Double Mass Analysis for ME-03



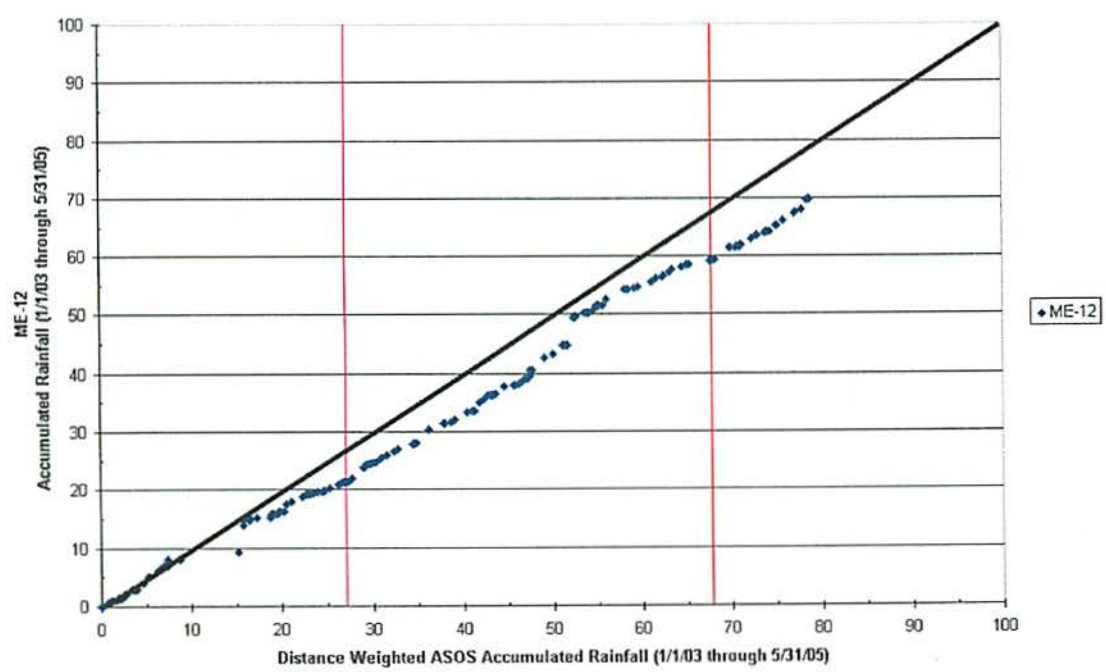
Double Mass Analysis for ME-07



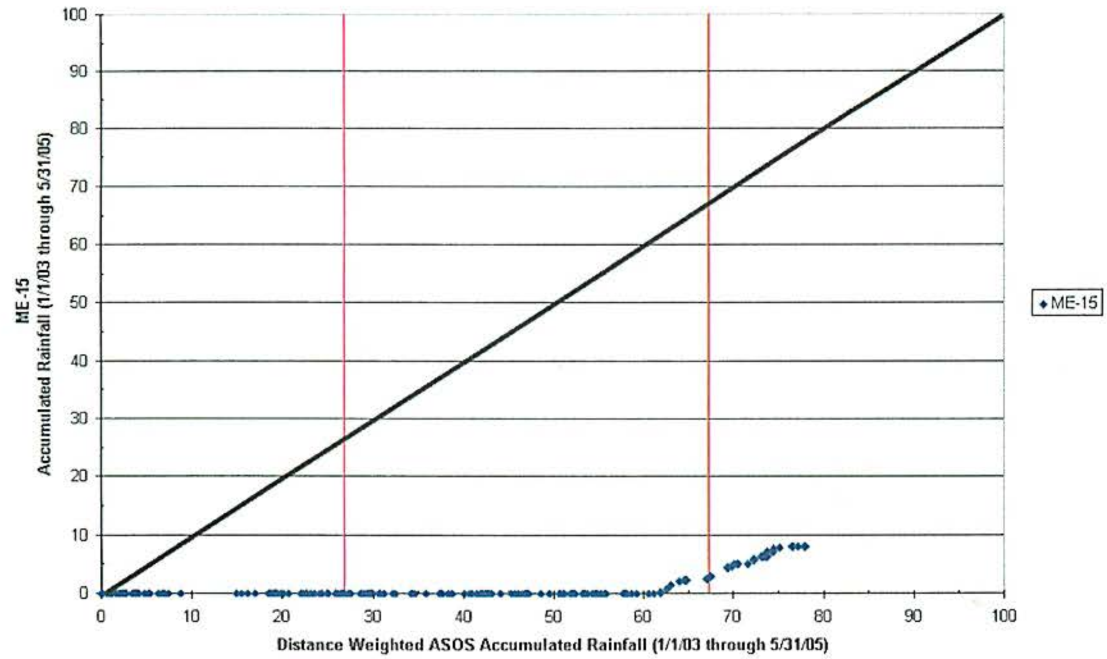
Double Mass Analysis for ME-10



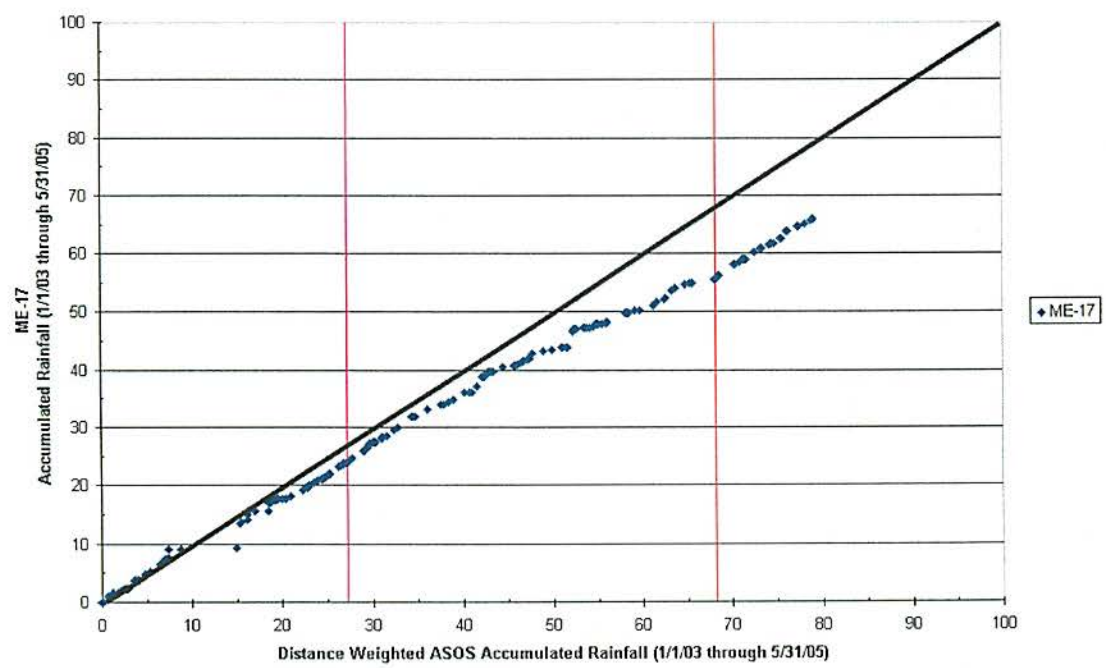
Double Mass Analysis for ME-12



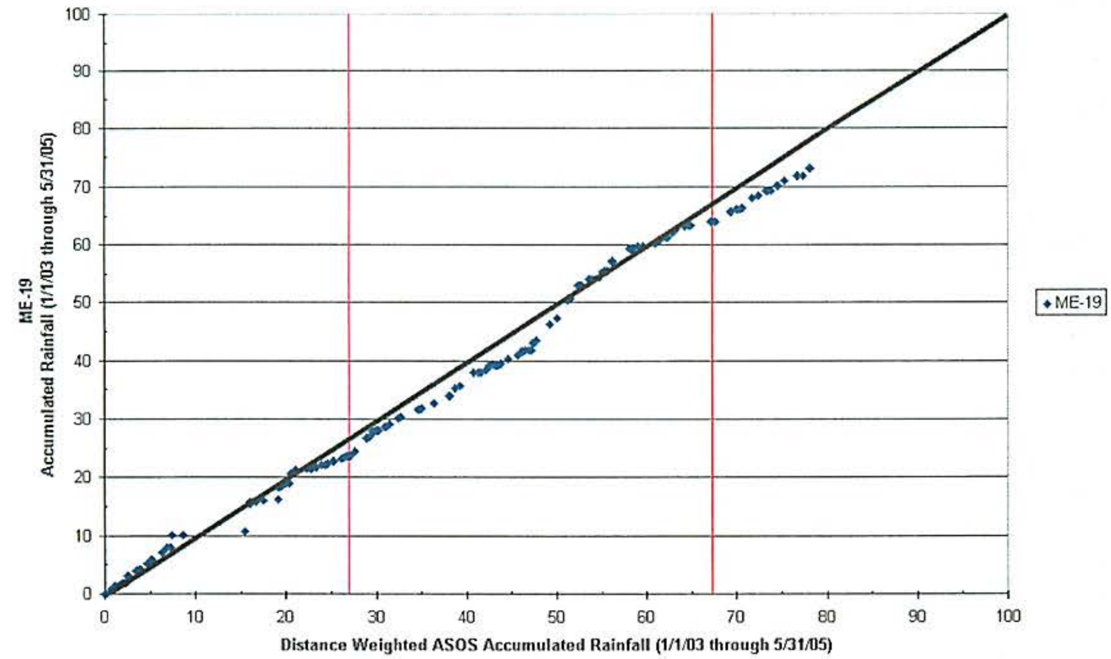
Double Mass Analysis for ME-15



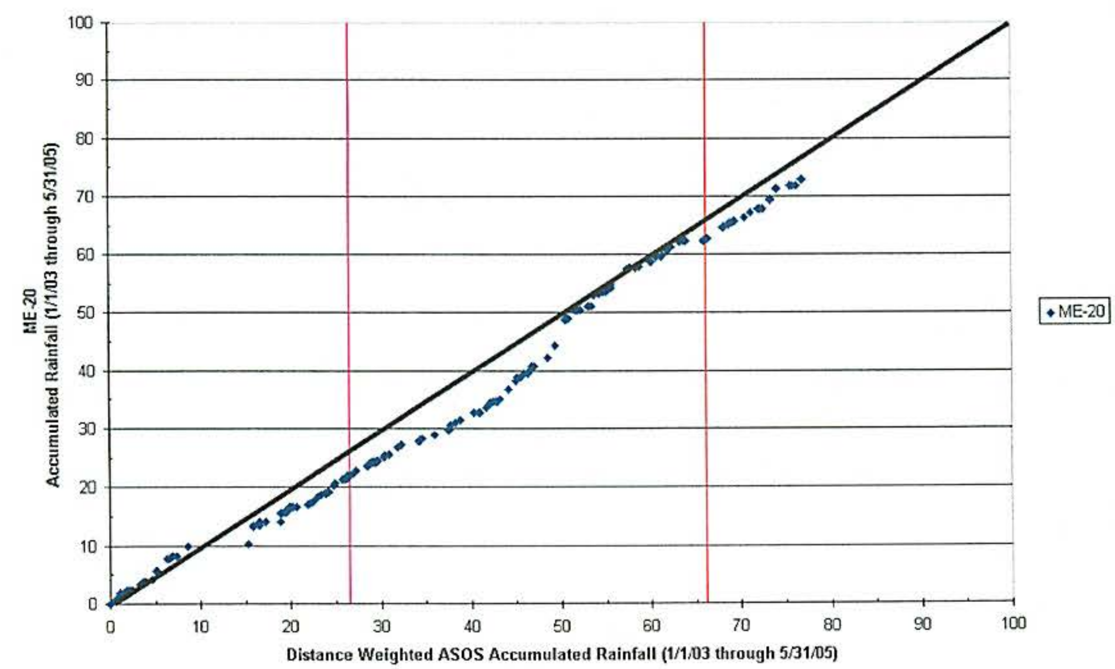
Double Mass Analysis for ME-17



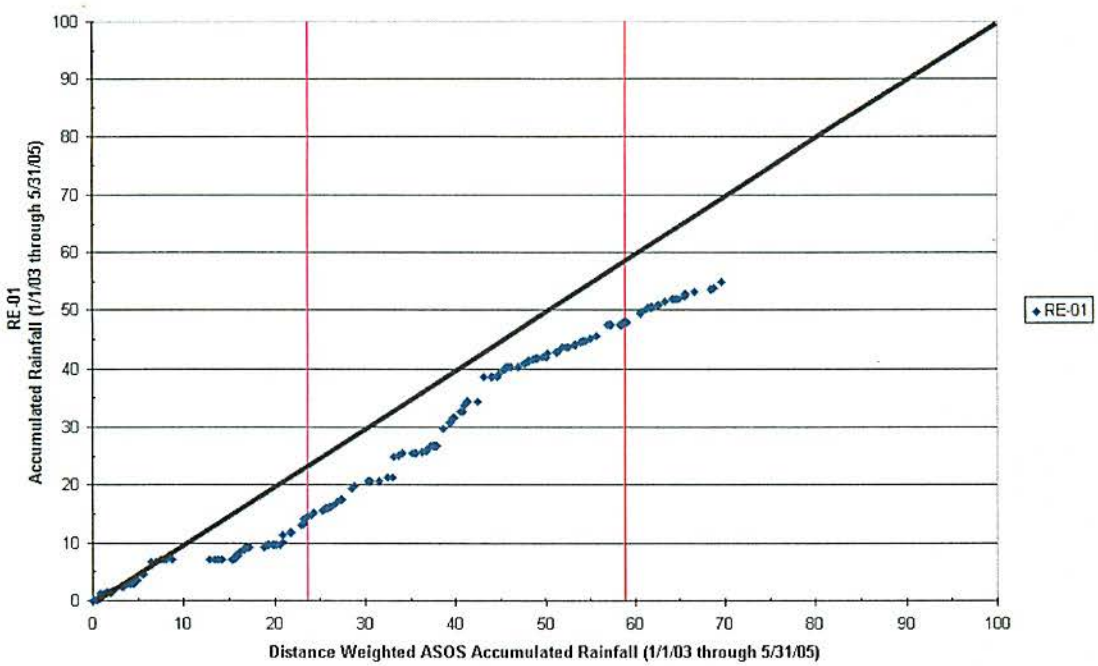
Double Mass Analysis for ME-19



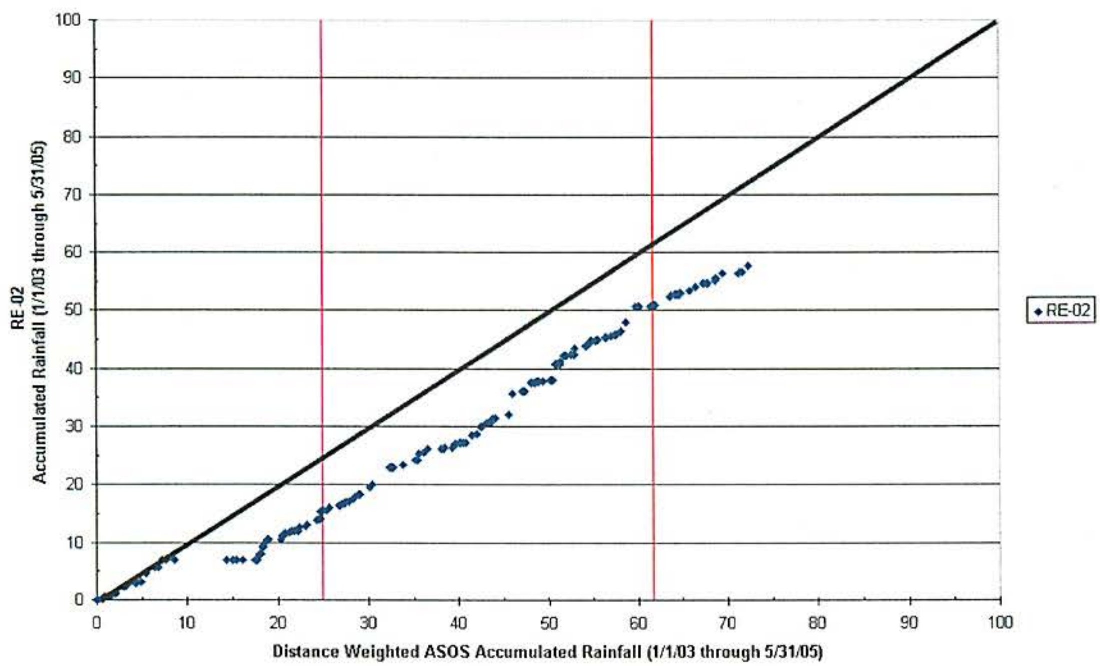
Double Mass Analysis for ME-20

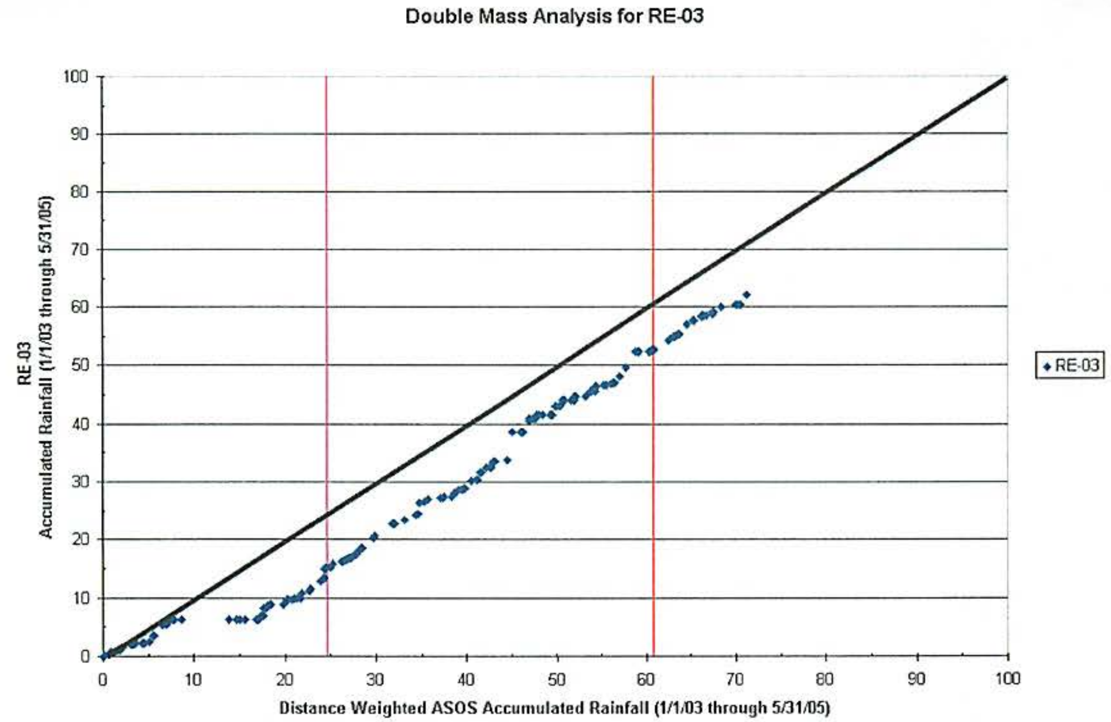


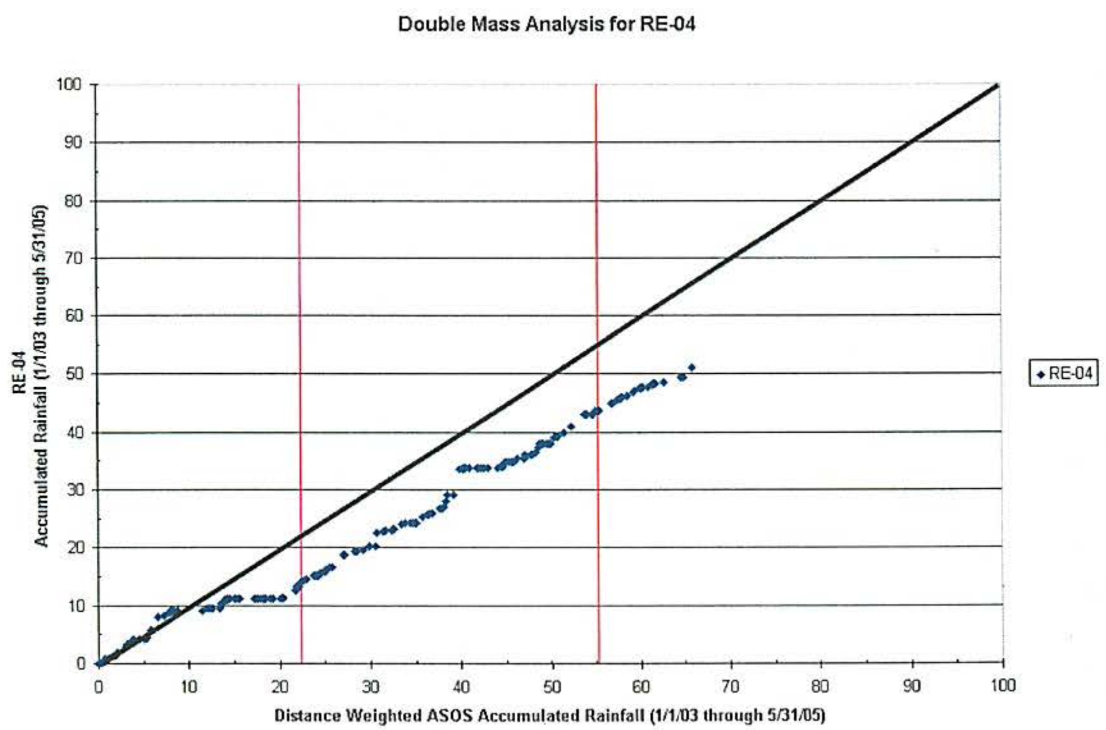
Double Mass Analysis for RE-01



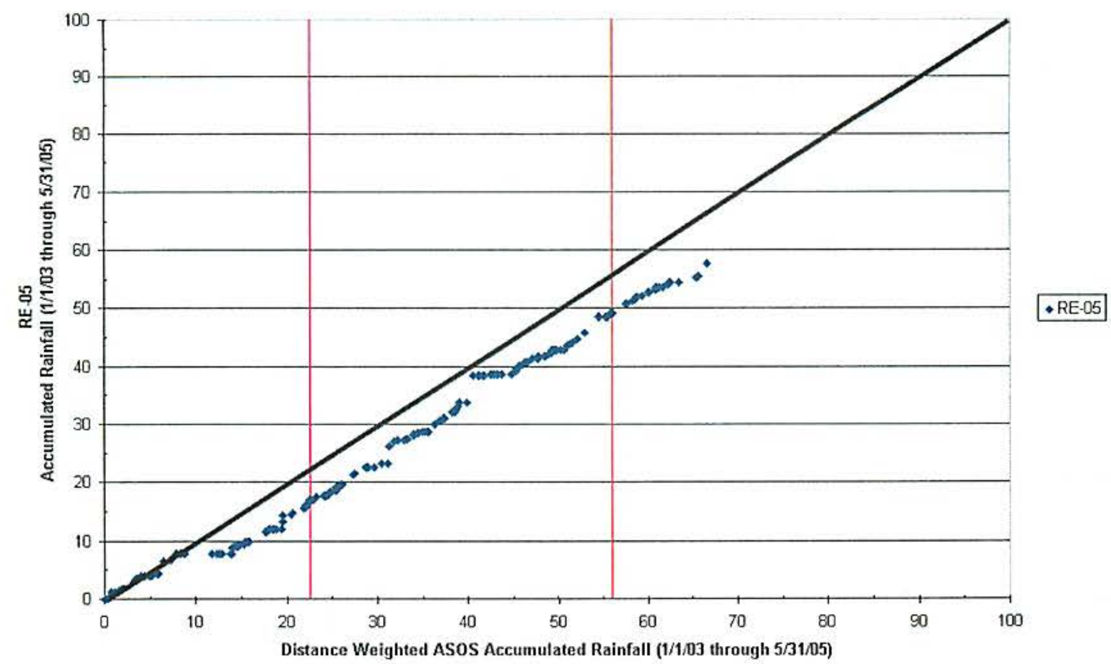
Double Mass Analysis for RE-02



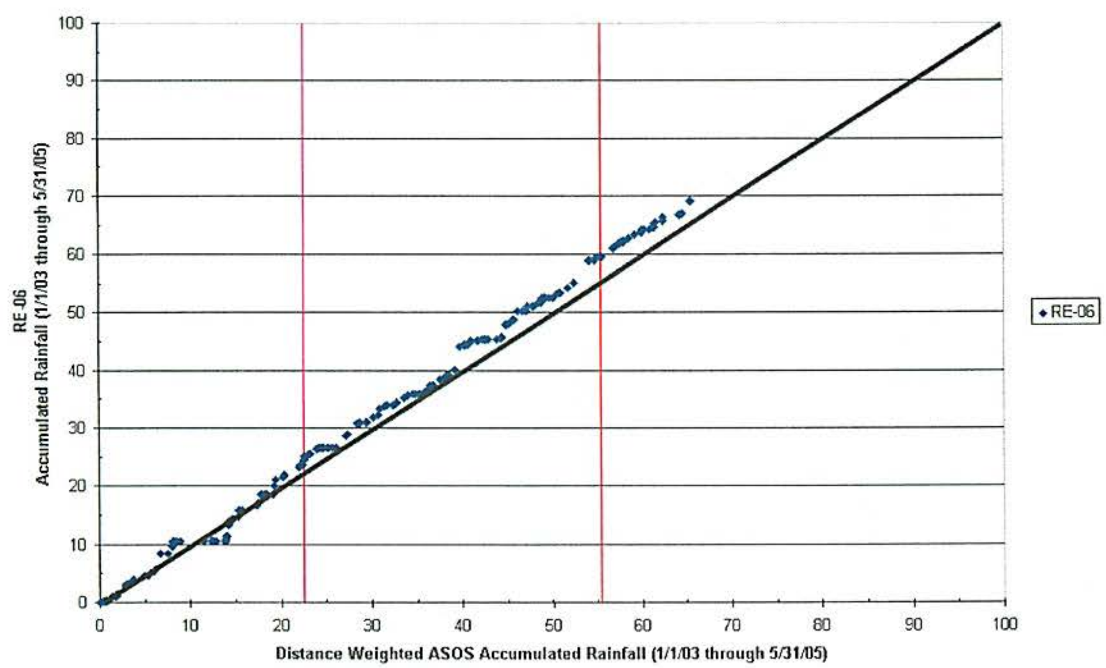

Double Mass Analysis for RE-03
RE-03
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
RE-03


Double Mass Analysis for RE-04
RE-04
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
RE-04

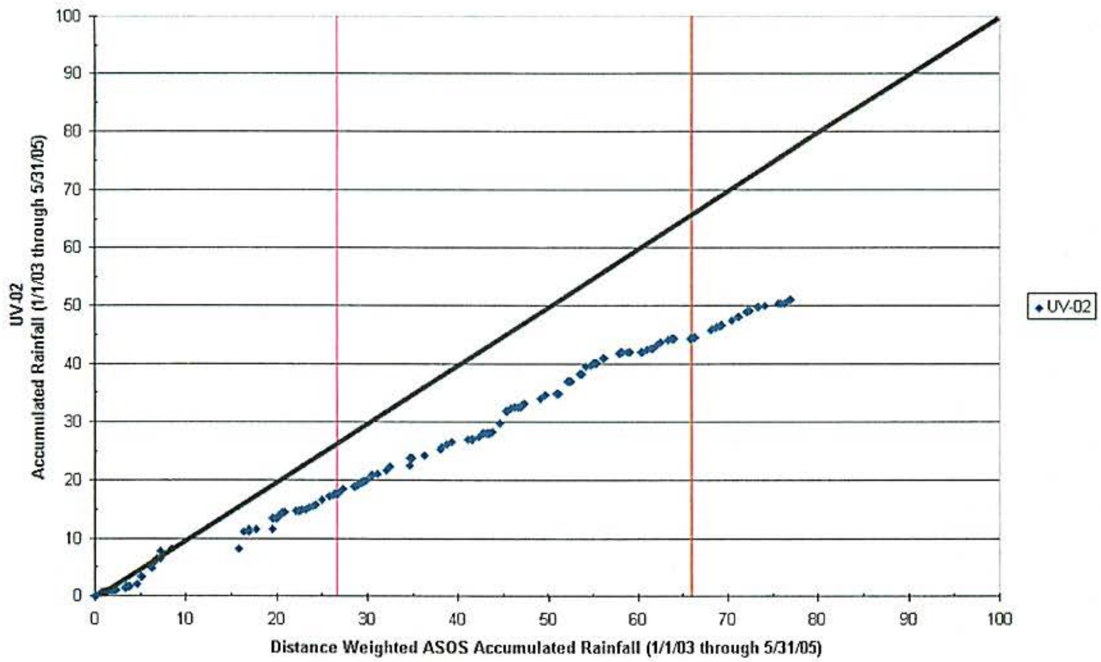
Double Mass Analysis for RE-05



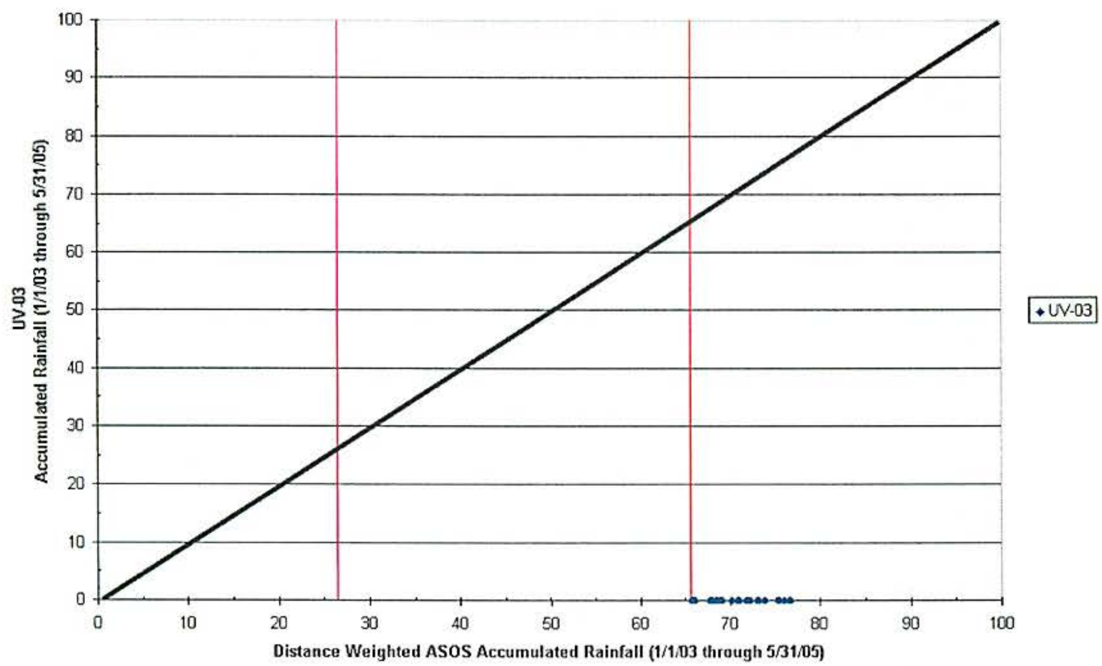
Double Mass Analysis for RE-06



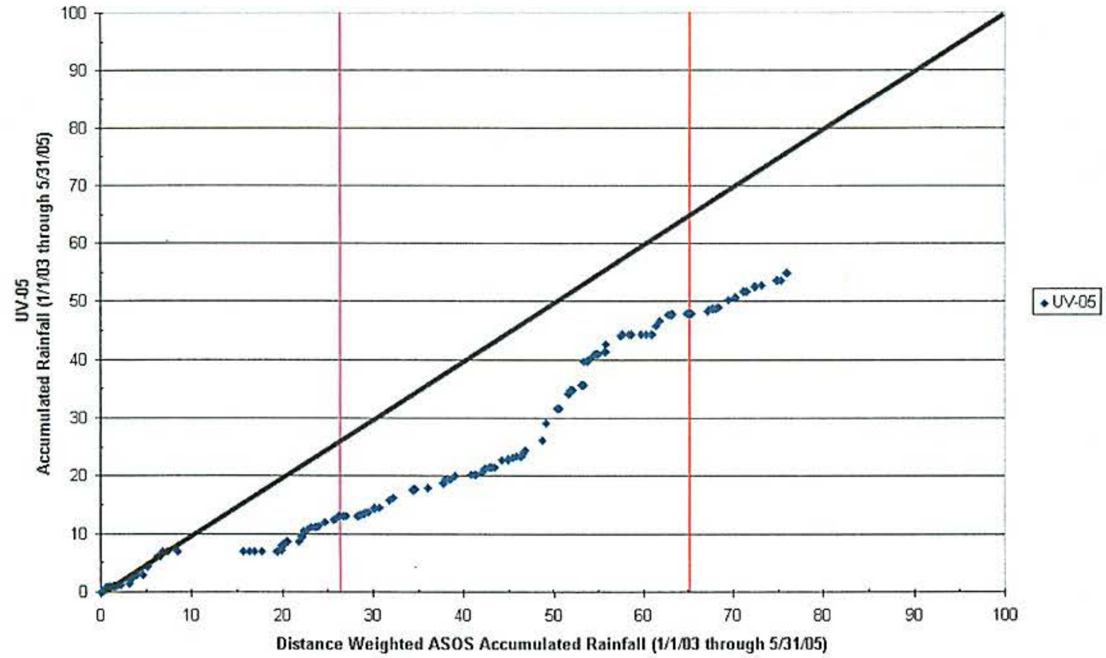
Double Mass Analysis for UV-02



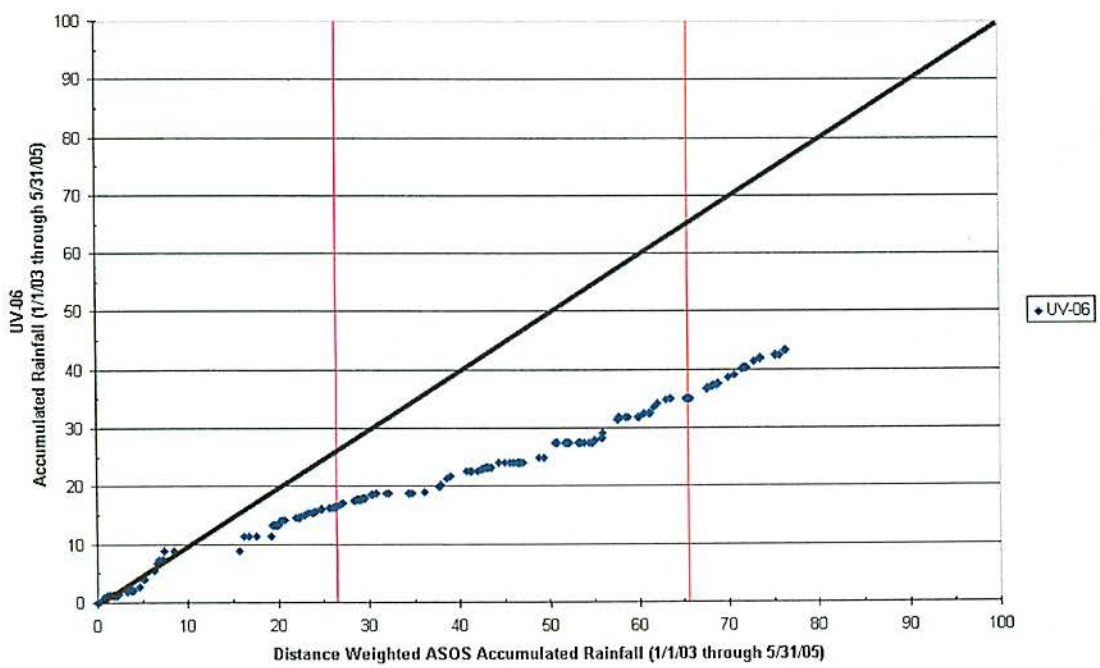
Double Mass Analysis for UV-03



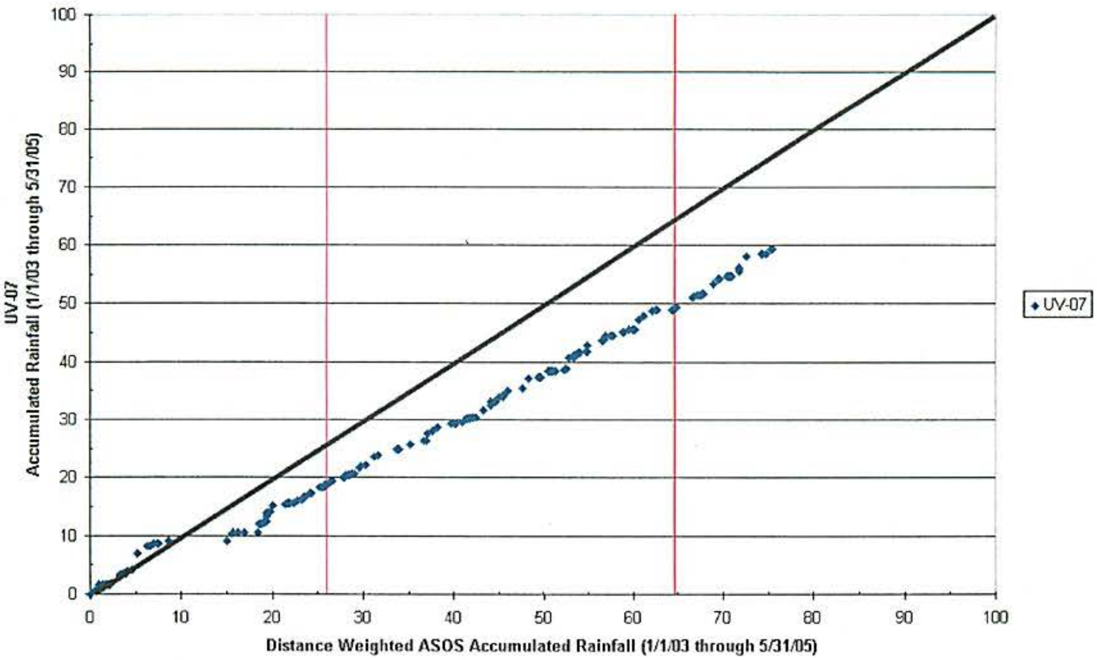
Double Mass Analysis for UV-05



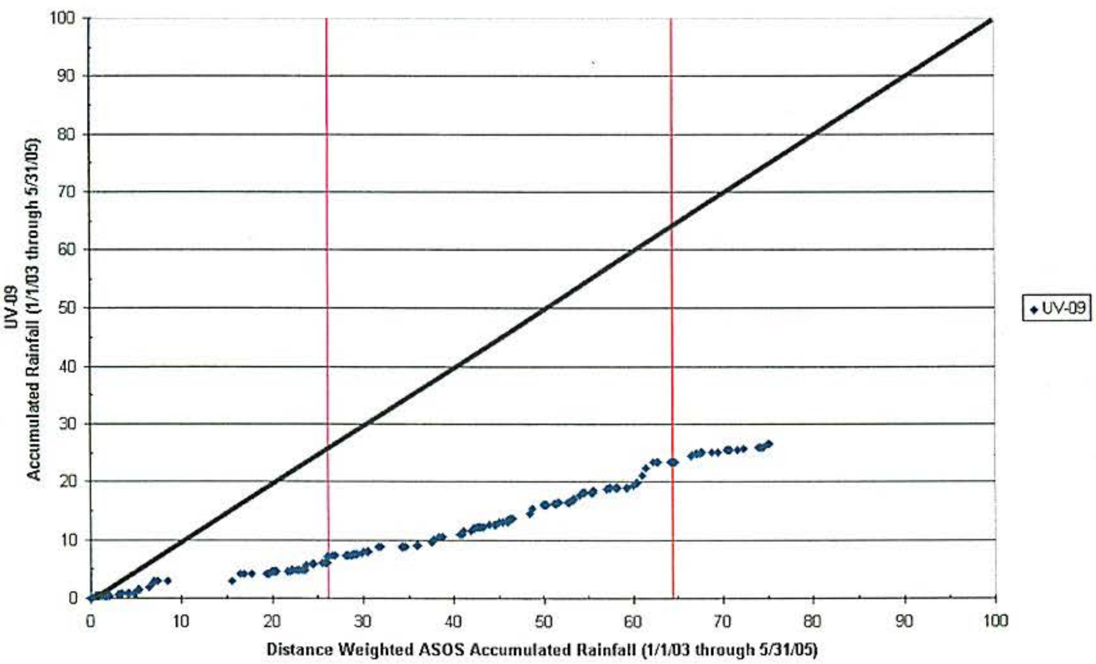
Double Mass Analysis for UV-06

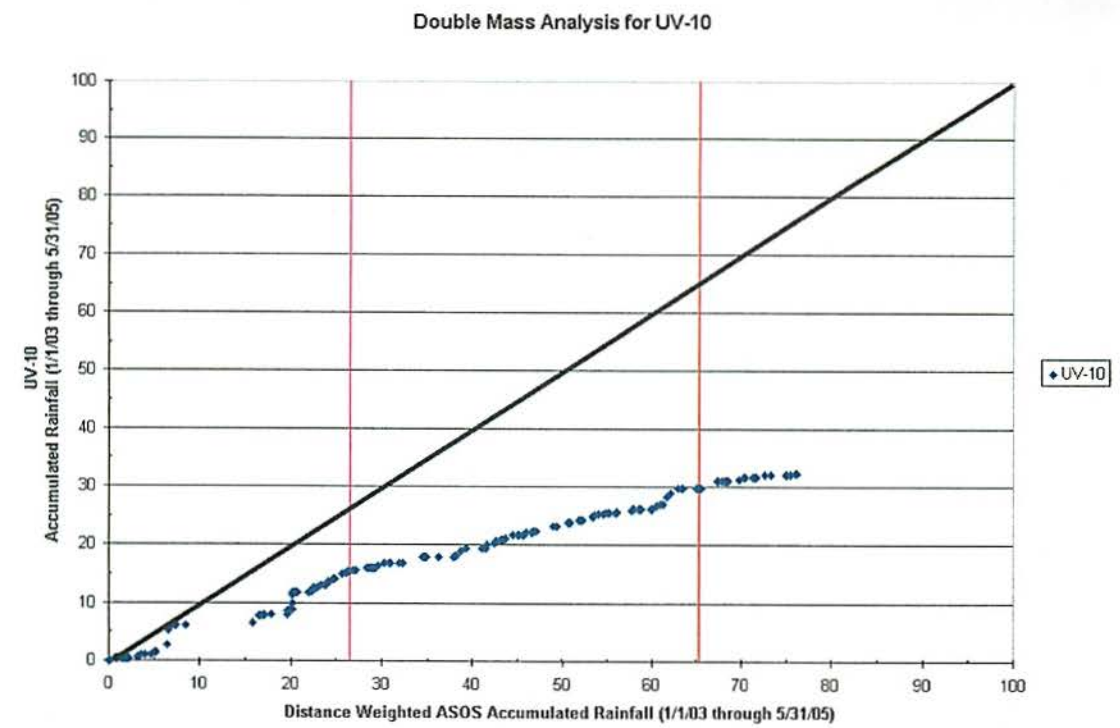


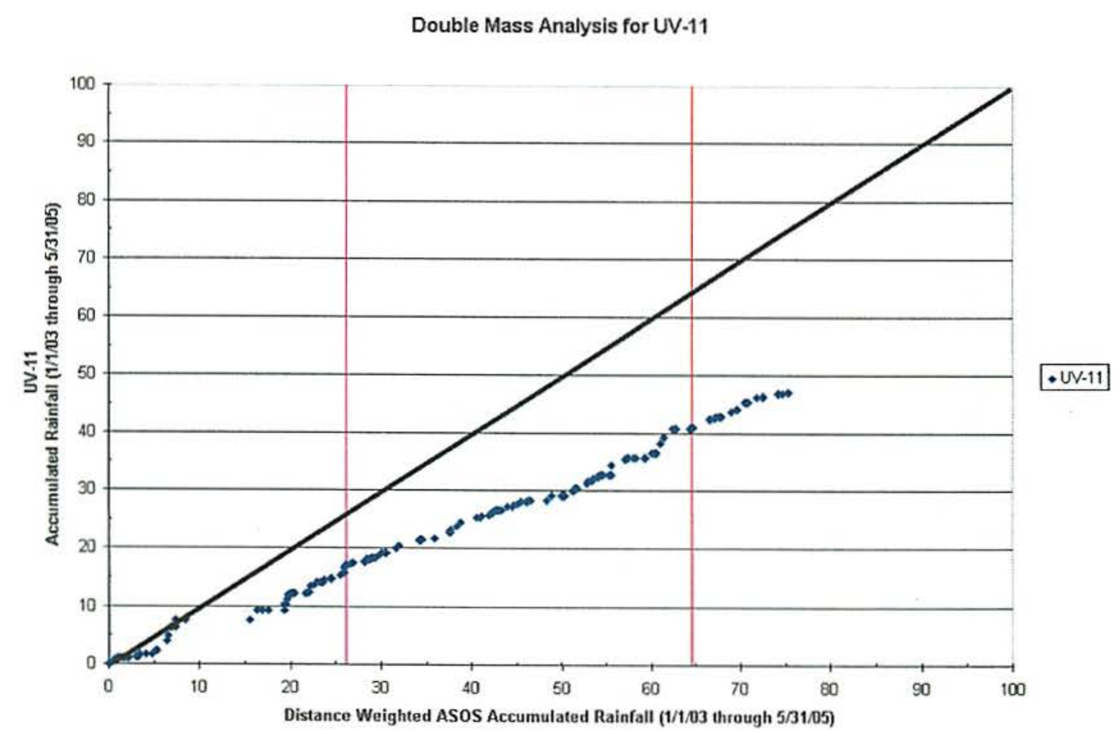
Double Mass Analysis for UV-07



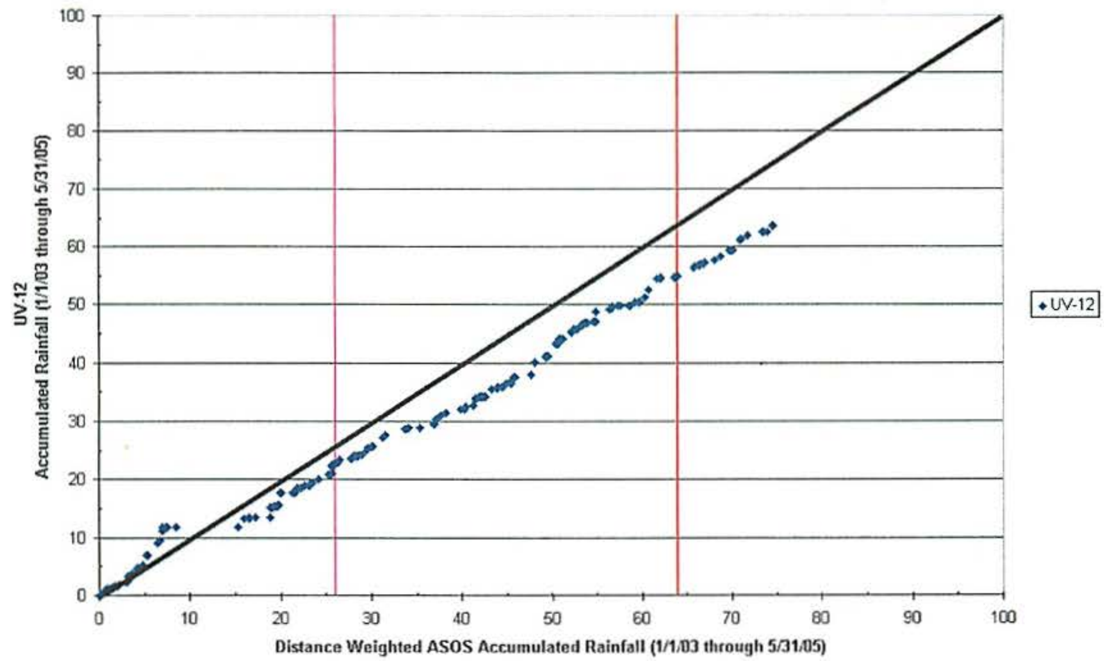
Double Mass Analysis for UV-09



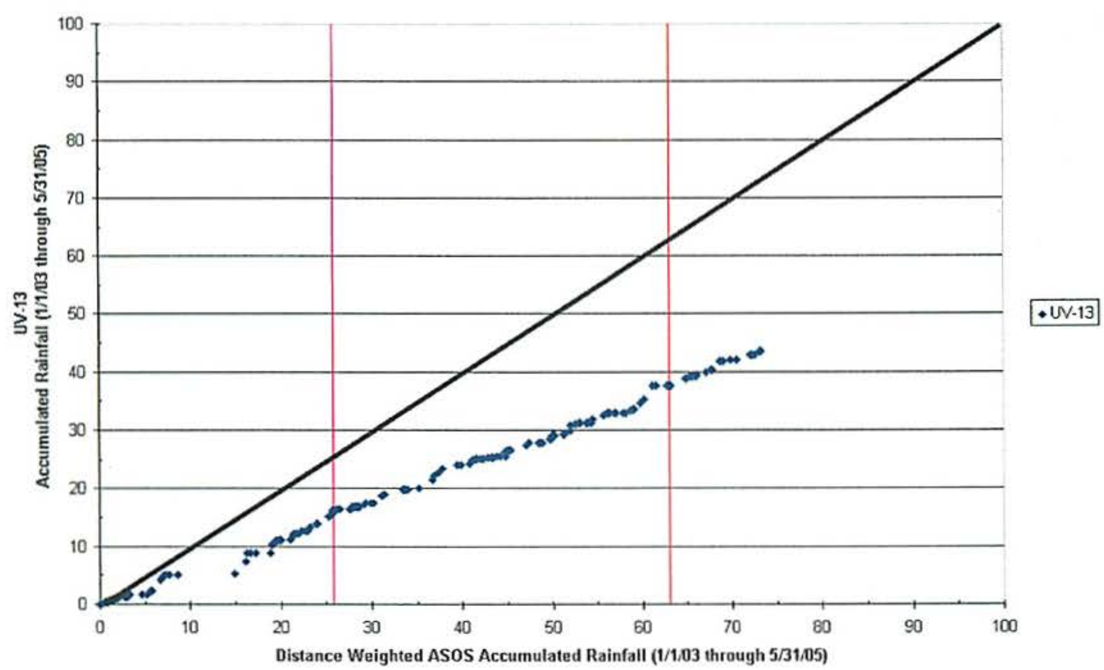

Double Mass Analysis for UV-10
UV-10
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
UV-10


Double Mass Analysis for UV-11
UV-11
Accumulated Rainfall (1/1/03 through 5/31/05)
Distance Weighted ASOS Accumulated Rainfall (1/1/03 through 5/31/05)
UV-11

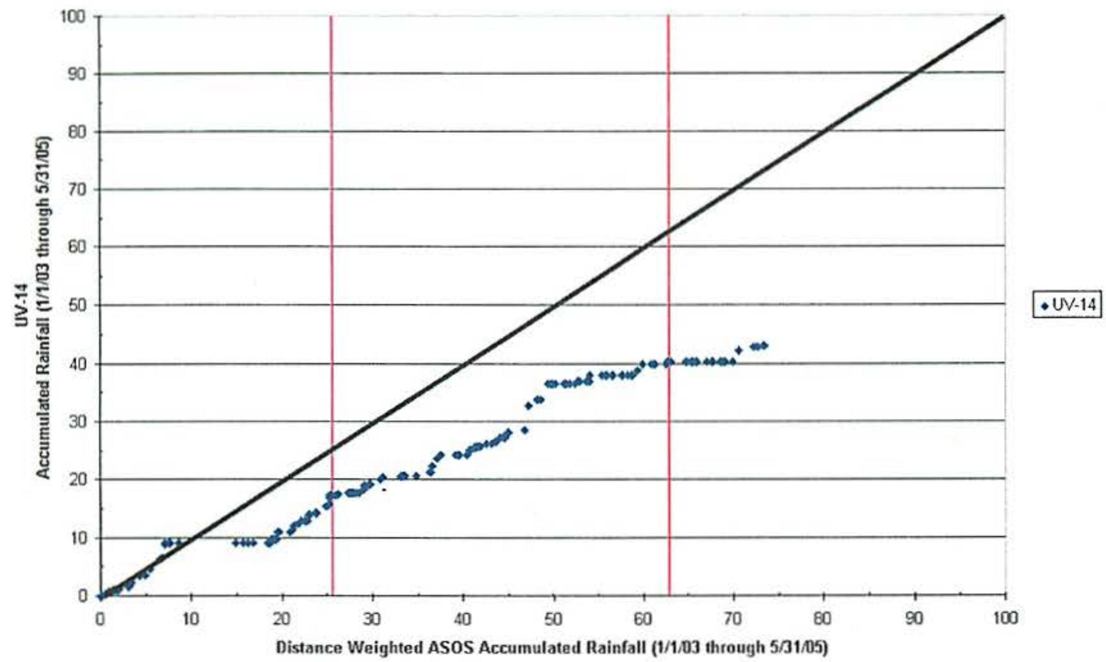
Double Mass Analysis for UV-12



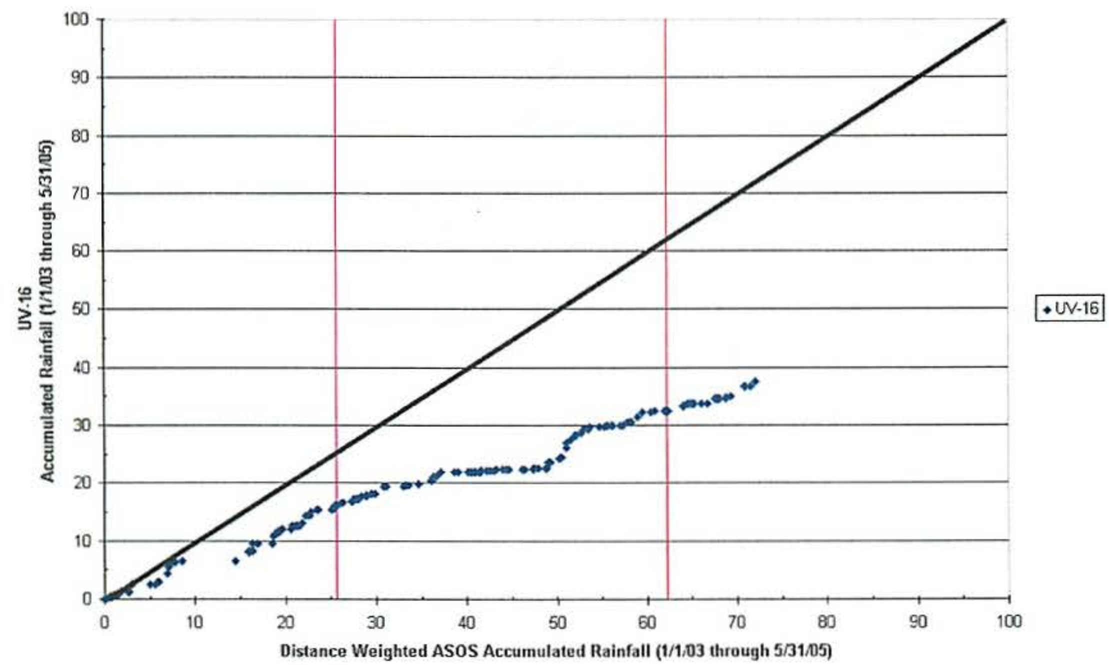
Double Mass Analysis for UV-13



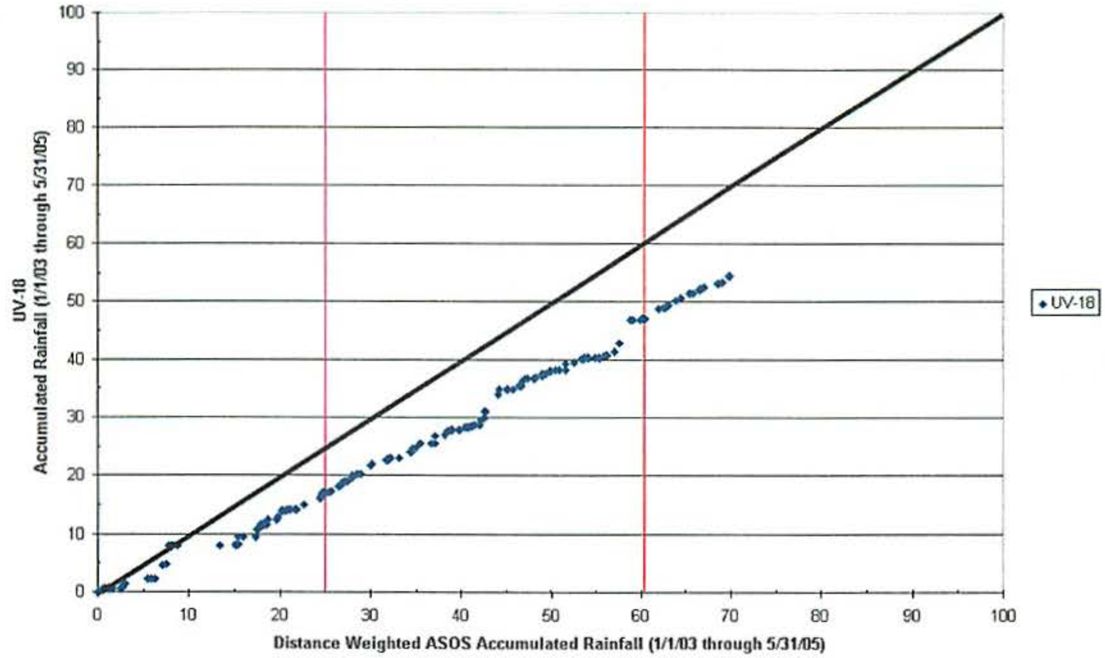
Double Mass Analysis for UV-14



Double Mass Analysis for UV-16



Double Mass Analysis for UV-18



Double Mass Analysis for UV-20