REPORT

URBAN DRAINAGE AND FLOOD CONTROL DISTRICT
RAIN GAGE SYSTEM AUDIT
SITE EVALUATIONS AND DATA ANALYSIS

Submitted to:

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1. Overview

The objective of this report is to establish the validity and quality of rain gage data for the real-time ALERT rain gage network that is owned and operated by the Urban Drainage and Flood Control District (the District). The District began building this network in 1979. OneRain conducted field surveys of each of the 130 stationary gage sites in order to qualify the data received and archived from these sites. Additionally, OneRain investigated the data through exploratory data analysis processes including:

- Double-mass analysis
- Nearest neighbor comparison (a table-based representation of the double-mass analysis data)

This report provides ratings for each rain gage for the 2007 season based on the field investigations and double-mass analyses. These ratings will enable OneRain to make decisions and recommendations about the gage sites and the validity of their data.

The intent of this report is to define the criteria for minimum acceptable performance of the rain gages. Appendix A provides summary information about each site, photographs, and a double-mass plot covering all of 2007.

2. System Description

The Urban Drainage and Flood Control District serves the City and County of Denver and seven surrounding counties covering 1608 square miles. The District's system covers 1600 miles of drainage ways and 2.3 million residents. The automated flood warning system (FWS) consists of 151 sites, and has been in operation since 1979. The District uses primarily point measurement (rain gages) to quantify rainfall falling in the eight county area.

The FWS has 133 rain gages, 90 water level gages, and 9 weather stations. However, 3 of the rain sites (Utah Park, Castle Oaks and Boulder Jail) are not currently installed. The rain measurement sites consist of a tipping bucket rain gage and battery-powered radio transmitter. These sites transmit their data via the Automated Local Evaluation in Real Time (ALERT) protocol.

In Figure 1 below, all of the gages in both the UDFCD and Boulder County systems are shown. However, only the District owned gages were evaluated as part of this study.

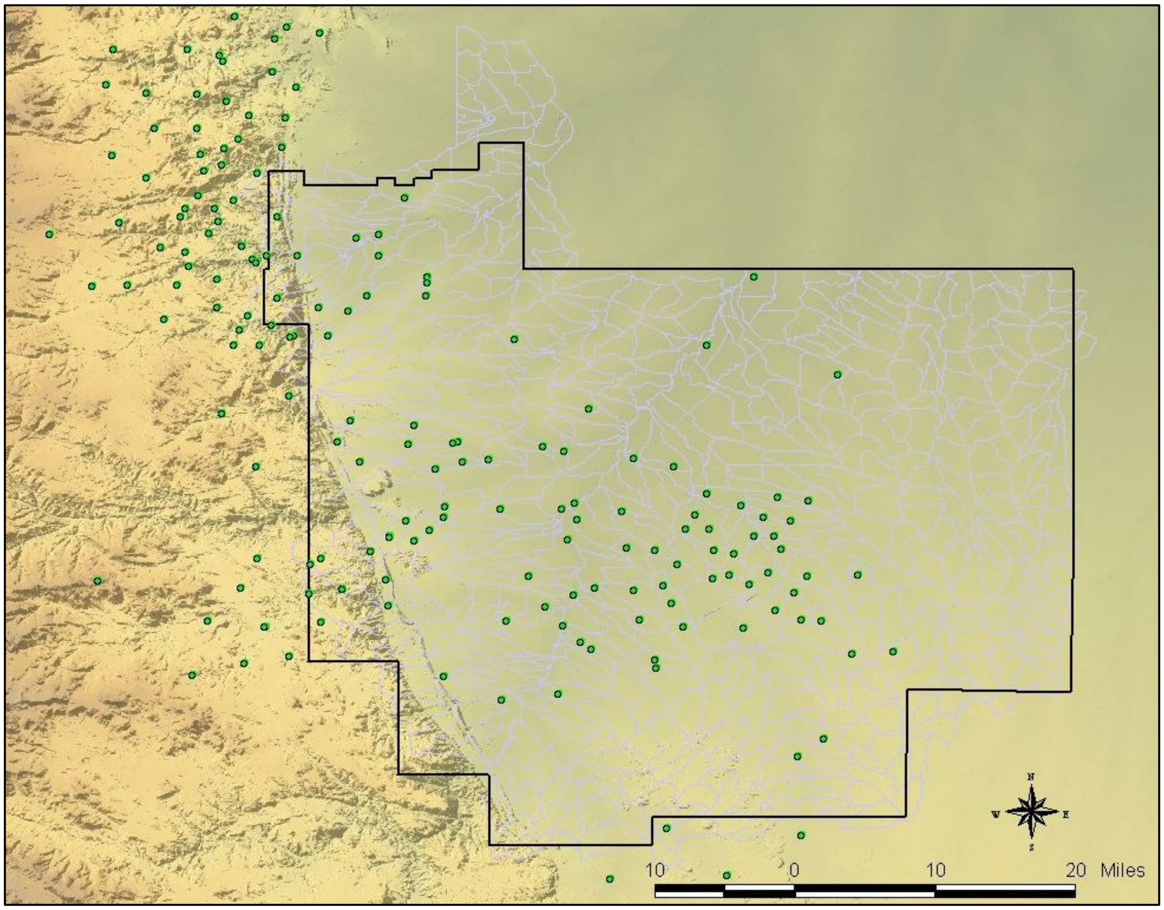


Figure 1: UDFCD and Boulder County rain gage locations, only the UDFCD gages are described in this study

3. DESCRIPTIONS OF ANALYSES

This section presents the background information for each of the analyses that were applied in this report. The analyses are:

- Double-mass (D-M) plot
- Nearest neighbor table
  - Accumulation
  - Number of reports
  - First and last reporting date

3.1 Double-Mass Plot

A double-mass plot is a graphical means to compare one rain gage to a nearby gage or gages over a period of time. The x-axis is the running accumulation of the gage of interest and the y-axis is the running accumulation of a neighboring gage during an identical time period. The neighboring gage can be a single gage or a pseudo-sensor composed of data from several gages. In the latter situation, the average of those multiple neighbors (a, b, c, d and e) is used. If the gage of interest and the neighbor(s) agree perfectly, the resulting plot will follow a 1:1 line. The following equations define the abscissa (x-axis) and ordinate (y-axis) coordinates.

$$X_t = \sum_{i=1}^{t} x_i \tag{1}$$

$$Y_t = \sum_{i=1}^{t} \frac{1}{N_i} \sum_{j=1}^{N_i} y_{ij} \tag{2}$$

Where t is time, i is the i^{th} time step, X_t is the accumulated rainfall at the target gage at time t, x_i is the rainfall at the target gage during the i^{th} time step, Y_t is the average total accumulated rainfall of the nearby gages at time t, y_{ij} is the rainfall during the i^{th} time step at the j^{th} nearby gage, and N_i is the number of non-missing nearby gages at the i^{th} time step.

Individual points, X_tY_t defined by Equations 1 and 2 are aggregated values. Daily values are used for the annual plots while hourly values are used for the storm double-mass plots.

Appendix A is a table of nearest neighbor data for each gage along with pictures and a description of the site. The title on each plot identifies the time period; 2007 for this study. An example plot is shown below.

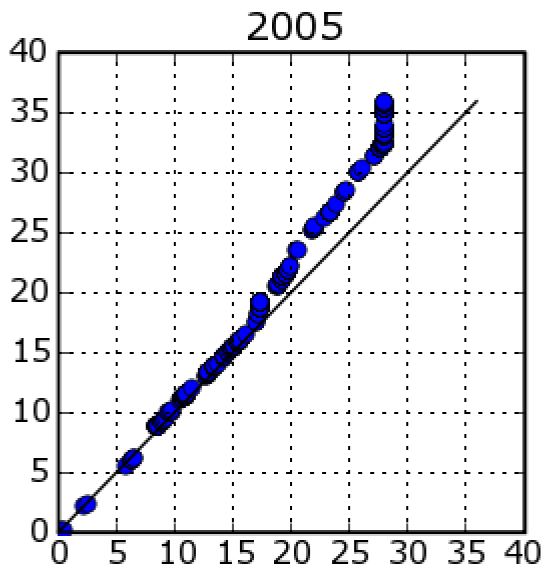


Figure 2: Example double-mass plot (the units for both axes are inches of accumulation)

Section 4.3 provides insight into methods for interpreting double-mass plots. The general rule of thumb is to give a site a low rating if there are significant changes in the course of the line but this is not a steadfast rule. Significant fluctuations in the slope of the target gage versus average surrounding gage accumulation indicate that the target gage may be faulty.

3.2 Nearest Neighbor Tables

Because the double-mass plot alone gives little information about the behavior of the neighboring gages and no information about the times of events, OneRain provides tabular data that is associated with the plot. These data can aid with interpreting the graphical results. Below is an example nearest neighbor table.

Table 1: Nearest neighbor table

	Accum	#Rpts	Start	End
ST43	29.64	1491	01/01/05	10/23/05
ST42	25.94	1369	01/01/05	09/20/05
ST37	33.14	1623	01/01/05	10/23/05
ST44	43.08	2045	01/01/05	12/30/05
ST36	31.88	1507	01/01/05	10/23/05
Bonfils	36.04	3604	01/01/05	12/30/05

The gage of interest is in the first row of each table (e.g. ST43 in the above example). The five closest gages are ordered by their proximity from closest to furthest. The columns contain additional information about the gages: total accumulation for the period, number of reports in the period and the dates of the first and last bucket tip event.

In this example, the Bonfils gage is a permanent real-time gage that reports every 0.01" tip. With the non-real-time temporary gages, accumulation is reported in 15-minute time series. This aggregates the rainfall and reduces the total number of reports even though the accumulation may be comparable.

3.3 Interpreting Double-Mass Plots

As stated above, if all points fall on the 1:1 line of the plot, this means that the accumulated depth for gage of interest agrees perfectly with the average of its neighbors. If the plot line falls above the 1:1, then the gage of interest over-reported rainfall relative to its neighbors while under-reporting is implied by plots below the 1:1 line. A horizontal line or line segments means that the gage of interest did not record rainfall when the neighbors did. Vertical sections imply that the gage of interest recorded rain when the neighbors did not.

If the double-mass plot for a rain gage does not fall exactly on the 1:1 line, this may not necessarily indicate a problem. During the course of a storm, any given gage may only record a fraction of the accumulation of the neighboring gages due to the spatial variation of rainfall. High winds are also a transient condition that could affect gage catch but may not show up in long-term trends. Over the course of a year it is expected that a given gage will accumulate rainfall at a rate consistent with the average of its neighbors.

If a gage tends to over-report (i.e. plot falls above the 1:1 line) this would point to a calibration issue or consistent funnel infiltration (e.g., drips from an overhanging structure or from a sprinkler system). The plot could also indicate over-reporting if a neighbor consistently under-reports. If a gage tends to under-report rainfall (i.e. plot falls below the 1:1 line) this would point to a calibration issue, adverse wind effects, or consistent obstruction (e.g., trees overhanging the funnel or water directed away from the tipping bucket mechanism inside the sensor enclosure). The plot could also indicate under-reporting if a neighbor is consistently over-reporting. The associated data table is used to identify such a condition.

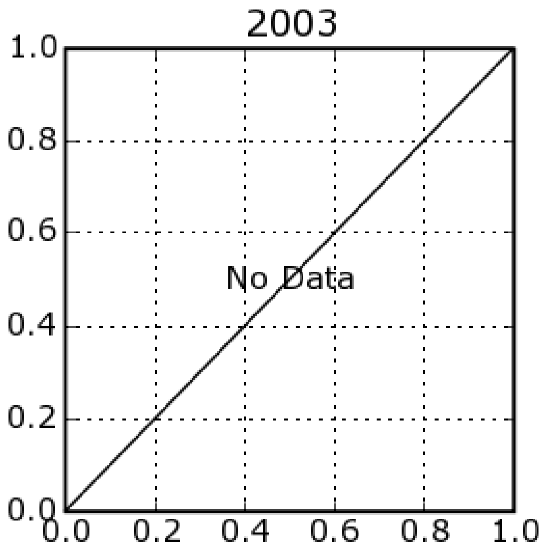
The nearest neighbor table associated with the double-mass plots allows the analyst to identify whether or not the gage of interest is the source of error on a non-linear, non-45° plot. If the line changes angle in two places, the table is used to quickly identify a neighbor that could have stopped reporting for a time and conclude that the apparent problem does not reside with the gage of interest. Or, if the gage falls above the 1:1 line, the problem could be attributed to a neighbor that has under-reported and skewed the neighbors' average toward lower accumulation. To find this problem, the neighboring gage with the lowest total accumulation is identified. Then the double-mass plot for that gage is reviewed. If it has under-reported relative to all of its neighbors, then this gage's error has likely propagated to the original gage of interest.

In the central United States, annual accumulated rainfall variation is spatially fairly consistent. While this is not the case for a given storm event, (e.g., two gages within five miles could differ by 2 inches or more in accumulation) these differences are generally smoothed out over a year. It is perfectly natural for one gage to have higher or lower accumulation relative to its neighbors, even over the course of a year. Wind effects from terrain, microclimate conditions from high humidity and other factors can cause a single site to trend higher or lower. The double-mass plots are intended to identify the natural and unnatural differences between neighboring gages.

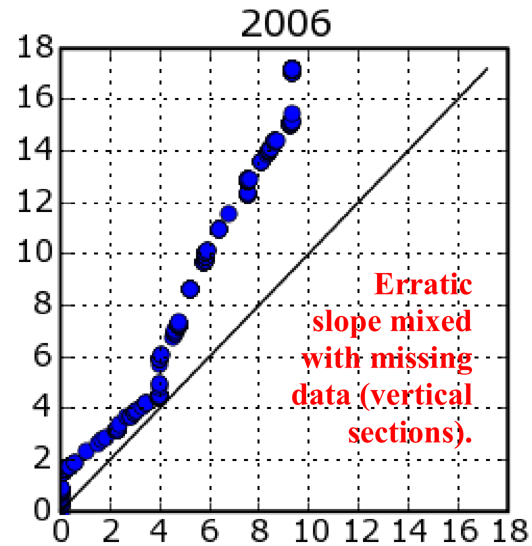
Each double-mass plot fits into one of four general categories. These are as follows:

- 0 ≡ No data for the period of interest
- 1 ≡ Gage behaves erratically - do not use at all during the year
- 2 ≡ Gage lost data for one or more times - mask only during those intervals
- 3 ≡ Gage data is of good quality - there is no indication of need to mask

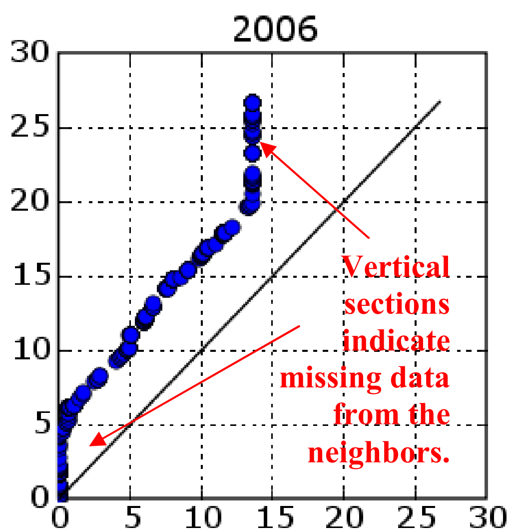
Examples of double-mass plots that met each of the four evaluation criteria are shown below.



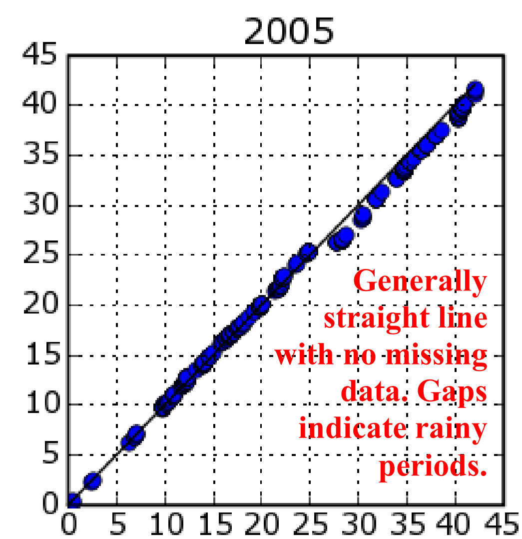
0 ≡ No data for the period of interest



1 ≡ Gage behaves erratically, do not use at all during the year



2 ≡ Gage lost data for one or more times, mask only during those intervals



3 ≡ Gage data is of good quality, there is no indication of need to mask

OneRain's scientists use these evaluations along with ratings described in the next section, Field Site Surveys, to assess gage data quality. This will provide a rigorous, non-arbitrary means of evaluating the sites.

4. FIELD SITE SURVEYS

Over the course of four weeks, OneRain photographed, located (via GPS) and conducted assessments of 133 sites in the ALERT gage network.

4.1 Evaluation Criteria

There are several factors that adversely affect tipping bucket rain gage accuracy. These include: calibration, funnel obstructions, overhead obstructions, wind behavior in the vicinity of the gage and man-made errors (e.g., sprinklers, run-off from the edge of a roof, vandalism). As described in Section 3, System Operations and Maintenance, calibration is completed each year and gages are checked for funnel obstructions and cleaned every week.

To assess the factors that relate specifically to location, OneRain evaluated each site against a theoretical "standard" rain gage installation. A site that matches this standard very well receives the highest rating of 5. A site that egregiously violates the standards of the theoretical site receives a rating of 1. This ideal standard is rare to find in practice.

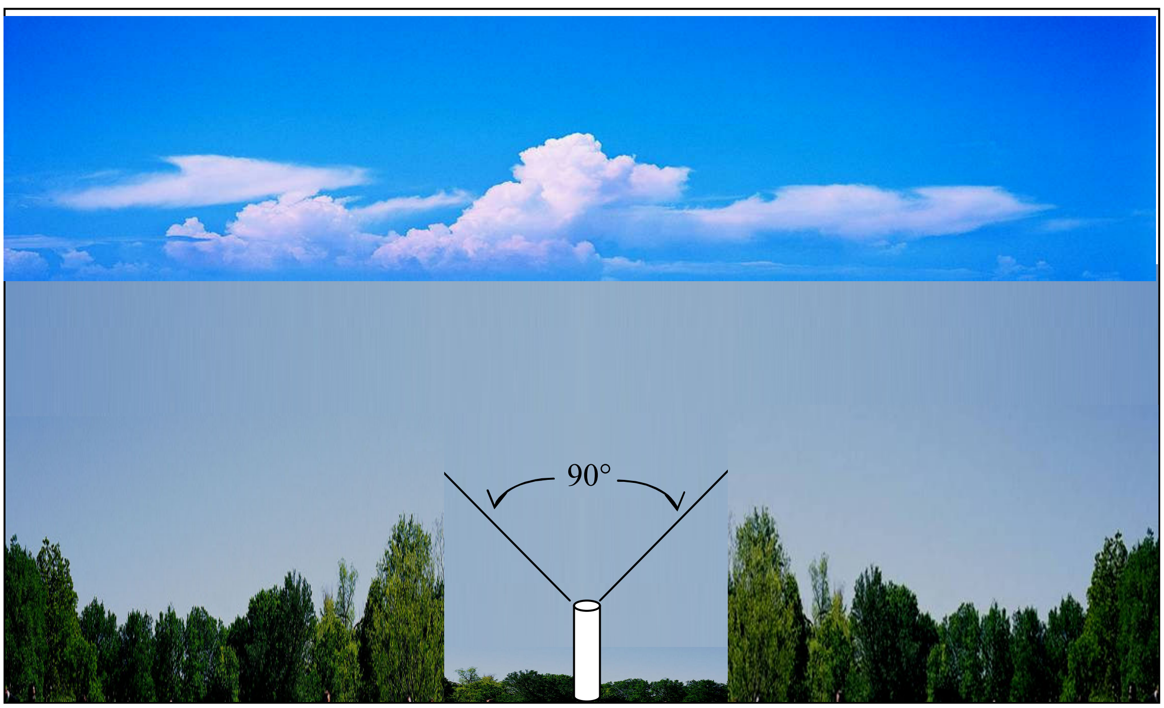


Figure 3: Theoretical rain gage site standard

4.1.1 Overhead Obstructions

The ideal site would have no obstructions within a right cone extending up and out from the top of the gage. The height of an isolated obstruction should be less than twice the distance from the gage to the obstruction.

4.1.2 Wind Behavior

Of all of the factors mentioned, wind has the greatest affect on rain catch. Generally, for every 1 mile-per-hour of wind at the gage orifice the rain gage will under-report by 1 percent. Locating gages in areas in the vicinity of trees or low buildings will reduce wind velocity and mitigate wind effects. Also, gages should be placed as low to the ground as possible. As per the principles of fluid dynamics: for a fluid moving past a fixed surface, friction slows the fluid's molecules down to zero as they approach the surface. This is called the boundary layer.

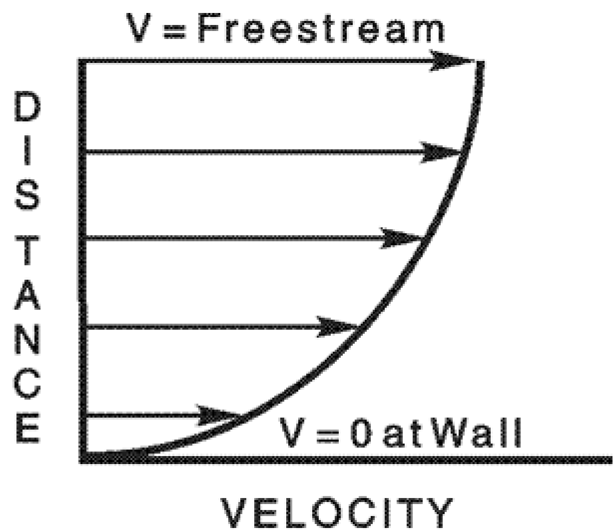


Figure 4: Wind speed and the boundary layer

As the surface (or wall as in the graphic) roughness increases this effect is more pronounced. Therefore, if a gage is located in a wooded park or surrounded by dense residential housing these factors will mitigate the adverse affects of wind for a rain gage.

In addition to free stream wind, turbulence can have a strong negative impact on catch. Gages located on top of buildings can lose rain due to the vertical eddy that forms when wind is forced up the side of the structure. Locating the gage as far as possible from the edge of the roof can mitigate turbulence effects if rooftop placement cannot be avoided. Turbulence can also be caused by a nearby, isolated object that does not directly obstruct the 90-degree cone. OneRain has encountered gages mounted on top of air-conditioning condenser fans, which causes both turbulence and vibration problems.

4.1.3 Man-Made Errors

Sprinklers, vandalism, AC units and dripping water from the edge of a roof will all cause serious problems for a rain gage. Even though wind has a decreasing effect as the gage opening is closer to the ground, it is usually best to keep the top of the funnel out of reach by the public.

4.1.4 Summary of the Ideal Gage

Given all of the above factors, the ideal rain gage would have the following characteristics:

- 10' height above the ground to inhibit vandalism, lower is better if vandalism is improbable
- Located in a open area surrounded by trees
- No obstructions in a right (90-degree) cone above the gage
- No single obstruction or edge that would cause air turbulence near the gage
- Bi-monthly or monthly site inspections (depending on occurrence of debris accumulation)
- On-going data inspection looking for failure mode indicators

4.1.5 Site Evaluation Scale

The scoring system used for the site evaluation was as follows:

- 1 ≡ Gage site problems, any information would be completely unreliable
- 2 ≡ Gage site problems, unlikely that rain catch consistent with actual rainfall
- 3 ≡ Gage site has problems, each event should be evaluated to determine usefulness of data
- 4 ≡ Gage site has some problems, but can generally capture representative rainfall
- 5 ≡ Gage site meets Ideal Gage characteristics

The images below show example sites that provide examples for each of the evaluation grades.

1 ≡ Gage site problems, any information would be completely unreliable (gage located on top of AC unit)

2 ≡ Gage site problems, unlikely that rain catch consistent with actual rainfall (gage located next to brick wall)

3 ≡ Gage site has problems, each event should be evaluated to determine usefulness for radar rainfall processing
(gage located on edge of roof)

4 ≡ Gage site has some problems, but can generally capture representative rainfall
(gage located in center of roof)

5. Conclusions

In general site locations for rain catch are very good; it is apparent that care was taken in selecting these sites. However, there are

Table 3 summarizes the site evaluations based on the field surveys. The detailed ratings for each site can be found in Table A-1 in Appendix A.

Table 2: Count of each rating type from field survey

Rating	Count of Rating
5	46
4	66
3	15
2	2
1	1
Not installed	3
Total:	**133**

The two sites given a "2" rating were Carr Street (site 100) and Goldsmith at Eastman (site 640). The Carr Street site has a fast growing tree encroaching badly into the 45° catch cone, and the Goldsmith site has trees growing over the gage on the north, west and south sides of the gage.

The Idledale site (2350) was given a "1" rating meaning that rainfall data is likely unreliable at best. There is a young, but fast growing tree almost enveloping the gage. This is a multi-trunk tree, but the largest is less than 6" in diameter.

The 15 sites with a "3" rating are generally affected by tree over-growth or no protection from the wind. One exception is the No Name at Quincy site, which has a failing foundation and is leaning at 15° from vertical.

With 84% of the sites rated either "4" or "5" the Districts rain gage network is very well outfitted to record point source rainfall data.

Table 4 summarizes the site evaluations based on the double-mass plots for each year. The individual plots for each gage site can be found in Appendix A.

Table 4: Count of each rating type from double-mass analysis

Rating	2003
3	96
2	31
1	3
Not installed	3
Total:	**133**

This data analysis using the double mass plots shows that less than 72% percent of the gages had consistent gage collection across the year. For 2007 23% of the gages require an event-by-event judgment of the rain catch because the double-mass plots showed changes in slope. These slope changes are probably due to spatial variation in the rainfall during events.

Three sites; Expo Park (420), Temple Pond (630) and Powers Park (1500); were all given a rating of “1” because of irrigation contamination. All of these sites reported approximately 100% more rainfall than their neighbors.

6. RECOMMENDATIONS

MSD will continue to have needs for high-quality rainfall information in order to calibrate hydrologic and hydraulic models. Rain gage network design and practices are paramount to collecting quality rainfall information.

6.1 Relocate Poorly Sited Gages

OneRain recommends relocating all gages with a field rating of "1" or "2" and the three sites with irrigation contamination. These sites are

- Carr Street (100)
- Goldsmith at Eastman (640)
- Idledale (2350)
- Expo Park (420)
- Temple Pond (630)
- Powers Park (1500)

This would require a new site surveys, radio path tests, contact landowners and receive permission to locate gages on private property.

APPENDIX A: DETAILED DOUBLE MASS PLOTS, LOCATION MAPS AND SITE PICTURES