EVALUATION OF THE EFFECTIVENESS OF THREE RAIN GARDEN PROJECTS IN THE DEER CREEK BASIN, ST. LOUIS, MISSOURI

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ABSTRACT

Rain gardens were constructed during 2010-2011 in three residential neighborhoods in the Deer Creek basin, St. Louis, Missouri. Runoff was monitored in culverts immediately downstream of the project sites, both before and after construction. Available data suggest that lag times between rainfall and runoff increased at two sites, and that peak stages in the culverts were reduced at all sites, for a given amount of antecedent rainfall. Runoff volumes may have decreased at two sites following rainfall.

INTRODUCTION

Deer Creek is an important stream in St. Louis County, draining an area of 36.5 square miles (USGS, 2014; DCWA, 2014; Fig. 1). The creek and its tributaries have many identified water quality problems (see Criss and Hasenmueller, 2010), and have also experienced repeated flash flooding in the past 20 years, with homes and businesses located in its "100-year" floodplain experiencing recurrent damage. The most destructive event occurred on September 14, 2008, following extremely heavy rainfall associated with the extratropical remnant of Hurricane Ike (e.g., Wilson, 2009).

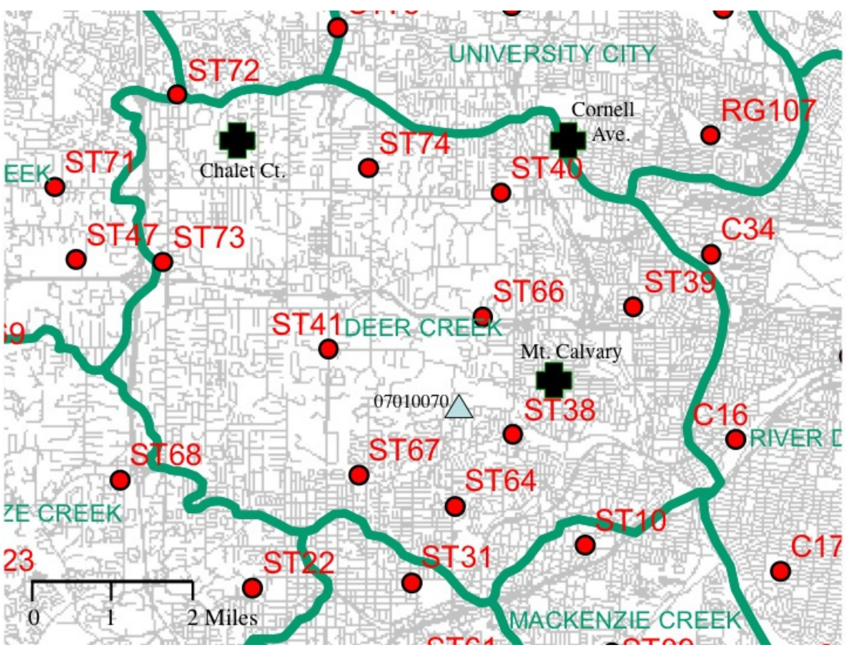

Figure 1. Map of the Deer Creek basin, showing locations of the rain gardens (black crosses), USGS gaging station 07010070 on Sebago Creek (triangle), and MSD rainfall monitoring sites (red dots). Base map from MSD.

The water quality and flooding problems in the Deer Creek basin have many interrelationships, and these conditions are worsening, partly because of new construction projects that have greatly increased the amount of impervious surface, particularly in the Black Creek sub-basin. Rain gardens are viewed as an effective means of reducing loads of pollutants and sediments, and also of retarding runoff delivery and reducing runoff volume. Note that Reese (2009) claims that the removal of runoff needing treatment is more effective than the treatment of runoff. Accordingly, in a collaborative effort involving many institutions, organizations and property owners, three rain gardens were planned and constructed; photos and descriptions of two of these sites are available at DCWA (2014). In addition, a long-term monitoring effort was initiated to gather data before and after rain garden construction to determine their effectiveness. This paper assembles and interprets the detailed data that are available.

DATA AND FILES

Raw Data Description. Data on the stage (water level) in the culverts draining the rain gardens at Mt. Calvary, Chalet Court, and Cornell Avenue were gathered at irregular calendar intervals, due to issues with freezing, factory recalls, battery malfunctions, etc., by Elizabeth Hasenmueller of WU (2010-2012) and by Danelle Haake of MoBot (2012-2014) (Fig. 2). These measurements were made with YSI Level Scouts, which utilize a pressure transducer to determine water levels; this device features a vented tube to correct the measurements for variations in atmospheric pressure. Precision is better than 0.02 feet, but instrumental drift can occur. These stage data were mostly collected at intervals of 1, 2 or 3 minutes. Details on the WU dataset are provided in the Final Report by Hasenmueller and Criss (2012) and in seven preceding quarterly reports.

Detailed rainfall data for multiple sites in the Deer Creek basin were collected by MSD at 15 minute intervals, and the data are complete for most sites for the entire 2010-2014 interval (Jeff Shiner, pers. com. 2012, 2014). These data are reported to the nearest 0.01 inch, and annual totals show good site-to-site agreement and reasonable agreement with the official NOAA data for Lambert Field, located about 10 miles to the north. Rainfall data were also collected at the rain garden sites by MoBOT, but are available only for the post-BMP period, so they cannot be used to make meaningful pre-BMP and post-BMP comparisons.

Nearly complete data on discharge and stage are available online at 5 minute intervals for USGS gaging station 07010070 at Sebago Creek, again for the entire study period (USGS (2014). This is the smallest monitored creek in the Deer Creek basin.

Data Files. All the aforementioned data for 2010-2014 except the MoBOT rainfall data have been assembled into a single data table (Appendix, on disk). This required initial assembly into tables with a 1 minute time interval, as unity is the only common factor for all of the various intervals (1, 2, 3, 5, and 15 minutes) for which data were reported. Because each normal year has 525,600 minutes, these tables are extremely long, and several tables were prepared because of software that restricts table length to 1 million rows. This initial compilation required five days and great care, because millions of numbers provided at irregular intervals in >50 original files had to be properly assigned to nearly 100 million distinguishable positions in these tables. Following this assembly, average values for the culvert stages were computed for each 5 minute interval, and

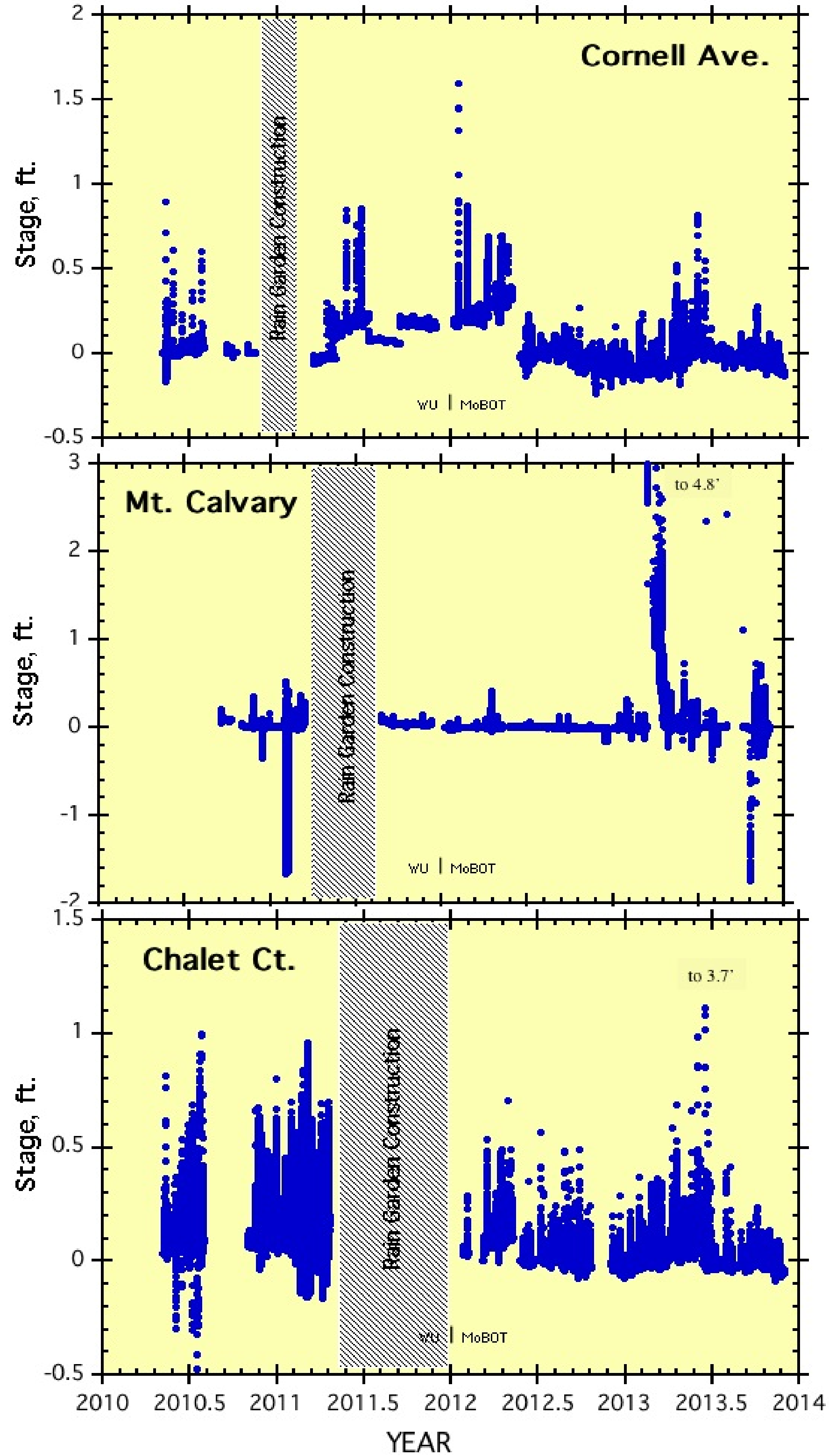

Figure 2. Raw stage data (blue dots) for the three rain garden sites. The period of rain garden construction, and the time of the transition of monitoring activity from WU to MoBOT are shown. Not all data are on scale.

a single Master Table (on disk) with >500,000 rows, each representing a 5-minute interval, was constructed for the entire study period. Note that all data points in this table are indexed to the time indicated in the left hand column. All computations and graphs in this report were made with this 5-minute Master Table.

Columns in the Master Table (on disk) are as follows, from left to right:
1. Time in years and decimal years; 5 minute interval.
2. Calendar time and date. Note that 2012 was a leap year.
3. Raw stage data in feet for Cornell Ave., determined from the pressure transducer
4. Raw stage data in feet for Mt.Calvary, determined from the pressure transducer
5. Raw stage data in feet for Chalet Ct., determined from the pressure transducer
6. Background corrected stage data for Cornell Ave., in feet.
7. Background corrected stage data for Mt.Calvary, in feet
8. Background corrected stage data for Chalet Ct., in feet
9. "Basin average" precipitation, in inches per 15 minutes
10. Precipitation at site ST 38, in inches per 15 minutes
11. Precipitation at site ST 40, in inches per 15 minutes
12. Precipitation at site ST 72, in inches per 15 minutes
13. Precipitation at site ST 74, in inches per 15 minutes
14. Stage Data for Sebago Creek gaging station 07010070, in feet
15. USGS discharge calculation for Sebago Creek, in cubic feet per sec.

The "basin average" precipitation data in column 9 are key to this study. These data were computed as the simple average of twelve different MSD sites, scattered throughout or very near the Deer Creek basin, for which data were complete for the entire study period, specifically including the entire pre-BMP and post-BMP intervals. These sites are C16, C17, ST10, ST31, ST38, ST40, ST41, ST47, ST66, ST67, ST68, and ST71 (Fig. 1).

Figure 2 shows the raw stage data for the three rain garden sites as a function of time for the 2010 to 2014 time interval. Brief periods of high flows are superimposed on an inconsistent background level. There are also several peculiar negative excursions below the background levels, which cannot represent real water levels as the sensors were placed in the bottom of the normally dry culverts. These effects demonstrate that a background correction is necessary, as is the filtering of spurious negative data.

Background Correction. Effective comparison of pre-BMP and post-BMP results requires uniform rules for the determination of background. Because human assessment of background for various intervals could introduce bias, this process was accomplished by a computer algorithm devised by the author. In effect, this algorithm computes background as the "long-term" running mean of the culvert levels, excluding data that significantly differ from that running mean. The moving interval selected for this computation was four days wide, centered on the datum of interest. Figure 3 illustrates the performance of this algorithm for part of the Cornell Ave. record. The variable background levels calculated in this manner were simply subtracted from the raw stage data given in the Master Table (disk) in columns 3-5 to determine the "Background-Corrected" stages provided in columns 6-8.

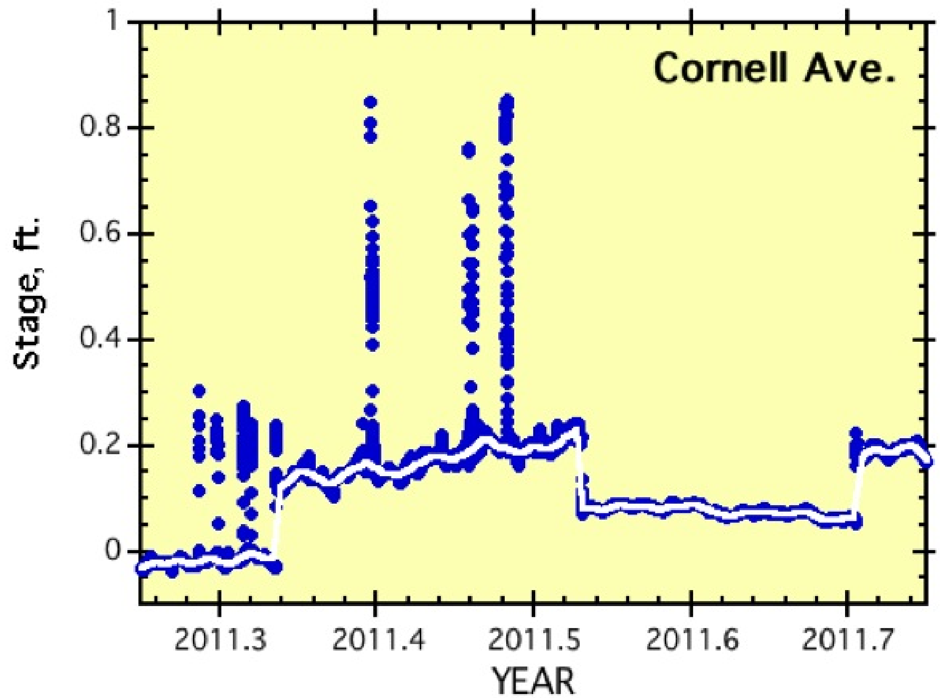

Figure 3. Illustration of the performance of the algorithm developed to estimate background (white band) for a half-year interval of stage data (blue dots) at Cornell Ave.

Negative Excursions and Chaotic Readings. The cause of occasional sharp, negative excursions of the stage sensors is not understood (see Fig 2). Nevertheless, following the background correction, these impossible, negative stages were simply "masked" from the data set so that they were not utilized in any computations.

More problematic are intermittent intervals of chaotic behavior in the Mt. Calvary sensor, involving dramatic changes in background levels as well as frequent negative excursions. Of greatest concern are data from Mt. Calvary after sensor redeployment on March 14, 2013, which feature these problems including repeated changes in the raw data to about +4.7 feet (far offscale in Fig. 2, middle). Culvert overflow was not observed at these times (Haake, pers com., 2014), so these readings are clearly spurious. Rather than "cherry pick" data intervals for processing, it was deemed best to eliminate all data collected at Mt. Calvary after March 14, 2013 from further consideration.

Chaotic readings including numerous negative excursions also occurred at Mt. Calvary during February 1-12, 2011. Data from NWS show that the daily maximum temperatures were well below freezing during most of this period (Table 1), so significant flow in the culverts would have been impossible. It is considered likely that the cold temperatures impacted the performance of the Mt. Calvary sensor, probably because the pressure transducer experienced ice compression (note that Hasenmueller observed ice on the sensor), or perhaps because the atmospheric vent tube became ice clogged. In any case, the spurious readings at Mt. Calvary for this interval were also excluded from the computational data base.

STATION: ST. LOUIS MO
MONTH: FEBRUARY
YEAR: 2011
LATITUDE: 38 45 N
LONGITUDE: 90 23 W

TEMPERATURE IN F: :PCPN: SNOW: WIND :SUNSHINE: SKY :PK WND

1 DY	2 MAX	3 MIN	4 AVG	5 DEP	6A HDD	6B CDD	7 WTR	8 SNW	9 12Z DPTH	10 AVG SPD	11 MX SPD	12 2MIN DIR	13 MIN	14 PSBL	15 S-S	16 WX	17 SPD	18 DR
1	31	20	26	-5	39	0	0.90	3.0	T	14.2	25	30	M	M	10	12469	32	290
2	21	11	16	-16	49	0	T	0.2	3	13.8	10	300	M	M	8	189	13	310
3	23	4	14	-18	51	0	0.00	0.0	3	3.0	10	310	M	M	2		12	190
4	30	10	20	-12	45	0	T	T	3	2.2	8	150	M	M	6		12	160
5	38	25	32	0	33	0	0.20	2.3	4	7.2	14	170	M	M	7	1	18	160
6	41	32	37	4	28	0	T	T	5	8.6	16	260	M	M	10	1	20	320
7	32	24	28	-5	37	0	T	T	3	11.7	21	290	M	M	10	8	24	280
8	24	9	17	-16	48	0	T	T	3	9.4	18	320	M	M	8		23	330
9	20	11	16	-18	49	0	0.00	0.0	3	6.3	12	310	M	M	8		15	310
10	32	8	20	-14	45	0	0.00	0.0	3	8.7	18	250	M	M	4		24	230
11	43	19	31	-3	34	0	0.00	0.0	3	10.1	18	250	M	M	5		22	250
12	51	30	41	6	24	0	0.00	0.0	2	9.8	16	220	M	M	3		20	220
13	65	40	53	18	12	0	0.00	0.0	1	11.5	21	240	M	M	3		26	240
14	50	33	42	7	23	0	0.00	0.0	T	9.2	22	280	M	M	5		26	280
15	54	33	44	9	21	0	0.00	0.0	0	12.2	23	150	M	M	8		29	150
16	74	38	56	20	9	0	0.00	0.0	0	7.7	24	200	M	M	6		29	170
17	76	58	67	31	0	2	0.00	0.0	0	14.7	29	200	M	M	6		37	200
18	64	39	52	16	13	0	0.00	0.0	0	6.7	M	M	M	M	4		M	M
19	54	37	46	9	19	0	0.01	0.0	0	10.4	18	120	M	M	8		22	130
20	74	47	61	24	4	0	0.00	0.0	0	16.1	28	210	M	M	9		36	190
21	64	31	48	11	17	0	0.43	0.0	0	11.8	25	310	M	M	9	1	31	310
22	37	26	32	-6	33	0	0.00	0.0	0	8.3	18	310	M	M	4		24	320
23	44	28	36	-2	29	0	0.08	T	0	11.4	22	140	M	M	8	46	28	140
24	44	33	39	1	26	0	0.80	0.2	0	10.3	26	50	M	M	8	1348	36	50
25	34	32	33	-6	32	0	0.40	0.8	1	9.0	21	350	M	M	10	13	27	350
26	44	32	38	-1	27	0	T	0.0	T	7.0	15	130	M	M	10	168	17	140
27	65	35	50	10	15	0	0.39	0.0	0	9.2	52	280	M	M	9	1358	67	280
28	46	31	39	-1	26	0	0.16	0.0	0	10.1	24	340	M	M	5	3	31	340

Table 1. NWS Weather Data from Lambert Field for February 2011. Note the protracted period of predominantly subfreezing temperatures during Feb 1-10 (columns 2-4).

DATA ANALYSIS

Goals and Philosophy. The goals of this study are straightforward, but the implementation is not. The goals are to compare pre-BMP and post-BMP data to determine if the rain gardens have had the following effects: 1) delay in post-BMP runoff delivery following rainfall, compared to what the pre-BMP delays would have been; 2) reduction of post-BMP peak stages following rainfall, compared to what the pre-BMP peak stages would have been; and 3) reduction of post-BMP runoff volumes following rainfall, compared to what the pre-BMP values would have been. The key point is that it is impossible to measure both pre-BMP and post-BMP responses for the same, actual rainfall event, so the evaluation of each effectiveness factor must be based on statistical or theoretical methods.

Given the above, it is essential to treat the available data in the most even handed manner possible. Computer algorithms that involve minimal human involvement provide the best means to accomplish this, particularly because certain conclusions can be considered to be humanly desirable, providing incentive for biased treatment. As was done for the assignment of background levels, computer algorithms were therefore designed by the author to accomplish various tests, and these were uniformly applied to the data. For the same reason, the "basin average" rainfall data was used in the calculations for all three sites.

Project Analysis: Lag Time. Lag times for the stages in the culverts and for the stage of Sebago Creek can be determined by processing the master data file. Because the data sets are so long and detailed, this was done by employing a simple algorithm developed for this project. Essentially, this algorithm determines the product of the rainfall increment and the background-corrected stage at the site of interest for each 5-minute interval, then computes the sums of those ~100,000 products for 1) the pre-BMP interval and for 2) the post-BMP interval. The rainfall and stage data are then offset by 5 minutes and the pre BMP and post BMP calculations repeated, then the data are offset by 5 additional minutes, etc. The average lag time between rainfall delivery and flow delivery is then indicated by the offset that gives the maximum sum. Finally, the results for the pre-BMP and post-BMP intervals can be compared (Fig. 4; Table 2).

Table 2. Pre-BMP and Post-BMP Lag Times. Calculations first used the basin average precipitation data (columns 2-4 below), then were repeated using the closest rainfall monitoring site (columns 6-8 below)

SITE	**Pre-BMP**	**Post-BMP**	**Precip.Site**		**Pre BMP**	**Post BMP**	**Precip. Site**
Cornell Ave.	70 min	80 min	Basin Avg		85 min	80 min	ST40
Mt Calvary	85	110	Basin Avg		90	115	ST38
Chalet Ct.	65 -75	65	Basin Avg		75	75	ST72
Sebago Ck.	95	100	Basin Avg				

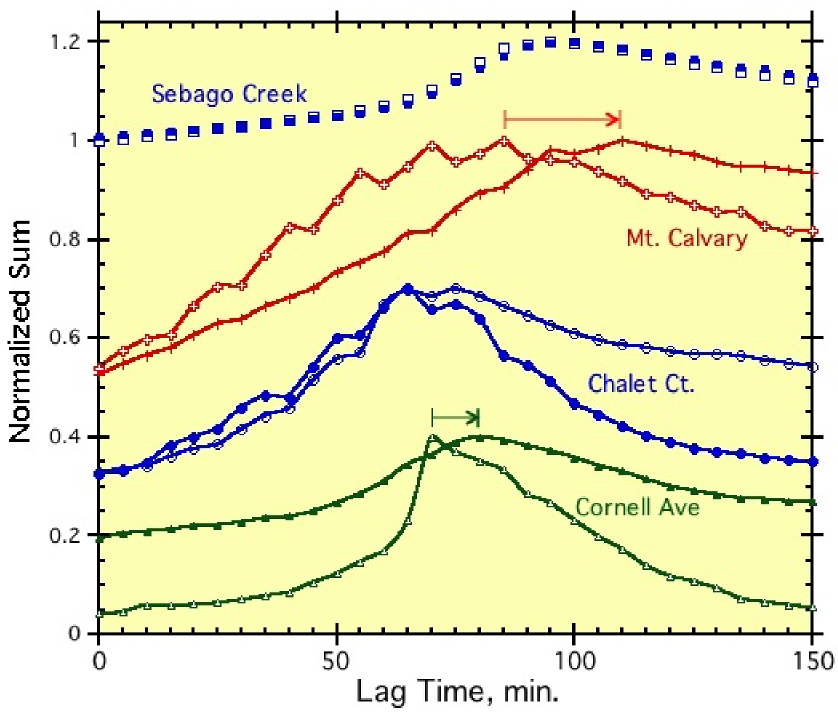

Figure 4. Lag time determination using the basin average precipitation data. The y- axis has arbitrary scaling but only the time of the maximum sum is significant. Pre-BMP sums are open symbols, post-BMP sums are closed symbols. Little change in lag time is seen for Sebago Creek or Chalet court, but significant change occurred at Mt. Calvary and probably at Cornell Ave. (horizontal arrows), where peaks have become later and broader (more diffusive).

Calculations were first made using the basin average rainfall data provided by the twelve MSD stations for which data were complete for the entire period. These calculations suggest that the lag time between rainfall delivery and peak stage in the culverts increased at Mt. Calvary and Cornell Avenue. Data are inconclusive at Chalet Ct., and if anything, suggest the opposite (Figure 4; Table 2). The curves for Sebago Creek show broad, flat-topped maxima that suggest little or no change in the lag times or curve shape between the pre-BMP and post BMP periods, as expected.

Calculations were repeated by comparing the culvert stage data to the closest MSD rainfall monitoring site. In particular, Mt. Calvary stage data was compared to rainfall at ST 38; the Cornell Ave stage data were compared to rainfall at ST 40; and the Chalet Ct. stage data were compared to rainfall at ST72. These results are not as regular as those based on the basin average precipitation data, but confirm the significant increase in lag time at Mt. Calvary, and show no clear difference at Cornell Ave. or Chalet Ct. (Table 2).

Project Analysis: Stage Maxima. Hasenmueller and Criss (2012) suggested that post-BMP peak stages were subdued compared to pre-BMP stages at Mt. Calvary and Cornell Ave., based on comparisons involving a few large rainfall events. They could not make this comparison for Chalet Ct. because the rain garden installation was not yet complete. Furthermore, this comparison was based on the daily rainfall data measured by NWS at Lambert Field.

Comparison of rainfall and peak stages in the culverts can now be made for all three sites, involving all peaks that were measured over the entire 2010-2014 study period, and utilizing the actual rainfall record obtained for the Deer Creek basin. In particular, an algorithm was devised to identify the stage maximum for each 5 hour interval, and then another algorithm computed the total antecedent rainfall delivered to the Deer Creek basin in the 2 hours prior to each of these stage maxima. Graphs of the Stage Peaks vs. this Antecedent Rainfall were then prepared, for the pre-BMP and post-BMP intervals at each site (Fig. 5). For many reasons including variable evapotranspiration effects the correlation coefficients are not strong. Nevertheless, these graphs suggest that there has been significant reduction in peak stage, for a given amount of antecedent rainfall, at all three sites (Fig. 5).

Two caveats are needed regarding the Chalet Ct. analysis. First, rain garden construction radically changed culvert conditions at this site. For example, the pipe was changed from an 18” corrugated metal pipe to cement. Moreover, because the corrugated pipe leaked and much runoff flowed below it, the pre-BMP sensor had to be positioned at the pipe orifice but about 2 inches below the pipe invert. Second, the calculations excluded the extraordinary storm of 6/17/13, when more than 3” of rain fell at site ST 72 shortly before the peak stage of 3.7’; this event was so extreme that its inclusion would uselessly distort the regression line. Given these issues, evidence for post-BMP reduction of stage peaks at Chalet Ct. cannot be considered to be strong.

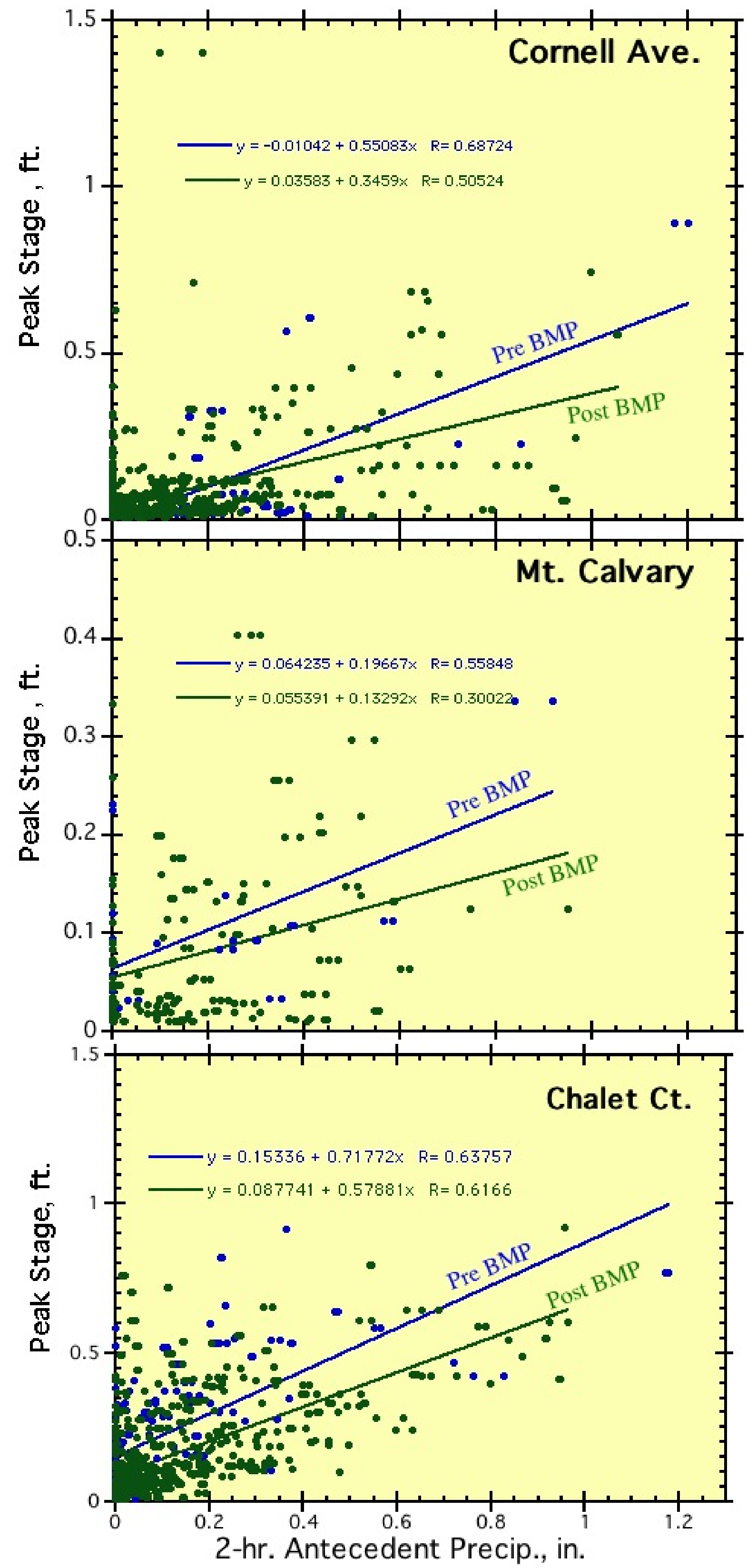

Figure 5. Scatterplots of peak stages vs. the 2-hour antecedent rainfall. Regression lines suggest reduction of stage heights for a given amount of rainfall at all sites. See text.

Project Analysis: Runoff Volume. The above comparison of stage peaks with antecedent rainfall suggests that runoff volumes were lower in the post-BMP period than in the pre-BMP period. Actual calculation of runoff volume is not straightforward, however, as it requires time-series tables of culvert discharge (flows in cubic feet per second, abbrev. cfs), from which the water volumes are computed by integration over a suitable time interval. There are several problems, including: 1) Discharge is a calculation, not a direct measurement, and calibrations have not been made that permit discharge to be related to the measured culvert stages; 2) The suitable integration time could differ between pre-BMP and post-BMP periods, because the lag times and possibly the hydrograph shape might have been changed by the rain gardens.

It is not possible to completely overcome the aforementioned problems, but the following approach was attempted. Regarding problem #1, the background-adjusted stage raised to the 2.5 power is a quantity that is roughly proportional to discharge. Simple equations are not available for flows in culverts, but a dependence between discharge and culvert stage raised to the 2.5 power should be a useful approximation; a similar relationship was found for discharge through a circular culvert at Bluegrass Spring (Frederickson, 1999), and this proportionality holds for flows through V-notched weirs (e.g., Chow, 1951). Regarding problem #2, an integration period spanning from the beginning of the antecedent rainfall interval, 120 minutes before peak stage, to 120 minutes after the peak, was arbitrarily chosen.

Results of this approach are inconclusive. Linear regressions on plots of "Runoff Volume" vs. 2 hr. antecedent precipitation show no differences in pre-BMP and post-BMP results at Cornell Ave. Results for Mt. Calvary provide weak support (lower regression slope) for volume reduction in the post-BMP period, but data are highly scattered and unpersuasive. Data at Chalet Ct. support volume reduction in the post-BMP period if the extraordinary event of 6/16/13 is excluded; if this event is included the conclusion would be very weak but reversed. Processing the stage data for Sebago Creek in this identical manner suggests a small (12%, and implausible) reduction in the slope of the regression line in the post-BMP period compared to the pre-BMP period. A possible explanation for these weak results is that volume analysis places great weight on the few largest storms, which are not statistically significant, yet these events would quickly overwhelm the capacity of the rain gardens, so their performance could approximate per-BMP conditions.

CONCLUSIONS

Statistical and theoretical means were applied to detailed, pre-BMP and post-BMP monitoring data on three rain gardens in the Deer Creek basin, in order to evaluate their performance. Results suggest that lag times increased at two sites, and that peak stages in the culverts were reduced at all sites, for a given amount of antecedent rainfall. Runoff volume may have decreased at two sites following rainfall.

Acknowledgement

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