Newcomb Avenue Green Street: Technical Appendix

This technical appendix compliments the Newcomb Avenue site report by providing greater detail on the monitoring and analysis methods, data quality and results, as well as providing some suggested improvements for future GI monitoring by the Team. Note that there are other accompanying appendices that also complement this and the other individual site reports including the Glossary of Terms (Appendix A) and Methods (Appendix B).

Project Characteristics

Green infrastructure (GI), other pervious features and canopy trees were installed at Newcomb Avenue in 2011. In total, 42% of the catchment surface area was converted to GI or other pervious surfaces (e.g. traditional landscaping). These features included 13,052 ft^2 of permeable paving in the parking strip and courtesy strip, 487 ft^2 of chicane islands, 6,280 ft^2 of traditional landscape planters along the sidewalk, planting of 23 additional trees, and 536 ft^2 of bioretention planters (Table 1 and Figure 1). These features are approximately evenly distributed on the northern and southern half of the block. The block slopes downward from east to west, towards Phelps Street. Stormwater runoff not infiltrated by the permeable pavers or otherwise captured by the traditional landscape planters was designed to flow along the gutter and into the bioretention planters via curb cut inlets. The planters were designed for runoff to infiltrate through the 18 inches of planting soil mix overlain by 2-4 inches of stone mulch until saturation. At the saturation point, water rises above the soil surface until it reaches the elevated overflow drain, which is connected directly to the combined sewer system (CSS). There are two catch basins at the end of the block, one located on the northwest corner and the other on the southwest corner of Newcomb Avenue near Phelps Street. Any runoff that bypasses the curb cut inlets to the planters flows directly into these catch basins.

Table 1. Select characteristics of the Newcomb Avenue subcatchments.

Metric	Newcomb North	Newcomb South
Drainage Area (ft^2)	23,750	25,050
Imperviousness of Drainage Area prior to construction	99.9%	99.9%
Area of Permeable Pavement (ft^2)[1]	13,052	
Area of Bioretention Planter (ft^2)[1]	536	
% of Impervious Area Converted to GI (post construction; only GI elements included)	28%	28%
% of Impervious Area Converted to Traditional Landscaping	14%	14%
Drainage Area Slope	0.8%	0.8%
Land Use	Residential	Residential

[1] Area is total area of GI type in both subcatchments, and assumed to be distributed approximately evenly across the two subcatchments.

Methods

The hydrologic analysis presented in this report was based on flow data collected in the culverts leading from the catch basins indicated in Figure 1[2]. Each catch basin drains approximately half of the block from the building facade out to the crown of the street. Pre-construction flow monitoring was conducted during Rainy Season 2009-2010 at the northwest catch basin (Newcomb North) only, while post-construction flow monitoring was conducted during Rainy Season 2011-2012 and 2012-2013 at both catch basins (Newcomb North and Newcomb South). Flow data were recorded by Hach Sigma 950 area-velocity (AV) sensors located in the culverts. Installation and maintenance of the measurement devices was carried out by the San Francisco Public Utilities Commission. Data from these sensors were downloaded manually throughout the period of record (Table 2).

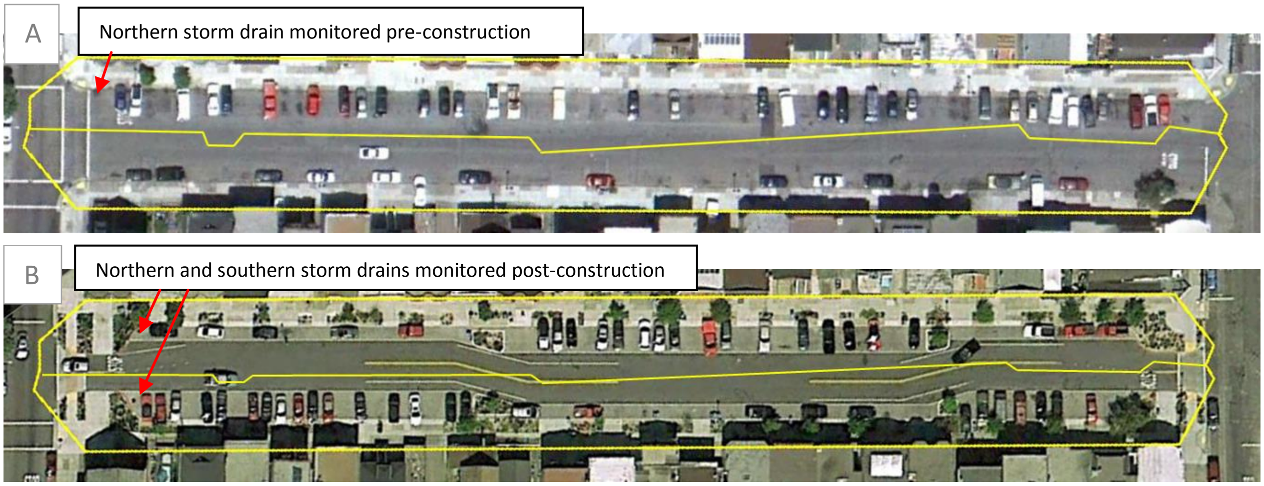

Figure 1. Aerial photos of the Newcomb catchment A) pre- and B) post-construction. The northern and southern subcatchments are outlined in yellow and monitored storm drains are annotated and marked with red arrows.

Table 2. Period of record in each subcatchment for flow and rainfall data.

Rainy Season	Newcomb North	Newcomb South
2009 - 2010	11/2/2009 – 4/16/2010	Not monitored pre-construction
2011 - 2012	3/13/2012 – 6/7/2012	3/13/2012 – 5/9/2012
2012 - 2013	9/1/2012 – 2/6/2013	11/1/2012 – 12/12/2012

Ideally, rainfall data collected within the catchment would be used for this analysis, Rainfall data were collected at nearby gauges since catchment gauges were installed. The Southeast Wastewater Treatment Plant (gauge SEP-20) is the nearest rain gauge and was used in this analysis for all of Rainy Season 2009-2010 and 2011-2012 through 4/13/2012. This gauge is located 0.43 miles (700 m) to the north of the Newcomb catchment. For Rainy Season 2011-2012 after 4/13/2012, and for all of Rainy Season 2012-13, Griffith Pump Station (gauge GFS-21) was used due to issues with the SEP-20 rain gauge. The GFS-21

[2] The elevated overflow drains in the bioretention planters are also connected to these culverts upstream of the flow monitoring equipment. Therefore, the flows into both the catchbasins and overflow drains are measured by the flow monitoring equipment.

gauge is located approximately 1 mile (1570 m) to the southeast of the Newcomb catchment. These data were recorded at 5-minute intervals. The data were evaluated for representativeness at the Newcomb GI site in terms of timing and magnitude. Representativeness of magnitude was evaluated based on a visual inspection of the isohyet map for the City, which suggested the spatial errors in average annual magnitude are negligible for the SEP-20 gauge and approximately 2-3% for the GFS-21 gauge. Likely differences in timing were assessed by considering the speed that storms typically move (10 to 50 mph, or an average of approximately 30 mph; personal communication with Jan Null, SF Bay Area meteorologist) and distance between the monitoring site and rain gauges. Based on these considerations, a storm moving directly parallel to the line of path between the monitoring site and the rain gauges could result in differences and potential errors in the lag time computations of a maximum of 2.6 and 5.9 minutes for the SEP-20 and GFS-21 gauges, respectively (with averages of 0.9 and 2.0 minutes). Storms moving at other angles in relation to the line of path between the monitoring site and the rain gauges would result in smaller time differences in rainfall between the sites. The influences of these differences and errors in relation to the interpretation of lag times are discussed in the lag time results section.

The method of analysis utilized in this report was a comparison of pre- and post-construction stormwater flows for individual storm events using measured data as well as model simulations. Individual storms and the corresponding flow from those storms were isolated and a suite of hydro-meteorological characteristics (storm duration, storm total rainfall depth, storm total rainfall volume, peak rainfall intensity, flow duration, total flow volume, peak flow rate, storm runoff coefficient, antecedent rainfall (for previous 1-, 2-, 3-, 4-, and 5-day time periods), various lag times) were determined for each isolated storm. Although pre-construction and post-construction flow data were available for Newcomb North, comparisons of runoff across years, or across storms, was problematic because storms differed in their intensity and duration, making it difficult to quantitatively assess GI-related differences in runoff. For that reason, pre- and post-construction stormwater flow characteristics were compared for the same storms, and stormwater models were utilized to enable this comparison. A hydrological model was developed to simulate Newcomb North's pre-construction runoff response (US EPA's Storm Water Management Model (SWMM)), and the model was calibrated using measured rainfall and flow data collected during Rainy Season 2009-2010. The calibrated model was then used to simulate flow that would have resulted under pre-construction conditions during Rainy Season 2011-2012 and 2012-2013 rain events, and the pre-construction modeled flows were compared to actual post-construction flow data collected during the same storms.

No pre-construction flow data were available for Newcomb South. Since the north and south pre-construction subcatchments were very similar (Table 1, Figure 1A), the calibration parameters developed for Newcomb North model were applied to the Newcomb South subcatchment, and the flow that would have occurred under pre-construction conditions was simulated for the Newcomb South subcatchment for Rainy Seasons 2011-12 and 2012-13. The simulated Newcomb South flows were then compared to actual flow measurements during those 2011-2012 and 2012-2013 storms. Additional details of the analysis methods are provided in Appendix B.

Data Quality

Pre-construction Data: Newcomb North

Pre-construction flow monitoring data in the Newcomb North subcatchment was recorded at 1-minute intervals. Rainy Season 2009-2010 data quality was initially evaluated by Sustainable Watershed Designs (SWD), an engineering consulting firm. SWD compared the measured flow data recorded by the AV sensor (which uses a continuity equation, referred to hereafter as "Q_{CONT}") against flow estimates calculated using the Manning's equation and the depth and velocity values recorded by the sensor (referred to hereafter as "Q_D" and "Q_V", respectively). A stronger correlation existed between Q_{CONT} and Q_D (R=0.95, all correlations reported are Pearson product-moment correlation coefficients) as compared to Q_{CONT} and Q_V (R=0.85), and SWD determined that Q_D provided a reliable correction for the few data points during a single stormy period where the velocity measurement was zero or negative due to apparent equipment malfunction. SFEI further corrected less than 1 % of the data using the flow estimates derived from Manning's equation during instances of erroneous or missing values. After making these corrections, SFEI analyzed the data in relation to rainfall events. A storm event was defined as having a minimum depth of 0.01 inches and at least 6 hours separation between storm events. Twenty-six storm events were initially identified in the data set for this analysis.

About one third of the pre-construction storm data (10 out of 26 storms) was censored from further analysis due to having runoff coefficients (RCs) (the portion of rainfall as runoff) greater than 1.0. Under pre-construction conditions there was little storage and no groundwater influence in the catchment, and confidence in the boundary delineation was high. Therefore, it was hypothesized that RCs greater than 1.0 resulted from stormwater run-on from adjacent catchments[3]. Although multiple factors could combine to influence when run-on from adjacent catchments occurs, rainfall intensity appears to be a primary driver. All storms with RCs greater than 1.0 had maximum rainfall intensities greater than or equal to 0.07 inches per 30 minutes (Figure 2). There are 3 to 5 outliers on the graph which are illustrative of the more complex factors that are sometimes present such as antecedent rainfall and saturation conditions or slight data quality discrepancies, for example, related to rainfall or flow measurements. All of the outliers could be discussed but for brevity and as an illustration, just one was highlighted on Figure 2. This outlier can be explained by the maximum 30 minute rainfall occurring at the very onset of the storm and therefore a portion of this initial rainfall was retained on the landscape in depression storage. Consequently the effective rainfall (rainfall neither retained nor infiltrated that results in overland runoff) during this maximum 30 minute rainfall was actually less than 0.09 inches. With the exception of this and the other 4 outlier points, the majority of the data points appear to suggest a relatively linear response between maximum 30 minute rainfall and the proportion of rainfall that runs off. During rainfall intensities at or above 0.07 inches in 30 minutes, this catchment likely received run-on from adjacent catchments.

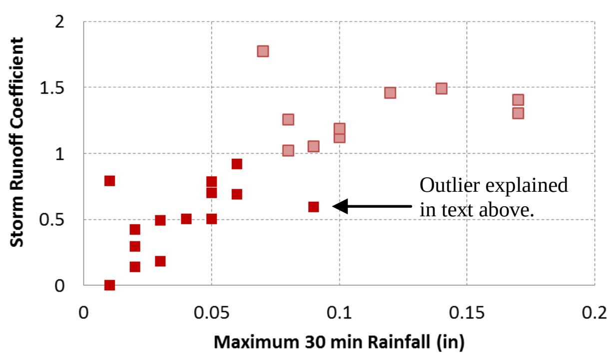

Figure 2. 2009-2010 Rainy Season runoff coefficients per storm in relation to 30-minute maximum rainfall for each storm. Storms with runoff coefficients ≥1.0 (pink) are excluded from further analysis.

Rainy Season 2009-10 Newcomb North data was used to calibrate the SWMM model of Newcomb under pre-construction conditions. The final calibrated model performed well at simulating the timing of flow (including the timing of peak flow rates) (Figure 3) and total flow volume per storm event (Figure 4). The model also performed reasonably well at predicting peak flow, although it may slightly over-predict the peak flow rate for storms with peaks smaller than 0.02 cubic feet per second (cfs), and may under-predict peaks during larger storms (Figure 5). The under-prediction of the larger peaks may be due to the smoothed flow routing simulated by the model in comparison to the rapidly changing flows measured for this very small subcatchment. These biases are mentioned in the following results section when they have bearing on the data interpretation.

[3] The hypothesis cannot be field-verified because project construction altered site drainage patterns. It is also worth noting that there is no certainty that storms with lower intensities did not produce run-on from adjacent catchments. SFPUC is currently monitoring two additional catch basins on Phelps Ave., the intersecting street on the west side of the Newcomb Avenue GI installation. Phelps Avenue has not been reconstructed and is intended to serve as a reference for correcting the Newcomb Avenue pre-construction data. The analysis of data captured from Phelps Avenue was outside of the scope of this report.

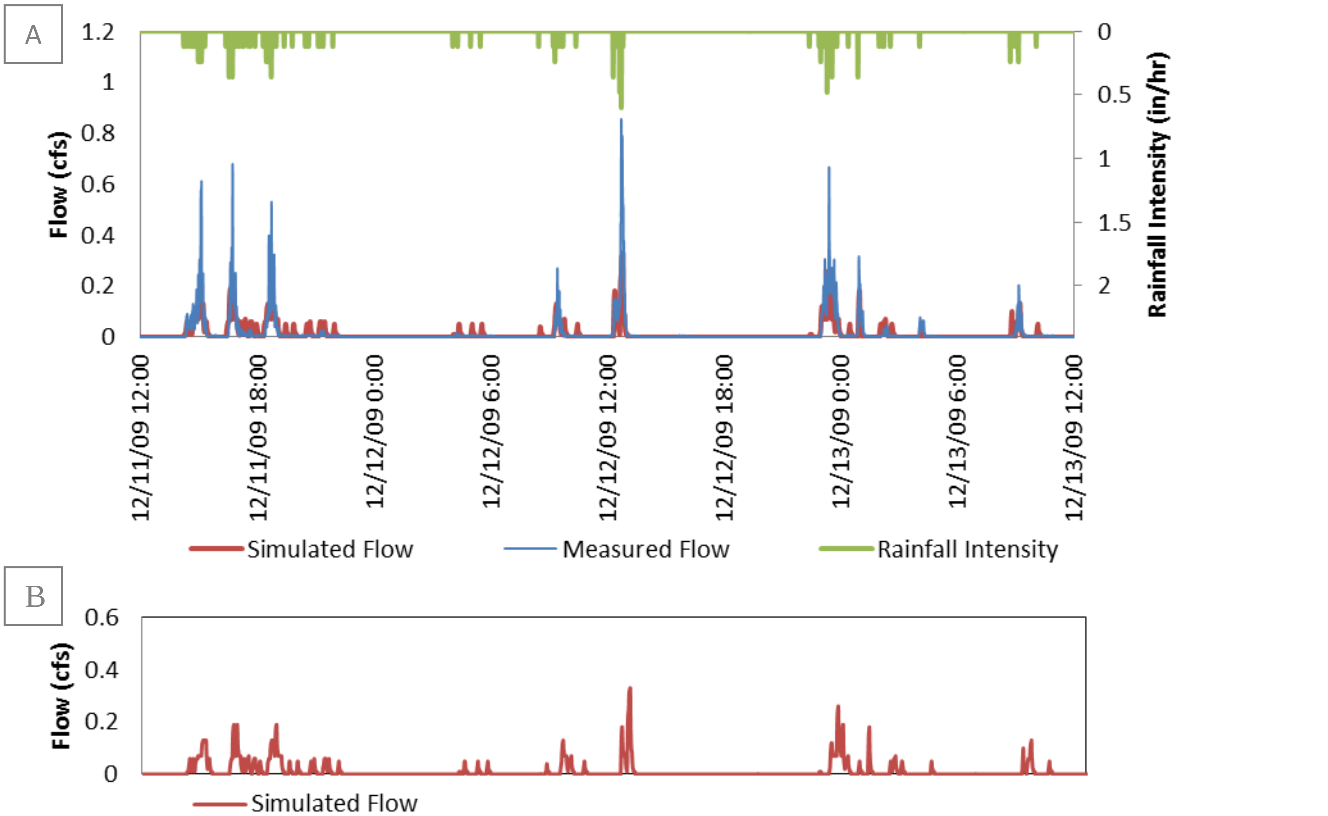

Figure 3. A) Newcomb North measured and simulated flow and rainfall intensity during a multi storm period from December 11 to December 13, 2009. B) Newcomb North simulated flow during the same multi storm period as shown in A), isolated here to show peak flow rates more clearly.

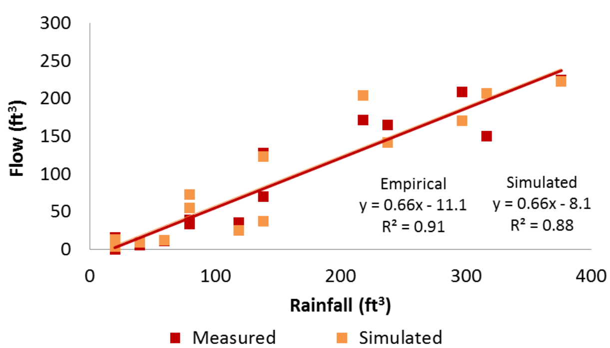

Figure 4. Newcomb North modeled pre-construction versus monitored pre-construction flow volume as a function of rainfall volume for the same storms in Rainy Season 2009-2010 [Note: Two trend lines are graphed and fall almost directly on top of one another]

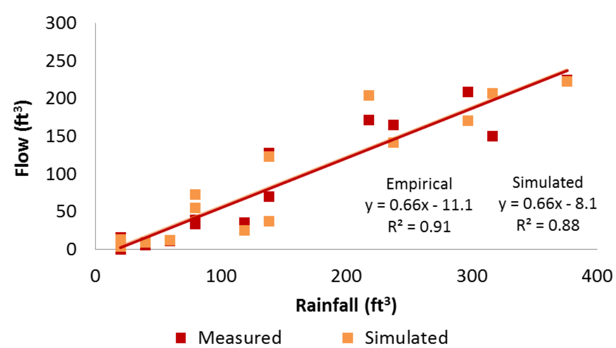

Figure 5. Newcomb North modeled pre-construction versus monitored pre-construction peak flow rates for the same storms in Rainy Season 2009-2010.

Post-construction Data: Newcomb North and South

Post-construction flow monitoring data in both subcatchments were recorded on 5-minute intervals (note that the pre-construction monitoring data at Newcomb North during Rainy Season 2009-10 were collected at 1-minute intervals). A data quality review was implemented for both subcatchment datasets. Flow data were first corrected for the level offset and default velocity values used in each subcatchment, censored during periods of anomalous spikes, and then evaluated by comparing Q_{CONT} to Q_D and Q_V.

In the Newcomb North post-construction data, both Q_D and Q_V had excellent correlation with Q_{CONT} (R=0.99 and R=0.97, respectively) and in less than 1% of the dataset, depth measurements were censored and flow estimates were replaced with Q_V. The Newcomb South data had good correlation between Q_{CONT} and Q_D (R=0.92) but weaker correlation with and Q_V (R=0.64). At Newcomb South, 0.4% of the dataset had questionable depth readings; since correlation between Q_{CONT} and Q_V was poor, storms containing questionable data were censored from the analysis. Following the QA/QC process, the data for each subcatchment were then analyzed in relation to rainfall. Storm events were defined in the same manner as described for the pre-construction data (minimum depth of 0.01 inches and at least 6 hours separation between storm events). Based on that definition and using only the data with quality sufficient for analysis, 37 individual storms were isolated for Newcomb North and 24 storms were isolated in the Newcomb South dataset for the post-construction period. The number of monitored storms varied between the northern and southern sides of the street because equipment malfunction caused some storms to be missed.

Results of Rainy Seasons 2011-2012 and 2012-2013

The combined effects of the constructed elements reduced total volume that flowed to the CSS, reduced peak flow rates to the CSS, and delayed flows to the CSS. Therefore, based on data collected to-date, the model block demonstration appears to have been successful in relation to programmatic objectives. The details of the results of the monitoring data are discussed below in relation to each of these three primary physical performance metrics.

Flow Volume Reduction

Over the two seasons of post-construction monitoring, Newcomb North had good quality flow data during storms producing a total of 16.08 inches of rainfall, while Newcomb South had good quality flow data during storms producing a total of 12.59 inches of rainfall. The maximum rainfall intensity (per 5 minute interval) with corresponding flow data at both sites occurred on December 2, 2012 (0.13 inches in 5 min, or 1.56 in/hr) (Figures 6 and 7). An event of this magnitude is estimated to occur between two and four times annually (between a 0.25 and 0.5-yr event return interval), while most rainfall events captured within the dataset were even more common (less than a 0.25-yr return based on intensity and depth duration)[4].

The continuous hydrographs for each rainy season and each subcatchment (Figures 6 and 7) provided an overview of runoff from Newcomb Avenue North and South subcatchments before (based on the calibrated simulation) and after construction of the GI elements. More detailed views of isolated storms are shown later, but at this scale it was possible to see that several storms that produced flow under pre-construction conditions did not produce flow post-construction. No measureable flow occurred in 12 of 37 storms at Newcomb North and 5 of 24 storms at Newcomb South[5]. Of the 21 storms measured in both subcatchments, each subcatchment produced no measureable flow in 5 storms, the largest of which was a storm with 0.07 in total rainfall over 5.25 hours. Additionally, at Newcomb North, a long duration and low intensity storm measuring 0.25 inches total rainfall over 14 hours did not produce any measurable flow (equipment was not functional at Newcomb South during this event). The monitoring instruments used to measure flow at these sites had some limitations (see footnote 5) measuring very low flows, and so it is possible that some of the storms measuring zero flow actually did discharge some small volume to the CSS. This volume was likely negligible and it is important to note that in the dataset gathered prior to construction, all storms with 0.02 inches of rainfall or more did result in measurable flow using the same monitoring instruments.

[4] Data for design storms was provided by the SFPUC and available online at: http://www.hydrocalc.com/apps/depth_duration/depth_duration.html. 1990 coefficients were used since SFPUC had not begun using the 2013 coefficients at the time of this analysis.

[5] Per manufacturer specifications, the Sigma 950 AV sensors used at this site required a typical minimum flow depth of 0.8 inches for accurate velocity measurement, and 0.2 inches for accurate depth measurement. Q_{CONT} and Q_D (described in Data Quality section) had excellent correlation (0.99) and this fact was used to verify the equipment accuracy at depths less than 0.8 inches. However, it is likely that some flows with a depth < 0.2 inches were not detected.

NEWCOMB NORTH

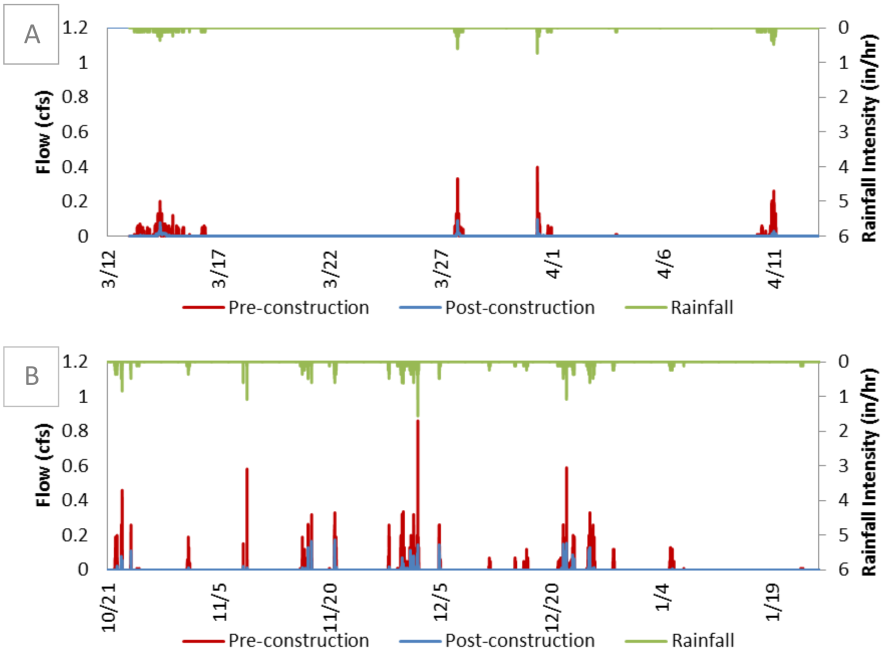

Figure 6. Modeled pre-construction versus monitored post-construction flow and rainfall intensity at Newcomb North during A) the 2011-2012 rainy season and B) the 2012-2013 rainy season[6]. Note: y-axis scales held constant to allow for an easier visual comparison between rainy seasons.

NEWCOMB SOUTH

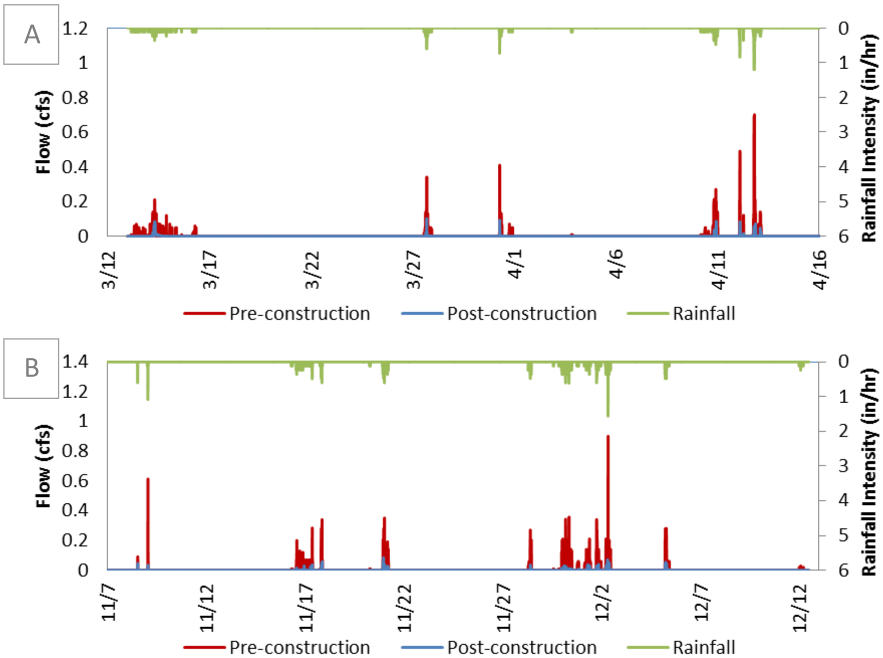

Figure 7. Modeled pre-construction versus monitored post-construction flow and rainfall intensity at Newcomb South during A) the 2011-2012 rainy season and B) the 2012-2013 rainy season[6].

[6] Graphs truncated to show only storms with good quality runoff data.

The volume of flow produced during the various storm events in both the North and South subcatchments showed a marked and similar decrease post-installation of the GI elements. As shown in Figure 8, the reduction in total annual flow volume expressed as the percentage of incident rainfall was similar for both subcatchments.

Typical storm hydrographs and select hydro-meteorological characteristics for isolated storm events at Newcomb North and South are shown in Figure 9 and Tables 3 and 4. These graphs provide a closer look at the reductions in flow volume in isolated storm events. In both events, outflows from both subcatchments were greater than 90% of the rainfall volume under pre-construction conditions whereas flow volume under post-construction conditions were less than 40%.

On an individual storm basis, the relationship between rainfall and flow volumes post-construction was well correlated. Figures 10B and 10C show the flow volume from each subcatchment and each storm for modeled pre-construction and measured post-construction conditions. Figure10A shows the same for smaller storms (<400 ft^3 total rainfall volume) from Newcomb North, where pre-construction flows were also measured in Rainy Season 2009-2010.

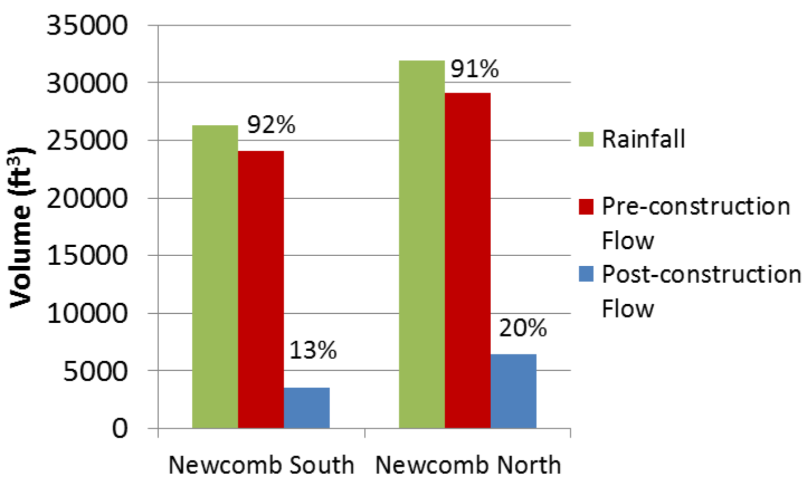

Figure 8. Total flow volume as a percentage of the incident rainfall for the monitoring period in each subcatchment.

The magnitude of antecedent rainfall and consequently the saturation condition of the catchment would be expected to vary the effectiveness of GI at reducing the flow volumes. However, accounting for antecedent rainfall did not improve the relationship with flow volume for any of the antecedent time periods tested (1-5 days) as compared with the simpler rainfall to flow volume relationships shown in Figure 10. One-day antecedent plus storm total rainfall (includes the total rainfall during the storm plus the rainfall from the 24-hour period preceding the start of the storm), which had the best relationship among the antecedent time periods tested, is illustrated in Figure 12. This lack of relationship with antecedent rainfall for the post-construction data may be explained by storage being a small component of the design coupled with the storage that is present being designed to dry out quickly. For example, given the small improvement in volume retention of the site after the adaptive management modifications to the curb cut inlets in December 2012, the permeable pavers appear responsible for the majority of flow reduction, and if those elements dry out relatively quickly (e.g. more quickly than soil), then antecedent rainfall would have little impact on volume retention.

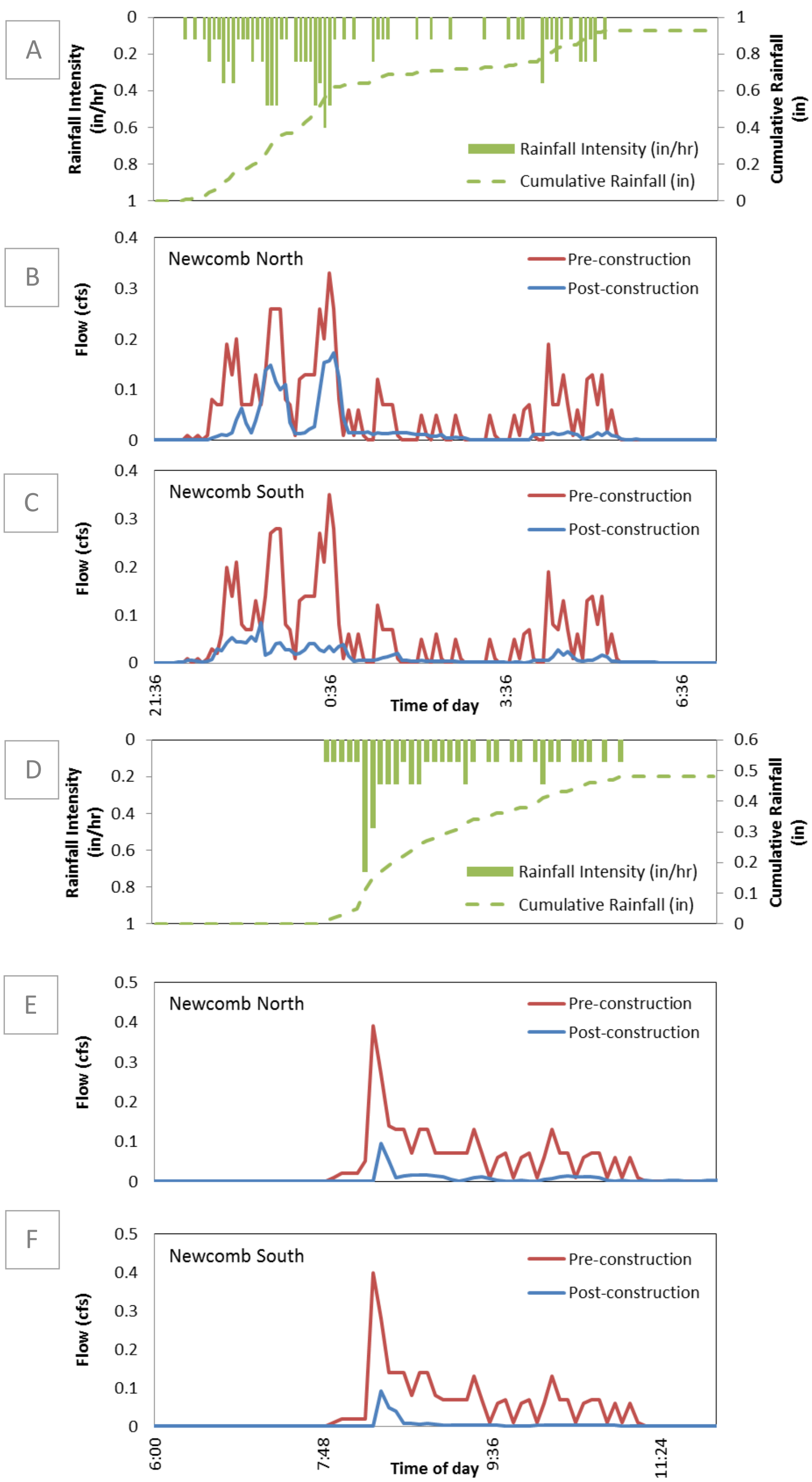

Figure 9. A) Rainfall intensity and cumulative rainfall during a November 2012 storm event. B) and C) Storm hydrographs with modeled pre-construction and monitored post-construction flow for this storm event. D) Rainfall intensity and cumulative rainfall during a March 2012 storm event. E) and F) Storm hydrographs with modeled pre-construction and monitored post-construction flow for this storm event.

Table 3. Storm and flow characteristics for the isolated storm event shown in Figure 9 graphs A-C.

Storm or Flow Characteristic	Newcomb North	Newcomb South
Storm Date(s)	Nov 20-21, 2012	
Storm Total Rainfall (in)	0.93	
Storm Duration (hrs)	7.25	
Peak 5-minute Rainfall Intensity (in/hr)	0.6	
% of Rainfall Flowing to CSS (pre-construction)	95%	95%
% of Rainfall Flowing to CSS (post-construction)	38%	22%
Peak Flow Rate (pre-construction) (cfs)	0.33	0.35
Peak Flow Rate (post-construction) (cfs)	0.17	0.08

Table 4. Storm and flow characteristics for the isolated storm event shown in Figure 9 graphs D-F.

Storm or Flow Characteristic	Newcomb North	Newcomb South
Storm Date(s)	Mar 31, 2012	
Storm Total Rainfall (in)	0.48	
Storm Duration (hrs)	3.2	
Peak 5-minute Rainfall Intensity (in/hr)	0.72	
% of Rainfall Flowing to CSS (pre-construction)	95%	93%
% of Rainfall Flowing to CSS (post-construction)	13%	8%
Peak Flow Rate (pre-construction) (cfs)	0.38	0.40
Peak Flow Rate (post-construction) (cfs)	0.09	0.09

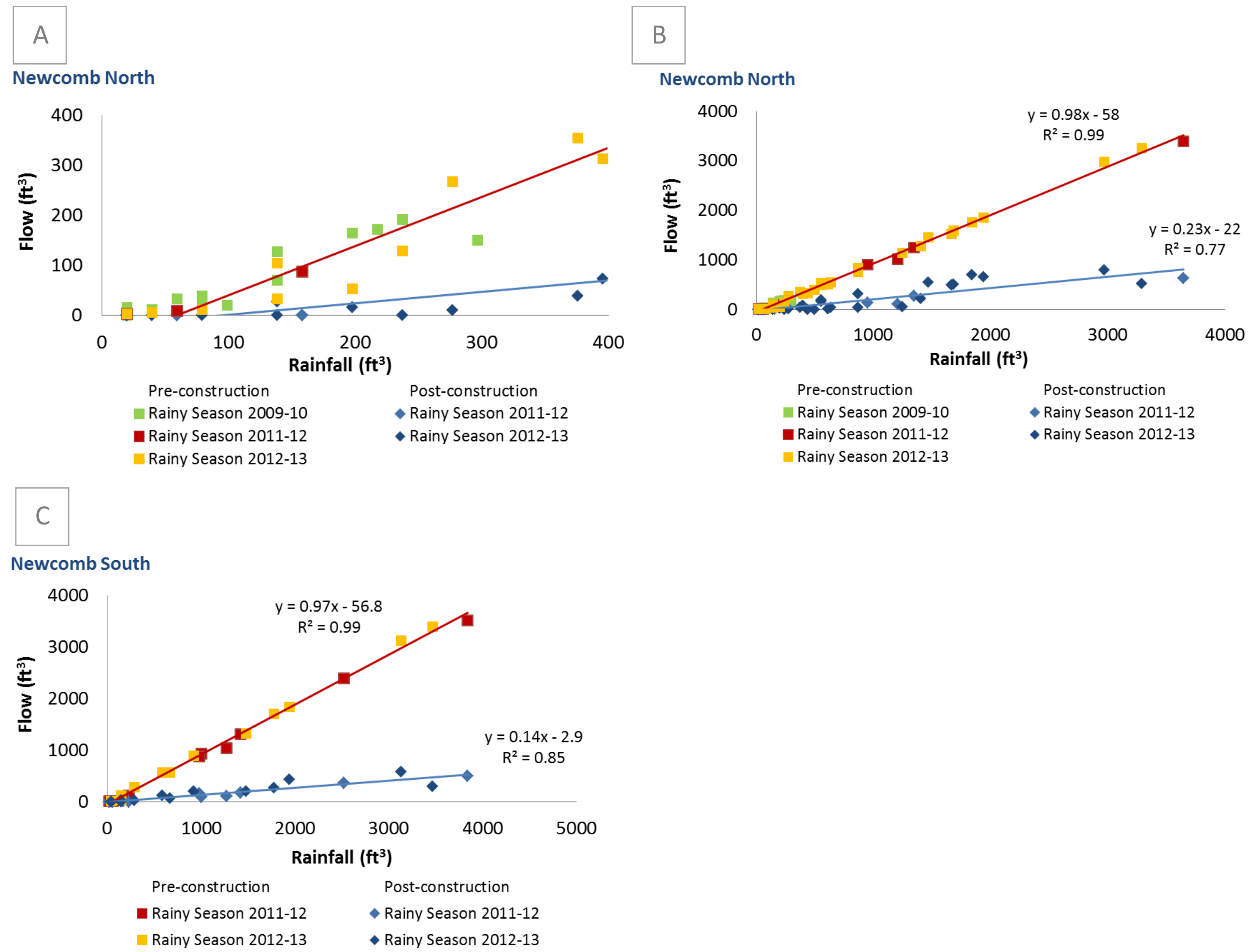

Figure 10. Rainfall and flow volume[7] for rainy seasons 2011-12 and 2012-13 for A) small storms at Newcomb North, B) all storms at Newcomb North, and C) all storms at Newcomb South.

In summary, flow volumes were reduced due to implementation of GI at Newcomb Avenue. In total, for the storms measured in each subcatchment, flow from Newcomb South was reduced from 92% to just 13% of the incident rainfall, and from 91% to just 20% of the incident rainfall on Newcomb North. On an individual storm basis, post-construction flow substantially decreased and was well correlated with total rainfall, though taking into consideration antecedent rainfall did not improve the relationship to volume retention. In this watershed, the data suggest that the permeable pavers and decreased impervious area in the catchment were responsible for the large majority of the flow reductions.

Peak Flow Rate Reduction

As noted in the Data Quality section, the calibrated model for simulating pre-construction flow had excellent correlation with the measured pre-construction data for total volume but underestimated most peaks greater than 0.1 cfs. It is therefore likely that the model underestimated pre-construction peak flow rates in this analysis and that the peak reduction due to GI

[7] Red and yellow data points are simulated modeling data; green and blue data points are measured monitoring data.

Adaptive management modifications were made at Newcomb Avenue in Nov/Dec 2012. The planter was originally constructed with the overflow drain at grade such that the facility did not pond water. Also, the curb-cut inlets were graded such that the majority of stormwater reaching the planter bypassed the inlet and flowed directly into the CSS. The facilities were re-graded and the overflow drains were raised after the 2012 wet season. At the beginning of December 2012, an extension was placed at the curb cut to force flow into the planter.

The effect of this grading and the curb extension retrofit on the bioretention planters is expected to have the greatest impact during smaller storm events since the total storage volume of each bioretention planter is relatively small (<150 ft^3), which is appropriate given the amount of permeable pavement included in the catchment area. The surface area of the bioretention planter is approximately 1% of the impervious surface area in the catchment, and provides storage volume in its soil equal to approximately 0.11 inches of rainfall onto the impervious portion of the catchment area. There appears to be evidence in the Newcomb North data that the curb extension improved the volume retention (as a percentage of the total rainfall volume), specifically in events smaller than a quarter inch of rainfall (Figure 11). No apparent relationship exists in the Newcomb South data; however, there are too few data at this time to quantify the specific effects of the curb extension in either catchment.

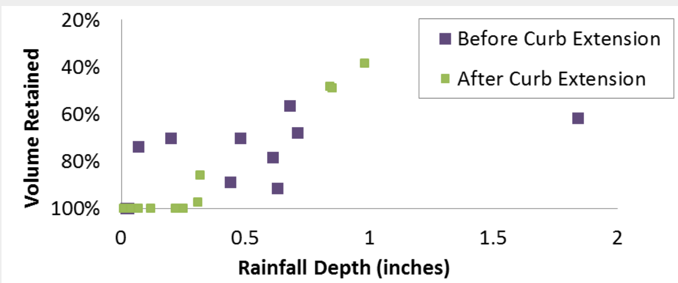

Figure 11. Post-construction volume retention at Newcomb North as a function of rainfall depth before and after placement of the curb extension (only for storms with no antecedent rainfall in the prior 24 hours).

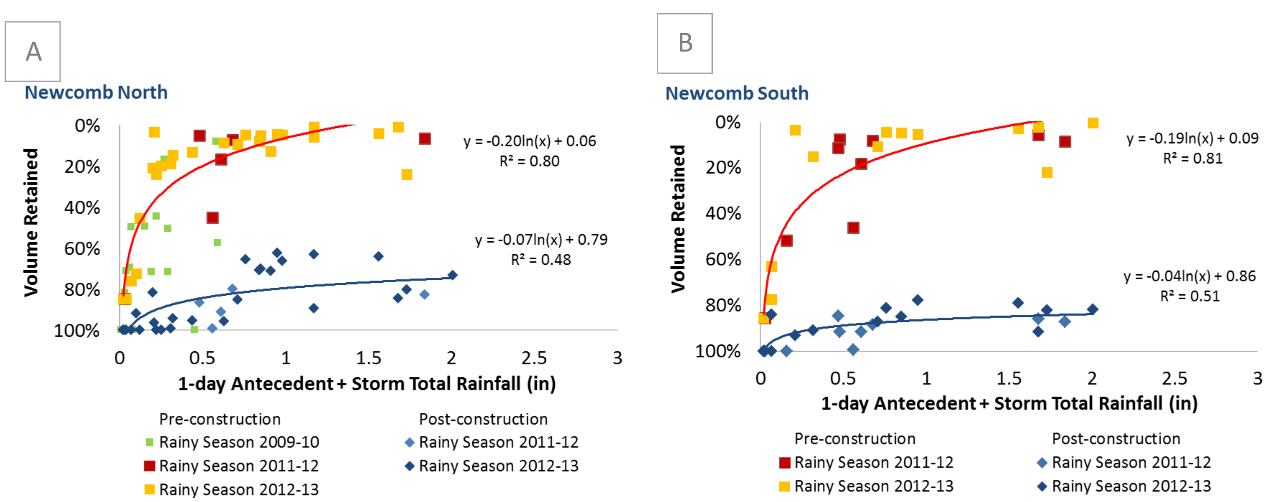

Figure 12. Percentage volume retained per storm event as a function of total storm rainfall plus 24-hour antecedent rainfall volume for modeled pre-construction versus monitored post-construction conditions[8] *(storms > 0.01 inch only)* at A) Newcomb North and B) Newcomb South.

[8] Red and yellow data points are simulated modeling data, green and blue data points are measured monitoring data.

was in fact even greater than reported here. Nevertheless, decreases in peak flow rates are substantial. In the Newcomb North subcatchment, peak flow rates ranged up to 0.86 cfs pre-construction and 0.17 cfs post-construction, with an average reduction of 73% for the 25 post-construction storm events that produced outflow to the CSS. Similarly, peak flow rates from Newcomb South ranged up to 0.90 cfs pre-construction and 0.10 cfs post-construction, with an average reduction of 82% for the 19 post-construction storm events that produced outflow to the CSS. For the 16 storms that produced outflows and were measured in both subcatchments, peak reduction averaged 71% in the northern subcatchment and 80% in the southern. Peak flow rates post-construction correlated best with the peak 30- and 25-minute rainfall depths at Newcomb North and Newcomb South, respectively (Figure 13), and had a better relationship than with the peak 5-minute rainfall depth at each monitoring site (not shown; R^2 = 0.41 and 0.37, respectively)[9].

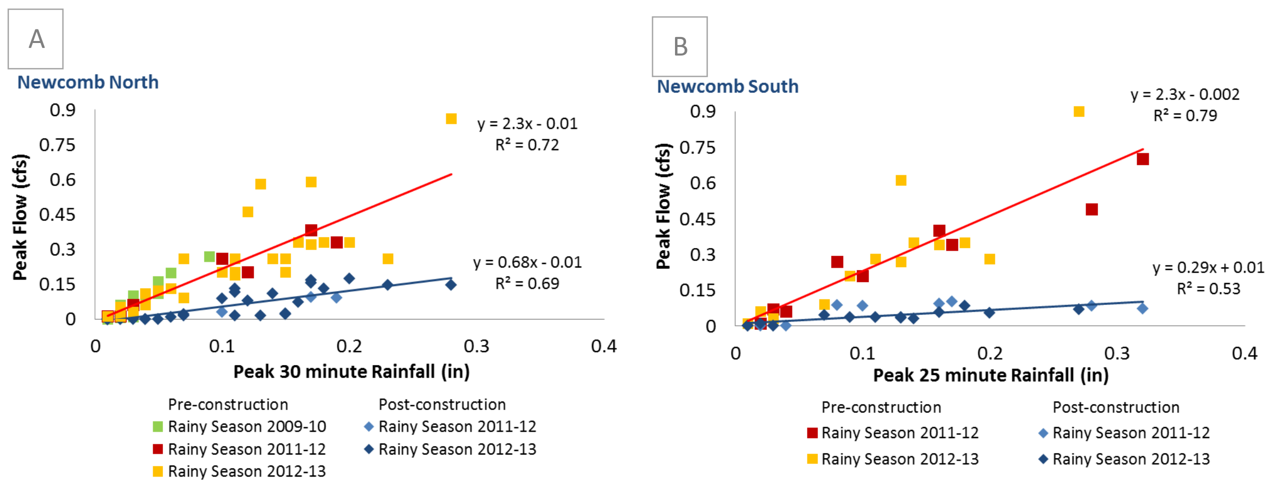

Figure 13. Peak flow rates organized relative to peak rainfall for 30 minute and 25 minute rainfall depths in each storm at A) Newcomb North and B) Newcomb South.[5]

Changes in Lag Time

Measures of lag time were assessed between flow measured onsite in the storm drains and rainfall measured at two nearby rain gauges (described further in the methods section). The computed lag times between the start of rainfall[10] to the start of flow ($Start_I$ to $Start_F$) and the centroid[11] of rainfall to the centroid of flow ($Centroid_I$ to $Centroid_F$) increased in both subcatchments after installation of GI and more permeable surface areas (Table 5)[12]. However, the lag time from peak rainfall[13] to peak flow rate ($Peak_I$ to $Peak_F$) was not substantially delayed. These characteristics are evident in the example hydrographs shown in Figure 9. $Start_I$ to $Start_F$ post-construction was highly variable depending on the amount of rainfall and the intensity of that rainfall. Low-intensity rainfall at the beginning of the storm increased the lag time for those storms (to as long as 14 hours) whereas flow began more quickly during storms when high-intensity rainfall occurred at the beginning of the storm.

[9] Peak rainfall time intervals that were tested include 5, 10, 15, 20, 25, 30 and 45 minutes
[10] The start of rainfall was actually the time of the second one hundredth of rainfall. If runoff started after the first hundredth and prior to the second hundredth, the lag from $Start_I$ to $Start_F$ was given a value of 0 rather than allow a negative lag to result from this definition for $Start_I$.
[11] Centroid is defined as the center of mass.
[12] The increase in $Start_I$ to $Start_F$ lag time may be exaggerated by the inability of equipment to measure very low flows during post-construction conditions.
[13] The time of peak rainfall used in this analysis was the time when the peak cumulative 10-minute rainfall occurred. Only storms with peak cumulative 10-minute rainfalls greater than 0.02 inches were included.

Table 5. Changes in lag times at Newcomb Avenue.

Newcomb North	Median Lag Times (minutes)		
	$Start_I$ to $Start_F$	$Peak_I$ to $Peak_F$	$Centroid_I$ to $Centroid_F$
Pre-construction (2009-10)	<1	8	16
Post-construction (2011-13)	25	10	35
Increase in Lag due to GI	**24**	**2**	**19**

Newcomb South	Median Lag Times (minutes)		
	$Start_I$ to $Start_F$	$Peak_I$ to $Peak_F$	$Centroid_I$ to $Centroid_F$
Pre-construction (Simulated)	<1	2	10
Post-construction (2011-13)	15	5	17
Increase in Lag due to GI	**14**	**3**	**7**

Given the rapid response time between rainfall on the catchment and runoff, the rain gauges may be located too far away to accurately assess absolute lag times. Further, very low flows were more likely to occur post-construction yet the flow monitoring instrumentation was not capable of recording these very low flows, and this may be an additional confounding factor in the lag time computations. Given these challenges, the slight changes in lag time computed at both sites for $Peak_I$ to $Peak_F$ may not be real differences, whereas it is likely that the changes in lag time between $Start_I$ to $Start_F$ and $Centroid_I$ to $Centroid_F$ are real (though not absolutely accurate).

Lessons Learned and Adaptive Management Suggestions

During visits to the site immediately after construction, the Team noted that the grading at the bioretention planter did not effectively direct stormwater runoff into the inlet; much of the runoff bypassed the inlet and flowed directly into the stormdrain. Additionally, the bioretention planters were graded so high that there was little capacity for ponding. In response, the Team performed a water truck test in the summer of 2012, at which time recommendations for grading improvements were developed (Figures 14 and 15). Grading on site was improved in December 2012.

A key management suggestion developed from this experience was to integrate water truck testing into the construction phase. This type of quality assurance task could be implemented to ensure proper drainage performance, and could occur prior to approving substantial completion and/or final completion. Such testing would also help train construction and maintenance crews on how to ensure the maximal function of GI installations.

Suggested Monitoring Program Improvements

Three key monitoring program recommendations are suggested as follows:

1) The amount of time required for analysis was extended due to initial misunderstandings of the offsets and default values applied to the flow monitoring record. Usage of defaults and offsets should be carefully considered and, when utilized, documented appropriately in the field notes.
2) Flows from these small catchments fluctuate very rapidly. Data collection intervals are currently 5 minutes. A 1-2 minute data collection interval would improve accuracy and precision of interpretations of peak flow rate and lag time. The disadvantage of a shortened time interval will be shortened times between manual downloads or larger data logging storage capacity requirements, larger overall data handling requirements, and increased frequency of battery replacement.
3) Observations should be made at GI monitoring sites during several intense rainfall events. Such observations should include (but not be limited to) verification of the watershed boundary, qualification of potential run-on from adjacent catchments, verification that the drainage patterns are as expected, and verification that GI elements are performing as expected.

Figure 14. Images from water truck test in the summer of 2012 showing runoff bypassing the inlet to the bioretention planter and draining into the storm drain inlet.

Figure 15. One of the two curb extensions added in December 2012 to better direct runoff into the facility.

Newcomb North Reference Table

Table 6. Select individual storm metrics for the simulated pre-construction and measured post-construction flows at Newcomb Avenue North (storms >0.05 inches only)[14].

Storm Start	Storm Duration (hrs)	Total Rainfall (in)	Rainfall (ft³)	Pre-construction			Post-construction			Peak Flow Rate Reduction
				Peak Flow (cfs)	Flow (ft³)	Volume Retention	Peak Flow (cfs)	Flow (ft³)	Volume Retention	
11/30/2012 19:25	2.1	0.07	139	0.05	105	24%	0.01	27	80%	75%
12/12/2012 1:10	5.3	0.07	139	0.03	33	76%	0.00	0	100%	100%
3/31/2012 19:05	4.4	0.08	158	0.06	87	45%	0.00	1	99%	98%
11/8/2012 13:45	0.1	0.10	198	0.09	54	61%	0.02	16	92%	77%
12/15/2012 14:00	3.3	0.12	238	0.06	129	46%	0.00	0	100%	100%
11/9/2012 1:30	1.1	0.14	277	0.58	267	4%	0.01	10	96%	98%
12/26/2012 4:55	7.7	0.19	376	0.26	354	6%	0.01	39	90%	94%
10/24/2012 4:00	1.6	0.20	396	0.26	312	21%	0.11	73	82%	58%
12/28/2012 22:50	5.7	0.22	435	0.12	330	24%	0.00	0	100%	100%
12/16/2012 19:20	14.1	0.25	495	0.11	396	20%	0.00	0	100%	100%
10/22/2012 21:00	4.3	0.28	554	0.46	483	13%	0.17	190	66%	48%
11/17/2012 19:15	2.9	0.28	554	0.32	528	5%	0.08	160	71%	83%
1/5/2013 16:30	15.0	0.31	614	0.13	498	19%	0.01	4	99%	94%
11/28/2012 8:10	3.8	0.32	633	0.26	540	15%	0.02	35	94%	93%
10/31/2012 20:00	9.8	0.44	871	0.19	756	13%	0.01	40	95%	93%
12/1/2012 4:10	7.8	0.44	871	0.20	834	4%	0.11	311	64%	43%
3/31/2012 7:50	3.2	0.48	950	0.38	900	5%	0.09	126	87%	75%
4/10/2012 5:35	20.3	0.61	1,207	0.26	1,005	17%	0.03	106	91%	89%
10/21/2012 23:30	9.3	0.63	1,247	0.20	1,140	9%	0.02	54	96%	88%
3/27/2012 14:50	9.2	0.68	1,346	0.33	1,248	7%	0.09	272	80%	73%
11/16/2012 8:20	25.9	0.71	1,405	0.26	1,275	9%	0.13	208	85%	50%
12/23/2012 5:40	11.8	0.74	1,465	0.20	1,452	1%	0.09	543	63%	56%
12/21/2012 10:40	35.8	0.84	1,663	0.59	1,527	8%	0.15	487	71%	74%
12/5/2012 6:10	5.3	0.85	1,682	0.26	1,593	5%	0.15	502	70%	44%
11/20/2012 23:05	7.3	0.93	1,841	0.33	1,755	5%	0.17	692	62%	48%
12/25/2012 9:35	13.0	0.98	1,940	0.33	1,845	5%	0.13	652	66%	61%
12/1/2012 18:40	17.6	1.50	2,969	0.86	2,973	0%	0.15	797	73%	83%
11/29/2012 21:15	16.0	1.66	3,285	0.33	3,249	1%	0.07	510	84%	78%
3/13/2012 5:00	53.5	1.84	3,642	0.20	3,396	7%	0.08	629	83%	61%
Total	**317**	**16.0**	**31,588**		**29,064**			**6,485**		
Average	**10.9**	**0.55**	**1,089**	**0.27**	**1,002**	**16%**	**0.07**	**224**	**84%**	**77%**
Maximum	**53.5**	**1.84**	**3,642**	**0.86**	**3,396**	**76%**	**0.17**	**797**	**100%**	**100%**

[14] Volume retention was calculated as the flow volume divided by the rainfall volume.

Newcomb South Reference Table

Table 7. Select individual storm metrics for the simulated pre-construction and measured post-construction flows at Newcomb Avenue South (storms >0.05 inches only)[15].

Storm Start	Storm Duration (hrs)	Total Rainfall (in)	Rainfall (ft^3)	Pre-construction			Post-construction			Peak Flow Rate Reduction
				Peak Flow (cfs)	Flow (ft^3)	Volume Retention	Peak Flow (cfs)	Flow (ft^3)	Volume Retention	
11/30/2012 18:25	2.1	0.07	146	0.06	114	22%	0.01	26	82%	85%
12/12/2012 0:10	5.3	0.07	146	0.03	33	77%	0.00	0	100%	100%
11/8/2012 12:45	0.1	0.07	146	0.09	54	63%	0.04	23	84%	50%
3/31/2012 18:05	4.4	0.08	167	0.07	90	46%	0.00	1	99%	98%
3/16/2012 4:20	4.3	0.11	230	0.06	111	52%	0.00	0.2	100%	99%
11/9/2012 0:30	1.1	0.14	292	0.61	282	4%	0.03	20	93%	94%
11/17/2012 18:15	2.9	0.28	585	0.34	558	5%	0.06	110	81%	83%
11/28/2012 7:10	3.8	0.32	668	0.27	567	15%	0.04	60	91%	87%
12/1/2012 3:10	7.8	0.44	919	0.21	891	3%	0.04	192	79%	82%
4/12/2012 2:10	5.2	0.47	981	0.49	870	11%	0.08	151	85%	83%
3/31/2012 6:50	3.2	0.48	1,002	0.40	927	7%	0.09	83	92%	77%
4/10/2012 4:35	20.3	0.61	1,273	0.27	1,041	18%	0.09	106	92%	68%
3/27/2012 13:50	9.2	0.68	1,420	0.34	1,302	8%	0.10	163	88%	70%
11/16/2012 7:20	25.9	0.71	1,482	0.28	1,323	11%	0.04	192	87%	87%
12/5/2012 5:10	5.3	0.85	1,774	0.28	1,692	5%	0.05	266	85%	81%
11/20/2012 22:05	7.3	0.93	1,941	0.35	1,836	5%	0.08	429	78%	76%
4/12/2012 18:35	9.5	1.21	80,828	0.70	2,385	97%	0.07	359	100%	90%
12/1/2012 17:40	17.6	1.50	3,131	0.90	3,117	0%	0.07	572	82%	92%
11/29/2012 20:15	16.0	1.66	3,465	0.35	3,387	2%	0.03	296	91%	91%
3/13/2012 4:00	53.5	1.84	3,841	0.21	3,516	8%	0.08	494	87%	60%
Total	**205**	**12.5**	**104,438**		**24,096**			**3,544**		
Average	**10.2**	**0.63**	**5,222**	**0.32**	**1,205**	**23%**	**0.05**	**177**	**89%**	**83%**
Maximum	**53.5**	**1.84**	**80,828**	**0.90**	**3,516**	**97%**	**0.10**	**572**	**100%**	**100%**

[15] Volume retention was calculated as the flow volume divided by the rainfall volume.