San Francisco State University Site 3 Basin and Swale System: Technical Appendix

This technical appendix complements the SFSU Site 3 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.

Project Characteristics

The basin and swale system on the north side of the SFSU Science Building (SFSU Site 3) receives stormwater runoff from a 3,100 ft^2 portion of the Science Building roof. The downspout from this roof was previously connected into the CSS, and has now been routed through a pipe into the basin and swale (Figure 1). The facility includes a two-stage system for infiltrating and detaining storm flows: the upper portion includes a flat, small infiltration basin surrounded by berms with a raised spillway, which first ponds the stormwater runoff and encourages infiltration. Although not analyzed here, this upper portion may also increase the settling of suspended solids and particulate-bound contaminants via detention. After reaching the top of the spillway, runoff then flows into a swale with a 3-4 foot wide flat channel, angled side slopes (less than 45°), and a longitudinal profile sloping at approximately 3% grade west toward the outlet drain.

Table 1. Select characteristics of the subcatchment.

Metric	Site Data
Drainage Area to monitored inlet (ft^2)	3,100
Drainage Area to outlet (ft^2)	6,550[1]
Area of basin and swale (ft^2)	550
% of Impervious Area Converted to GI	0 %
% of Drainage Area that is GI	8.4%[2]
Land Use(s)	Roof

Methods

The hydrologic analysis presented in this report is based on the comparison of flow data modeled at the inlet and collected at the outlet of the basin and swale system post-construction (Figure 1). Modeled inlet flow represents pre-construction flow patterns into the CSS, and measured outlet flow represents post-construction flow patterns into the CSS. Inlet flows were empirically measured using a weir box with an internal pressure transducer mounted inside a stilling well with a v-notch weir, located at the downspout from the Science Building roof (Figure 1b). However, the inlet data collected at the downspout of the roof was inconsistent and compared poorly to a reasonable conceptual estimate of stormwater runoff from a 100% impervious roof. Two possible explanations were explored: 1) the gutters on the roof did not function correctly and stormwater spilled over the edge or through holes in the gutters rather than to and down the rainspout, and 2) the rainspout monitoring equipment malfunctioned. SFSU groundskeepers verified high quantities of drip from the gutters. Equipment

[1] The drainage area to outlet includes the Science Building roof into the basin and swale system (3,100 ft2), the two-stage basin and swale system itself (550 ft2; outlined in orange in Figure 1), plus the area outlined in yellow (2900 ft2), which receives drip from the rooftop and drains towards the basin and swale system and outlet drain.

[2] Only the basin and swale system was included as contributing to GI surface area, not the surrounding landscaped area also draining to the outlet. The SFPUC recommends a 5-10% ratio for parcel-based rain gardens.

malfunction was considered less likely since similar equipment used at the outlet and at SFSU Site 1 all performed well. Also, the pattern of flow presence/absence correlated with rainfall, indicating the equipment was likely functioning properly.

Consequently, the measured inlet flow data were not usable and inlet flow for this analysis had to be modeled. The Stormwater Management Model (SWMM) was the model of choice because it has a simple platform, can be programmed to provide reasonably reliable outputs at a time step of minutes, and is widely accepted and verified for use in simulating runoff processes in small, urban catchments. With no corresponding empirical data to calibrate the inlet model parameters, conservative input parameters were selected to characterize the rooftop in order to ensure the performance of the basin and swale was not over-predicted.

The outlet measurements were also taken using a weir box located in the overflow drain located at the end of the swale (Figure 1c). Flow monitoring was conducted during Rainy Season 2011-2012 and 2012-2013 and data were collected at a 1 minute interval. 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; the details of which are shown in Table 2. The San Francisco State University rain gauge (gauge SFS-16) is the nearest rain gauge and was used in this analysis. This gauge is located 0.065 miles (105 m) to the east of the SFSU Site 3 basin and swale system. Rainfall data were recorded at 5-minute intervals.

The method of analysis utilized in this report was a comparison of inlet and outlet stormwater flows for individual storm events. 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), and various lag times were determined for each isolated storm. These characteristics were compared between the modeled inlet and measured outlet datasets to understand the effectiveness of the basin and swale system.

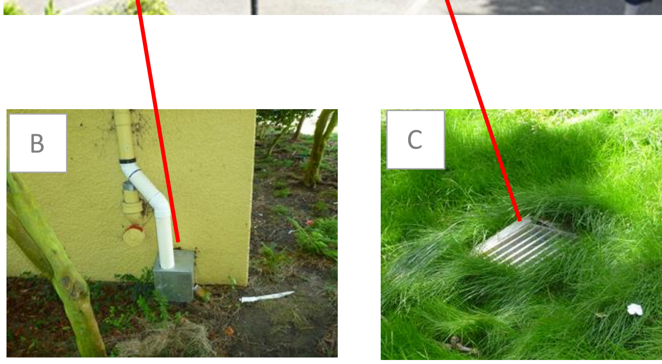

Figure 1. SFSU Site 3 has a paired inlet-outlet monitoring set-up. A portion of the Science Building roof (area highlighted in red in (A)) is the area managed by the basin and swale. Runoff from the roof either drips through holes in the gutter directly onto the landscaping surrounding the basin and swale, or flows through the downspout (B) and then through piping into the basin and swale system. Stormwater runoff fills and infiltrates the unlined basin and swale during a storm. Runoff that does not infiltrate is allowed to flow to the overflow drain (C) connected to the sewer system. Below the overflow drain grate is a v-notch weir box where flows exiting the swale are measured.

Table 2. Period of record with both flow and rainfall data for SFSU Site 3.

Rainy Season	SFSU 3
2011 - 2012	2/15/2012 – 6/30/2012
2012 - 2013	9/1/2012 – 2/20/2013

Data Quality

During Rainy Seasons 2011-12 and 2012-13, outlet flow data were of high quality. Flow was determined by measurement of absolute pressure using a pressure transducer located in a weir box. Absolute pressure data from the sensor drifted temporally in unison with the regional atmospheric pressure (Gauge: San Francisco, USAF-WBAN_ID 994016; available from NOAA.gov) except during storm events in which pressure was elevated above atmospheric pressure due to water level inside the weir box. The absolute pressure data were normalized to atmospheric pressure and converted to water level within the weir box. A v-notch weir equation was applied to calculate flows from water level. Quality of the water level and the calculated flow data for the overflow drain outlet were evaluated based on presence/absence and reasonableness in relation to rainfall magnitude and timing, general shape of the hydrograph, and results of the analytical outputs. The analyses resulted in hydrologic characteristics that matched a reasonable conceptual model for a site in which the ratio of GI surface area to managed impervious area is more than 15%. Results were consistent relative to factors affecting the saturation conditions of the site, and were therefore deemed to be of good quality.

Modeled flow at the inlet generally fits well with a reasonable conceptual model of hydrologic characteristics of a 100% impervious roof. However, due to the use of conservative input parameters specifically in regards to storage depth, slope and overland flow roughness coefficient, start of flows were delayed beyond those typically expected for a 100% impervious roof. A higher priority was to ensure modeled flows were conservative rather than ensure the model results did not exaggerate facility performance. The impacts of this model result are described further in the results subsection on lag time.

Storm events at this site were defined as beginning at the initiation of measured rainfall (minimally 0.01 inches) and ending at the last measured rainfall preceding minimally a 6 hour period of no rainfall. Based on this definition, 20 individual storms were isolated during the Rainy Season 2011-2012 period of record and 33 storms were isolated for the Rainy Season 2012-2013 period of record. Data for all 53 of these individual storm events were considered of sufficient quality for interpretative analysis.

Results of Rainy Seasons 2011-2012 and 2012-2013

The basin and swale system at SFSU Site 3 reduced the total volume flowing into the CSS as well as reduced peak flow rates and delayed flows to the CSS. Therefore, based on data collected to-date, SFSU Site 3 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

SFSU Site 3 received a total rainfall of 20.7 inches during the period of record for which runoff data were also available (Feb 15, 2012 – Feb 20, 2013, with some data gaps), and was roughly distributed equally across the two rainy seasons. The maximum rainfall intensity (per 5 minute interval) occurred on April 12, 2012 (2.04 in/hr (Figure 4)) and was approximately a 1-year event based on the 5-minute duration (0.25-yr event based on the 3-hour duration). Most 5-minute rainfall intensities remained below 0.9 in/hr and most storm events were of the 0.5-yr events or smaller based on the 3-hour duration.

The seasonal hydrographs for Rainy Season 2011-12 (Figure 2A) and 2012-13 (Figure 2B) show the changes to stormwater flows before and after construction of the basin and swale system. Simulated flows from the roof (surrogate for pre-construction flows to the CSS, assuming runoff from landscaped area was negligible during pre-construction) were highly correlated with rainfall and occurred during most storm events whereas bypass from the basin and swale via the overflow drain occurred infrequently, at reduced volumes and reduced peak flows. Overall, the basin and swale system substantially reduced the total volume of runoff entering the CSS (Figure 3). For the period monitored, total runoff volume entering the CSS was reduced by 95%; decreasing from 82% of the incident rainfall before installation down to only 4% of the incident rainfall after installation. In total, over 31,000 gallons of runoff were retained by the basin and swale system during the monitoring period.

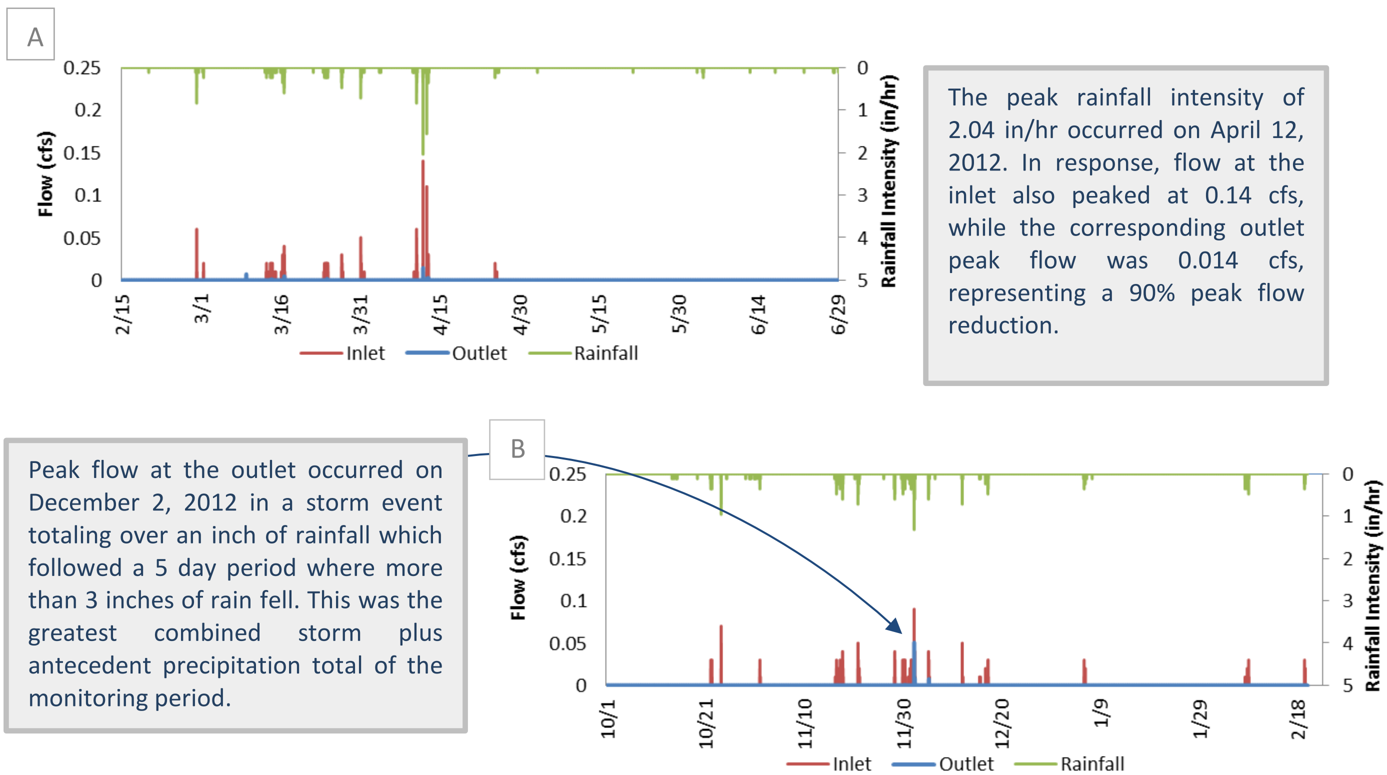

Figure 2. Seasonal hydrographs at the inlet and outlet of SFSU Site 3 and rainfall intensity for A) Rainy Season 2011-2012 (February 15 – June 30, 2012), and B) Rainy Season 2012-2013 (September 1, 2012 – February 20, 2013). Inlet flows are modeled.

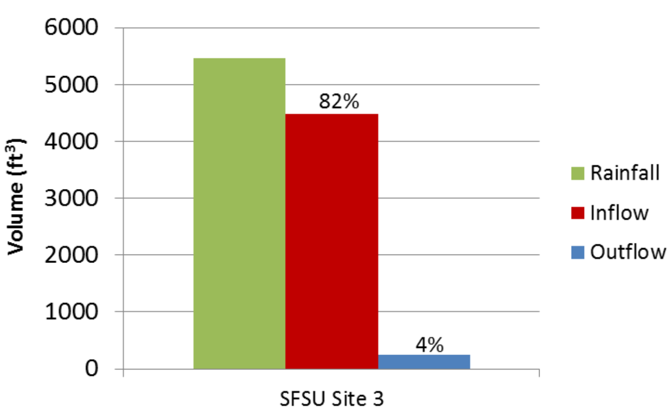

Figure 3. Total flow volume as a percentage of the incident rainfall for the monitoring period.

Typical storm event hydrographs in which outlet flow was measured (only 20 of 53 events had measurable outflow) (Figures 4 and 5) illustrate the changes to runoff patterns on the site now that runoff from the rooftop is routed into the basin and swale system. The patterns shown in these hydrographs follow a typical model of modifications to hydrology due to GI installations. Total volumes to the CSS decreased substantially as compared with pre-construction conditions (as exhibited by flows modeled at the inlet).

The hydrographs shown in Figure 4 illustrate a stormy period in April 2012 with associated typical hydrograph response. During this period, over two inches of rain fell but only 5% of that rainfall flowed to the CSS. The hydrograph in Figure 4 is a detailed view of the extended storm period depicted in Figure 5 of the Site Report, focusing on the outlet flow that occurred at the end of this storm period. During this storm period, no flow occurred from the 3.15 inches of rainfall in the preceding four days. Bypass to the overflow drain (which drains to the CSS) occurred after rainfall had saturated the basin and swale system and an intense period of rainfall occurred. Even under these conditions retention and detention still occurred; the flow volume and rate were still only half the volume and rate that would have flowed to the CSS prior to GI installation.

On an individual storm basis, the relationship between rainfall and flow volumes at the inlet had excellent correlation for both rainy seasons (Figure 6). The correlation between rainfall and outlet runoff was poor because bypass of the basin and swale via the overflow drain were only partly driven by rainfall volume. Antecedent rainfall also played a role as it affects the storage capacity of the basin and swale system going into the storm event. The importance of antecedent rainfall was demonstrated by the high outlet outlier in Figure 6, which is the data point for the storm shown in Figure 4.

The magnitude of antecedent rainfall and consequently the saturation condition of the catchment would be expected to vary the effectiveness of GI at reducing flow volumes. Retention volume (the proportion of rainfall that was retained within the system) per storm was found to have an improved correlation with the combined 4-day antecedent plus storm rainfall total as compared with just the storm total rainfall depth (Figure 7) (antecedent time periods tested included 1-5 days).

In summary, flow volumes were reduced post construction of the two-stage basin and swale system at SFSU Site 3. In total, for the storms measured, flow was reduced from 82% to just 4% of the incident rainfall. On an individual storm basis, outlet flows were substantially lower than inlet flows and were correlated with total rainfall, though the correlation improved when also accounting for antecedent rainfall.

Peak Flow Rate Reduction

For storm events that produced runoff at the outlet during the monitoring period (n=20), reductions in peak flows from those measured at the inlet ranged from 44% to 99% and averaged 94%. An additional 10 storms produced flow at the inlet but were entirely retained within the basin and swale and did not outflow to the CSS at all (100% peak flow reduction). Another 23 storms involved only trace rainfall producing no runoff at the inlet or outlet.

Peak flows simulated for the inlet to the basin and swale had good-to-excellent correlation ($R^2 > 0.88$ in all cases) with all peak rainfall depths tested (5-, 10-, 15-, 20-, 25-, and 30-minute peaks) across the range of storms, with the strongest correlation at the peak 5 minute peak rainfall depth (Figure 8 and Table 5). Peak measured flows at the outlet did not correlate well with any peak rainfall durations tested ($R^2 < 0.28$ in all cases). As described previously, outflows from the basin and swale were driven more by factors that affect the saturation condition of the system (e.g. storm rainfall total, antecedent precipitation) than by rainfall intensity.

Changes in Lag Time

Computed lag times from the start of rainfall[3] to the start of flow ($Start_I$ to $Start_F$), the peak rainfall[4] to the peak flow ($Peak_I$ to $Peak_F$), and the centroid[5] of rainfall to the centroid of flow ($Centroid_I$ to $Centroid_F$) would all be expected to increase due to the roof runoff now passing through the basin and swale. The simulated lag times for the inlet were longer than expected and

[3] 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 $Start_I$.
[4] 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.
[5] Centroid is defined as the center of mass.

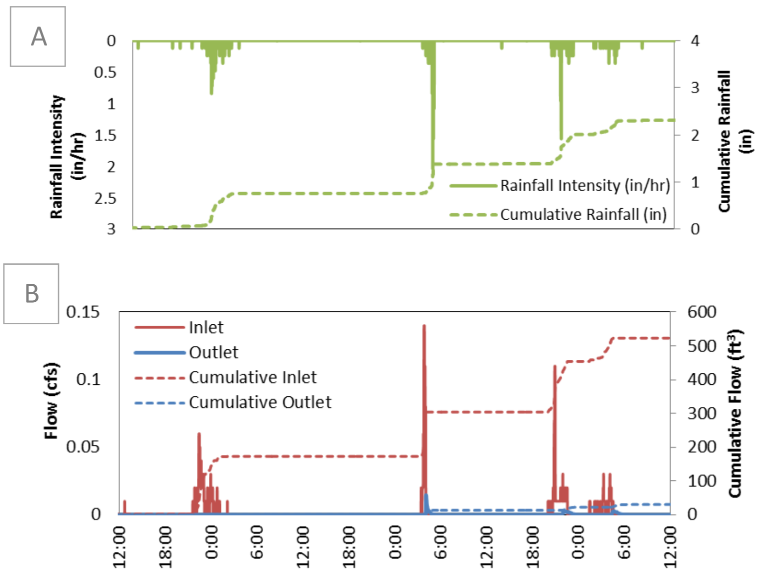

Figure 4. A) Rainfall intensity and cumulative rainfall over multiple days in April 2012. B) Storm hydrographs and cumulative flow volumes during the same storm period.

Table 3. Storm and flow characteristics for the storm series shown in Figure 4 graphs A-B.

Storm or Flow Characteristic	SFSU Site 3
Storm Date(s)	Apr 10 - 13, 2012
Storm Total Rainfall (in)	2.31
Storm Duration (hrs)	70
Peak 5-minute Rainfall Intensity (in/hr)	2.04
% of Rainfall Flowing to Basin and Swale Inlet	85%
% of Rainfall Flowing to CSS	5%
Peak Flow Rate at Inlet (cfs)	0.14
Peak Flow Rate to CSS (cfs)	0.014

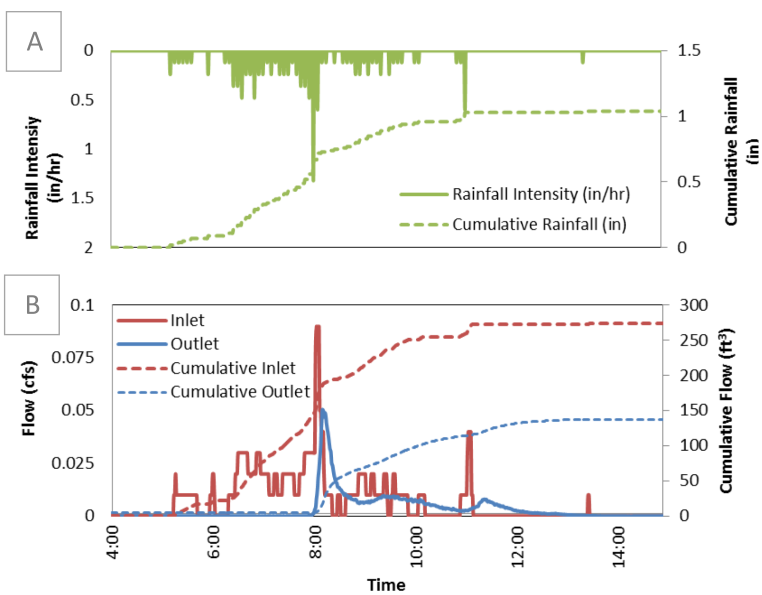

Figure 5. A) Rainfall intensity and cumulative rainfall during a storm in December 2012. B) Storm hydrographs and cumulative flow volumes during the same period.

Table 4. Storm and flow characteristics for the isolated storm event shown in Figure 5 graphs A-B.

Storm or Flow Characteristic	SFSU Site 3
Storm Date(s)	Dec 2, 2012
Storm Total Rainfall (in)	1.04
Storm Duration (hrs)	8.2
Peak 5-minute Rainfall Intensity (in/hr)	1.32
% of Rainfall Flowing to Basin and Swale Inlet	99%
% of Rainfall Flowing to CSS	50%
Peak Flow Rate at Inlet (cfs)	0.09
Peak Flow Rate to CSS (cfs)	0.05

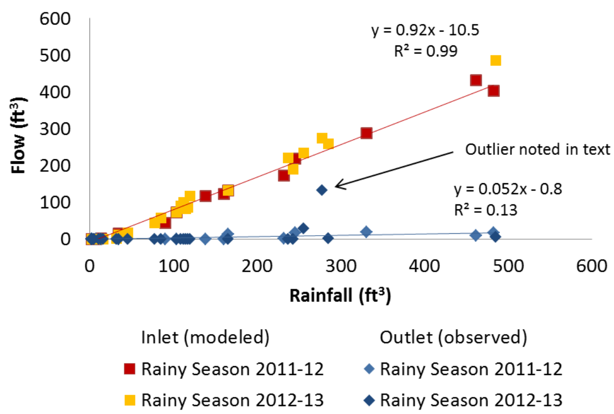

Figure 6. Rainfall and flow volume for all individual storm events monitored at SFSU Site 3 during Rainy Seasons 2011-12 and 2012-13.

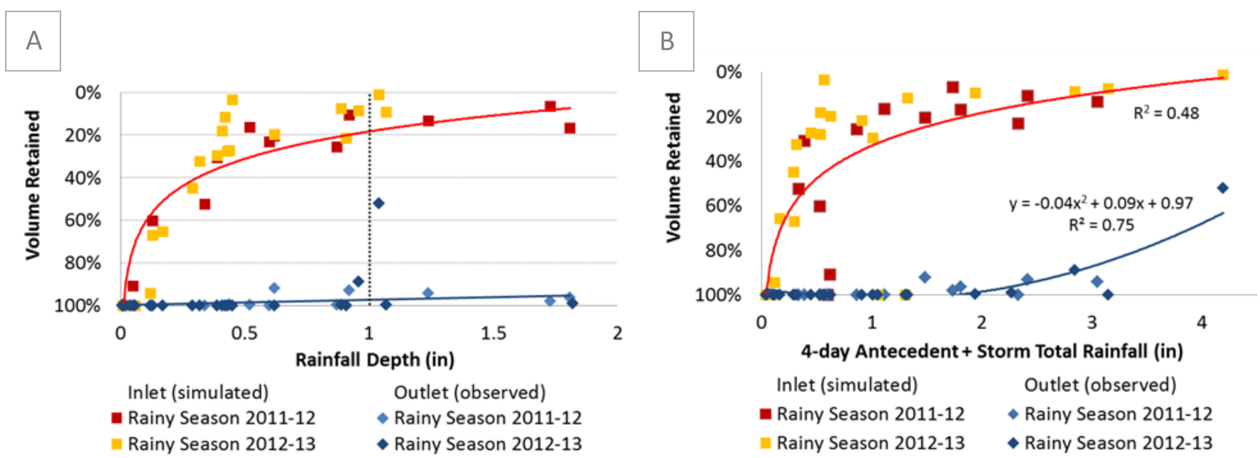

Figure 7. Percentage of rainfall volume retained within the basin and swale system per storm event relative to A) the storm total rainfall depth, and B) the storm total rainfall depth plus antecedent rainfall depth over the preceding four days. [*Storms > 0.01 inch only*]

Table 5. Coefficient of determination for peak inlet and outlet flow relative to peak rainfall for each storm event.

Rainfall Depth-Duration	Inlet R^2	Outlet R^2
5 minute peak rainfall	0.97	0.27
10 minute peak rainfall	0.96	0.23
15 minute peak rainfall	0.93	0.23
20 minute peak rainfall	0.92	0.22
25 minute peak rainfall	0.91	0.22
30 minute peak rainfall	0.88	0.22

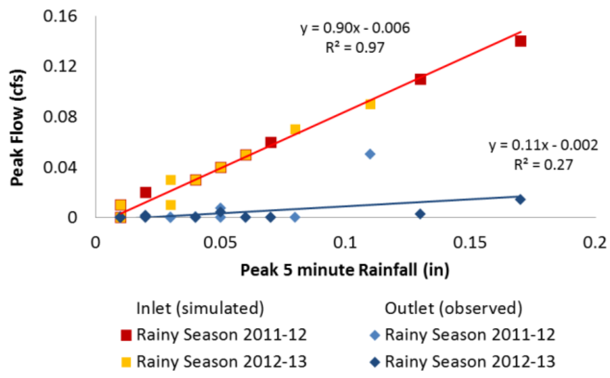

Figure 8. Peak flow at the inlet and outlet for corresponding peak 5 minute rainfall depths in each storm event.

Table 6. Changes in lag times at SFSU Site 3.

	Median Lag Times (minutes)		
	$Start_I$ to $Start_F$	$Peak_I$ to $Peak_F$	$Centroid_I$ to $Centroid_F$
Inlet - Modeled	73	<1	16
Inlet - Best Professional Estimate	*<10*	*<10*	*<10*
Outlet	230	100	95
Increase in Lag due to GI	**157 - 230**	**90 - 100**	**79 - 95**

were likely confounded by the conservative input parameters utilized for the SWMM model for runoff from the roof into the basin and swale. Conservative parameters were selected to ensure performance was not exaggerated. However, these conservative parameters led to simulation results that delayed the start of runoff after the beginning of the storm. The simulated inlet median lag time for $Start_I$ to $Start_F$ of 73 minutes is unlikely for a 100% impervious roof. This extended inlet lag between $Start_I$ and $Start_F$ also caused a longer lag between $Centroid_I$ and $Centroid_F$ than would otherwise be anticipated. Consequently we have provided two results for each inlet lag time metric – the simulated result as well as our best professional estimate supported by similar results for a nearby and similar GI site (SFSU Site 1). The result in the bottom row of Table 6 summarizes the increase in lag due to GI as a possible range based on both the simulated and professional best estimate results.

Lessons Learned and Adaptive Management Suggestions

SFSU Site 3 is an effective site design and is performing well in the small and moderate storm events monitored to date. The installation was implemented using student volunteers, allowing them to engage hands-on with green infrastructure principles. During installation of this site, the pre-existing turf grasses were uprooted and turned upside down. The intent of this installation step was to preserve all of the existing soil and plant nutrients on site, and reduce the amount of pre-existing materials needing to be hauled off-site. However, the rye grasses persisted on site, negating to some degree the original design intent of using only native species selected for their drought adaptability and to demonstrate their usage to the public. In similar future situations, the project leaders stated they would instead opt to compost the turf grasses.

Figure 6. Student volunteers completed the conversion of the traditional lawn grass to the basin and swale system. Photographs provided courtesy of D. Wentworth-Thrasher.

Suggested Monitoring Program Improvements

Three monitoring program recommendations are suggested as follows:

1) Observations should be made at this site 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. These observations should also verify the drip from the holes in the roof gutters.
2) The v-notch weir design worked well in this location and the pressure transducers performed well. However, data processing could be improved for this site by utilizing a vented pressure transducer or deploying a secondary transducer to measure atmospheric pressure on-site rather than relying on the regional hourly atmospheric data for normalization.
3) Standing water levels in weir box should be recorded during every field visit to aid interpretation of the data.

SFSU Site 3 Basin and Swale System Reference Table

Table 7. Select individual storm metrics modeled at the inlet and measured at the outlet at SFSU Site 3 basin and swale system (storms >0.01 inches only)[6].

Storm Start	Storm Duration (hrs)	Total Rainfall Depth (in)	Total Rainfall Volume (ft^3)	Inlet			Outlet			Peak Flow Rate Reduction
				Peak Flow (cfs)	Flow (ft^3)	Volume Retention	Peak Flow (cfs)[A]	Flow (ft^3)	Volume Retention	
10/15/2012 2:40	5.3	0.02	5	0	0	100%	0	0	100%	NA
11/20/2012 7:05	2.3	0.02	5	0	0	100%	0	0	100%	NA
4/3/2012 21:00	0.6	0.03	8	0	0	100%	0	0	100%	NA
10/29/2012 23:10	7.7	0.04	11	0	0	100%	0	0	100%	NA
3/31/2012 20:20	3.8	0.05	13	0.01	1.2	91%	0.000004	0.001	100%	100%
10/25/2012 7:30	1.8	0.05	13	0	0	100%	0	0	100%	NA
10/30/2012 22:45	9.4	0.06	16	0	0	100%	0	0	100%	NA
2/7/2013 8:00	4.2	0.12	32	0.01	1.8	94%	0	0	100%	100%
3/1/2012 7:50	4.7	0.13	35	0.02	14	60%	0	0	100%	100%
12/15/2012 13:20	4.8	0.13	35	0.01	11	67%	0	0	100%	100%
12/11/2012 23:15	5.8	0.17	45	0.05	16	66%	0	0	100%	100%
1/5/2013 15:25	9.0	0.29	77	0.03	43	45%	0	0	100%	100%
2/19/2013 8:40	4.3	0.32	85	0.03	58	32%	0	0	100%	100%
4/25/2012 19:30	17.8	0.34	91	0.02	43	52%	0	0	100%	100%
2/28/2012 23:45	6.2	0.39	100	0.06	72	31%	0	0	100%	100%
10/24/2012 3:55	2.3	0.39	100	0.07	73	30%	0.00005	0.02	100%	100%
12/16/2012 18:05	14.8	0.41	110	0.03	89	18%	0.000001	0.0005	100%	100%
11/17/2012 19:20	3.1	0.42	110	0.04	99	12%	0.000007	0.002	100%	100%
10/31/2012 21:00	7.4	0.43	110	0.03	83	28%	0.000007	0.002	100%	100%
11/28/2012 6:55	4.2	0.44	120	0.04	85	27%	0.0001	0.1	100%	100%
2/7/2013 19:00	8.9	0.45	120	0.03	120	4%	0.000003	0.0003	100%	100%
3/31/2012 7:40	3.2	0.52	140	0.05	120	16%	0.00007	0.1	100%	100%
3/27/2012 14:50	8.3	0.60	160	0.03	120	23%	0.000001	0.00004	100%	100%
4/12/2012 2:30	1.5	0.62	170	0.14	130	21%	0.01	13	92%	90%
10/22/2012 0:20	9.1	0.62	170	0.03	130	20%	0	0.0	100%	100%
4/10/2012 5:20	20.8	0.87	230	0.06	170	26%	0.00008	0.4	100%	100%
12/1/2012 2:45	19.9	0.89	240	0.03	220	7%	0.00007	0.1	100%	100%
11/16/2012 5:20	28.0	0.91	240	0.03	190	22%	0	0	100%	100%
4/12/2012 19:35	12.1	0.92	250	0.11	220	11%	0.003	17	93%	97%
12/5/2012 4:30	6.1	0.96	260	0.04	230	9%	0.008	29	89%	81%
12/2/2012 5:10	8.2	1.04	280	0.09	270	1%	0.05	130	52%	44%
11/20/2012 21:25	9.7	1.07	290	0.05	260	9%	0.0001	0.8	100%	100%
3/16/2012 3:05	19.3	1.24	330	0.04	290	13%	0.005	19	94%	88%
3/24/2012 4:45	22.4	1.73	460	0.02	430	7%	0.002	8.4	98%	91%
3/13/2012 3:55	52.8	1.81	480	0.02	400	17%	0.001	18	96%	94%
11/29/2012 18:00	20.0	1.82	490	0.03	490	0%	0.0007	4.4	99%	98%
Total	**369**	**20.3**	**5400**		**4500**			**240**		
Average	**10.3**	**0.56**	**150**	**0.035**	**120**	**40%**	**0.002**	**6.6**	**98%**	**96%**
Maximum	**52.8**	**1.82**	**490**	**0.14**	**490**	**100%**	**0.05**	**130**	**100%**	**100%**

[A] Note: Peak outflow rates reported in Table 2 of the Site Report are simplified for ease of reading. Here the more detailed results are reported.

[6] Volume retention was calculated as the flow volume divided by the rainfall volume. "NA" was assigned in the Peak Flow Rate Reduction column for storms which did not result in flow at the inlet based on the model simulations. These storms were not included in the summary statistics (at the bottom of the table) for this column.