San Francisco State University Site 1 Vegetated Infiltration Basin: Technical Appendix

This technical appendix complements the SFSU Site 1 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 1,000 ft^2 area (SFSU Site 1) adjacent to the San Francisco State University Mail Room (Figure 1a) was previously an undeveloped area dominated by a large willow shrub and common weeds. Stormwater runoff from the Mail Room rooftop, as with most other rooftops throughout SFSU, was routed unabated to the combined sewer system (CSS). The undeveloped area was identified as capable of receiving stormwater runoff from the adjacent Mail Room rooftop, and in 2010 the area was re-graded to encourage infiltration and surface ponding, and planted with a new mix of water-loving vegetation. The grading work was completed with campus resources, campus Facilities Operations staff and student volunteers. The site was composed primarily of sandy loam, an excellent drainage soil, and there was no need for engineered media aside from a shallow drain rock trench to prevent erosion where runoff flows in. The downspout from the Mail Room roof was redirected into the small, vegetated infiltration basin, and the area was outfitted with a vertical overflow drain.

This site design at SFSU Site 1 was intentionally highly visible, simple and relatively inexpensive to construct, which allowed it to also be a model of GI that passersby could consider replicating at their own home. Stormwater runoff into the unlined vegetated basin infiltrates into the underlying soils. After the soil reaches saturation capacity, the stormwater ponds on top until it reaches the elevation of the overflow drain, at which point it drains to the sewer drain. This overflow drain ensures that flooding does not occur during larger storm events when the basin capacity is exceeded. By first routing stormwater runoff into this infiltration basin, total stormwater runoff from the site is reduced and peak flow rates are both reduced and delayed.

Table 1. Select characteristics of the catchment.

Metric	Site Data
Drainage Area to monitored inlet (ft^2)	4,900
Drainage Area to outlet (ft^2) [1]	5,900
Area of vegetated infiltration basin (ft^2)	1,000
Maximum ponding depth (ft)	2
% of Impervious Area Converted to GI	0%
% of Drainage Area that is GI	17%[2]
Land Use(s)	Roof

[1] The drainage area to the outlet includes the roof draining to the inlet (4900 ft^2), the infiltration basin itself (1000 ft^2, although approx. 800 ft^2 flows to the outlet) plus approx. 200 ft^2 of the adjacent parking lot). Performance reported in this study is conservative; we assume runoff from the parking lot is negligible because sheet flow from the lot into the facility cannot be measured, though the parking lot contributes some runoff and performance is therefore likely better than reported.

[2] The SFPUC recommends 5-10% for parcel-based features. This site is likely to show higher performance than some other GI sites sized 5-10% of the impervious drainage area.

Methods

The hydrologic analysis presented in this report is based on flow data collected at the inlet and outlet of the vegetated infiltration basin post-construction (Figure 1). Inlet flow represents pre-construction flow patterns into the CSS, and outlet flow represents post-construction flow patterns. Inlet flow was measured using a weir box with an internal pressure transducer mounted inside a stilling well with a v-notch weir, which is located at the downspout from the Mail Room roof (Figure 1b). The outlet measurements were also taken using a similar weir box located in the overflow drain (Figure 1c). Because of the paired inlet-outlet monitoring design, the effectiveness of the basin at treating runoff from the managed impervious area could be quantified by direct comparison of inlet and outlet data, and there was no need to simulate any records using modeling software. Flow monitoring was conducted during Rainy Seasons 2011-2012 and 2012-2013 at both the inlet and outlet. Flow data were collected at a 1 minute interval. Installation and maintenance of the measurement devices were carried out by the San Francisco Public Utilities Commission. Data from these sensors were downloaded manually throughout the period of records detailed 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 0.3 miles (500 m) to the east of the SFSU Site 1 vegetated infiltration basin. 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 using measured data. 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 directly compared between the inlet and outlet datasets to understand the effectiveness of the infiltration basin.

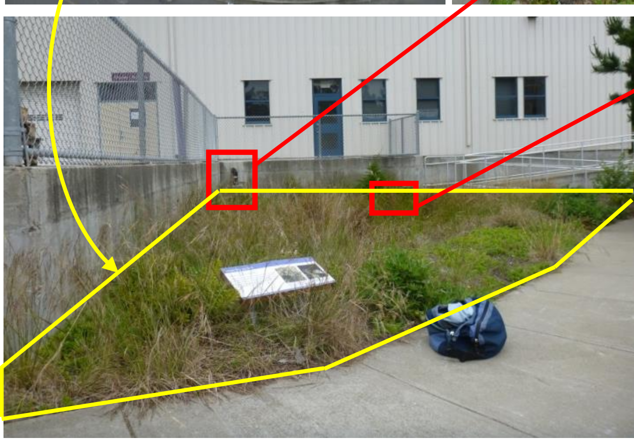

Figure 1. SFSU Site 1 paired inlet-outlet monitoring set-up. The Mail Room roof (A) is the main area managed by the vegetated infiltration basin. Runoff from the roof was measured in a v-notch weir box (B) immediately prior to entering the infiltration basin. When the infiltration basin capacity is exceeded, stormwater flows into an overflow drain connected to the sewer system. At the entrance to the overflow drain was another v-notch weir box (C) where flows exiting the infiltration basin were measured.

Table 2. Period of record with both flow and rainfall data for SFSU Site 1.

Rainy Season	SFSU 1
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, both inlet and outlet flow monitoring produced high quality data for the entire period of record. A pressure transducer measured absolute pressure in each of the inlet and outlet weir boxes. During base flow conditions, the pressure data from the sensors standing in a pool of water inside the weir box drifted temporally in unison with the regional atmospheric pressure (gauge: San Francisco, USAF-WBAN_ID 994016; available from NOAA.gov). During storm events, pressure also varied inside the box in relation to stage after correction for atmospheric pressure. The site gauge pressure data were normalized to atmospheric pressure using the San Francisco gauge and then converted to water level within the weir box. The San Francisco gauge used to normalize to atmospheric pressure is located approximately 8 km to the north and this distance could result in some error in the corrected data. A v-notch weir equation was applied to calculate flows from water level. Quality of the water level and the calculated flow data were evaluated based on presence/absence and flow peak and volume relative to rainfall magnitude and timing, general shape of the hydrograph, and results of the analyses. The analyses resulted in hydrologic characteristics that matched our conceptual model for a site in which the ratio of GI surface area to managed impervious area is >15%, were consistent relative to factors affecting the saturation conditions of the site, and were therefore deemed to be of good quality. The quality was also verified by an excellent relationship between rainfall and flow at the inlet (see Figure 6); the data contained no scatter or anomalous values. No data were censored.

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-hr period of no rainfall. Based on this definition, 25 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. All 58 storm events were evaluated as having data sufficient for analysis, a result of excellent data quality.

Results of Rainy Seasons 2011-2012 and 2012-2013

The vegetated infiltration basin reduced total flow volume to the CSS, reduced peak flow rates to the CSS, and delayed flows to the CSS. Therefore, based on data collected to date, SFSU Site 1 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

During the monitoring period at SFSU Site 1, a total of 9.4 inches of rain fell during Rainy Season 2011-2012 and 10.06 inches of rain fell during Rainy Season 2012-2013 (Figures 2A and 2B). Maximum rainfall intensities (per 5 minute interval) were less than 0.9 in/hr in all events except during the peak intensity on April 12, 2012 (2.04 in/hr, Figure 2A), approximately a 1-year event based on the 5-minute intensity, and the second highest intensity on December 2, 2012 (1.32 in/hr, Figure 2B). The April 12th storm had a 0.5 year return frequency based on total depth and duration, while all other storms monitored were 0.25 year return or lower.

The seasonal hydrographs (Figure 2) visually illustrate how infrequently the infiltration basin overflowed into the CSS. When overflow did occur, peak runoff was greatly reduced and delayed relative to inlet flows. While peak flows at the inlet directly mimicked instantaneous rainfall intensities, peak flows at the overflow outlet were governed more by total storm rainfall in combination with antecedent rainfall, both factors which affect the saturation condition of the vegetated infiltration basin (discussed in more detail later).

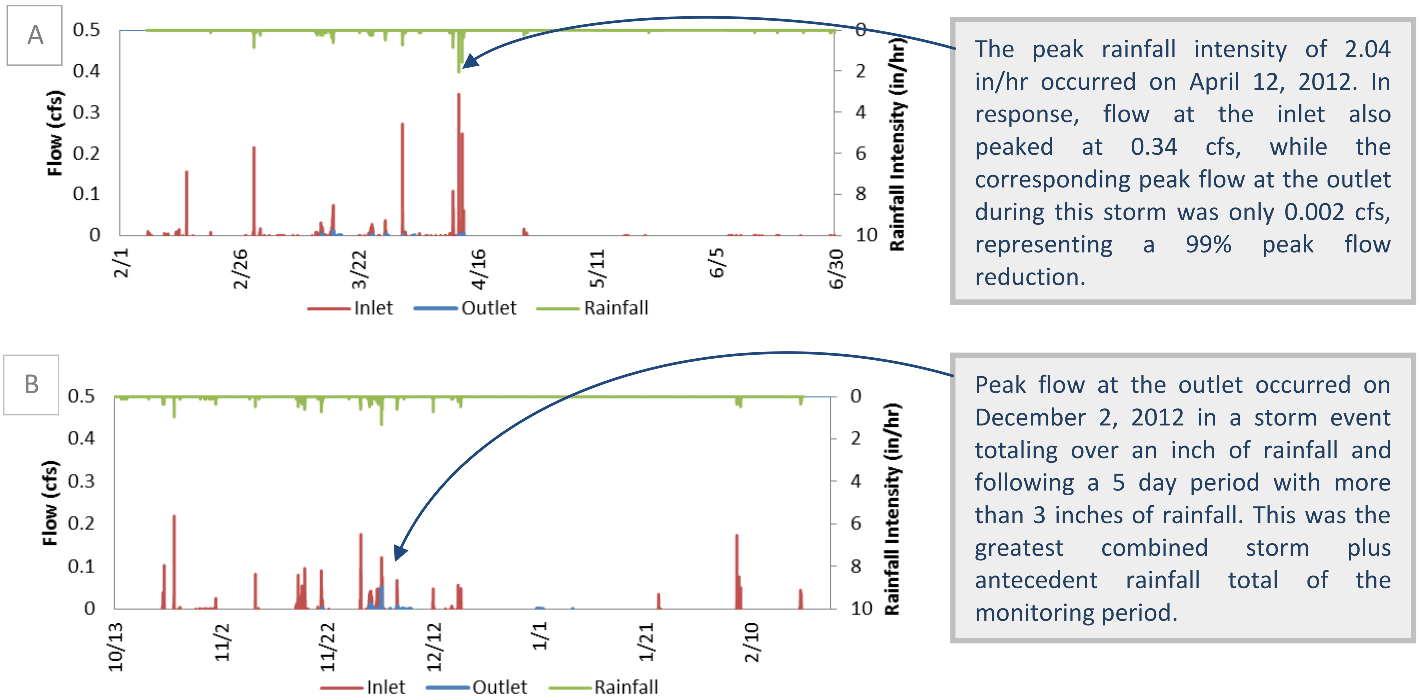

Figure 2. Seasonal hydrographs at the inlet and outlet of SFSU Site 1 for A) Rainy Season 2011-2012 (February 15 – June 30, 2012), and B) Rainy Season 2012-2013 (September 1, 2012 – February 20, 2013).

Typical storm event hydrographs that included measurable outflow (only 13 of 58 events had measurable outflow) (Figures 3 and 4) illustrate the flow patterns observed at this location. The patterns shown in these hydrographs follow a typical model of modifications to hydrology due to GI installations. The total volume that flowed to the CSS decreased substantially compared with pre-construction conditions (as exhibited by flows measured at the inlet).

The hydrographs shown in Figure 4 were selected to illustrate the conditions that resulted in the highest outflows recorded during the monitoring period. The rainfall event at the beginning of that period resulted in a relatively intense inlet peak flow but no outflow from the infiltration basin. Midway through the second event (on the third day of the graph) minimal outflow finally began. Finally, on the fifth day after 3.8 inches of cumulative rainfall during this period, the outflows peaked at less than half the peak at the inlet. This period represents a period of relatively poor performance for the infiltration basin due to the high rainfall totals, and still total flow to the CSS was reduced by 87% over the five days. None of the storms measured during the monitoring period approached the magnitude of the average annual storm event (1 year – 24 hour) or the Level of Service storm event (5 year – 3 hour); during such higher magnitude events the infiltration basin would not be expected to perform as well, though at this time it is not possible to report the range of performance for such events based on the monitoring data.

Overall, the vegetated infiltration basin reduced the total volume of flow entering the CSS. For the period monitored, total flow volume entering the CSS was reduced by more than 93%; decreasing from 67% of the incident rainfall down to only 4% of the incident rainfall (Figure 5). In total, over 41,000 gallons of stormwater were retained by the vegetated infiltration basin during the monitoring period (Feb. 15, 2012 to Feb. 20, 2013).

The volume of flow produced during the various storm events showed a marked decrease post installation of the vegetated infiltration basin. 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 outlet correlation between rainfall and runoff was poor, largely driven by the fact that the outlet had no flow for the majority of the storms, and also because outlet flow was impacted by antecedent rainfall.

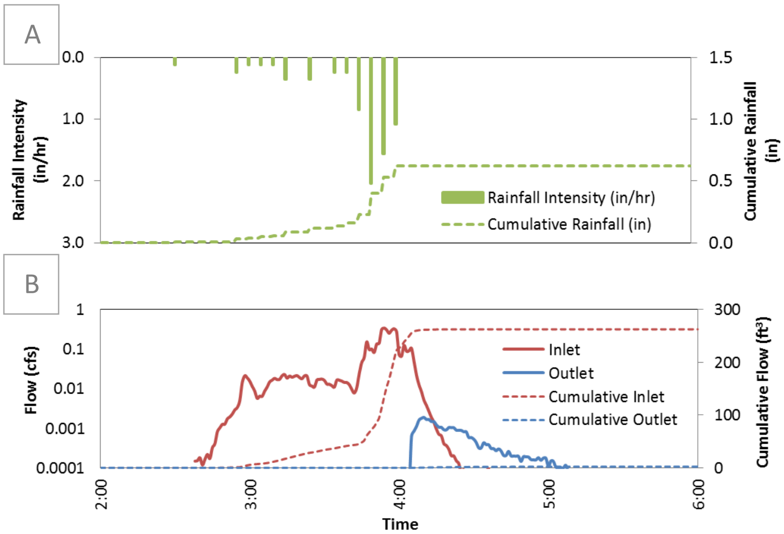

Figure 3. A) Rainfall intensity and cumulative rainfall during an April 2012 storm event. B) Storm hydrographs during the same storm event. Note: log scale on y-axis.

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

Storm or Flow Characteristic	SFSU Site 1
Storm Date(s)	Apr 12, 2012
Storm Total Rainfall (in)	0.62
Storm Duration (hrs)	4
Peak 5-minute Rainfall Intensity (in/hr)	1.56
% of Rainfall Flowing to Infiltration Basin Inlet	98%
% of Rainfall Flowing to CSS	0.8%
Peak Flow Rate at Inlet (cfs)	0.34
Peak Flow Rate to CSS (cfs)	0.002

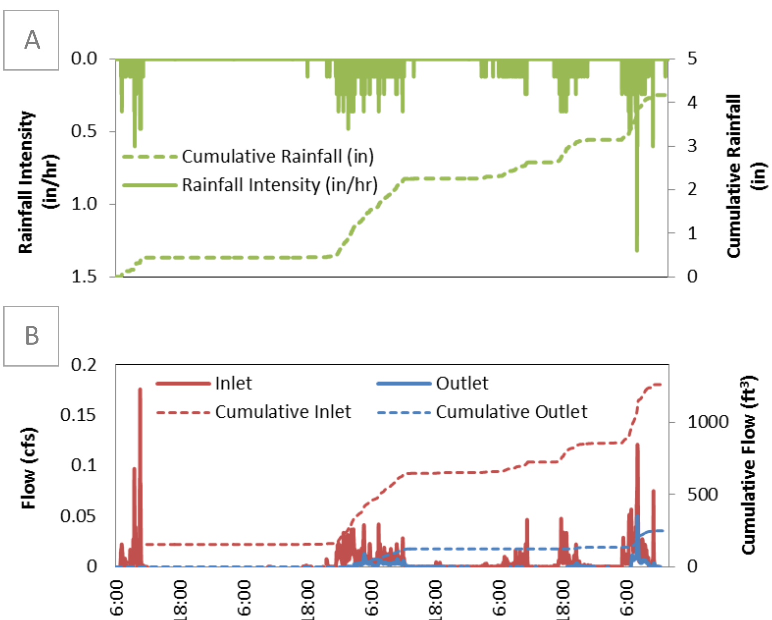

Figure 4. A) Rainfall intensity and cumulative rainfall during an extended storm period in late 2012. B) Storm hydrographs during the same period illustrating how extensive antecedent rainfall leads to increased outlet flows, although still less than half the inlet peak.

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

Storm or Flow Characteristic	SFSU Site 1
Storm Date(s)	Nov 28 – Dec 02, 2012
Storm Total Rainfall (in)	4.19
Storm Duration (hrs)	118
Peak 5-minute Rainfall Intensity (in/hr)	1.32
% of Rainfall Flowing to Infiltration Basin Inlet	70%
% of Rainfall Flowing to CSS	14%
Peak Flow Rate at Inlet (cfs)	0.18
Peak Flow Rate to CSS (cfs)	0.05

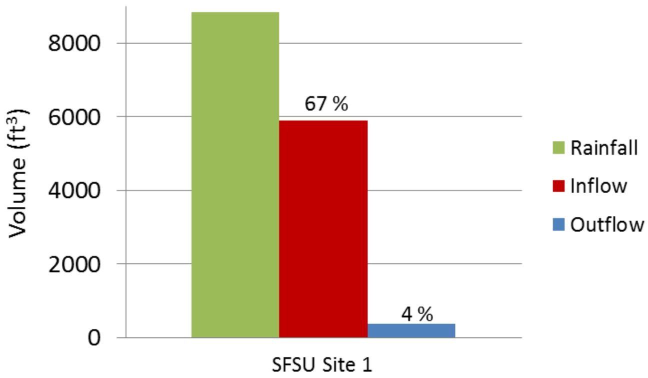

Figure 5. Total flow volume as a percentage of the incident rainfall for the monitoring period.

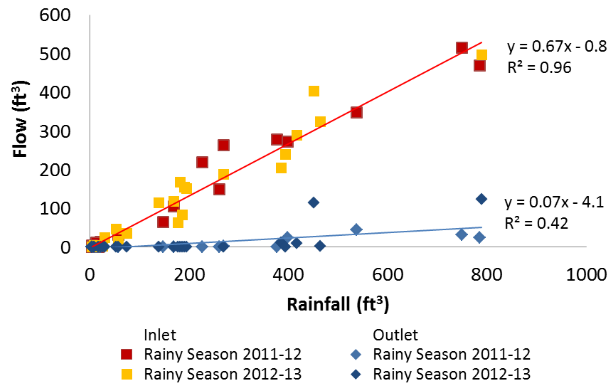

Figure 6. Rainfall and flow volume for all individual storm events monitored at SFSU Site 1 during Rainy Seasons 2011-12 and 2012-13.

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 3-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 due to construction of the vegetated infiltration basin at SFSU Site 1. In total for the storms measured, flow was reduced from 67% 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 substantially when antecedent rainfall was also accounted.

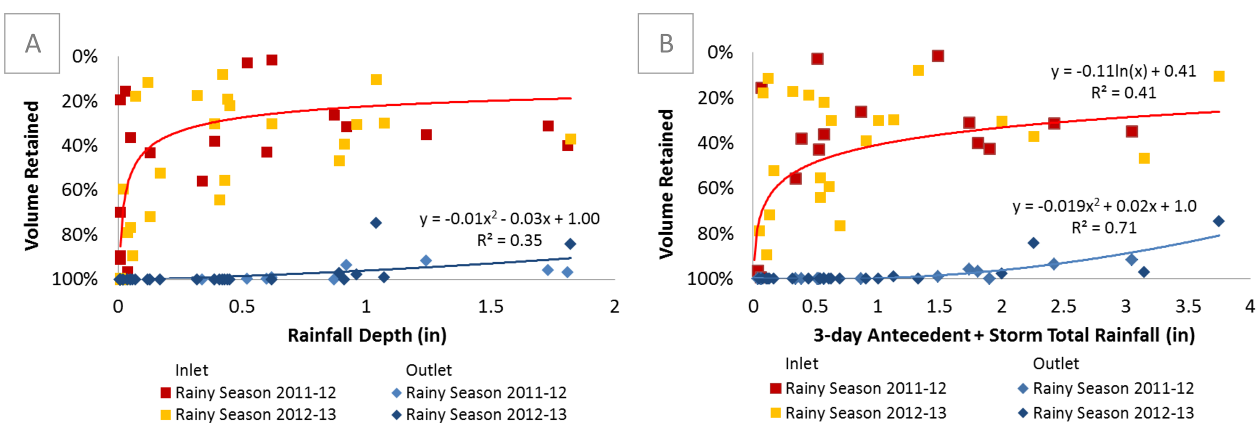

Figure 7. Percentage of rainfall volume retained within the infiltration basin per storm event relative to the total volume of A) storm total rainfall depth, and B) to storm total rainfall plus antecedent rainfall depth over the preceding three days. [*Storms > 0.01 inch only*]

Peak Flow Rate Reduction

For storm events that produced runoff at the outlet during the monitoring period (n=13), reductions in peak flows from those measured at the inlet ranged from 59% to 99% and averaged 90%. An additional 30 storms produced flow at the inlet but did not overflow into the CSS at all (100% peak flow reduction). Another 15 storms involved only trace rainfall producing no runoff at the inlet or outlet.

Peak flows at the inlet correlated well with all peak rainfall depth-durations tested across the range of storms, with a slightly stronger correlation at the peak 10 minute rainfall depth (Table 5 and Figure 8). Alternatively, peak flows at the outlet did not correlate with the peak rainfall intensities tested. As described previously, outflow rates from the vegetated infiltration basin were more directly governed by factors that affected saturation of the infiltration basin (e.g. storm rainfall total, antecedent rainfall) than by rainfall intensity.

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	0.77	0.17
10 minute peak rainfall	0.78	0.13
15 minute peak rainfall	0.76	0.13
20 minute peak rainfall	0.74	0.13
25 minute peak rainfall	0.73	0.14
30 minute peak rainfall	0.71	0.14

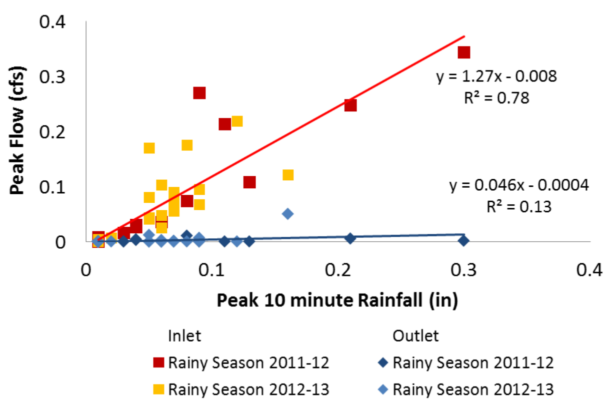

Figure 8. Peak flows measured at the inlet and outlet for corresponding peak 10 minute rainfall depths in each storm event.

Changes in Lag Time

The computed lag time from the start of rainfall[3] to the start of flow ($Start_I$ to $Start_F$) increased due to runoff first being routed into the vegetated infiltration basin. Similarly, the lag time between peak rainfall[4] and peak flow ($Peak_I$ to $Peak_F$), as well as the centroid[5] of rainfall and the centroid of flow ($Centroid_I$ to $Centroid_F$), also increased. Changes in lag times (median across all storms with measurable flow at the outlet) at SFSU Site 1 increased for all lag metrics analyzed between approximately 2 and 3 hours (Table 6).

[3] Rainfall start was measured at 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.

Table 6. Changes in lag times at SFSU Site 1.

	Median Lag Times (minutes)		
	Start$_I$ to Start$_F$	Peak$_I$ to Peak$_F$	Centroid$_I$ to Centroid$_F$
Inlet	<1	<1	4
Outlet	160	117	187
Increase in Lag due to GI	**160**	**117**	**182**

Lessons Learned and Adaptive Management Suggestions

SFSU Site 1 has a simple and effective site design and is performing as expected given that the site has a high ratio of GI surface area to impervious area (21:100 post-construction) and well-drained soils. The plants are adapting well to infrequent irrigation (Figure 9). During heavier rains, minimal overflow does occur and the site could be modified with higher berms to retain even higher volumes. However, to the extent that this site already retains 93% of the annual stormwater runoff volume and serves nicely as a public demonstration project, these adaptive management measures may not be cost-effective.

Figure 9. View of SFSU Site 1 shortly after installation completion (left) and in summer 2013 (right).

Suggested Monitoring Program Improvements

Three monitoring program recommendations are suggested as follows:

1) 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.
2) Notation of standing water levels in weir box should be recorded during every field visit to aid interpretation of the data.
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.

SFSU Site 1 Vegetated Infiltration Basin Reference Table

Table 7. Select individual storm metrics measured at the inlet and outlet at SFSU Site 1 vegetated infiltration basin (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	
6/30/2012 1:35	4.0	0.02	9	0.00002	0	100%	0	0	100%	100%
6/30/2012 21:45	1.8	0.02	9	0	0	100%	0	0	100%	NA
11/20/2012 7:05	2.3	0.02	9	0.005	4	59%	0	0	100%	100%
10/15/2012 1:40	5.3	0.02	9	0	0	100%	0	0	100%	NA
4/3/2012 21:00	0.6	0.03	13	0.005	11	16%	0	0	100%	100%
6/29/2012 2:15	4.5	0.04	17	0.0003	1	97%	0	0	100%	100%
10/29/2012 22:10	7.7	0.04	17	0.0005	4	79%	0	0	100%	100%
3/31/2012 20:20	3.8	0.05	22	0.01	14	36%	0.000003	0.0003	100%	100%
10/25/2012 6:30	1.8	0.05	22	0.004	5	77%	0	0	100%	100%
10/30/2012 21:45	9.4	0.06	26	0.001	3	89%	0	0	100%	100%
11/8/2012 12:05	1.5	0.07	30	0.08	25	18%	0	0	100%	100%
2/7/2013 8:00	4.2	0.12	52	0.17	46	12%	0	0	100%	100%
3/1/2012 7:50	4.7	0.13	56	0.02	32	43%	0	0	100%	100%
12/15/2012 13:20	4.8	0.13	56	0.01	16	72%	0	0	100%	100%
12/11/2012 23:15	5.8	0.17	74	0.05	35	52%	0	0	100%	100%
2/19/2013 8:40	4.3	0.32	139	0.04	115	17%	0	0	100%	100%
4/25/2012 19:30	17.8	0.34	147	0.02	65	56%	0	0	100%	100%
2/28/2012 23:45	6.2	0.39	169	0.21	105	38%	0	0	100%	100%
10/24/2012 2:55	2.3	0.39	169	0.22	118	30%	0	0	100%	100%
12/16/2012 18:05	14.8	0.41	178	0.06	64	64%	0	0	100%	100%
11/17/2012 19:20	3.1	0.42	182	0.10	167	8%	0	0	100%	100%
10/31/2012 20:00	7.4	0.43	186	0.02	83	56%	0	0	100%	100%
11/28/2012 6:55	4.2	0.44	191	0.18	154	19%	0	0	100%	100%
2/7/2013 19:00	8.9	0.45	195	0.08	152	22%	0	0	100%	100%
3/31/2012 7:40	3.2	0.52	225	0.27	219	3%	0.0001	0	100%	100%
3/27/2012 14:50	8.3	0.6	260	0.04	149	43%	0.0001	0	100%	100%
4/12/2012 2:30	1.5	0.62	269	0.34	264	2%	0.002	2.3	99%	99%
10/21/2012 23:20	9.1	0.62	269	0.10	188	30%	0	0	100%	100%
4/10/2012 5:20	20.8	0.87	377	0.11	278	26%	0	0	100%	100%
12/1/2012 2:45	19.9	0.89	386	0.05	205	47%	0.004	11	97%	93%
11/16/2012 5:20	28.0	0.91	394	0.08	240	39%	0	0	100%	100%
4/12/2012 19:35	12.1	0.92	399	0.25	273	31%	0.005	25	94%	98%
12/5/2012 4:30	6.1	0.96	416	0.07	289	30%	0.007	9.2	98%	89%
12/2/2012 5:10	8.2	1.04	451	0.12	404	10%	0.05	110	76%	59%
11/20/2012 21:25	9.7	1.07	464	0.09	325	30%	0.002	3.3	99%	98%
3/16/2012 3:05	19.3	1.24	537	0.07	349	35%	0.01	44	92%	85%
3/24/2012 4:45	22.4	1.73	750	0.03	516	31%	0.003	32	96%	89%
3/13/2012 3:55	52.8	1.81	784	0.03	470	40%	0.004	25	97%	86%
11/29/2012 18:00	20.0	1.82	789	0.04	496	37%	0.01	120	85%	70%
Total	**372**	**20.2**	**8,800**		**5,900**			**380**		
Average	**10**	**0.52**		**0.076**	**150**	**43%**	**0.003**	**10**	**98%**	**96%**
Maximum	**53**	**1.82**		**0.34**	**520**	**100%**	**0.1**	**120**	**100%**	**100%**

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

[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 that did not result in flow at the inlet. These storms were not included in the summary statistics (at the bottom of the table) for this column.