Oak & Fell EIP Annual Monitoring Report: 2015-2016

Project Overview

The San Francisco Public Utilities Commission (SFPUC) is currently implementing the first phase of the 20-year $6.9 billion citywide Sewer System Improvement Program (SSIP). As part of the first phase of the SSIP, the SFPUC is constructing eight green infrastructure (GI) Early Implementation Projects (EIPs), one in each of San Francisco's urban watersheds. Completed in Spring 2015, Phase I of the Permeable Wiggle (Oak & Fell) is located within the Channel watershed. Prior to the Oak & Fell EIP, the project area was a highly impervious streetscape with little to no stormwater storage and infiltration. Before construction most of the rain falling onto the street and sidewalk during storm events ran off into the combined sewer system (CSS). The GI elements were designed and installed to slow and infiltrate stormwater runoff, thereby reducing flows to the sewer, increasing groundwater recharge, and returning some of the natural hydrologic function to the watershed. The SFPUC will be monitoring the performance of each EIP for two wet seasons after construction; this report presents the results for the first year of monitoring the Oak & Fell EIP.

The Oak & Fell EIP features permeable paving in the parking lane and bioretention bulbouts at four intersections along Oak and Fell Streets that receive stormwater runoff from the adjacent streets and sidewalk. Overflow from the permeable pavement is routed to the bioretention bulbout, where the stormwater ponds and infiltrates before overflowing to the sewer system. The four bioretention bulbouts and permeable pavement installations (Figure 1) are located at:

- the southwestern corner of Oak Street at Baker Street (Baker St)
- the northwestern corner of Fell Street at Broderick Street (Broderick St NW)
- the southwestern corner of Broderick Street at Fell Street (Broderick St SW – Figure 3a and 3b)
- the northwestern corner of Fell Street at Divisadero Street (Divisadero St)

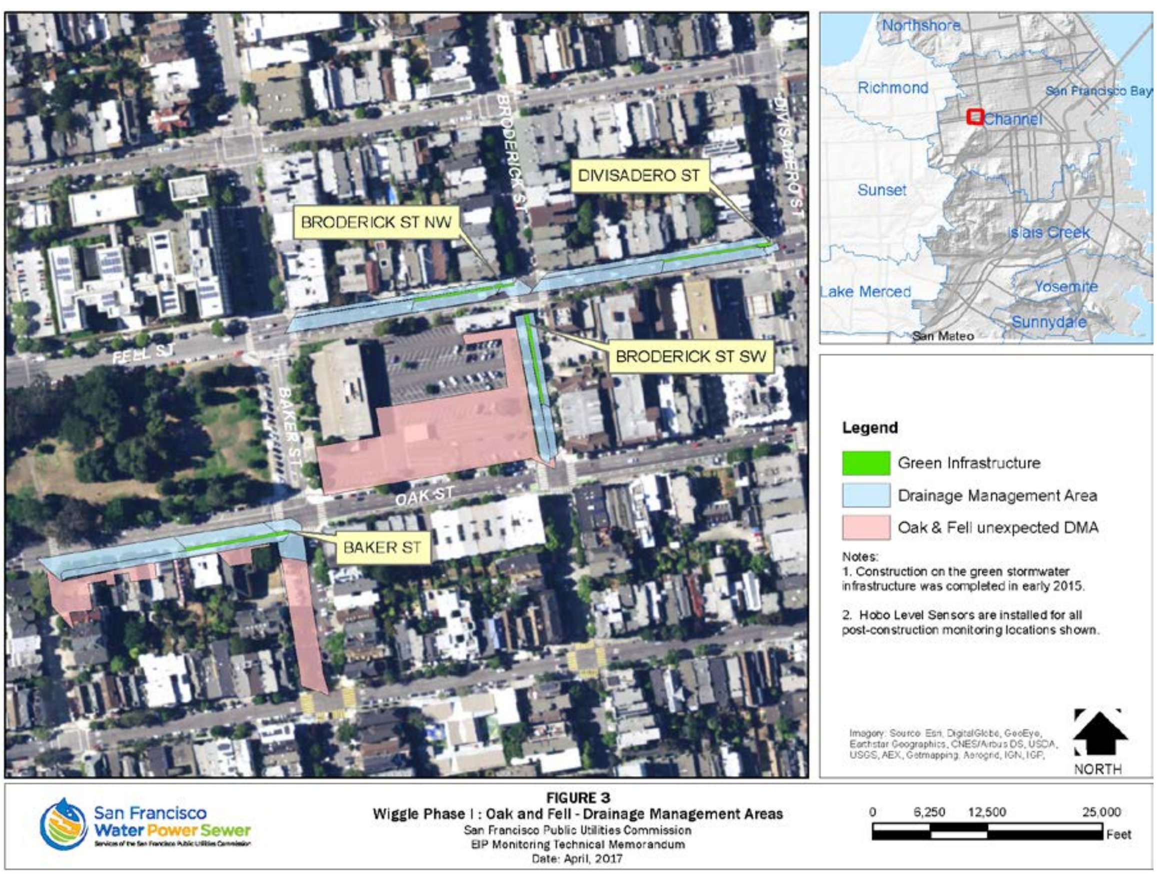

Figure 1: Project overview map

Figure 2 shows a schematic with the typical site configuration at all four blocks. Baker St and Broderick St SW were space constrained and required smaller outlet structures that were unable to house the v-notch weirs, so outlet monitoring was not conducted at those two blocks for this monitoring period.

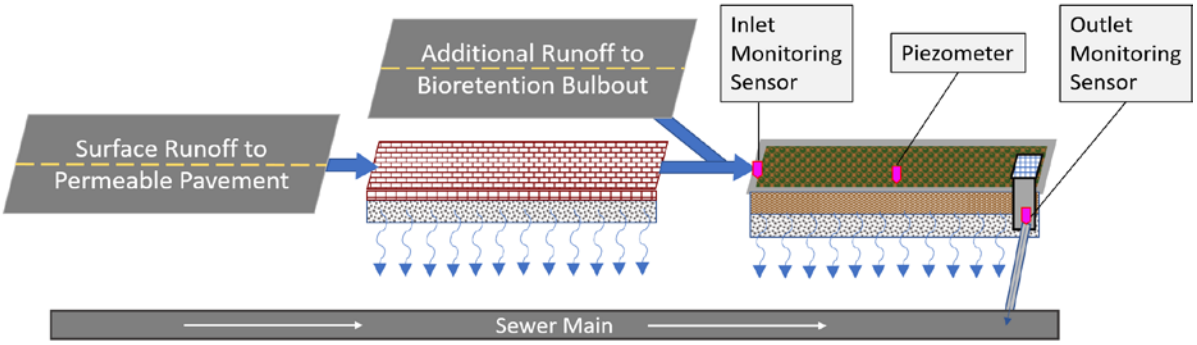

Figure 2: Schematic of typical green infrastructure and monitoring configuration (no outlet monitoring at Baker St or Broderick SW)

Figure 3a and 3b: The bioretention bulbout planter and permeable paving on the Broderick St SW (a) from the northern perspective, and (b) from the western perspective

Facilities were sized using a desktop GIS analysis to evaluate the Drainage Management Area (DMA) flowing to each facility in relationship to the footprint of the facility itself. All GI facilities were intentionally undersized by designers due to space constraints and community concerns over lost parking spaces. The permeable pavement was designed with an extra-deep storage layer to help mitigate performance impacts, assuming the surface area is adequate to allow stormwater to infiltrate to the storage layer. After construction was complete, the monitoring team conducted a site visit during a storm event and observed that drainage inlets were failing upstream of the Broderick St SW and Baker St GI, resulting in stormwater from large adjacent impervious areas unexpectedly contributing to the DMA of those bioretention bulbouts and further reducing their effective sizing ratio. Figure 1 shows the unexpected DMA in pink. The performance-based design goal was to provide an aggregate 0.75 inches of unit storage[2] using both permeable pavement and bioretention for each of the 4 blocks. Table 1 shows that this metric was almost achieved at Divisadero St and that Broderick St NW was fairly close, but the other two blocks were well short due largely to the unexpected DMAs.

Table 1: Characteristics of the Oak & Fell GI facilities and Drainage Management Areas (DMAs)

Metric		Baker St	Broderick St NW	Broderick St SW	Divisadero St
Total DMA (ft^2)		40,556	19,210	63,434	15,190
Bioretention Bulbout	Area (ft^2)	87	140	167	130
	Sizing Ratio (%)	0.2%	1.0%	0.2%	1.4%
Permeable Pavement	Area (ft^2)	718	785	629	867
	Sizing Ratio (%)	15%	16%	18%	16%
Unit Storage Depth (in) [2]		0.21	0.52	0.14	0.70

[1] Sizing Ratio is a measure of GI facility footprint relative to its DMA. It is equal to the facility size divided by the DMA.

[2] Unit Storage Depth is a measure of the storage capacity provided by GI relative to its DMA. It is equal to the depth of water that, if multiplied by the DMA, is equal to the storage provided by the GI facilities.

Over the 2015-2016 monitoring period, 38 separate storms producing measurable runoff occurred from 11/12/2015 through 04/30/2016. The measured rainfall for those 38 storms totaled 23.56 inches. Flow at the inlets and outlet as well as interior ponding depth were monitored at two of the bulbouts (Broderick St NW & Divisadero St), to assess the total stormwater volume and peak flow reduction of each individual bulbout. The remaining two bulbouts (Baker St & Broderick SW) were space constrained so that only inflow and ponding depth were able to be monitored; therefore, stormwater reductions were estimated using a computer model built with EPA Stormwater Management Model (SWMM, Version 5.1), which was calibrated with measured inflow and ponding depth data. The permeable pavement strips were not monitored directly so this analysis assumes that the permeable pavement strips fully manage their DMA for all storms, which does not impact overall block-level performance estimates because any overflow from the permeable pavement drained to the bioretention bulbout where it was measured. More detailed information on the methods used to obtain the monitoring results is included in the Technical Appendix.

The Oak & Fell EIP is estimated to have reduced the total volume of stormwater entering the sewer system from the project area by 47% (870,000 gallons) during the 2015-16 rainy season.

Learning Goal

Oak & Fell was the first EIP designed and constructed, and it was created with an in-facility monitoring approach that allows performance at individual bioretention units to be monitored. The main learning goal for this EIP is to assess the variability between multiple bioretention bulbouts within the same project. This site also will provide insight into the performance of GI on busy, arterial streets.

Results of Monitoring Period 2015-2016

All of the bioretention bulbouts reduced total stormwater volume and peak discharge rates to the CSS, and they produced a slight delay of peak discharge to the CSS. Results of the monitoring data are discussed below in relation to each of these three primary metrics and at different scales: performance of each individual bioretention bulbout, performance of each permeable pavement installation, and performance at the block scale (i.e., bioretention and permeable pavement at each intersection). More detailed information on the methods used to obtain these results is included in the Technical Appendix.

Was Flow Volume Reduced?

The overflow was significantly less than the inflow at both Divisadero St and Broderick St NW bulbouts during the various storm events. Averaged across the whole rainy season, the measured volume reduction on these blocks was 185,000 gallons (90%) and 220,000 gallons (80%), respectively (Figure 4). Model predictions for performance-based green infrastructure designed according to City standards, including a 5% sizing ratio for bioretention and a 25% sizing ratio for permeable pavement, would forecast a total runoff reduction of 435,000 gallons (91%) for these two blocks during the typical year. The overall sizing ratios were 1.2% for bioretention and 16% for permeable pavement, and the total measured volume reduction was 405,000 gallons (85%), very close to the expected performance for full-sized facilities.

The two bulbouts that received unexpected run-on due to failing drainage inlets upstream (Baker St and Broderick St SW) did not perform as well because they could not infiltrate the extra stormwater fast enough and a majority of the stormwater overflowed to the sewer system. The modeled performance for the Baker St and Broderick St SW blocks show a volume reduction of 190,000 gallons (36%) and 275,000 gallons (33%), respectively (Table 2, Figure 4). While overall annual volume reduction is high given the amount of GI on Baker St and Broderick St SW, the bioretention facilities on these two blocks are too small relative to their DMA to manage runoff effectively during larger storms. It is interesting to note that these two blocks manage a comparable volume of water annually as the other two blocks with larger sizing ratios, but it is important to note that they are ineffective during intense storms when the hydraulic capacity of the larger CSS is challenged.
In total, the Oak & Fell EIP is estimated to have reduced runoff to the CSS by 870,000 gallons for the 2015-16 monitoring period. The total volume of runoff from the entirety of the Channel Watershed to the CSS was estimated to be 2.7 billion gallons for that same period.

The results in Table 2 summarize stormwater volume reduction from the individual bioretention bulbouts and permeable pavement installations, as well as reduction on a block scale (i.e., combined bioretention and permeable pavement performance).

Table 2: Estimated volume reduction during the 2015-2016 rainy season

	Bioretention				Permeable Pavement		Block-scale Reduction Volume	
	Unit Storage	Area	Volume Reduction		Volume Reduction			
Site	(in)	(ft²)	(%)	(gallons)	(%)	(gallons)	(%)	(gallons)
Divisadero St (measured performance)	**0.24**	130	**83%**	110,000	100%	75,000	**90%**	185,000
Broderick St NW (measured performance)	**0.17**	140	**73%**	155,000	100%	65,000	**80%**	220,000
Baker St (modeled performance)	**0.042**	87	**27%**	125,000	100%	65,000	**36%**	190,000
Broderick St SW (modeled performance)	**0.048**	167	**29%**	230,000	100%	45,000	**33%**	275,000
TOTAL			**39%**	**620,000**	**100%**	**250,000**	**47%**	**870,000**

NOTE: Bioretention was monitored for inflow, overflow, and ponding depth. Permeable pavement was not monitored directly, and it is assumed to fully manage its DMA for all storms. Overall block-level performance estimates account for all flows because any overflow from the permeable pavement drained to the bioretention bulbout where it was measured.

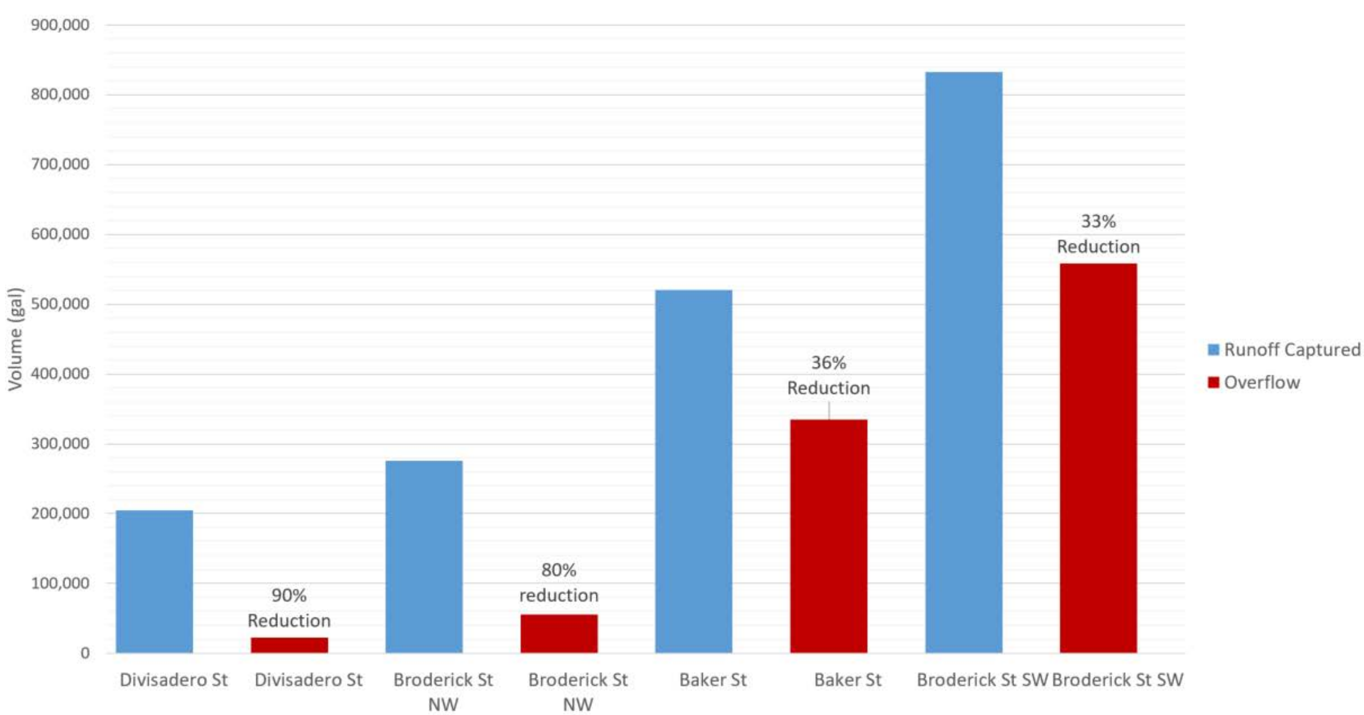

Figure 4: Block-scale performance for the 2015-2016 monitoring period. Divisadero St and Broderick St NW measured performance, Baker St and Broderick St SW modeled performance.

Figure 5 through Figure 8 provide an overview of the runoff from the catchments entering the bioretention bulbouts and the overflow from the bulbouts. Many smaller storms produced little to no overflow from the planters, meaning that all runoff entering the facility was fully infiltrated by the bioretention bulbout. A 0.76-inch storm occurring over 32 hours from April 8 to April 10 was the storm with the largest depth fully managed with no overflow from the two blocks with higher bioretention sizing ratios (Divisadero St and Broderick St NW). The largest storm managed by the two blocks with smaller bioretention sizing ratios (Baker St and Broderick St SW) was 0.23 inches occurring over 12 hours on December 23. More detailed analysis of individual storms is provided in the Technical Appendix.

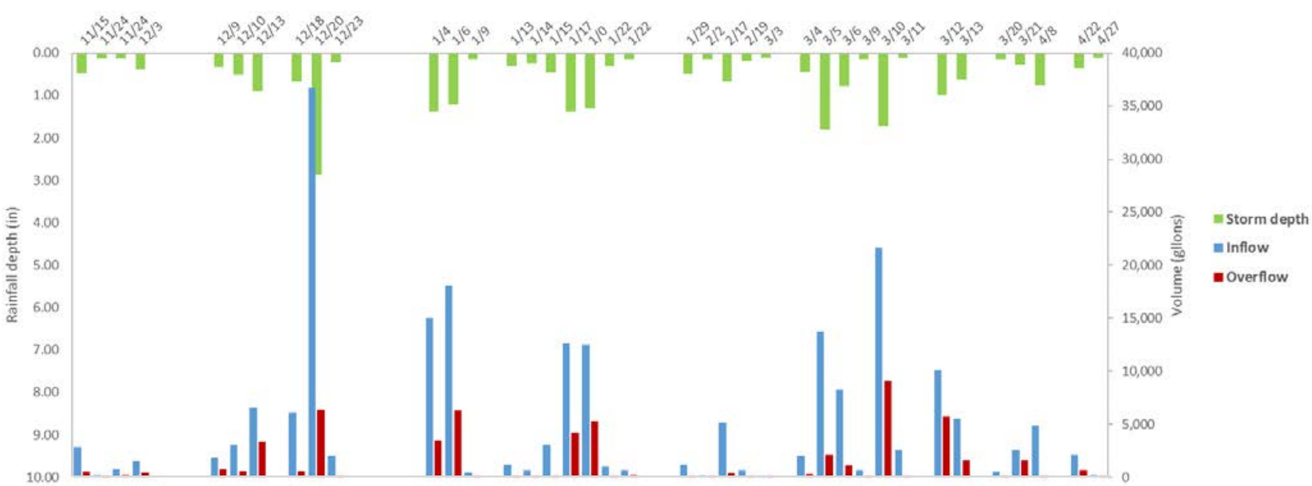

Figure 5: Hydrograph showing inlet and outlet volume at Broderick St NW during the 2015-2016 Monitoring Period

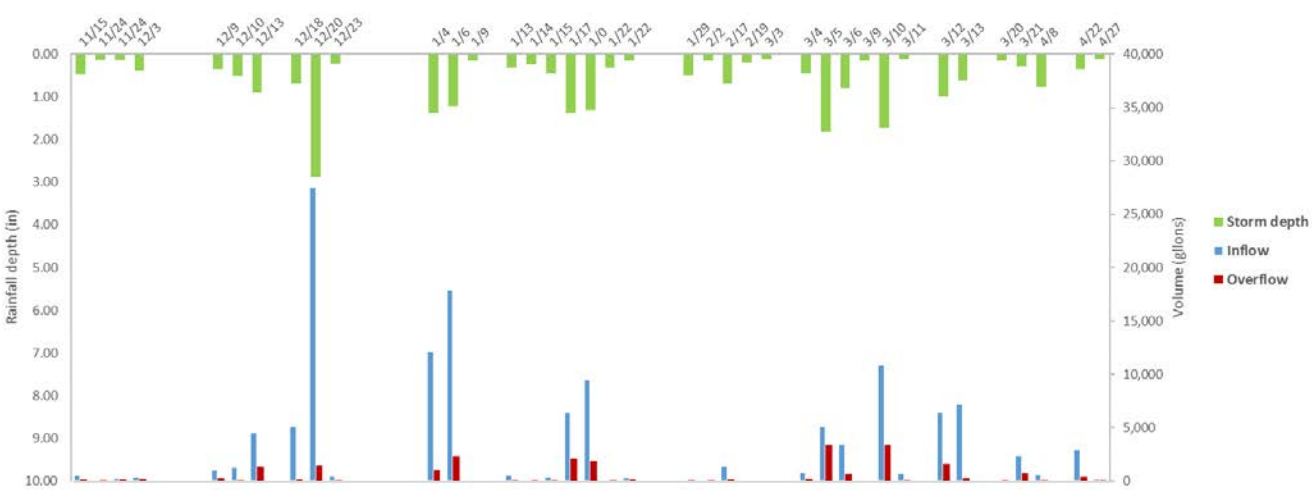

Figure 6: Hydrograph showing daily inlet and outlet volume at Divisadero St during the 2015-2016 monitoring period

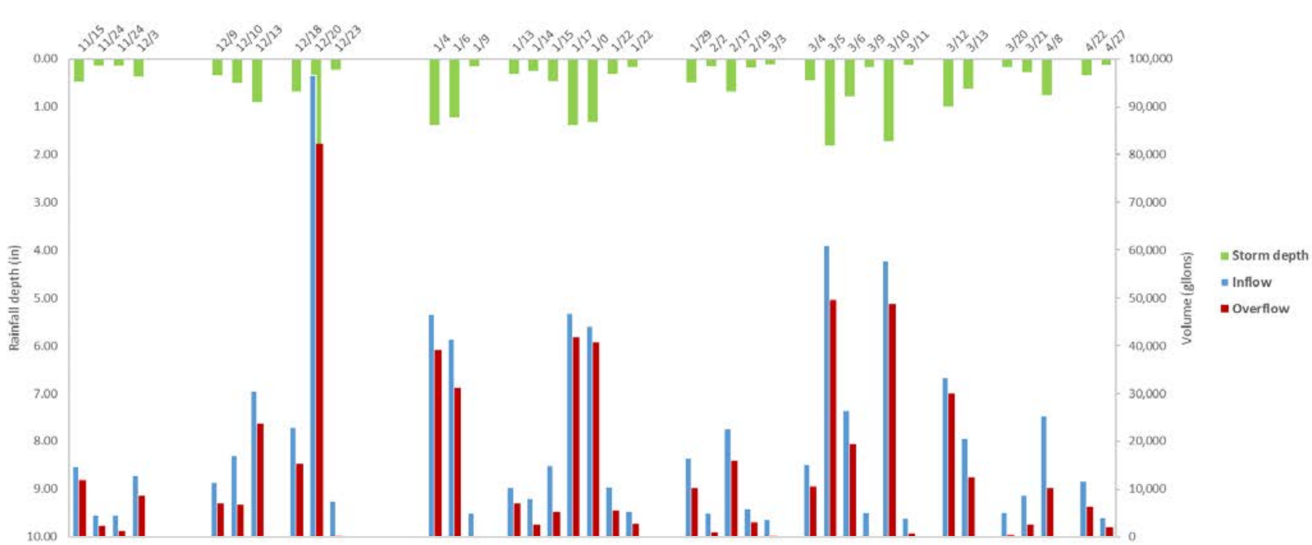

Figure 7: Hydrograph showing daily inlet and outlet volume at Broderick St SW during the 2015-2016 monitoring period

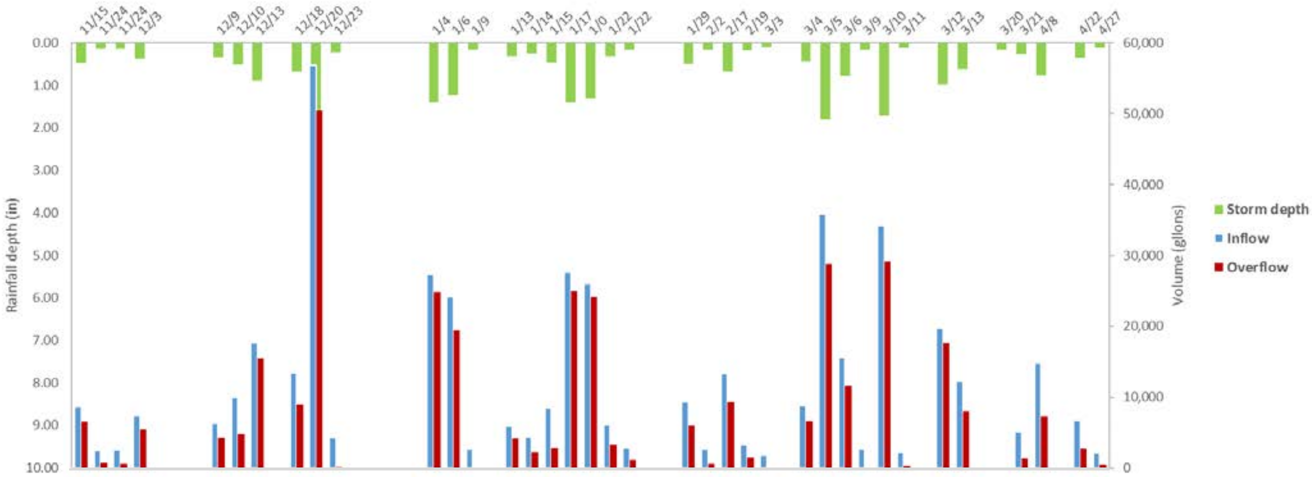

Figure 8: Hydrograph showing daily inlet and outlet volume at Baker St during the 2015-2016 monitoring period

How Did GI Hold Up During Back-to-Back Storms?

Performance during back-to-back storms was analyzed for the two bulbouts with outlet monitoring (Divisadero St and Broderick St NW). Back-to-back storms were defined as successive storm events with the second starting within 6 to 24 hours of the end of the first. Fourteen of the 38 storms during the monitoring period were categorized as back-to-back storms (Table 3). Volume reduction by the bioretention planters averaged 71% for the second of back-to-back storms and 83% for isolated storms. However, the average rainfall depth was 0.82 inches for the second storm in back-to-back events and 0.50 inches for all other storms. Since larger storms generally result in lower percentage volume reduction, even with isolated storms, back-to-back storms had no discernible impact on bioretention bulbout performance during the second of those storms. The bioretention facilities regenerated management capacity between successive storm events.

Table 3: Back-to-back storm performance at bulbouts with no unexpected DMA

Site	2nd of Back-to-Back Storms		All Other Storms	
	Average Storm Depth (in)	Average Volume Reduction (%)	Average Storm Depth (in)	Average Volume Reduction (%)
Divisadero St	0.82	77	0.50	83
Broderick St NW		66		82
Average		**71%**		**83%**

Were Peak Flow Rates Reduced?

The bioretention bulbouts at Divisadero St and Broderick NW both reduced peak flow rates passing through the bulbouts by an average of 70%. Storms without any overflow had a 100% peak flow rate reduction. In general, the more intense the storm, the higher probability of an overflow, but the storm must also last long enough and produce enough runoff volume to exceed the storage capacity of the bulbout, meaning that duration is also a factor in which storms produce overflow.

At the two facilities with no unexpected DMA, 14-15 storms were fully managed, while 3-5 storms were fully managed at the two facilities with unexpected DMA.

Of the 38 storm events, no overflow occurred for 15 and 14 storms at Divisadero St and Broderick St NW, respectively, with the largest storm of those storms producing 0.76 inches of rainfall over 32 hours. Average peak flow reductions were 69% and 70% for these two blocks, respectively, and ranged from 0% to 95% during storm events producing overflow (Table 4). Six of the 38 storms resulted in minimal peak flow reduction (<10%) at Broderick St NW, and five of the 38 storms at Divisadero St resulted in minimal peak flow reduction. Storm 10 resulted in no discernible peak flow reduction at either location. This storm produced 0.9 inches of rainfall over 14 hours with a very high peak 5-minute intensity of 2.9 inches per hour. Virtually all of the rain fell between 3:00 AM and 10:00 AM, and the peak intensity occurred at 9:00 AM. That burst of rainfall exhausted storage capacity in the bioretention such that runoff flowed through the planter with no attenuation during peak storm intensity. The highest peak flow reduction at Divisadero St (95%) occurred during Storm 9, which lasted 15 hours and produced 0.51 inches of rainfall with a peak 5-minute rainfall intensity of 0.84 in/hr, and the rainfall was relatively evenly distributed over the course of the storm.

Table 4: Peak flow reduction characteristics for the events in each bioretention unit

	Storms with Overflow				Storms with no overflow (fully managed)	
Site	# of Storm Events	Min Peak Reduction	Max Peak Reduction	Average Peak Reduction	# of Storm Events	Largest Storm Event with No Overflow (in)
Divisadero St (measured performance)	23	0%	95%	69%	15	0.76
Broderick St NW (measured performance)	24	0%	84%	70%	14	0.76
Baker St (modeled performance)	33	0%	67%	29%	5	0.16
Broderick St SW (modeled performance)	35	0%	57%	25%	3	0.23

Were Lag Times Between Rainfall and Flow Increased?

Lag time was evaluated by assessing the length of time between the peak inflow rate at the inlet and the peak discharge rate at the outlet of the bioretention planters. Under the highly impervious pre-project conditions, runoff entered the CSS at essentially the same time it now enters the bioretention planters. The maximum and average peak lag times were minimal, reflecting the frequency with which the bulbouts' undersized storage became exhausted, overflowed, and created flow-through conditions in the bulbout. The performance value provided by the bioretention bulbouts was mostly by diminishing the magnitude of total runoff and peak flow to the CSS, rather than by delaying the peak flow.

Table 5: Changes in lag times

Site	Max $Peak_{inlet}$ to $Peak_{outlet}$ (minutes)	Average $Peak_{inlet}$ to $Peak_{outlet}$ (minutes)
Divisadero St[3]	17	3.5
Broderick St NW	11	2.5

Example of Individual Storm Analysis

Figure 9 shows the hydrograph for a large storm event, Storm 27, which produced 1.31" of rainfall over the course of eight hours with the peak happening around 8:00 AM. The difference between inflow and overflow is the flow reduction provided by the bioretention planters. Among the storms during the monitoring period, this storm is closest to the SFPUC's level-of-service storm, which has a depth of 1.28" over three hours. The data for Divisadero St show that the total volume reduction for this storm on a block scale was 12,000 gallons (86%), and peak flow reduction was 39%. As can be seen in the graphs, there is little overflow until around 7:45 AM when the rainfall became more intense and inflow significantly exceeded infiltration capacity, causing water to overflow steadily for about an hour.

[3] There is a storm with a lag time of 9h13min at Divisadero St that was deemed an anomaly and excluded from the analysis.

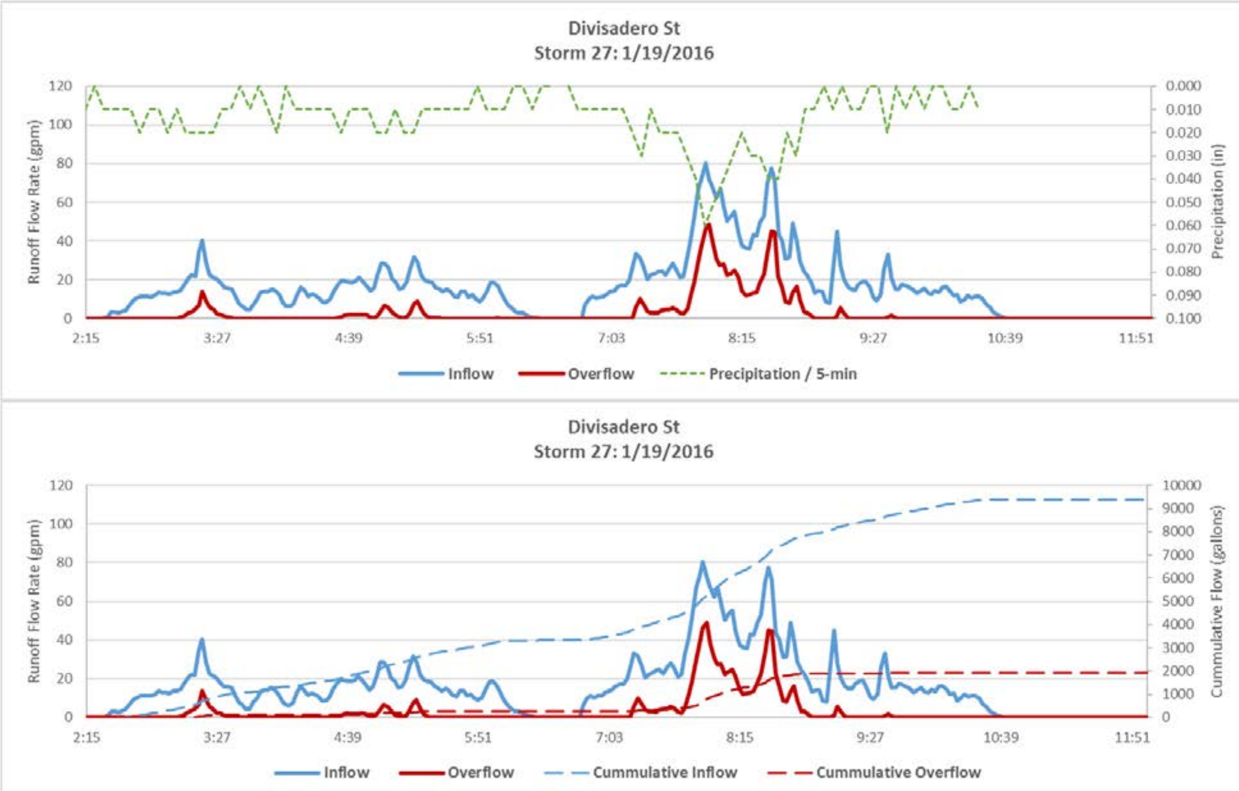

Figure 9: Storm Hydrographs for Storm 27 at Divisadero St

Summary

GI reduced the volume of stormwater entering the CSS considerably in all four catchment areas where GI was installed. The total volume reduction from the four blocks was approximately **870,000 gallons (47%)** for the 2015-2016 wet season. Discharge volumes were reduced by 80-90% at Divisadero St NW and Broderick St NW. Discharge volumes were reduced by only 36-37% for the two blocks with unexpected run-on due to non-functional upstream drain inlets. On an individual storm basis, post-construction overflow was well correlated with total rainfall. Smaller storms had greater reduction in terms of both peak flow and volume. Volume reduction as a percentage of total runoff generally decreased as total storm depth increased, and peak flows during larger more intense storms were only slightly reduced.

Model predictions for performance-based green infrastructure designed according to City standards, including a 5% sizing ratio for bioretention and a 25% sizing ratio for permeable pavement, would forecast a total runoff reduction of 435,000 gallons (91%) for Divisadero St NW and Broderick St NW during the typical year. The rainfall total during the 2015-16 monitoring period was 24.1 inches, almost identical to the typical year total of 23.8 inches. The overall sizing ratios for Divisadero St NW and Broderick St NW were 1.2% for bioretention and 16% for permeable pavement, and the total measured volume reduction was 405,000 gallons (85%), very close to the expected performance for full-sized facilities. This is likely the result of highly infiltrative soils increasing actual stormwater management capacity well above model predictions.

Out of the 38 storms producing measurable runoff during the monitoring period, 14 storms were fully managed at Divisadero St NW and 15 at Broderick St NW. The average peak flow reduction by these two planters was 69-70%. Due to the unexpected run-on, only three of the 38 analyzed storms were fully managed at Broderick St SW, and five of 38 at Baker St. The average peak flow reduction by the two planters was 25-29%.

Oak & Fell is the first of eight EIPs featuring GI that are being implemented by SFPUC. The first year of monitoring at Oak & Fell demonstrated that, within limits, undersized GI located in good soils can effectively manage stormwater. Monitoring results for six other EIPs are expected in the next several years and will provide a more complete view of how different types of GI perform in various settings across San Francisco.

Lesson Learned

The Oak & Fell EIP was the SFPUC's first designed and constructed large-scale GI project as part of the SSIP. It was also the SFPUC's first EIP project designed with the intent to directly monitor performance at the inlet and outlet. A number of lessons learned were gathered during the design and construction of this project, which we have summarized here to inform future project implementation:

1) Unfortunately, none of the four constructed bioretention planters completely met the original design intent that allowed for the combination of a HOBO level sensor and a v-notch weir to measure flows at both the inlet and the outlet. Two of the facilities were constructed with no outlet monitoring due to spatial constraints, and the rim elevation at the other two planters with outlet monitoring was above the invert of the v-notch weir at the inlet, resulting in backwater conditions at the inlet when those facilities were fully ponded. Due to these construction issues, the amount of time required for data analysis was more extensive than originally intended. Should similar facilities be constructed in the future with the intent of monitoring at both the inlet and outlet, stricter construction administration/management measures (e.g., tighter elevation control) should be enforced to ensure realization of the design and monitoring intent. For the 2016-2017 monitoring period, the field crew was able to retrofit the outlets at Baker St and Broderick St SW to include monitoring so analysis should be more streamlined for the 2016-2017 rainy season.

2) Field reconnaissance should be conducted at the onset of design during wet weather to verify the City's sewershed subcatchments GIS layer, which may not be accurate enough for block-scale GI design. Also, field reconnaissance can identify inadvertent run-on due to clogged upstream catch basins or other unanticipated field conditions, as was the case with roughly half of the DMV parking lot unexpectedly draining to the Broderick St SW bulbout due to a perpetually clogged drain.

3) Regularly scheduled maintenance is critical to maintain the appearance and function of bioretention facilities. The construction contract for this project required that the contractors maintain the bioretention bulbouts on at least a monthly basis for 3 years once construction was complete. The SFPUC Flow Team was also scheduled to visit the bioretention bulbouts on a monthly basis to download data from the HOBO sensors. On the Flow Team's initial visits, the facilities were found to often contain excessive trash and debris as well as substantial clogging the inlet forebay. In turn, the PUC requested the contractor increase maintenance frequency to meet the contract requirements. Having a second set of eyes on the bulbouts spurred the SFPUC to enforce the contractor's maintenance requirements.

4) The small box inlets for the four planters at this project were quickly overwhelmed with leaf debris from street trees (Figure 10 a, b, and c). Should facilities be constructed in the future with the intent of monitoring at the inlet, the inlet forebay should be over-sized to ensure there is not clogging that could impact data collection. Perhaps a full catch basin should be installed just upstream of the facility and used as a forebay with overflow directed to the facility.

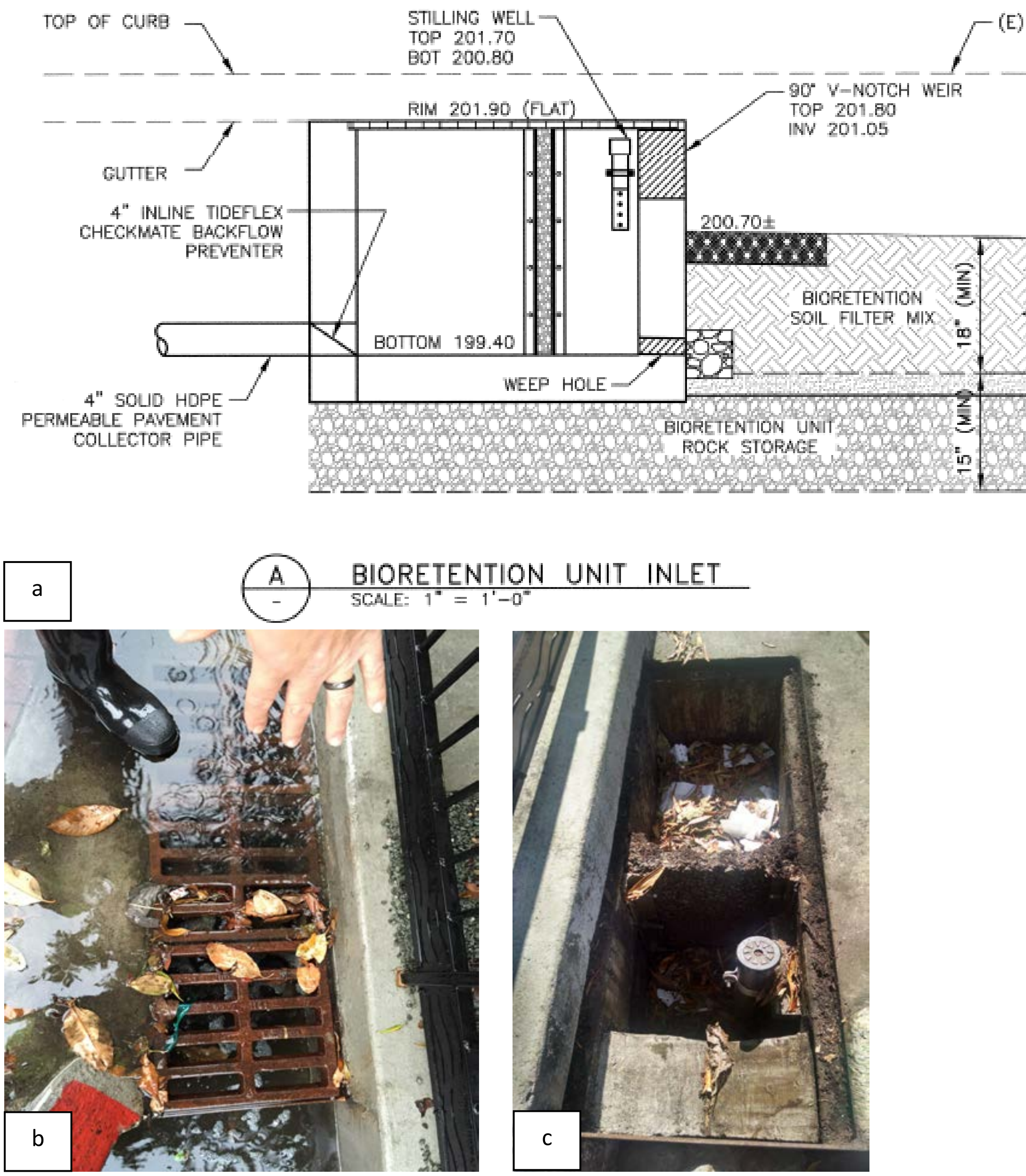

Figure 10a, b, and c: Inlet structure of Oak & Fell bulbouts (a) construction drawing, (b) clogged with debris during a storm event, and (c) with debris in dry conditions.

5) The interior grading inside the four bioretention facilities that was intended to reduce the visual impact of these unusually deep bioretention bulbouts did not maximize available ponding area, which did not allow the bulbouts to perform to their maximum potential (Figure 11 a and b). In the case of the facility at Broderick St NW, a utility corridor forced a portion of the facility interior to be raised, but the other facilities could be more efficient in terms of fully realizing available storage. The highlighted area in Figure 11b shows the area not utilized for storage when the facility is fully ponded.

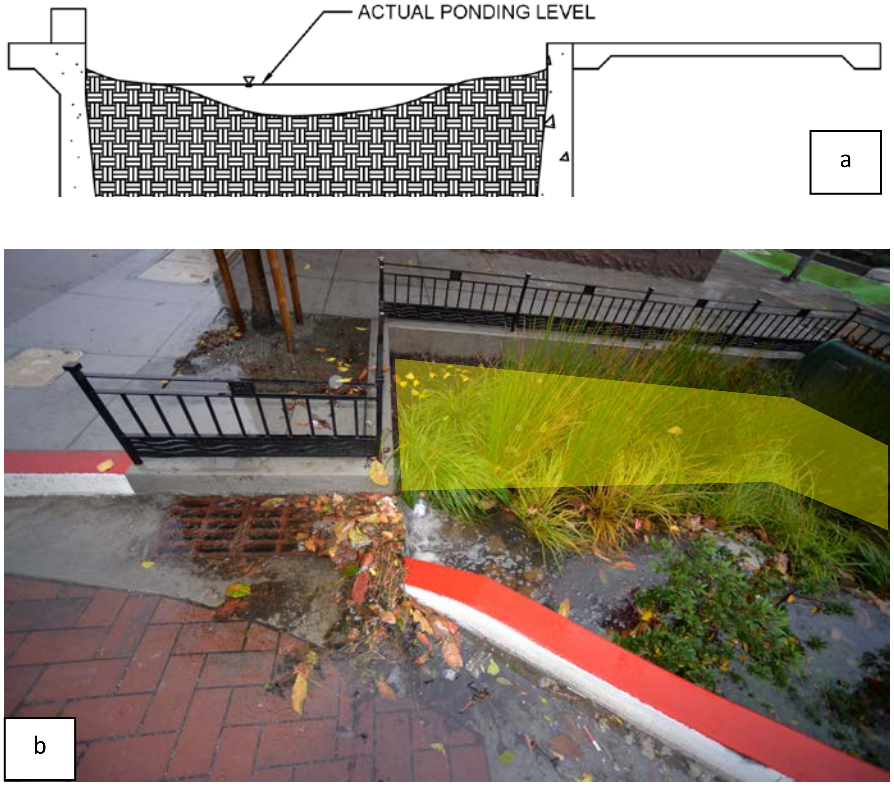

Figure 11 a and b: (a) Schematic section of a typical Oak & Fell bioretention bulbout, (b) the Broderick St SW bulbout during a very large storm event in Dec 2015