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Green Infrastructure Planning for the City of Sunnyvale with GreenPlan-IT

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July 2018

CONTRIBUTION NO. 881 /July 2018

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ACKNOWLEDGEMENT

The authors wish to acknowledge the U.S. Environmental Protection Agency Region 9 for funding the project and the San Francisco Estuary Partnership for the implementation of the larger Urban Greening Bay Area project. The authors also wish to thank members of the project Technical Advisory Committee (TAC) for their review and technical recommendations on the project. TAC members included: Jill Bicknell, Josh Bradt, Steve Carter, Chris Halford, Kristin Hathaway, Christy Leffall, Joanne Le, Keith Lichten, Elaine Marshall, Dino Marshalonis, Brian Rowley, Cece Sellgren, Mark Shorett, Jeff Sinclair, Chris Sommers, John Steere, Melody Tovar, Luisa Valiela.

Suggested citation:

Wu, J., Kauhanen, P., Hunt, J.A., and McKee, L.J., Green Infrastructure Planning for the City of Sunnyvale with Greenplan-IT. A technical report. Contribution No. xx. San Francisco Estuary Institute, Richmond, California**.**

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EXECUTIVE SUMMARY

The City of Sunnyvale, via the San Francisco Municipal Regional Stormwater Permit (MRP),is required to develop and implement a Green Infrastructure (GI) Master Plan to reduce stormwater mercury and PCB loads. This project used GreenPlan-IT, a planning tool developed by the San Francisco Estuary Institute (SFEI) and regional partners, to identify feasible and cost-effective GI locations within the City boundary to support the development of GI Plans for permit compliance.

GreenPlan-IT comprises four distinct tools: (a) a GIS-based Site Locator Tool that combines the physical properties of different GI types with local and regional GIS information to identify and rank potential GI locations; (b) a Modeling Tool that is built on SWMM5 to establish baseline conditions and quantify anticipated runoff and pollutant load reductions from GI implementation; (c) an Optimization Tool that uses an evolutionary algorithm to identify the best combinations of GI types and numbers of sites within a study area for achieving flow and load reduction goals; and (d) a Tracker Tool that tracks GI implementation and reports the cumulative programmatic outcomes for regulatory compliance and other communication needs.

GreenPlan-IT was applied at the City scale on three major watersheds (Sunnyvale West Channel, Sunnyvale East Channel, and Calabazas Creek). Four GI feature types - bioretention, permeable pavement, tree well, and flow-through planter, were included in this application. The GIS Site Locator Tool identified a list of feasible locations based on landscape and GI characteristics and ranked those locations based on local priorities, which could serve as a starting point for implementation. The Modeling Tool estimated baseline PCB load at 1,148 g/year for the City which translates to an average PCB yield of 0.11 g/acre. The Optimization Tool identified the best combinations of feasible GI locations for achieving a range of management goals at minimal cost. For a 20% reduction in PCB loads from the City landscape, the optimal, most cost-effective solution consists of 1,317 GI features that include 386 bioretention units, 718 permeable pavement installations, 70 tree wells, and 143 flow-through planters. Collectively, these GI features would treat 324 acres of impervious area. Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 50 of the subwatersheds with the highest PCB loads.

The outputs of the GreenPlan-IT applications provided the City with important information regarding tradeoffs among competing objectives for GI and a strong scientific basis for planning and prioritizing GI implementation efforts in relation to other competing City needs. Results from the application of GreenPlan-IT can be used to: 1) identify specific GI projects; 2) support the City’s current and future planning efforts, including GI plans and Stormwater Resources Plans; and 3) help comply with future Stormwater Permit requirements.

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1. INTRODUCTION

The San Francisco Bay polychlorinated biphenyl (PCB) and mercury Total Maximum Daily Loads (TMDLs) (SFBRWQCB, 2006) called for implementation of control measures to reduce stormwater PCB and total mercury (HgT) loads from Bay Area watersheds. In support of the TMDLs, the Municipal Regional Stormwater Permit requires the Permittees to develop and implement a Green Infrastructure (GI) Master Plan within each jurisdiction to help attain the mercury and PCB wasteload allocations. Specifically, the MRP requires that the GI Master Plan must be developed using “a mechanism (e.g., SFEI’s GreenPlan-IT tool or another tool) to prioritize and map areas for potential and planned projects, both public and private, on a drainage-area-specific basis” for implementation by 2020, 2030, and 2040.

The objective of this project is to use GreenPlan-IT, a planning tool developed by the San Francisco Estuary Institute (SFEI) and regional partners, to identify feasible and cost-effective GI locations within the boundary of the City of Sunnyvale to support the development of GI Plans for permit compliance. Results from the application of GreenPlan-IT can be used to: 1) identify specific GI projects; 2) support the City’s current and future planning efforts, including GI plans and Stormwater Resources Plans; and 3) help comply with future Stormwater Permit requirements.

GreenPlan-IT is a planning tool that was developed over the past five years with strong Bay Area stakeholder consultation. GreenPlan-IT was designed to support the cost-effective selection and placement of GI in urban watersheds through a combination of GIS analysis, watershed modeling, and optimization techniques. GreenPlan-IT comprises four distinct tools: (a) a GIS-based Site Locator Tool (SLT) that combines the physical properties of different GI types with local and regional GIS information to identify and rank potential GI locations; (b) a Modeling Tool that is built on the US Environmental Protection Agency’s SWMM5 (Rossman, 2010) to establish baseline conditions and quantify anticipated runoff and pollutant load reductions from GI implementation; (c) an Optimization Tool that uses an evolutionary algorithm to identify the best combinations of GI types and numbers of sites within a study area for achieving flow and load reduction goals; and (d) a Tracker Tool that tracks GI implementation and reports the cumulative programmatic outcomes for regulatory compliance and other communication needs. The GreenPlan-IT package, consisting of the software, companion user manuals, and a demonstration report, is available on the GreenPlan-IT Web site hosted by SFEI (http://greenplanit.sfei.org/).

This report documents the application of GreenPlan-IT within the City of Sunnyvale. The report describes the input data used, assumptions going into the modeling and optimization, and key results and findings of the application.

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2. PROJECT SETTING

The City of Sunnyvale is one of the major cities comprising Silicon Valley, with an area of 22 square miles (14,080 acres) and a population in 2018 of 153,389 people (Figure 2-1). Like many cities in the Bay Area, Sunnyvale has undergone significant growth over time and experienced environmental issues typically associated with urbanization including increased loadings of sediment, PCBs, mercury, and pathogens. The City is regulated by the Municipal Regional Stormwater NPDES Permit (MRP), and stormwater management is a driver for a number of City activities and area-wide programs.

2.1 Study Area

Sunnyvale is one of the co-permittees within the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) that is making a contribution to TMDL load reductions that are specified in the MRP at a county scale. GreenPlan-IT was applied at the City scale at the request of City staff to pilot GreenPlan-IT as a potential management tool. Within the City boundary, the analysis focused on three major watersheds (Sunnyvale West Channel, Sunnyvale East Channel, and Calabazas Creek) which cover about 27%, 26%, and 33% of the Sunnyvale footprint respectively (86% combined) (Figure 2-1). Application of GreenPlan-IT should be accompanied by an intimate understanding of the study area and all influential factors that affect local stormwater management in order to ensure meaningful interpretation of outputs.

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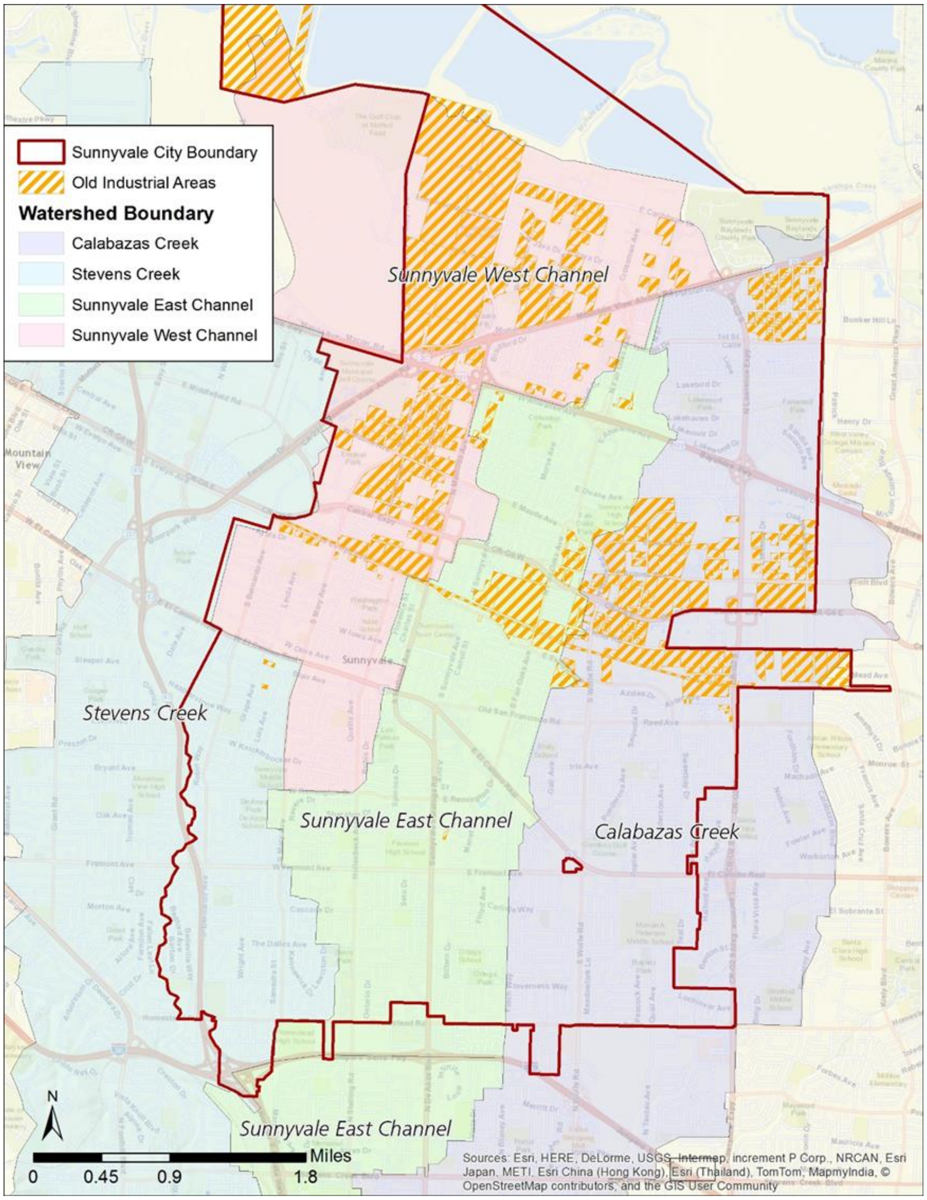

Figure 2-1 The City of Sunnyvale and three watersheds within the City boundary

2.2 Project Objectives

The initial goal of this project was to identify potential GI locations for Peery Park where redevelopment is planned. Over time, the goal evolved into using GreenPlan-IT to identify cost-effective solutions to support the development of a City-wide GI master plan. Currently, the City is working with SCVURPPP on a county-wide Reasonable Assurance Analysis (RAA) on the proposed GI plans, which is also part of permit compliance. The outputs of this study are intended to supplement that effort. This is consistent with a number of cities in the Bay Area that are part of county-wide efforts as well as city-scale planning efforts.

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3. SITE LOCATOR TOOL APPLICATION

Application of GreenPlan-IT usually begins with the GIS SLT to identify and rank potential GI locations based on the physics of GI feature types and physical aspects of the landscape. At the recommendation of the project's Technical Advisory Committee (TAC) and in consultation with City staff, four GI feature types were included in this GreenPlan-IT application: bioretention, permeable pavement, tree well, and flow-through planter. A standard size of each feature type was specified and used. Details on design specification of each GI feature are discussed later in Section 5.1.

3.1 Data Layers Used

The GIS SLT integrates regional and local GIS data and uses these data to locate and rank potential GI locations. The SLT can accommodate a wide range of data and information. Decisions about which data to include were primarily driven by the planning needs of the City of Sunnyvale and data availability. Table 3-1 shows the regional and local GIS data layers included in the SLT and the analysis that each layer was used for. For more information on the different analyses that are built into the GreenPlan-IT SLT see the GreenPlan-IT online documentation (http://greenplanit.sfei.org/books/green-plan-it-siting-tool-technical-documentation).

Table 3-1. GIS layers used in the Site Locator Tool for City of Sunnyvale.

Layers:	**Analysis:**
Parks	Locations
City managed school fields	Locations
Open Street Map parking lots	Locations
On-street parking custom layer	Locations
Bay ponds	Locations
Public facilities parcels	Local Opportunities and Constraints Ownership Locations
School parcels	Local Opportunities and Constraints
Shopping center parcels	Local Opportunities and Constraints
Old industrial areas	Local Opportunities and Constraints
Street lights	Local Opportunities and Constraints
Fire hydrants	Local Opportunities and Constraints
PG&E gas pipes	Local Opportunities and Constraints
Gas valves	Local Opportunities and Constraints

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Layers:	Analysis:
Gas stations	Local Opportunities and Constraints
Electric lines (underground)	Local Opportunities and Constraints
Water mains	Local Opportunities and Constraints
Sewer lines	Local Opportunities and Constraints
Major truck routes	Local Opportunities and Constraints
Storm lines	Local Opportunities and Constraints
Storm inlets	Local Opportunities and Constraints
Road Condition Index	Local Opportunities and Constraints
Priority development areas	Local Opportunities and Constraints
Change Opportunity Areas	Local Opportunities and Constraints
SFEI regional suitability GI layers	Local Opportunities and Constraints
Peery Park boundary	Local Opportunities and Constraints
Peery Park improvement streets	Local Opportunities and Constraints
Right of way custom layer	Ownership
CARI Wetlands	Knockout
Existing GI	Knockout
Open Street Map building footprints	Knockout
Red curbs	Knockout
Golf courses	Knockout
Wastewater Treatment Plant Parcel	Knockout

3.2 Custom Ranking

The custom ranking was determined by a nested, weighted overlay of the GIS layers based on seven factors that were identified as important to the City. This weighting was conducted by consulting with City staff through an iterative process. Each of the seven factors was assigned a weight based on the City's priorities, and each data layer within the factors was assigned a weight that summed up to 1 within each factor. Higher weights were given to the data layers that were deemed more important within each factor. Through this process, the weights were customized and adjusted to reflect local priorities and management goals of the City of Sunnyvale.

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An initial goal for the City was the redevelopment of Peery Park and its pedestrian districts, and this was reflected in the custom ranking. Sunnyvale also wanted to give higher rankings to locations within the priority development areas due to increased funding opportunities. In addition, Sunnyvale considered installation feasibility in relation to existing infrastructure, as well as historically industrial areas and places that are more visible and likely to engage the public. Overall, the City wanted to identify prioritized locations for GI investment as part of the Green Infrastructure Plan development.

Table 3-2 shows a complete list of the GIS layers and how they were used in the custom ranking. Each data layer was given a weight and categorized within a factor, which in turn had its own weight. Within each factor, layer weights added up to 1. The sum of factor weights also added up to 1. This allowed for a maximum rank value of 1 under the condition where all ranking layers overlapped a location and positively impacted the rank. Each layer either positively or negatively impacted the rank of the location it overlapped, indicated by a "1", if it positively impacted the score, or a "-1", if it negatively impacted the score. Lastly, each layer could be buffered, indicated by a type other than "None" and by a specified amount of feet, recorded under "Buffer (ft)".

Table 3-2. Relative weights for GIS data layers applied to the site ranking analysis.

Factor	**Factor_weight**	**Layer name**	**Layer weight**	**Buffer type**	**Buffer (ft)**	**Rank**
Visibility	0.08	schools	0.33	Full	100	1
Visibility	0.08	public parcels	0.33	Full	100	1
Visibility	0.08	Shopping Centers	0.33	Full	100	1
Water Quality	0.10	Old Industrial	1.00	None	0	1
Install Feasibility	0.15	street lights	0.05	Full	20	-1
Install Feasibility	0.15	fire hydrants	0.05	Full	60	-1
Install Feasibility	0.15	PG&E gas pipelines	0.05	Full	20	-1
Install Feasibility	0.15	gas valves	0.05	Full	20	-1

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Factor	Factor_weight	Layer name	Layer weight	Buffer type	Buffer (ft)	Rank
Install Feasibility	0.15	gas stations	0.05	Full	20	-1
Install Feasibility	0.15	Electric lines (underground)	0.05	Full	20	-1
Install Feasibility	0.15	water mains	0.05	Full	20	-1
Install Feasibility	0.15	sewer	0.05	Full	20	-1
Install Feasibility	0.15	major truck routes	0.09	Full	80	-1
Install Feasibility	0.15	storm lines	0.14	Full	80	1
Install Feasibility	0.15	storm inlets	0.09	Full	20	1
Install Feasibility	0.15	public facilities	0.14	None	0	1
Install Feasibility	0.15	Road Condition Index <25	0.09	Full	40	1
Install Feasibility	0.15	Road Condition Index <50*	0.09	Full	40	1
Financing Opportunity	0.21	Priority Development Areas	1.00	None	0	1
Change Opportunity	0.17	Change Opportunity Areas	1.00	None	0	1
Base Analysis	0.13	Regional Suitability Layer	1.00	None	0	1
Peery Park	0.17	Peery Park	0.67	None	0	1

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Factor	Factor_weight	Layer name	Layer weight	Buffer type	Buffer (ft)	Rank
Peery Park	0.17	Improvement Streets	0.33	None	0	1

*Overlap between the two Road Condition Index layers was intentional in order to boost the ranking for areas with a lower condition index.

3.3 Site Locator Tool Outputs

The outputs of the Site Locator Tools are driven by availability, coverage, resolution, and accuracy of the underling GIS data, and different resolution data can be used to answer management questions at different scales. Running the Site Locator Tool for the City of Sunnyvale was an iterative and interactive process of adding and subtracting data layers and adjusting weights as City staff reviewed the preliminary results against their own perceptions and experiences. After four iterations of ranking and adjustment, the potential locations for each of GI features were identified and ranked (Figure 3-1 and 3-2). Using bioretention as an example, a set of feasible locations covering 9.8% of the 22 square mile City jurisdiction and 20.9% of the public right-of-way were identified for consideration. These potential locations provide a starting point for the City's GI planning and implementation effort, but further planning work is required to determine which of these may be optimal (described in sections 4 and 5).

In the two maps of the SLT outputs below (Figure 3-1 and 3-2), a standardized symbology has been used in order to capture the full range of possible ranking values. For this particular run of the SLT there are not many negatively ranked locations, which show up as orange to red in color. This is common and is the case because there are more layers included in the ranking that have a positive impact on the overall rank. The full list of layers and how they were used in the ranking can be found in Table 3-2. There are some examples of negatively ranked locations which can been seen more clearly in Figure 3-2 (adjacent to the freeway "four-leaf-clovers") and show up as a light orange.

The SLT identified thousands of feasible GI locations for potential implementation. As an example, 1000 acres of public locations within the City were identified as potential locations for bioretention (with underdrain) and for tree wells. Of these 1000 acres, 76 acres (8%) of area suitable for bioretention and 50 acres (5%) of the area suitable for tree wells were highly ranked (rank of 0.5 or higher). The SLT also identified 400 acres of private property as potential locations for bioretention and for tree wells. Of this area, 42 acres of the area suitable for bioretention and 32 acres of the area suitable for tree wells were highly ranked (10% and 8%, respectively). These rankings are relative within the analysis and should not be compared to SLT output from other studies. Also the cutoff for the 'highly ranked' category is arbitrary and City staff can make their own determination based on the distribution of the rankings and the number of sites needed to meet programmatic goals.

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It is recommended that the highest ranked sites should be considered first when City staff are looking for implementation locations. These locations provide a starting point for the GI planning and implementation effort for the City. But further planning work can be done to determine which of these may be optimal by using the Modeling and Optimization tools, as described in next sections.

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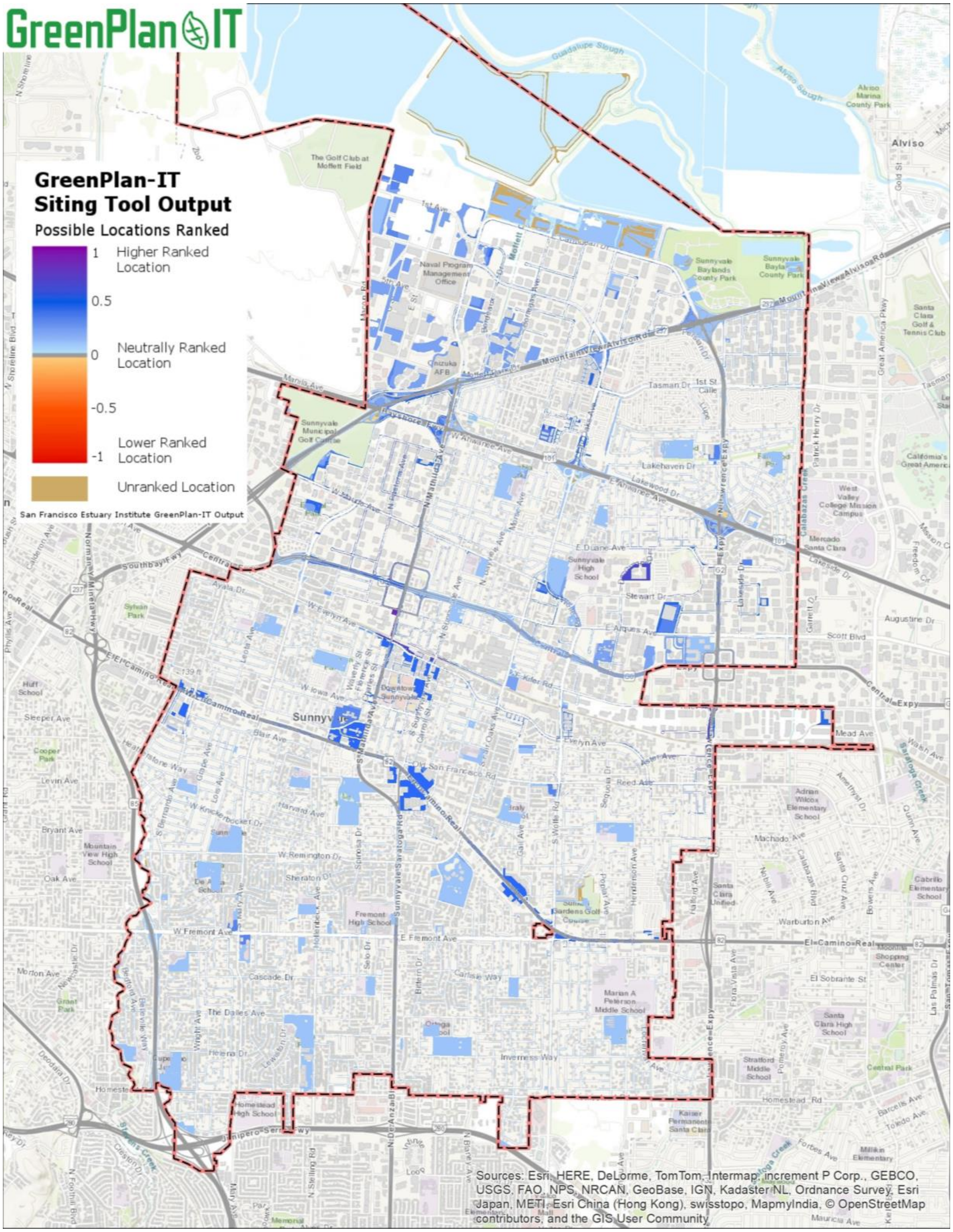

Figure 3-1 Ranked potential locations for bioretention in the City of Sunnyvale. Of the 22 square mile area of Sunnyvale, 9.8% of the total area and 20.9% of the public right-of-way has been identified as feasible for GI implementation.

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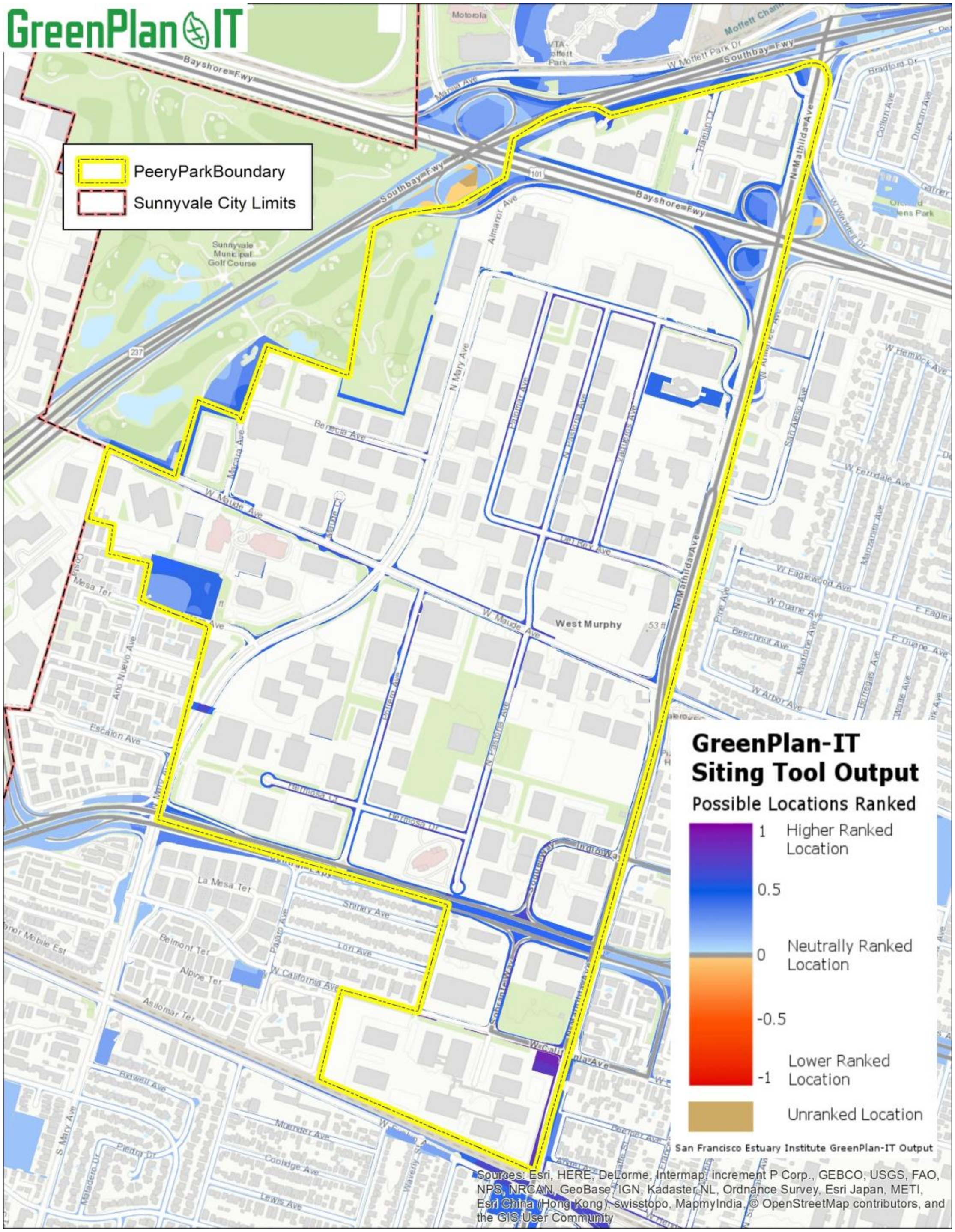

Figure 3-2 Ranked potential locations for bioretention in the City of Sunnyvale, showing Peery Park and on-street parking locations.

4. MODELING TOOL APPLICATION

The application of the Modeling Tool (SWMM5) involved watershed delineation, input data collection, model setup, model calibration, and the establishment of a baseline condition.

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4.1 Watershed Delineation

The first step in setting up the Modeling Tool for Sunnyvale was to delineate the study area into smaller, homogeneous sub-basins (model segments). Storm drainage data provided by Sunnyvale were used to delineate all three watersheds into a total of 200 sub-basins based on their connections and flow direction. These sub-basins ranged from 4.6 to 173 acres in size (Figure 4-1).

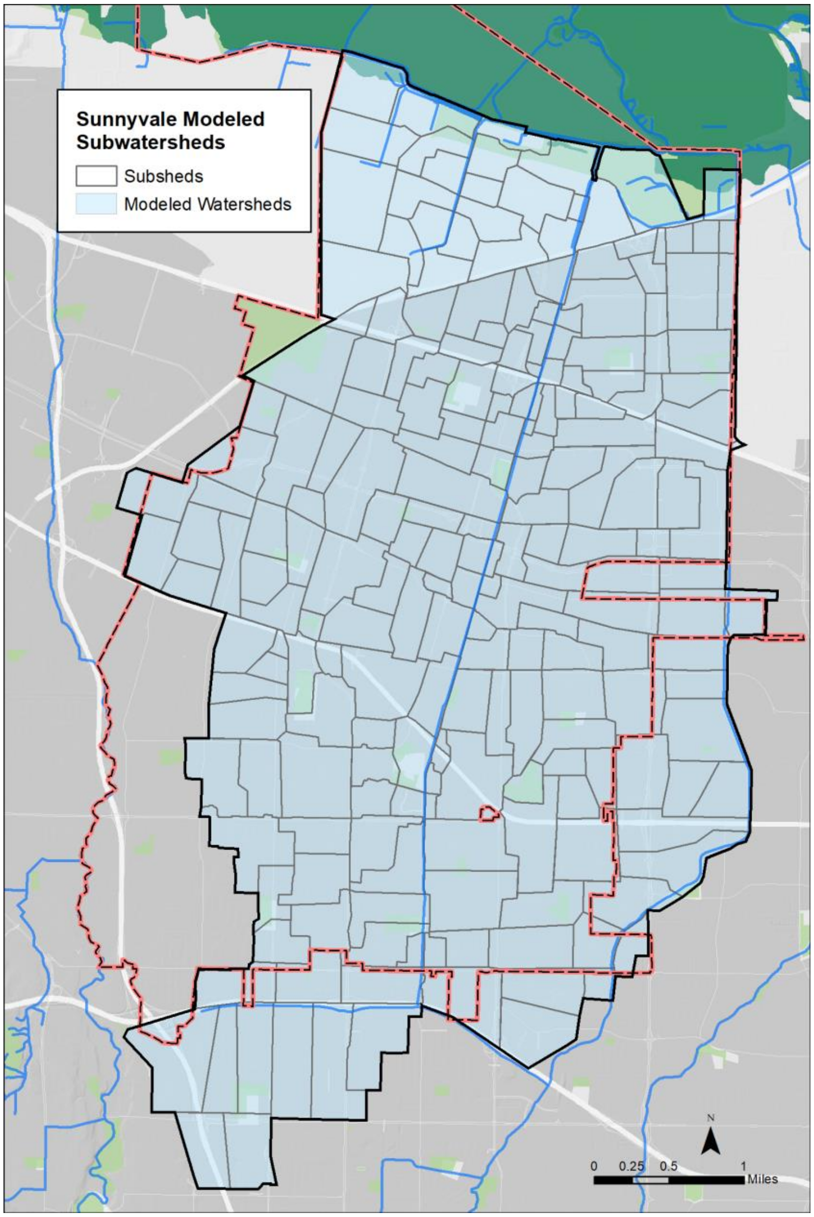

Figure 4-1. Delineated sub-basins within the City of Sunnyvale

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4.2 Input Data

A large amount of data were collected to support the application of the Modeling Tool. The input data that were used for developing a SWMM5 model for the City of Sunnyvale are described below.

Precipitation Data

High-resolution precipitation data (15-minute intervals) from 2012 to 2014 were collected at a station on East Sunnyvale Channel (Figure 4-1) and used for model calibration since this is the period for which PCB concentration data are also available. Average annual rainfall for these three years was 8.0 inches; considerably lower than the long term average (~14 inches) due to a prolonged drought. Ideally, the model calibration should cover dry, average, and wet conditions in order to ensure that it captures a wide spectrum of hydrologic conditions. But in reality, the calibration is often dictated by data availability. In the case of Sunnyvale, the flow and PCB data were collected during these drought years and thus model calibration had to be performed for these conditions. This may have led to the model performing better in dry conditions than average or wetter conditions.

Evaporation Data

Monthly evaporation data for Water Year (WY) 2011-2014 at Los Alamitos Recharge Facility in San Jose were obtained from Santa Clara Valley Water District (SCVWD). These data were then converted to monthly averages in inches/day as required by SWMM5 (Table 4-1).

Table 4-1. Monthly evaporation (inches/day) at Los Alamitos Station.

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MA Y	JUN	JUL	AUG	SEP
2011-2012	1.85	0.87	0.95	0.88	1.21	2.2	3.17	3.96	4.41	4.79	4.33	2.75
2012-2013	2.00	0.88	0.73	0.78	1.10	1.93	3.53	4.25	3.78	5.47	3.95	3.23
2013-2014	2.18	1.03	0.83	1.08	1.37	1.93	3.00	4.58	5.33	5.13	4.10	3.89
Average	2.01	0.93	0.84	0.91	1.23	2.02	3.23	4.26	4.51	5.13	4.13	3.29

Land Use Data

SWMM5 requires input of land use percentages for each segment to define hydrology and pollutant loads. Land use data were obtained from the Association of Bay Area Governments (ABAG) 2005 GIS coverage, and aggregated down to six model categories. The percentages of each land use category for each of three watersheds are listed in Table 4-2.

Table 4-2 Land use distribution in the City of Sunnyvale by watershed (acres).

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Watersheds	Commercial	Industrial	Open	Residential	Transportation	Source areas	Total
West Channel	390	1076	195	718	480		2860
East Channel	709	378	287	1947	950	69	4340
Calabazas	653	921	165	1872	972		4583
Total	1752	2375	648	4537	2402	69	11782
Percent	14.9%	20.2%	5.5%	38.5%	20.4%	0.6%	100%

Percent Imperviousness

The percentage of imperviousness is an important input data set for SWMM5 hydrology simulation. The GIS layer for imperviousness was from the National Land Cover Dataset (NLCD) 2011 at a spatial resolution of 30m x 30m pixels (http://www.mrlc.gov/nlcd2011.php).

Soil Data

Soil data were obtained from the State Soil Geographic Database (STATSGO) and intersected with the subbasin boundary layer to determine the percentages of each soil group for each model segment. The City of Sunnyvale is almost entirely composed of type D soils with low infiltration rates and high runoff rates.

Diversion Data

A junction located on the west side of Blaney Ave off Highway 280 (south side) diverts water from Sunnyvale East Channel to Calabazas Creek. A rating curve calculated by a simple hydraulic model from SCVWD (email communication, 07/11/2017) was used to estimate the flow split between these two watersheds (Table 4-3).

Table 4-3. Flow diversion at a junction at Blaney Ave off Highway 280

Upstream Inflow (cfs)	Flow to Sunnyvale East Channel (cfs)
0	**0**
50	**21**

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Upstream Inflow (cfs)	Flow to Sunnyvale East Channel (cfs)
80	35
100	44
140	64
200	98
300	144
330	162
400	188

4.3 Model Calibration

The SWMM5 calibration for the City of Sunnyvale was an iterative process of adjusting key model parameters to match model predictions with observed data for a given set of local conditions. The model calibration is necessary to ensure that the resulting model will accurately represent important aspects of the actual system so that a representative baseline condition can be established to form the basis for comparative assessment of various GI scenarios.

The model calibration was done for Sunnyvale East Channel watershed (Figure 4-1), where monitored flow and PCB concentration data from 2012 to 2014 were available (Gilbreath et al., 2015). For PCB calibration, SWMM5 allows for input of the wash off coefficients for different land uses and then the calibration proceeds by iterative adjustments of these coefficients until the modeled PCB concentrations match the observed data at the monitoring station as well as possible (with minimum difference). The yield ratios reported by Mangarella et al. (2010) were used as general guidance to differentiate the wash off coefficients between land uses, and transportation land use was assumed to have the same coefficients as commercial land use. The calibration results for flow and PCB concentrations are provided in Figure 4-2 and Figure 4-3, respectively. Overall, hourly modeled flow matched the volume and timing of observed data reasonably well, but the peaks of the biggest storms were consistently over-simulated. For PCBs, since there is only a small dataset available, the model calibration was aimed to match the magnitude of data. The model didn’t capture the very high concentrations in March 2014, which may have been caused by anthropogenic activities in addition to the transport energy supplied by rainfall during storms.

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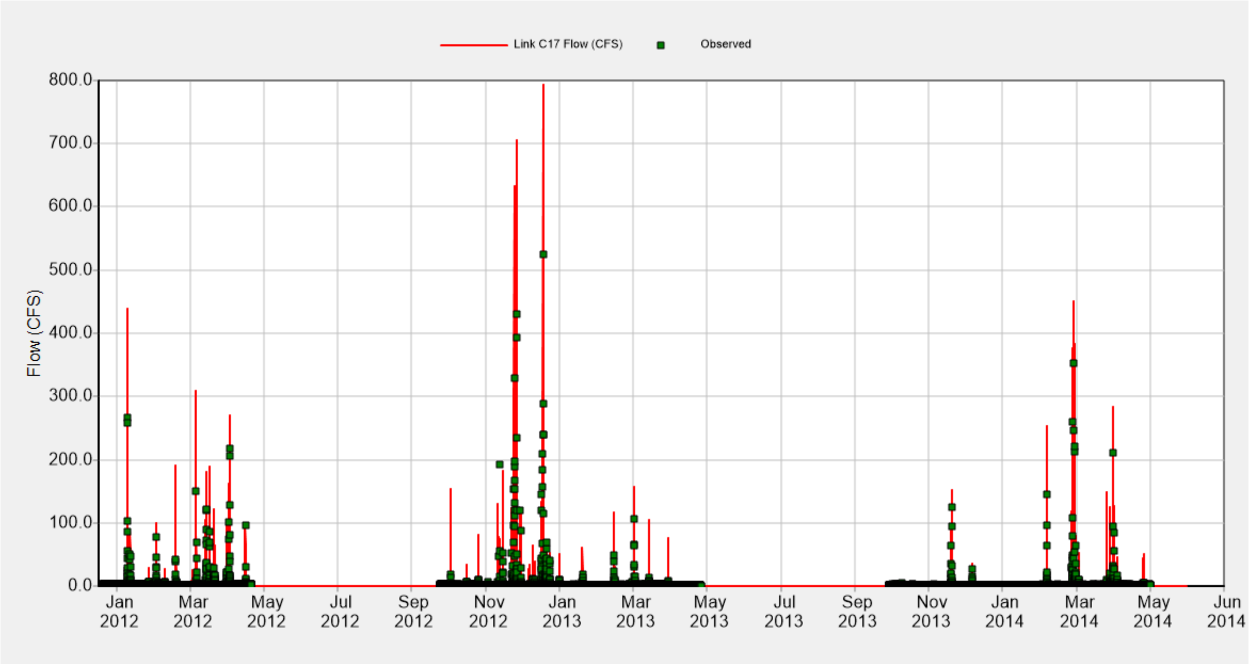

Figure 4-2. Modeled and observed hourly flow at Sunnyvale East Channel.

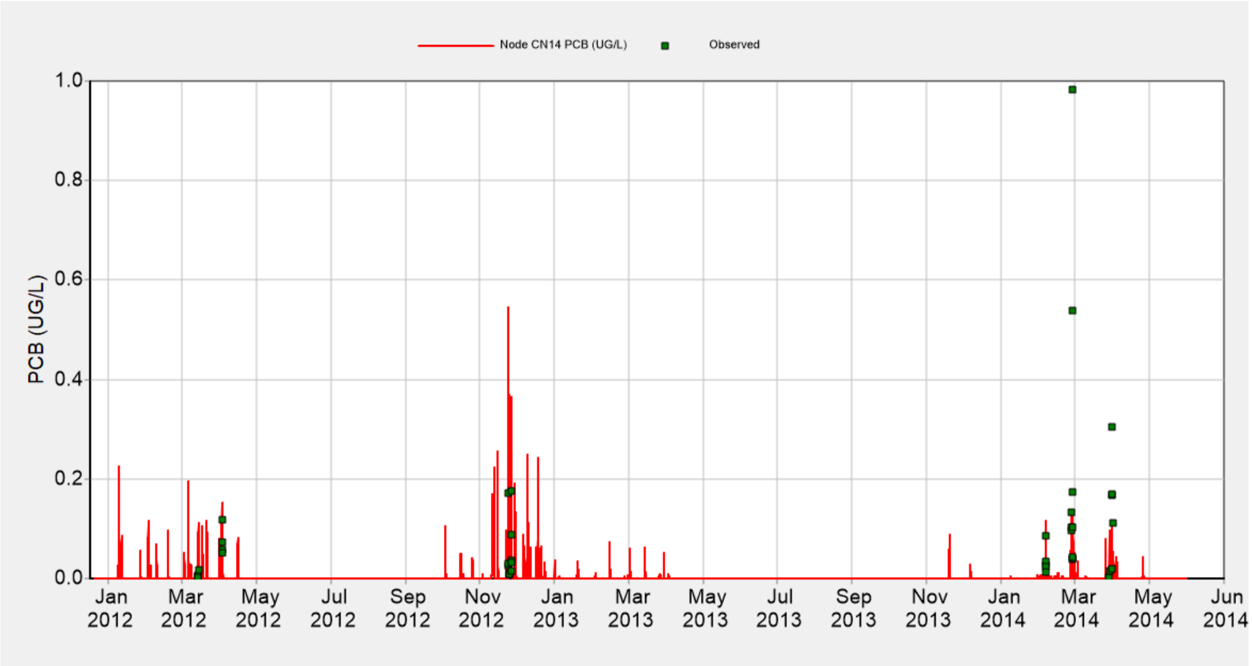

Figure 4-3. Modeled and observed PCB concentrations at Sunnyvale East Channel.

4.4 Baseline Flow and PCB Loads

The model baseline is the foundation upon which all subsequent analyses depend and is crucial for meaningful results. The calibrated model parameters from East Channel were extrapolated to the West Channel and Calabazas Creek watersheds since there are no monitoring data available for model calibration in these two watersheds. The extrapolation was done by assigning model parameters such as PCB wash off coefficients on a land use basis. This is a standard modeling

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practice for watersheds without data that have characteristics similar to calibrated watersheds, and the three watersheds in Sunnyvale fall into this category.

The baseline flow and PCB loads were then calculated to serve as the basis for the comparison of various GI solutions in the optimization. Water Year (WY) 2002 was chosen to establish a baseline condition for the City of Sunnyvale based on the recommendation of BASMAA's RAA guidance (BASMAA, 2017), which considers WY2002 as representative of average condition. Hourly rainfall data for WY2002 from a gauge at the Sunnyvale wastewater treatment plant were obtained from SCVWD and used to estimate baseline stormwater runoff and PCB loads. Prior to use, a basic quality assurance assessment was completed that involved checking the data at a monthly time step against other neighboring NOAA rainfall station locations, graphical inspection of the data and comparison of the data to the frequency depth duration published in the NOAA 14 Atlas (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html). The total annual rainfall for this station was 11.1 inches in WY 2002, lower than the long-term average rainfall of 14 inches for Sunnyvale. The monthly distribution of WY2002 precipitation is shown in Table 4-4.

Table 4-4. Monthly distribution of precipitation for WY2002 for the City of Sunnyvale.

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Rainfall (in)	0.08	3.23	4.28	0.88	0.84	1.36	0.24	0.20	0	0	0	0

Annual PCB loads for WY 2002 from each of the three watersheds are summarized in Table 4-5. The total estimated PCB baseline load for the three watersheds was 1,148 g/year. The pollutant yields, expressed as loads per unit area, were also included. Estimated average PCB yields were 0.10 g/acre for the City with a range from 0.05 to 0.89 g/acre for each watershed. Overall, Sunnyvale West Channel watershed had the highest estimated loads and yields, because of the higher percentage of industrial land use and impervious area (Table 4-2). The distribution of stormwater runoff and PCB yields is shown in Figure 4-4 and 4-5.

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Table 4-5. Baseline PCB loads for the City of Sunnyvale.

Watershed	Area (acre)	WY 2002 load (g)	WY 2002 yield (g/acre)
Sunnyvale West Channel	2860	490	0.17
Sunnyvale East Channel	4340	268	0.06
Calabazas Creek	4583	390	0.09
Whole city	**11,782**	**1148**	**0.10**

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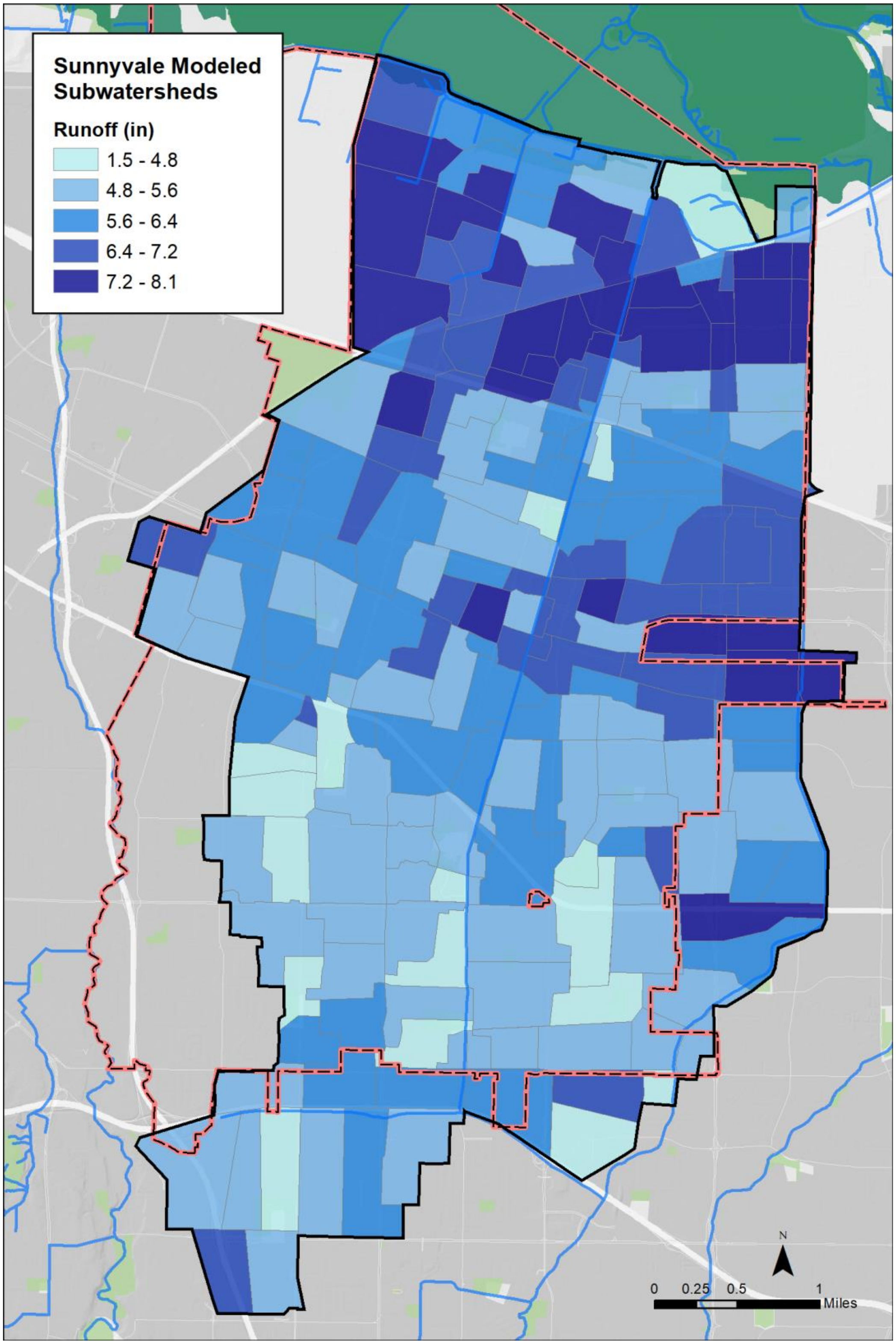

Figure 4-4. Annual runoff for City of Sunnyvale watersheds for WY 2002.

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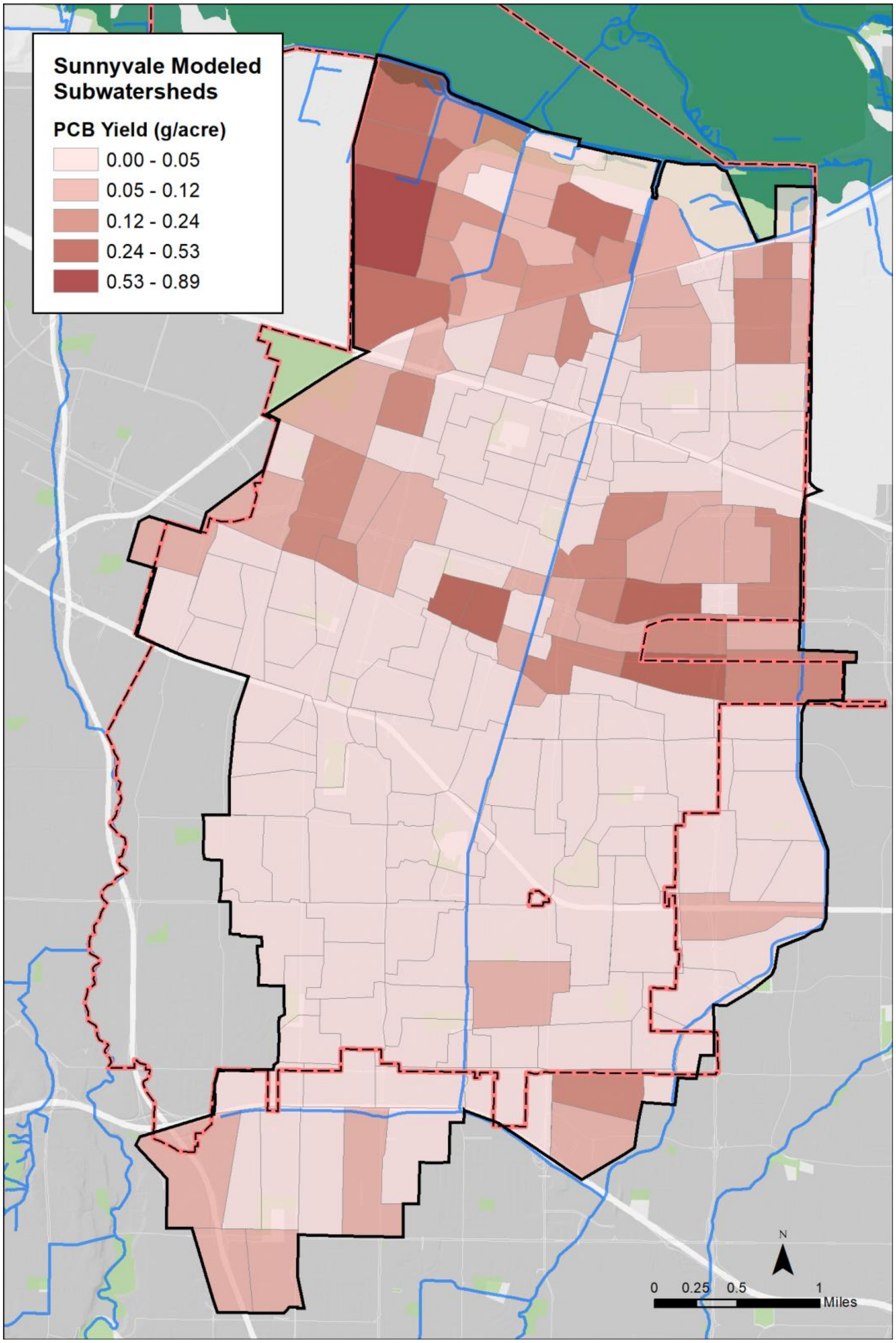

Figure 4-5 Annual PCB yield for City of Sunnyvale watersheds for WY 2002.

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5. OPTIMIZATION TOOL APPLICATION

As the last step in the GreenPlan-IT application, the Optimization Tool was used to determine the optimal combinations of GI projects within the City boundary to achieve various flow and PCB load reduction goals with minimal cost.

5.1 Optimization Tool Input

Four components are required as inputs to run the optimization tool. They are 1) baseline flow and PCB loads at the sub-basin level; 2) design specifications of each GI type; 3) GI costs; and 4) constraints on GI locations.

Baseline Flow and PCB Loads

The baseline flow and PCB loads serve as the basis for the comparison of various GI solutions. The time series of runoff and PCB loads for WY2002 for each of 200 sub-basins were generated as a reference point from which the effectiveness of any GI scenarios were estimated.

GI Types and Design Specifications

Four GI types (bioretention, permeable pavement, tree well (proprietary media), and flow-through planter) were included in the optimization. Each GI type was assigned typical size and design configurations that were reviewed and approved by the Technical Advisory Committee (Table 5-1). These design specifications remained unchanged during the optimization process. Thus, the decision variable was the number of each GI type within each subbasin. As such, the configuration of each GI type affected their performance and utilization during the optimization process. If a user is interested in larger GI features, this can be accomplished by increasing the number of features implemented; for example, implementing two would be equivalent to implementing one of twice the size, implementing three would be equivalent to implementing one of three times the size.

Table 5-1. GI types and specifications used in the Optimization Tool.

GI Specification	Surface area (sf)	Surface depth (in)	Soil media depth (in)	Storage depth (in)	Infiltration rate (in/hr)	Underdrain	Sizing factor*	Area treated (ac)
Bioretention	500 (25x20)	9	18	12	5	Yes: Underdrain at drainage layer	4%	0.29
Permeable pavement	5000 (100x50)		0	24	100	Yes: 8 inch for underdrain	50%	0.23

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GI Specification	Surface area (sf)	Surface depth (in)	Soil media depth (in)	Storage depth (in)	Infiltration rate (in/hr)	Underdrain	Sizing factor*	Area treated (ac)
Tree well	60 (10x6)	12	21	6	50	Yes: Underdrain at bottom	0.4%	0.34
Flow-through planter	300 (60x5)	9	18	12	5	Yes: Underdrain at bottom	4%	0.17

* In relation to the drainage management area of the unit.

GI Costs

The optimization strongly depended on the available GI cost information, and uncertainties in local cost data can greatly influence the management conclusions. Interpretation and application of the optimization results should take this limitation into account. While it is important to have accurate cost information for each GI type, it is the relative cost difference between GI types that determines the optimal GI types and combinations. It is therefore important to have reliable estimates on relative cost difference of various GI types and interpret the overall costs associated with each GI scenario as indications of the relative merits of one scenario versus another.

GI cost information for the four GI types were collected from local sources (Table 5-2). For this project, the costs considered were construction, design and engineering, and maintenance and operation (with a 20 year lifecycle). In general, only limited cost information was available, and these costs vary greatly from site to site due to varying characteristics, varying designs and configurations, and other local conditions and constraints. The cost assigned to each GI type was reviewed and approved by the Technical Advisory Committee (Table 5-2). A unit cost approach was used to calculate the total cost associated with each GI scenario. Cost per square foot of surface area of the GI feature type was specified for each GI type and the total cost of any GI scenario was calculated as the sum of the number of each GI type multiplied by the cost of that GI type (surface area x unit cost). These cost estimates were used to form the cost function in the Optimization Tool, which were evaluated through the optimization process at each iteration.

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Table 5-2 Green Infrastructure costs used in the optimization.

GI Types	Surface Area of GI feature (ft^2)	Estimated Cost ($\$/ft^2$)	Estimated Cost/Unit ($)
Bioretention	500	104	52,000
Permeable pavement	5000	34	170,000
Tree well	60	1312	78,720
Flow-through planter	300	149	44,700

Tree Well cost from average of City of Fremont and CW4CB project
Flow-through planter - average cost from 8 planters in Contra Costa County

Constraints on GI Locations

For each GI type, the number of possible sites was constrained by the maximum number of feasible sites identified through the Site Locator Tool. This constraint confines the possible selection of GI types and numbers within each subbasin in the optimization process. Within each subbasin, the number of possible sites for different GI types are mutually exclusive, and the optimization process will determine which ones to pick based on their performance and relative costs.

5.2 Optimization Formulation

For this study, the objectives of the optimization were to: 1) minimize the total relative cost of GI projects; and 2) maximize the total PCBs load reduction at the City scale.

In the optimization, since GI design specifications were user specified and remained constant, the decision variables were therefore the number of units of each of the GI types in each of the subbasins within each of the watersheds. For each applicable GI type, the decision variable values range from zero to a maximum number of potential sites as specified by the boundary conditions identified by the GIS SLT. The decision variables were also constrained by the total area that can be treated by GI within each subbasin. Through discussion with the Technical Advisory Committee, a sizing factor (defined as the ratio between GI surface area and its drainage area) for each GI type was specified and used to calculate the drainage area for each GI and also the total treated area for each scenario (Table 5-1). During the optimization process, the number of GI units were adjusted when their combined treatment areas exceed the available area

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for treatment within each subbasin.

5.3 Optimization Results

5.3.1 Cost-effectiveness Curve

The optimization process generated a range of optimal solutions along a cost-effectiveness curve that defines the upper points along what is called an optimal front (Figure 5-1). The curve relates the levels of PCB reduction to various combinations of GI (total number and type) throughout the City and their associated relative cost[1]. Figure 5-1 illustrates the relationship between project relative costs and PCB load reduction. All individual solutions are plotted together (each solution shown as an individual dot), with the optimum solutions forming the upper boundary of the search domain (the upper boundary of the curve). Each point along the cost-effectiveness curve represents a unique combination of the number of bioretention units, permeable pavement, tree wells, and flow-through planters across the study area.

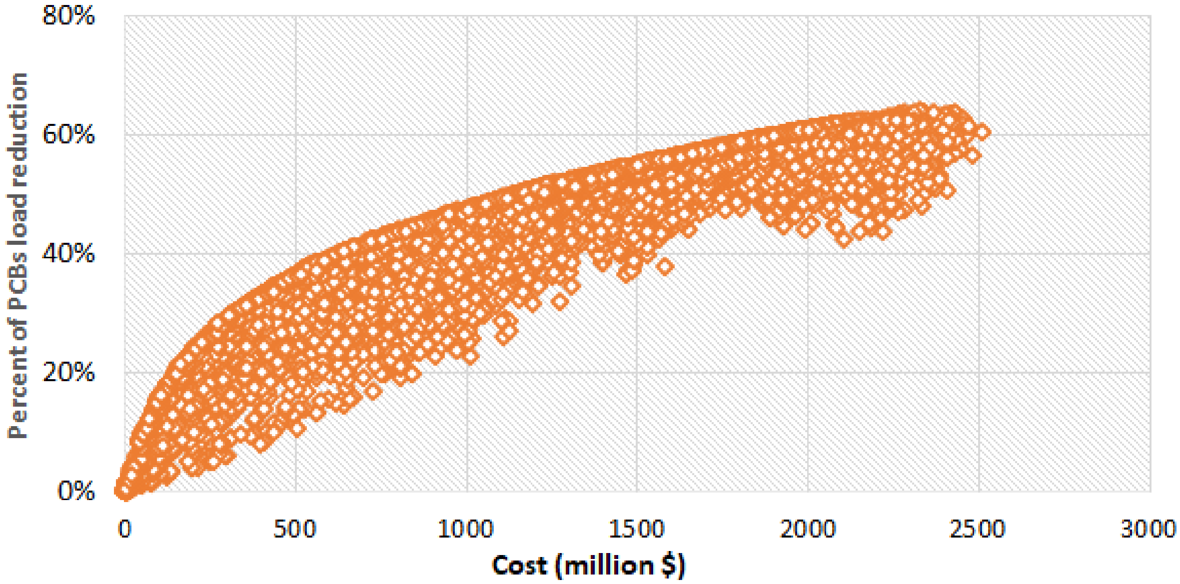

Figure 5-1. PCB cost-effectiveness relationship: the relative cost of each implementation scenario in relation to the load reduction from the estimated baseline.

Figure 5-1 shows many GI solutions for PCB load reductions. At the same level of cost, the percentage removal could vary by as much as 30%, while for the same level of pollutant

[1] The term relative cost is used to denote that this is a cost estimate based on all the assumptions in the optimization and not an estimate of the actual capital cost of implementation. The capital improvement plan (CIP) that would normally be developed in the later stages of GI planning or after the GI plan is completed would need to take into account cost savings associated with standardized designs, batch implementation, implementation during other maintenance and upgrade activities, and may include sources of funding from state and federal capital improvement grants, metropolitan transport commission (MTC) funds, and funding matches gained through public-private partnership.

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reduction, the difference in total relative cost could be well over several hundred million dollars between an optimal solution and a non-optimal solution. This highlights the benefit of using an optimization approach to help stormwater managers identify the most cost-effective solution for achieving load reduction goals with a limited budget. The slope of the optimal front in Figure 5-1 represents the marginal value of GI, and the decreasing slope of the front indicates diminishing marginal returns associated with an increasing number of GI. For example, 20% PCB removal can be achieved at a relative cost of about $150 million dollars, but only 20% additional removal can be expected for the next $500 million dollar investment. This makes sense given the heterogeneous nature of PCB sources and the relatively large variation in PCB loads across this urban landscape (McKee et al., 2015; Gilbreath et al., 2015). In the Sunnyvale baseline model, the relative variation between the least and most polluted areas was about 30-fold (Figure 4-4). Thus, after treating the most polluted areas, subsequent implementation of treatment measures will need to be placed in areas with lower baseline yields of PCBs, and therefore the load available for treatment will be less, resulting in a gradual increase in cost per unit mass treated[2]. The maximum reduction achievable appears around 65% for the City of Sunnyvale, after which the curve starts to level off and little reduction can be achieved with additional investment. With this information, City staff can set realistic goals on how much PCB reduction can be achieved and the level of investment required, as well as determining at what point further investment on GI on treating PCB will become less desirable as the marginal benefit decreases.

Since PCB loads are primarily reduced through retaining and infiltrating stormwater runoff, it is also of interest to examine the relationship between implementation cost and runoff volume reduction as ancillary results of the optimization (Figure 5-2). The cost-effectiveness curve for runoff exhibits a largely linear relationship with a tight range of solutions, due to the comparatively homogeneous nature of runoff production compared to PCB load in the study area. The model calibration shows that spatial variability in runoff production is about 4-fold in this highly urbanized watershed where sub-watersheds have similar levels of imperviousness. The maximum achievable runoff volume reductions at the outlet of the study area, given the objectives and constraints associated with the study, were estimated to be about 70% (Figure 5-2), at which point PCB loads were also mostly captured and treated. Note that these solutions are optimized for PCB reduction and therefore not necessarily optimal for runoff reduction.

[2] Note - these increasing costs will likely be partially offset by decreasing implementation costs as GI becomes standardized in urban planning and design.

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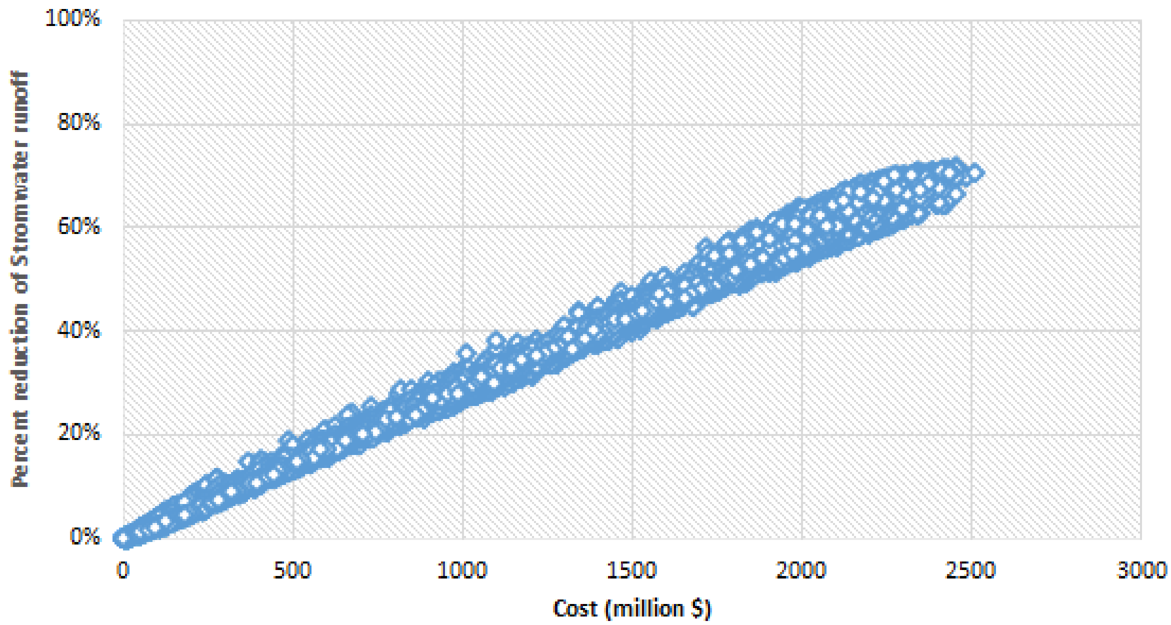

Figure 5-2. Runoff cost-effectiveness relationship: the relative cost of each implementation scenario in relation to the flow reduction from the estimated baseline.

The Optimization Tool performs iterative searches to identify cost-effective solutions. The search process is dependent on the problem formulation, model assumptions, GI cost and GI performance. Therefore, the cost-effective solutions from the optimization process very much depends on the user-defined goals and assumptions and should be interpreted within the context that defines each specific application. If one or more of the above factors are changed, the optimization may result in a very different set of solutions in terms of GI selection, distribution, and cost.

It also should be noted that because of the large variation and uncertainty associated with GI cost, the estimated total costs associated with various reduction goals do not necessarily represent the true cost of an optimum solution. The interpretation and application of the optimization results should take this limitation into account. As the region starts to build more GI features over time, more reliable and localized cost data can be collected to inform and refine the optimization results. The investments needed are large, but they will be spread over multiple decades. In addition, cost savings will likely be realized during implementation associated with standardized designs, batch implementation, and implementation during other maintenance and upgrade activities. Therefore, these costs should be interpreted as a common basis to evaluate and compare the relative performance of different GI scenarios during planning and are likely much greater than would be incurred during the implementation.

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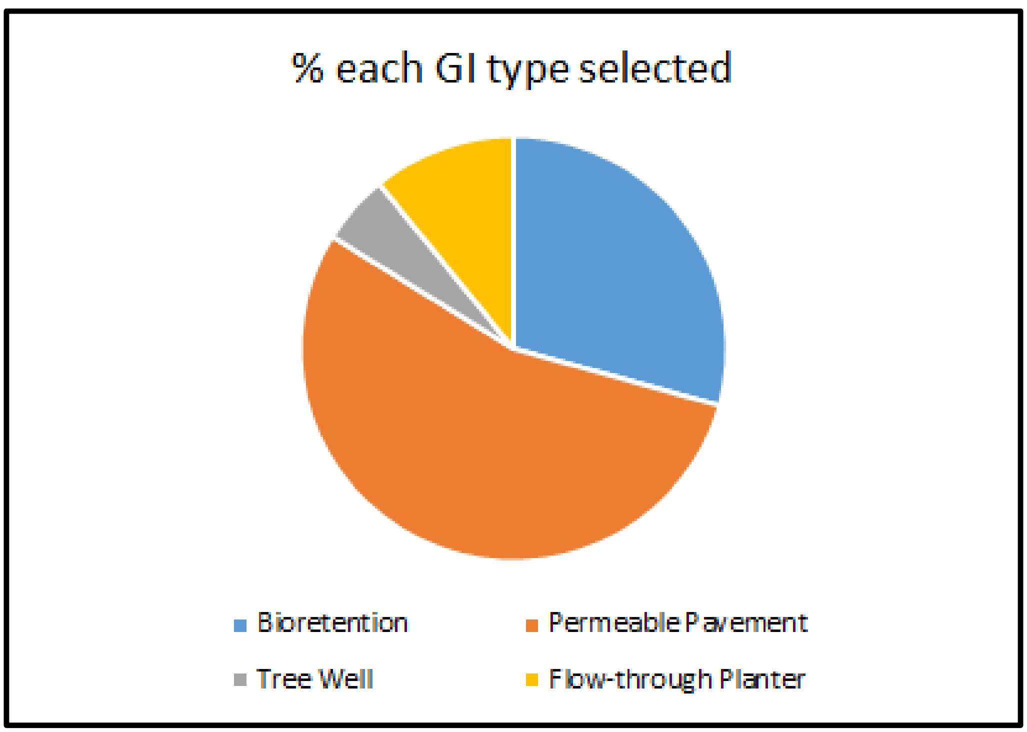
5.3.2 GI Utilization and Spatial Distribution for Example Scenario

The optimal combinations of GI types and numbers for any user-defined reduction goals can be examined to gain insight into the rationale and order of selecting individual projects. For a given solution, the selection of GI features can be (1) evaluated in terms of the magnitude of build-out and percent utilization; and (2) analyzed spatially in terms of GI selections throughout each subwatershed. At the recommendation of the City, an example of 20% PCB load reduction goal was selected for detailed evaluation.

For this reduction goal, the optimal solution consists of a total of 1,317 GI features, including 386 bioretention units, 718 permeable pavement installations, 70 tree wells, and 143 flow-through planters. Collectively, these features treat 324 acres of impervious area. The percent utilization of each GI type was quantified for the selected solution (Figure 5-3a). Permeable pavement accounted for 55% of the total GI units identified, as a result of a large surface area and lowest unit cost. In reality, this feature is often built along with other GI types to form a more complex treatment system. Tree wells were least utilized because of a high unit cost (Table 5-1, 5-2). These results were highly dependant on the cost information specified in Table 5-2. The percent utilization of each GI type can also be viewed in terms of area treated (Figure 5-3b). While bioretention accounted for 29% of the total number of GI units, it treated 34% of impervious area. Permeable pavement treated 51% of impervious area because of a low sizing factor (Table 5-1). Tree wells and flow-through planters were each estimated to treat about 8% of impervious area.



(a)

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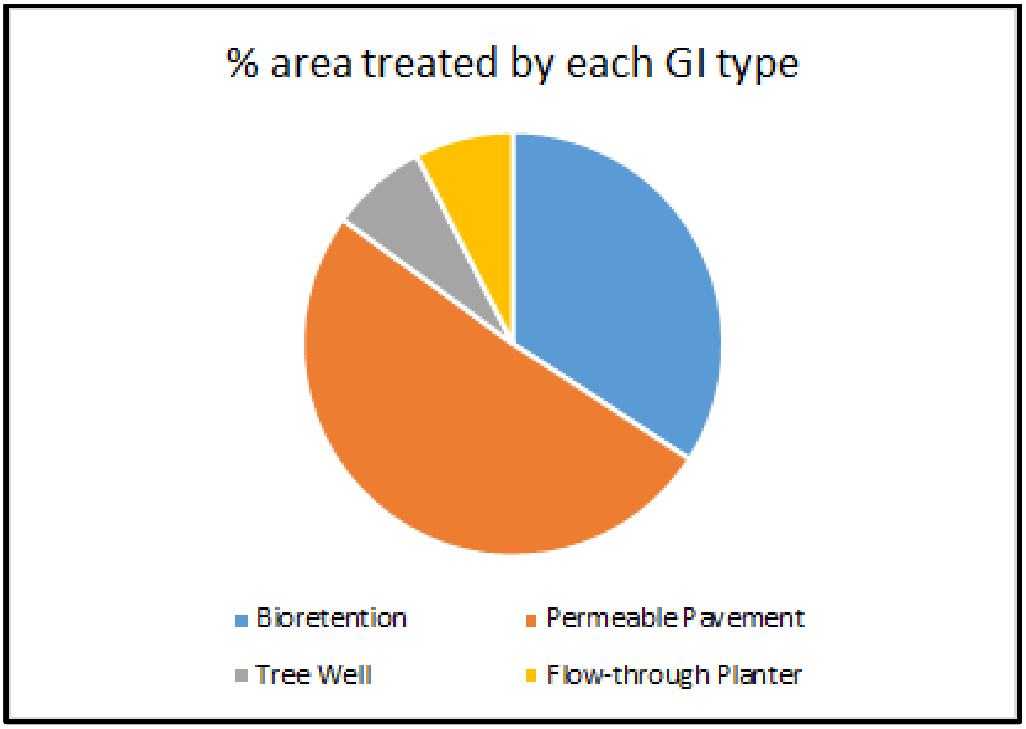

(b)

Figure. 5-3 Percentage of each GI type selected and area treated by each type.

Since there are three watersheds within the study area, it is also of interest to understand how selected GI features were distributed among each. Of 1317 total GI units identified, 79% were estimated to be best placed in the Sunnyvale West Channel watershed, 15% in the Calabazas Creek watershed and only 6% in the Sunnyvale East Channel watershed. In terms of area treated, a total of 248 acres of impervious area was estimated to be associated with the optimal treatment solution in the Sunnyvale West Channel watershed, 56 acres in the Calabazas Creek watershed, and 20 acres in the Sunnyvale East Channel watershed. More GI was identified in the Sunnyvale West Channel watershed because it has the highest PCB yields associated with a high percentage of old industrial land uses and imperviousness (Table 4-4). Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 50 of the subwatersheds that have the highest relative amount of PCB loads.

GI utilization results can be mapped by sub-basin to gain insight into the optimal spatial placement of these features given the defined objective and constraints. Figure 5-4 shows the number of GI units identified in each sub-basin for the 20% PCB load reduction scenario. In general, the optimization process identified more GI units in the areas with high PCB loads (i.e., Sunnyvale West Channel watershed), where GI could be most cost-effective.

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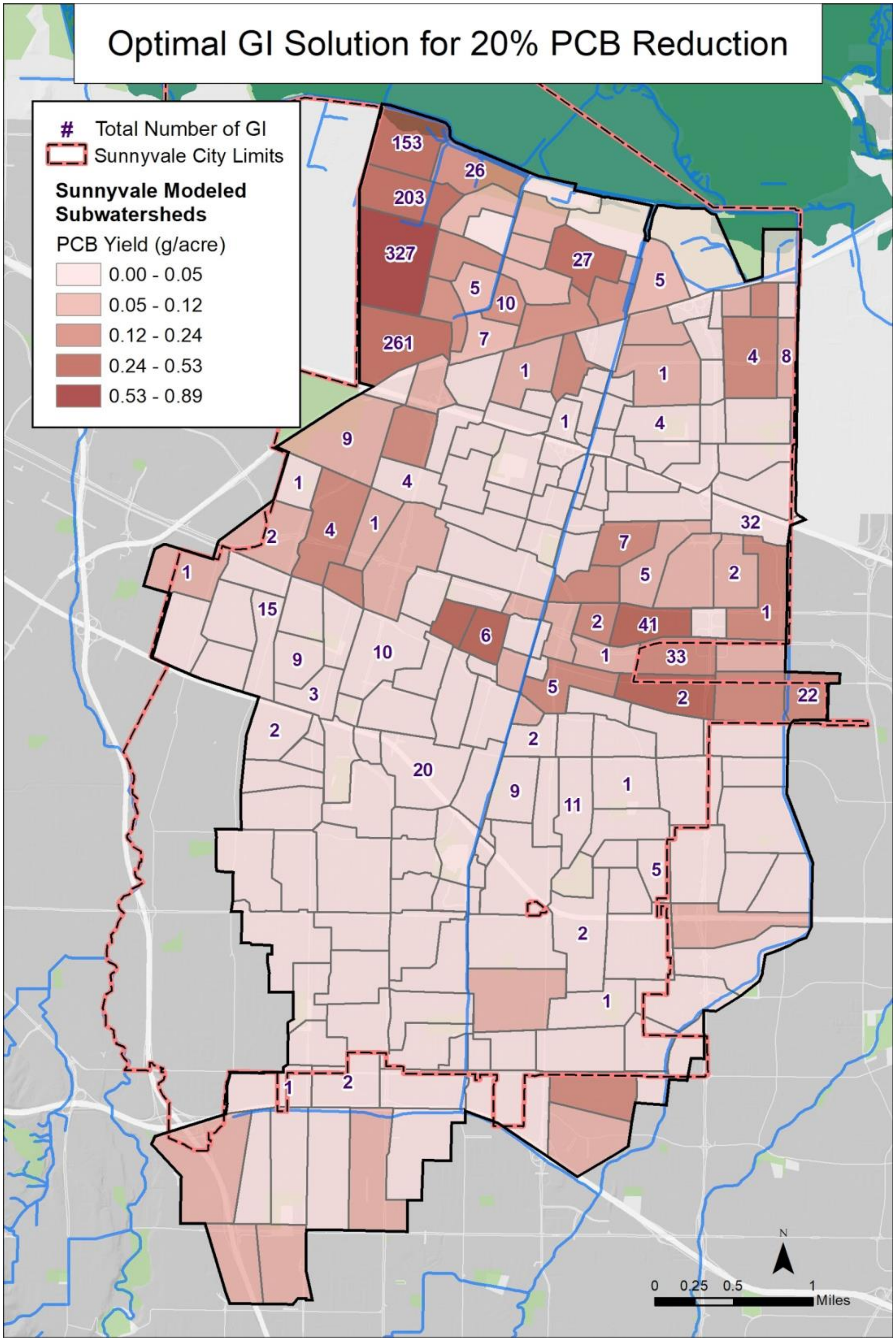

Figure 5-4. The number of GI units identified in each sub-basin for the optimal scenario that achieved a 20% PCB load reduction.

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5.4 Incorporating GreenPlan-IT Results into Planning Documents

The optimal solutions identified through Greenplan-IT can serve as a starting point for developing a city-wide GI master plan. Since GreenPlan-IT is a planning tool, it identifies the number of GI units at a sub-basin level without specifying the actual locations of these projects. To help prioritize management actions, one can work at the sub-basin level to identify and evaluate potential GI sites based on their ranking assigned by the Site Locator Tool, once a reduction goal is set.

Take for example a subbasin within the Peery Park area (Figure 5-5, highlighted in light green). If a 20% PCB reduction goal by 2025 is assumed, the number of bioretention units needed within this sub-basin to achieve the goal is nine. For this GI feature, there are 1045 potential sites, a large number to choose from and each with its own ranking. City staff could begin by exploring the highest ranking potential bioretention sites to evaluate the suitability of implementing a bioretention unit on each site. This can be done within a GIS (such as ArcGIS or Google Earth) by selecting and exploring the highest ranked locations within this subbasin (perhaps starting with the top 10% ranked locations). If one potential location is not suitable, then other ranked sites can be considered, until the best nine locations are selected. A similar process could be applied for selecting the best locations for other GI types within the Park area, as well as selecting sites in other sub-basins within the City boundary.

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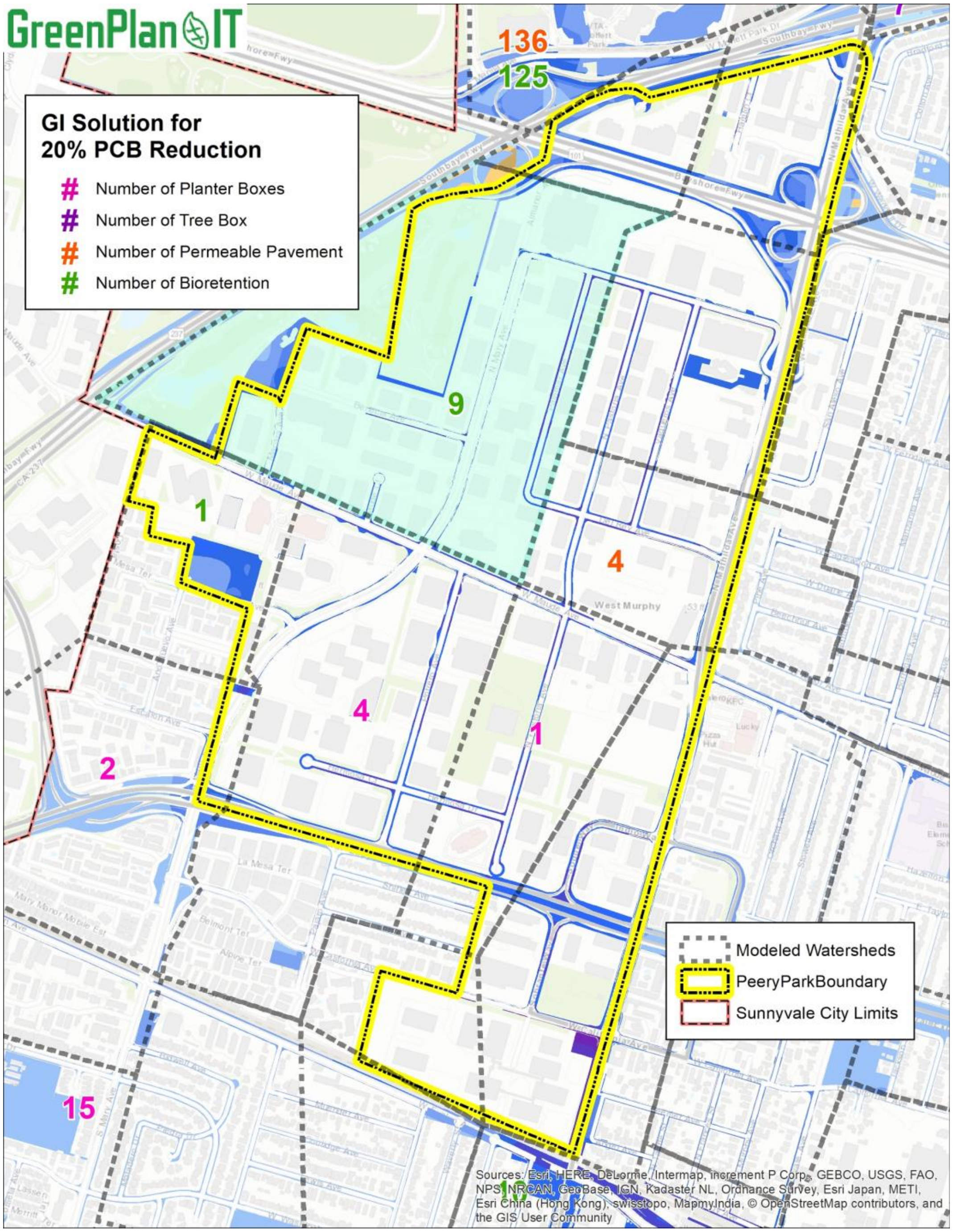

Fig. 5-5 Peery Park showing Optimization Tool Outputs for a 20% PCB reduction. Numbers within each sub-basin are color coded for each GI type (see map legend), depicting the number of each GI type needed to reach 20% city wide PCB reduction.

In addition to the rankings, other factors that were not included in the GreenPlan-IT analysis can also be taken into account to help prioritize the locations. These factors include but are not limited to funding opportunities, public-private partnership opportunities, community needs, existing flooding or pollution source problems areas, and infrastructure age and condition.

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Combining these factors with the GreenPlan-IT optimal solutions allows for locations to be selected that reflect local priorities and management goals.

6. SUMMARY

The GreenPlan-IT Toolkit is a planning tool that provides users with the ability to evaluate the cost-effectiveness of GI for managing stormwater in urban watersheds. It is a data-driven tool whose performance is dependent on the availability and quality of the data that support it. In this study, the GIS Site Locator Tool was used to identify a ranked list of feasible locations for the City of Sunnyvale. This provided the City with a list of feasible locations identified based on landscape and GI characteristics and ranked based on local priorities. The Modeling Tool was used to quantify the baseline flow and PCB loads from the City landscape, and to estimate flow and PCB loading reductions associated with implementing GI, thereby providing quantitative information on water quality and quantity benefits. The Optimization Tool was then used to identify the best combinations of feasible GI locations (among tens of thousands of options) for achieving management goals at minimal cost.

The results of the GreenPlan-IT application are maps and tables of feasible locations and a range of optimal solutions for different reduction goals. These potential locations can be compared and overlaid with maps of flooding, trash build up areas, planned capital projects, funding sources, and community needs as the basis for a GI plan. The outputs of the GreenPlan-IT applications provided the City with important information regarding tradeoffs among competing objectives for GI and a strong scientific basis for planning and prioritizing GI implementation effort in relation to other competing City needs. This kind of systematic approach has been found to be important for providing City officials with the information they need to make difficult funding decisions, weighing investment in stormwater infrastructure against other competing priorities such as fire protection, schools, police, parks and recreation, and libraries.

Below is a summary of the findings for the project:

- The Site Locator Tool identified thousands of feasible locations for potential implementation of GI. As an example, 1000 acres of public locations within the City of Sunnyvale were identified as potential locations for bioretention (with underdrain) and for tree wells. Of this area, 76 acres (8%) of the area suitable for bioretention and 50 acres (5%) of the area suitable for tree wells were highly ranked.The highest ranked sites should be considered first as implementation locations.
- The Site Locator Tool also identified 400 acres of private property as potential locations for bioretention and for tree wells. Of this area, 42 acres of the area suitable for bioretention and 32 acres of the area suitable for tree wells were highly ranked (10% and 8%, respectively).

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- For the three watersheds modeled within the City of Sunnyvale, the estimated baseline PCB load is 1,148 g/year. This translates to an average PCB yield of 0.10 g/acre for the whole City.
- Sunnyvale West Channel had the highest estimated PCB loads and yields due to the higher proportion of industrial land uses and impervious area in this watershed.
- To achieve a 20% reduction in PCB loads from the City landscape, the optimal, most cost-effective solution consists of 1,317 GI features that include 386 bioretention units, 718 permeable pavement installations, 70 tree wells, and 143 flow-through planters.
    - Of the 1317 total GI units identified, 79% of them should be placed in the Sunnyvale West Channel watershed, 15% in the Calabazas Creek watershed and only 6% in the Sunnyvale East Channel watershed.
    - Collectively, these GI features would treat 324 acres of impervious area, with 248 acres in the Sunnyvale West Channel watershed, 56 acres in the Calabazas Creek watershed, and 20 acres in the Sunnyvale East Channel watershed.
- Similarly, optimal solutions and GI combinations are available for other reduction goals of management interest.
- Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 50 of the subwatersheds with the highest PCB loads.

7. REFERENCES

BASMAA 2017. Bay Area Reasonable Assurance Analysis Guidance Document. Prepared by Geosyntec Consultants and Paradigm Environmental. Project Number WW2282, June 30th 2017. http://basmaa.org/Announcements/bay-area-reasonable-assurance-analysis-guidance-document

Gilbreath, A.N., Hunt, J.A., Wu, J., Kim, P.S., and McKee, L.J., 2015. Pollutants of concern (POC) loads monitoring progress report, water years (WYs) 2012, 2013, and 2014. A technical report prepared for the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP), Sources, Pathways and Loadings Workgroup (SPLWG), Small Tributaries Loading Strategy (STLS). Contribution No. 741. San Francisco Estuary Institute, Richmond, California. http://www.sfei.org/sites/default/files/biblio_files/FINAL_WY2014_POC%20loads%20progress%20report.pdf

Mangarella, P., Havens, K., Lewis, W., and McKee, L.J., 2010. Task 3.5.1: Desktop Evaluation of Controls for Polychlorinated Biphenyls and Mercury Load Reduction. A Technical Report of the Regional Watershed Program: SFEI Contribution 613. San Francisco Estuary Institute, Oakland, CA. 41pp.

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McKee, L.J. Gilbreath, N., Hunt, J.A., Wu, J., and Yee, D., 2015. Sources, Pathways and Loadings: Multi-Year Synthesis with a Focus on PCBs and Hg. A technical report prepared for the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP), Sources, Pathways and Loadings Workgroup (SPLWG), Small Tributaries Loading Strategy (STLS). SFEI Contribution No. 773. San Francisco Estuary Institute, Richmond, CA. http://www.sfei.org/sites/default/files/biblio_files/MYSR%20Final%20Report.pdf

Rossman, L. A (2010). Storm Water Management Model User's Manual, Version 5.0, U.S. Environmental Protection Agency. Office of Research and Development. EPA/600/R-05/040.