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

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EXECUTIVE SUMMARY

The City of Oakland, 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, with the GIS SLT applied to the entire city while the Modeling and Optimization tools focused on the Ettie Street Pump Station (ESPS) watershed for detailed analysis. Two GI feature types - bioretention and tree well, 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 loads at 98.4 g/year for the ESPS watershed which translates to an average PCB yield of 0.08 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 watershed, the optimal, most cost-effective solution consists of 418 bioretention units, which would treat 120 acres of impervious area. Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 10 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 (MRP) requires the Permittees to develop and implement a Green Infrastructure (GI) Master Plan within their jurisdiction to help attain the mercury and PCB wasteload allocations. Specifically, the MRP requires that the GI 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 was to use GreenPlan-IT, a planning tool developed by the San Francisco Estuary Institute (SFEI), to identify feasible and cost-effective GI locations within a polluted watershed in the City of Oakland to support the development of GI Plans for permit compliance. Results from the application of GreenPlan-IT could be used to: 1) identify specific GI projects; 2) support the City's current and future planning efforts, including GI Master Plans and Stormwater Resources Plans; and 3) help comply with future Stormwater Permit requirements.

GreenPlan-IT is a planning level 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 sites; (c) an Optimization Tool that uses a cost-benefit analysis 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 demonstration report, is available on the GreenPlan-IT web site hosted by SFEI (http://greenplanit.sfei.org/).

This report documents the application of the GreenPlan-IT in the Ettie Street Pump Station (ESPS) watershed located in West Oakland as well as the outcomes of applying the Site Locator Tool for the entire City of Oakland. The report describes the input data used, assumptions going into the modeling and optimization, and key results and findings of the application.

2. PROJECT SETTING

The City of Oakland is the largest city and is the county seat of Alameda County as well as a major West Coast port city, with a total area of 77.86 square mile and a population over 400,000. Like many cities in the Bay Area, the City of Oakland 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. Within the City boundary, there are several watersheds with elevated concentrations of PCB in sediment in mostly historical industrial areas where PCBs were used. These watersheds are targeted for management actions. One of them, the Ettie Street Pump Station watershed, was selected by the City staff for this case study (Figure 2-1).

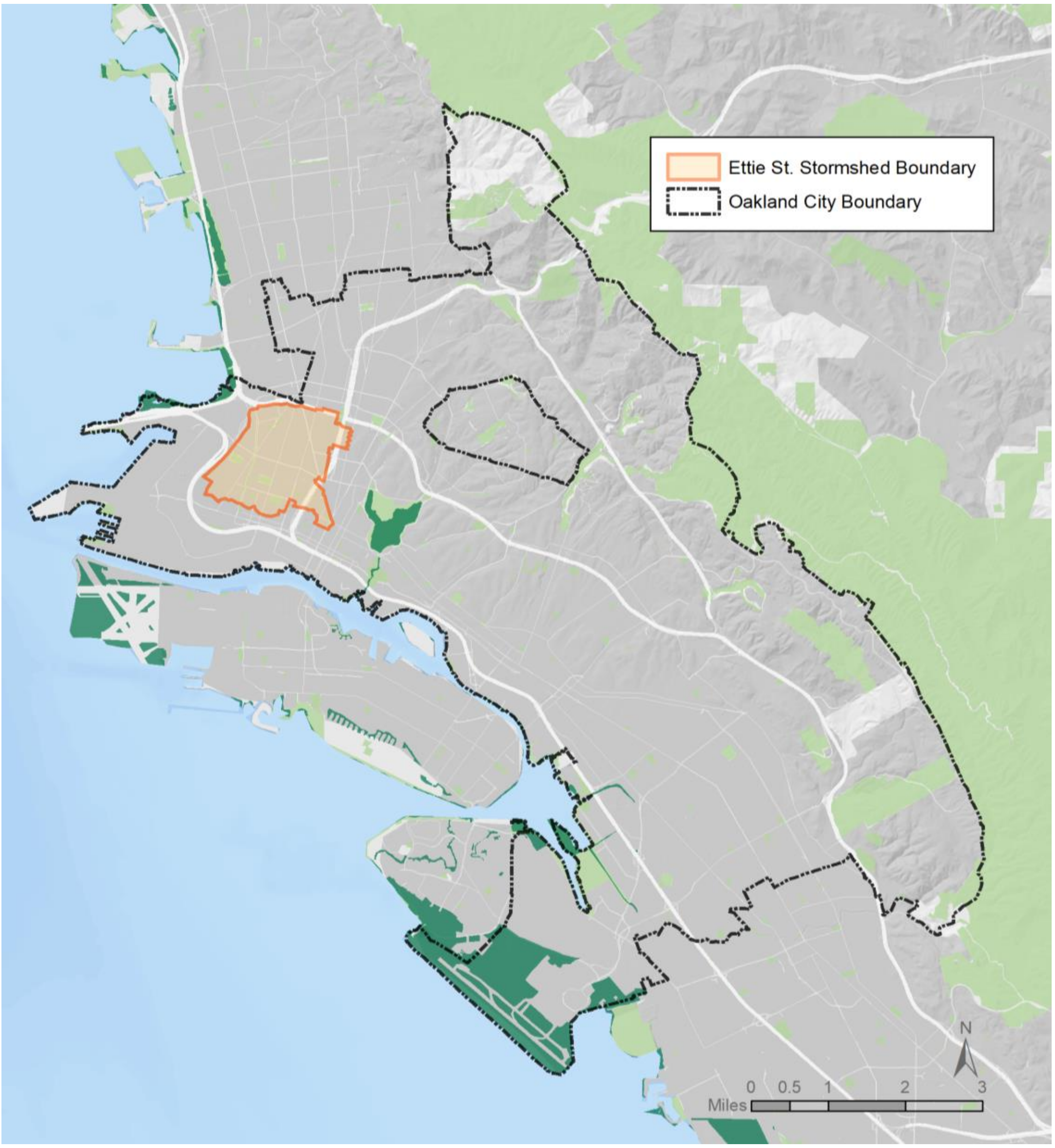

Figure 2-1 Ettie Street Pump Station watershed in West Oakland

2.1 Study Area

The study area for this case study is different for different toolkit applications. The GIS Site Locator Tool (SLT) was applied to the entire city, while the Modeling and Optimization tools were applied to the ESPS watershed for detailed analysis. The ESPS watershed is an Alameda County Flood Control and Water Conservation District (ACFCD) facility that discharges stormwater runoff into the Emeryville Crescent area of San Francisco Bay. The watershed, located in the western portion of the City, is a small, highly urbanized watershed with a drainage area of 1.86 square miles (1192 acres) and a high percentage of imperviousness (Figure 2-1). The watershed consists of diverse land use areas, including residential, commercial, and industrial zones. Application of GreenPlan-IT should be accompanied by an understanding of the study area and all influential factors (i.e. climates, soil, land uses, community needs, local drivers) that affect local stormwater management in order to ensure meaningful interpretation of outputs.

2.2 Project Objectives

The goal of this project was to use GreenPlan-IT to identify potential GI locations within the City boundary, as well as cost-effective solutions for the ESPS watershed where management action is planned. In addition, the City of Oakland is required by the MRP to develop a GI plan for PCB reduction, this application and its outputs can support that effort for permit compliance as well as other city-scale planning efforts.

3. SITE LOCATOR TOOL APPLICATION

Application of the 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. The SLT was applied to the entire city. The City of Oakland selected all nine GI types currently available in SLT: bioretention with and without underdrain, flow through planter, infiltration trench, permeable pavement, stormwater wetland, vegetated swale, wet pond and tree wells. A standard size of each feature type was specified and used, using the default sizes that are described in the default GI size table available on the GreenPlan-IT website (http://greenplanit.sfei.org/content/greenplan-it-site-locator-tool). This section provides an overview of the use of the SLT in the City.

3.1 Data Layers Used

The GIS SLT integrates regional and local GIS data and uses these data to locate 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 Oakland 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 Oakland.

Layers:	**Analysis:**
East Bay Trails	Locations
Bay Trails	Locations
On Street Parking Estimate	Locations
Sidewalks that are over 10ft wide	Locations
Street Medians	Locations
Parking Facilities	Locations
Parcels with City Facilities	Locations Ownership
City Owned Property	Locations Ownership
Oakland Parks	Locations
Land Cover Metrics - Parks	Locations
Bare Soil	Locations
Storm Pipes	Local Opportunities and Constraints Analysis
Curb Ramps	Local Opportunities and Constraints Analysis
Storm Inlets	Local Opportunities and Constraints Analysis
Truck Routes	Local Opportunities and Constraints Analysis
Poad PCI	Local Opportunities and Constraints Analysis
Bikeways	Local Opportunities and Constraints Analysis
Capital Improvement Projects	Local Opportunities and Constraints Analysis
Oakland Trash Generation	Local Opportunities and Constraints Analysis
Oakland Tree and Vegetation Cover	Local Opportunities and Constraints Analysis
SFEI regional suitability GI layers	Local Opportunities and Constraints Analysis
CARI Wetlands	Knockout
Oakland City Facilities	Knockout
Open water	Knockout
Impaired_WaterBodies_EPA2010_303d	Knockout

Layers:	Analysis:
GreenPrint Vernal Pools and Baylands	Knockout

3.2 Custom Ranking

The custom ranking was determined by a nested, weighted overlay of the GIS layers based on four factors that were identified as important to the City. The weighting was conducted by consulting with City staff through an iterative process. Each of the four factors was assigned a weight based on the City's priorities, and each data layer within the factors was assigned a weight that sums 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 Oakland.

The primary focus or priority for City of Oakland's ranking was funding opportunities for GI placement, which is reflected in the custom ranking. In addition to these priorities, Oakland also considered installation feasibility in relation to existing infrastructure, accounting for additional benefits, such as trash capture and adding shade and vegetation to areas, and prioritizing regional suitability for each GI type.

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 the 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 spatially buffered in the analysis, indicated under "Buffer type" by a type other than "None", such as "Full". The number of feet the layer is buffered by is recorded under "Buffer (ft)". As an example, if you wanted to include areas within 50 ft of a storm pipe as higher ranked locations, you would have a buffer type of "Full" and indicate 50 ft to buffer it by (see first row in Table 3-2).

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
Install Feasibility	.18	Storm Pipes	0.2	Full	50	1
Install	.18	Curb Ramps	0.2	Full	25	-1

Factor	Factor_weight	Layer name	Layer weight	Buffer type	Buffer (ft)	Rank
Feasibility						
Install Feasibility	.18	Storm Inlets	0.3	Full	50	1
Install Feasibility	.18	Truck Routes	0.3	Full	50	-1
Funding Opportunity	.36	Road Pavement Condition Index	0.375	Full	40	1
Funding Opportunity	.36	Bikeways (Permeable Pavement Only)	0.125	Full	40	1
Funding Opportunity	.36	Capital Improvement Projects	0.5	None	0	1
Multi Benefit	.18	Oakland Trash-Moderate	0.25	None	0	1
Multi Benefit	.18	Oakland Trash-High	0.25	None	0	1
Multi Benefit	.18	Oakland Trash-Very High	0.25	None	0	1
Multi Benefit	.18	Areas with less trees and veg50	0.25	None	0	1
Multi Benefit	.18	Areas with less trees and veg60*	0.25	None	0	1
Multi Benefit	.18	Areas with less trees and veg70*	0.25	None	0	1
Multi Benefit	.18	Areas with less trees and veg80*	0.25	None	0	1
Regional Suitability	0.27	Base Analysis	1	None	0	1

*Overlap between the four tree and vegetation cover layers was intentional in order to boost the ranking for areas with a lower tree and vegetation cover.

3.3 Site Locator Tool Outputs

The outputs of the Site Locator Tools are driven by availability, coverage, resolution, and accuracy of the underlying GIS data, and different resolution data can be used to answer management questions at different scales. Running the Site Locator Tool for the entire City of Oakland was an iterative process of adding and subtracting data layers and adjusting weights as City staff reviewed the preliminary results againsts their own thoughts and needs. After four iterations of ranking and adjustment, the potential locations for each GI feature type were identified and ranked (Figure 3-1). Using bioretention as an example, a set of feasible locations covering 17% of the 77.86 square mile City jurisdiction and 13% 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 appear 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.

The SLT identified thousands of feasible GI locations for potential implementation. As an example, 6200 acres of public locations within the City of Oakland were identified as potential locations for bioretention (with underdrain) and for tree wells. Of this area, 150 acres (2%) of the area suitable for bioretention and 137 acres (2%) of the area suitable for tree wells was highly ranked (rank of 0.5 or higher). The SLT also identified 2000 acres of private property as potential locations for bioretention and for tree wells. Of this area, 50 acres (1%) of the area suitable for bioretention and for tree wells were highly ranked. 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.

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 demonstrated in the ESPS watershed and described in next section.

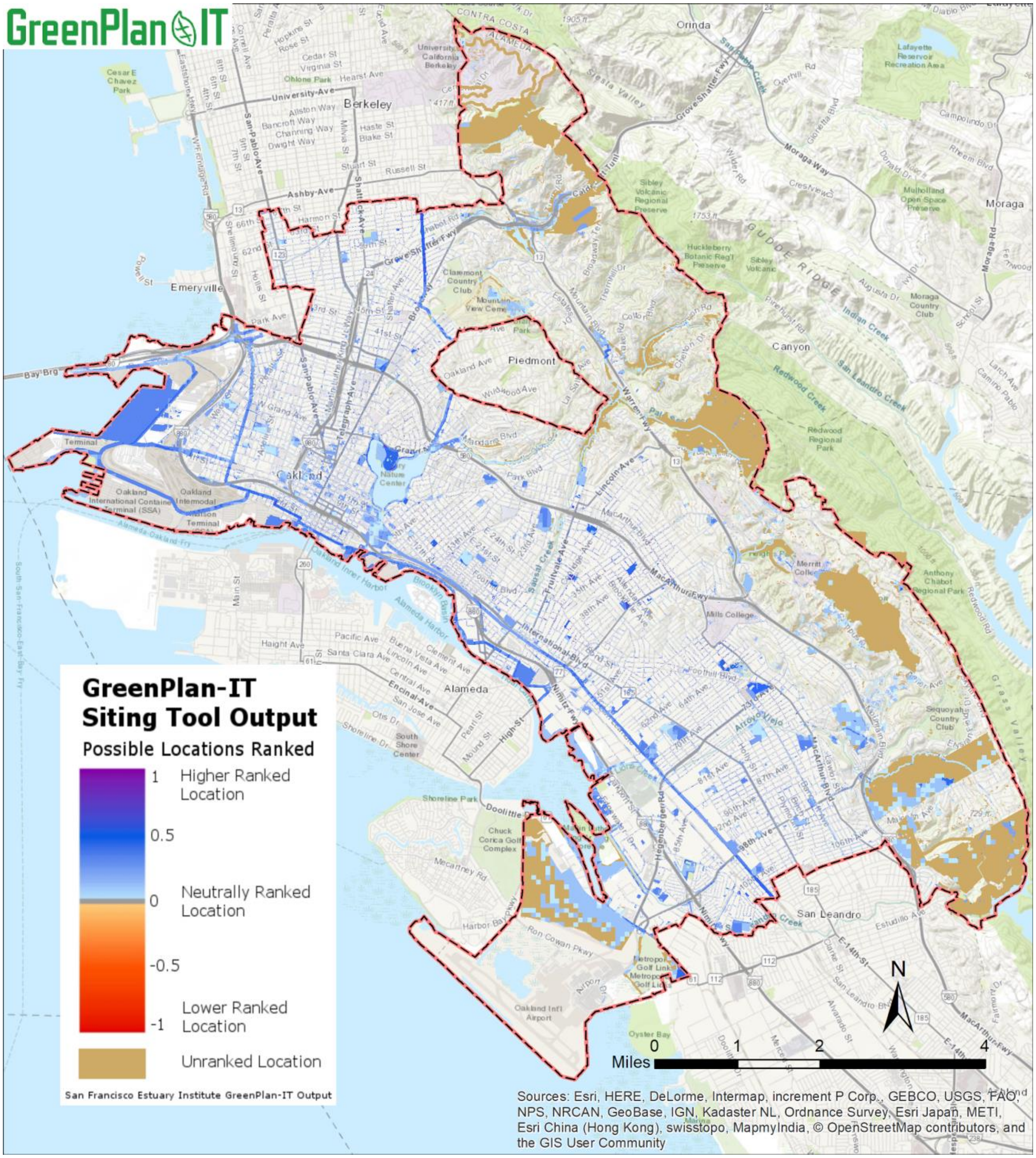

Figure 3-1 Ranked potential locations for bioretention within the City of Oakland.

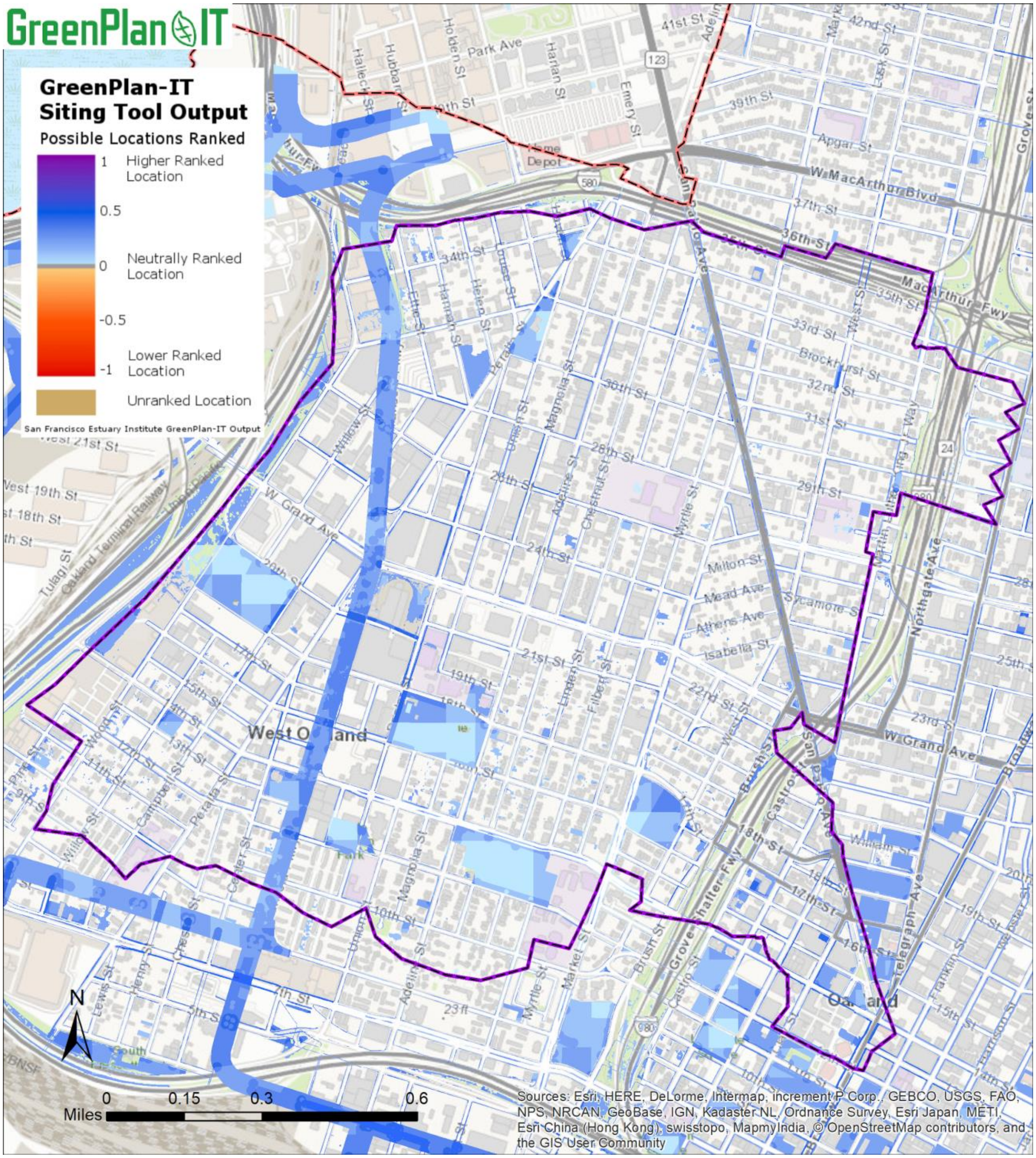

Figure 3-2 Ranked potential Locations for bioretention in ESPS watershed.

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. The Modeling Tool was applied to the ESPS watershed.

4.1 Watershed Delineation

The first step in setting up the Modeling Tool for the ESPS watershed was to delineate the watershed into smaller, homogeneous sub-basins (model segments). Storm drainage data provided by Oakland were used to delineate the watershed into 59 sub-basins based on their connections and flow direction. These sub-basins range from 3.2 to 53 acres (Figure 4-1).

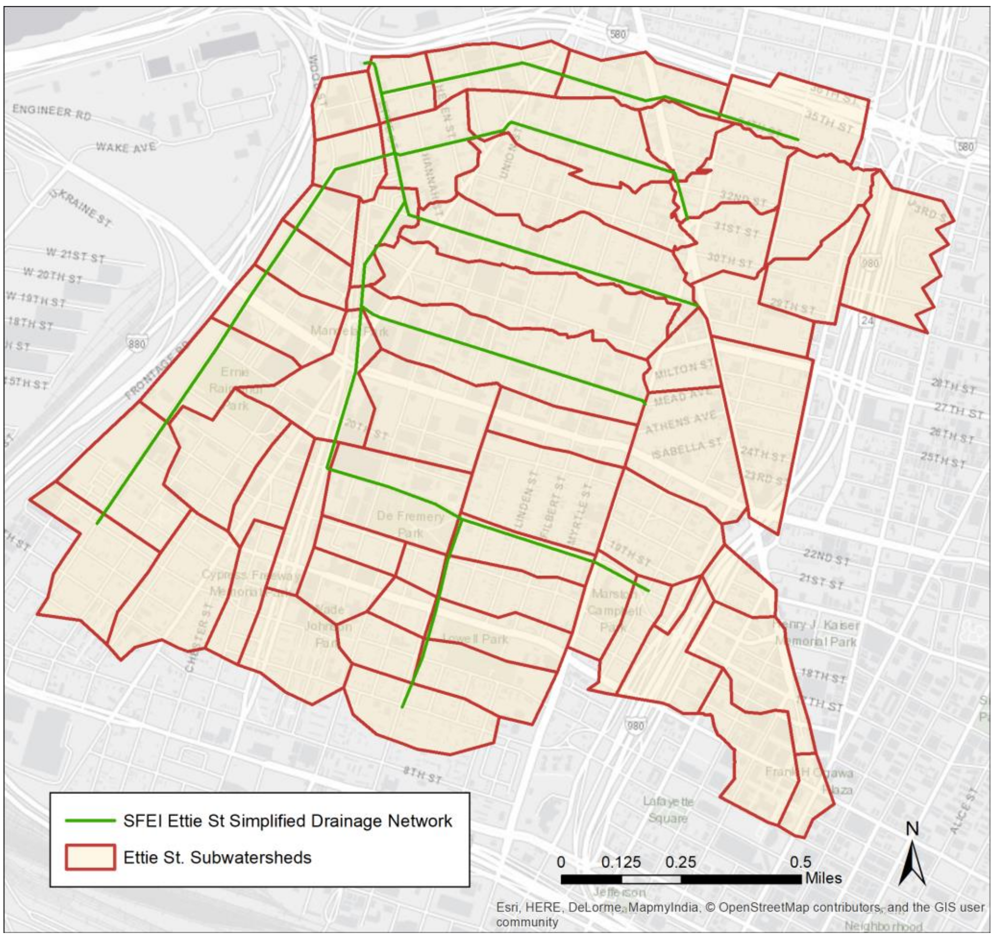

Figure 4-1. Delineated sub-basins for Ettie Street Pump Station watershed.

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 ESPS watershed are described below.

Precipitation Data

High-resolution precipitation data (1-minute intervals) from 2008 to 2011 at 27th Street Fire station (Figure 4-1) were obtained from Alameda County Public Works Agency and used for model calibration for which multiple storms were sampled for PCB concentrations. Average annual rainfall for these four years was 17.3 inches, which was lower than long term average of 22.4.

Evaporation Data

Monthly evaporation data for the City of Oakland were obtained from California Irrigation Management Information System (CIMIS) reference evapotranspiration map, where Oakland falls into ETo Zone 1 (https://cimis.water.ca.gov/App_Themes/images/etozonemap.jpg). The reference evapotranspiration data were converted to evaporation data using monthly Pan factors. The monthly evaporation data were then converted to monthly average in inches/day as required by SWMM5 (Table 4-1).

Table 4-1. Monthly evaporation for City of Oakland.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference evapotranspiration	0.9	1.4	2.5	3.3	4.0	4.5	4.7	4.0	3.3	2.5	1.2	0.6
Pan Factor	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7
Evaporation	0.6	1.0	1.7	2.5	3.0	3.6	3.7	3.2	2.5	1.9	0.8	0.4

Land Use Data

The SWMM5 model 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 five model categories. The percentages of each land use category for the ESPS watershed are listed in Table 4-2.

Table 4-2. Land use distribution in ESPS watershed (acres).

Category	Commercial	Industrial	Open	Residential	Transportation	Total
Area	132	257	58	329	416	1192
Percent	11%	22%	5%	28%	35%	100%

Percent Imperviousness
The percentage of imperviousness is an import input data set for SWMM5 model hydrology simulation. The GIS layer for imperviousness was from the National Land Cover Dataset (NLCD) 2011 at a spatial resolution of 30m by 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 ESPS watershed is composed of 60% type A soils, 15% of type C soils and 25% of type D soils. Type A soils have high infiltration rates and low runoff rates, while type C and D soils have low infiltration rates and high runoff rates.

4.3 Model Calibration

Model calibration is 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 importance of a representative baseline model highlights the importance of model calibration. However, in this case, a flow calibration was not done for ESPS watershed, because no quality flow data were available[1]. Instead, a reasonable assurance check was performed to build some confidence on model performance. The model parameters use either default values from the SWMM5 manual or values from similar urbanized watersheds. In addition, in working with City staff, the modeled flooding area in the watershed was compared with the City's record on historic flooding and they generally matched, suggesting the model likely captured the main characteristics of the watershed. However, since flow simulation is the foundation for subsequent

[1] Flow data derived from pump records at the Ettie Street Pump station are not reliable and possibly overestimated by a factor of ~2-fold. Therefore these data could not be used for model calibration as initially planned.

PCB simulation, it is important that future efforts should include collecting some flow data in this watershed for hydrologic calibration.

SFEI has collected multiple storms for PCB concentrations from 2008 to 2011, and these data were used for PCB calibration. Since there are only a small set of data available, the model calibration was aimed to match the magnitude of data (Figure 4-2). For PCB calibration, SWMM5 allows for input of the washoff 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 washoff coefficients between land uses, and transportation land use was assumed to have the same coefficients as commercial land use. Overall, the modeled PCB concentrations were within the range of monitored data.

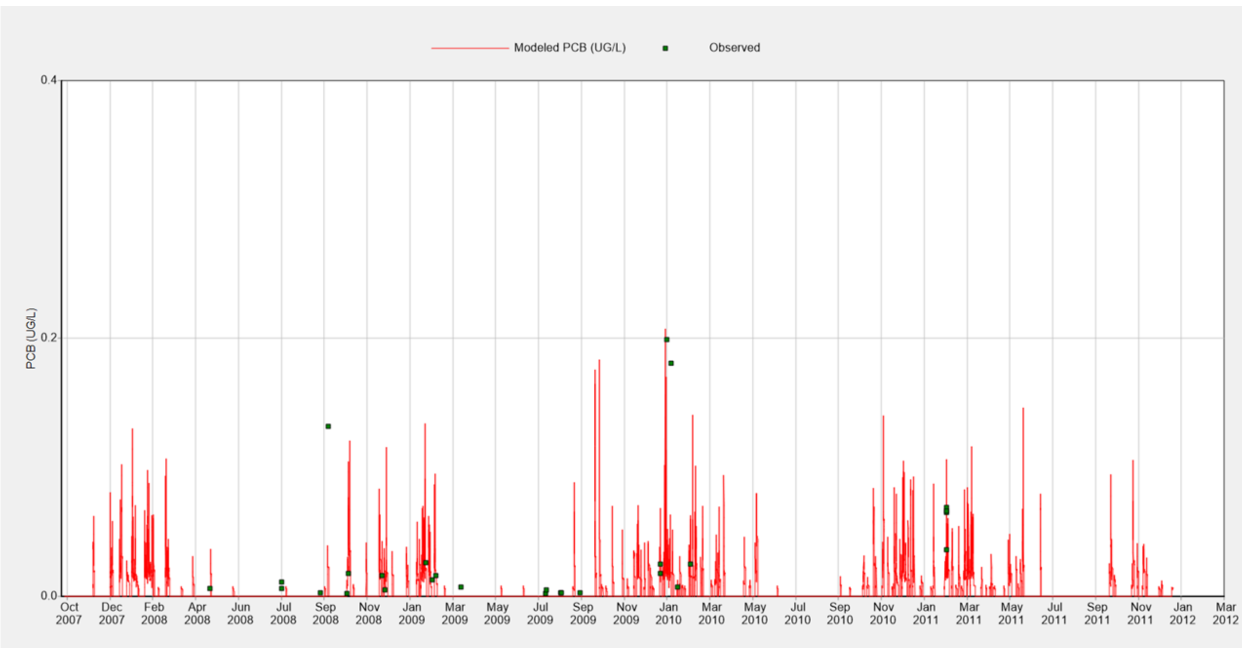

Figure 4-2. Modeled and observed PCB concentrations at ESPS watershed, Oakland.

4.4 Baseline Flow and PCB Loads

The model baseline is the foundation upon which all subsequent analyses depend and is important for meaningful results. The baseline flow and PCB loads were 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 ESPS watershed 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 27th Street

Fire Station were obtained from Alameda County Public Works Agency 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 steps 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). Based on these checks, no evidence of any serious data issues were found. The total annual rainfall for this station was 23.8 inches in WY 2002. The monthly distribution of WY2002 precipitation is shown in Table 4-4.

Table 4-4. Monthly distribution of precipitation for WY2002 for the ESPS watershed.

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Rainfall (in)	0.58	4.96	10.6	1.74	1.76	2.63	0.43	1.06	0	0	0	0

Annual PCB loads for WY 2002 from the ESPS watershed was 94.8 grams. The average pollutant yields, expressed as load per unit area, were estimated at 0.08 g/acre for the ESPS watershed, with a range from 0.02 to 0.29 g/acre. The distribution of stormwater runoff and PCB yield is shown in Figure 4-3 and Figure 4-4.

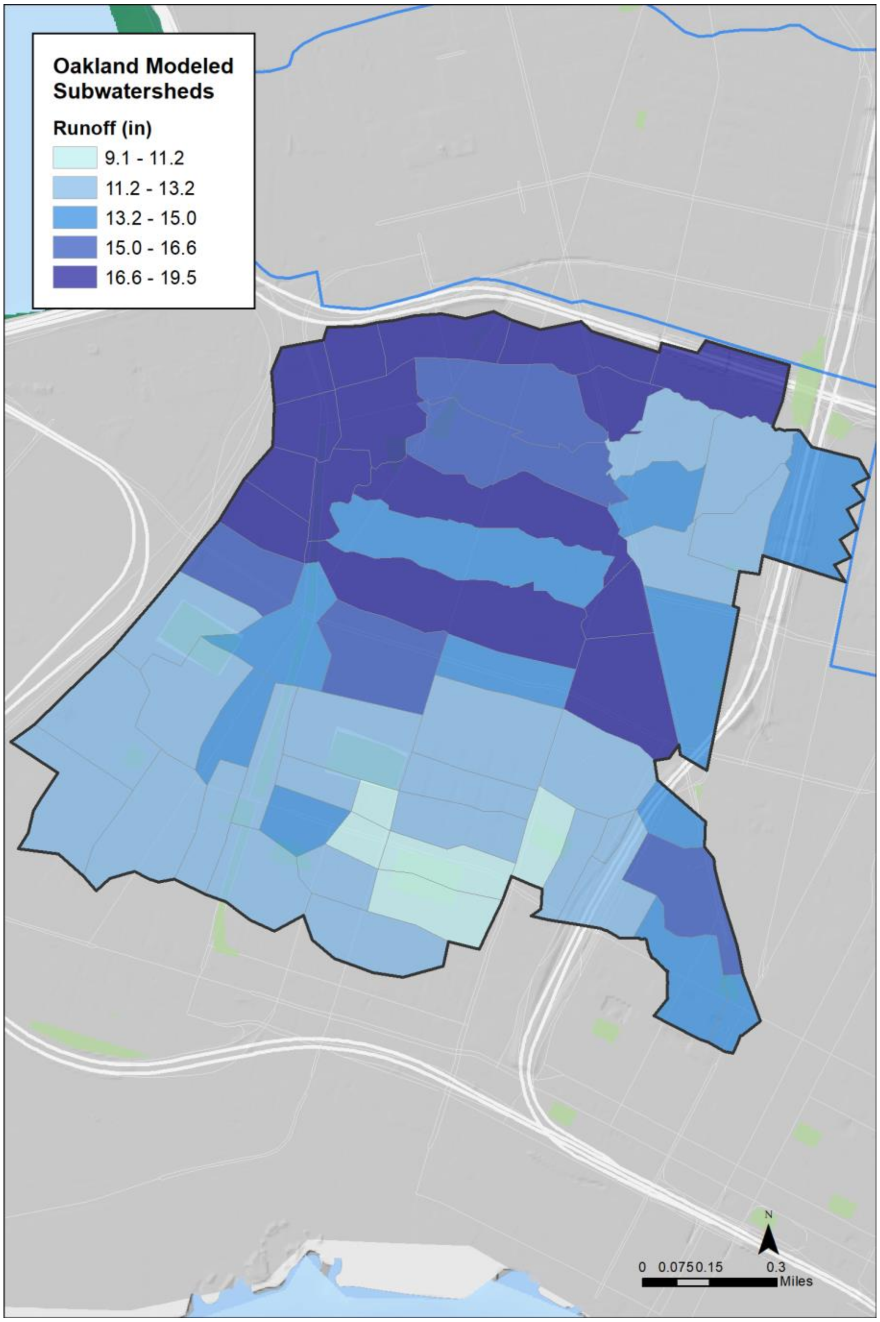

Figure 4-3. Annual runoff for ESPS watershed for WY 2002.

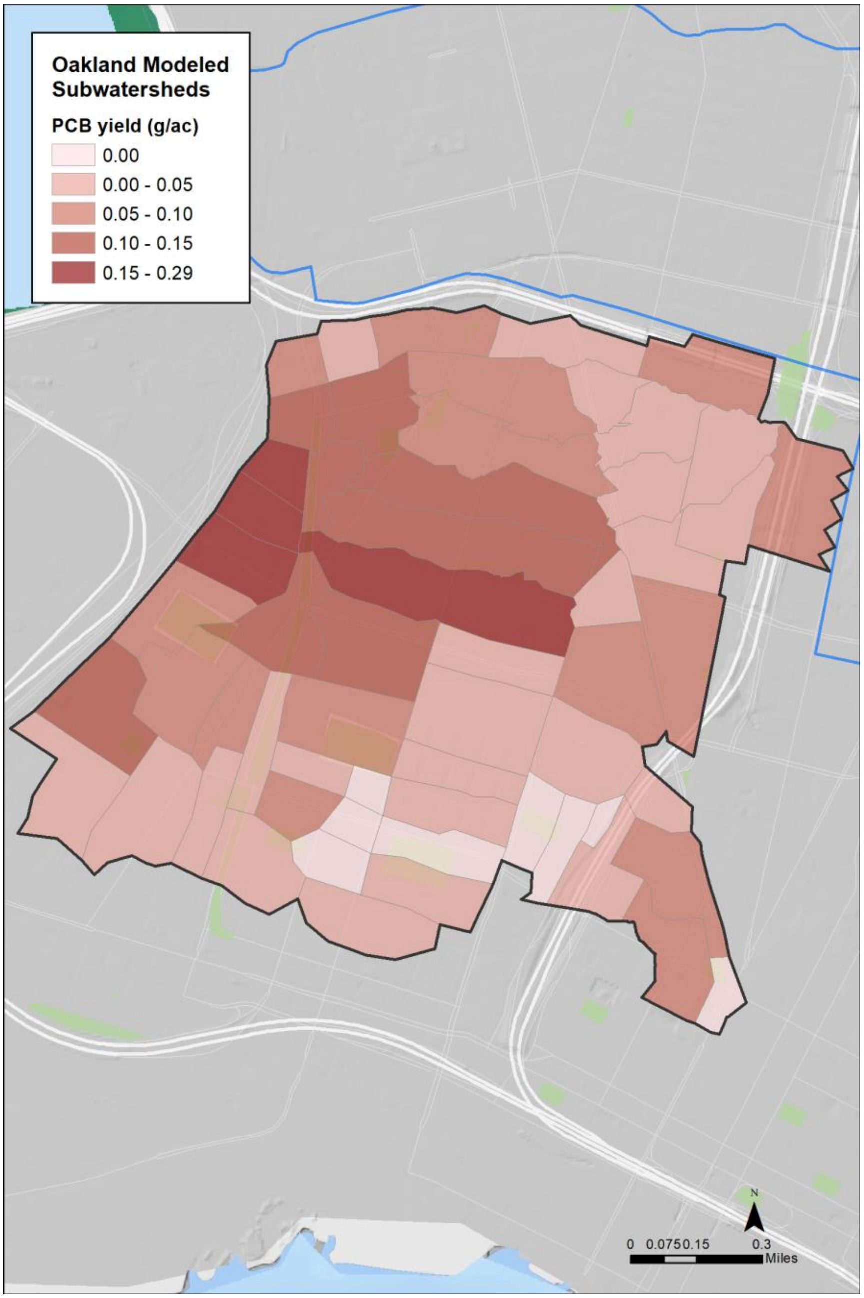

Figure 4-4. Annual PCB yields for ESPS watershed for WY 2002.

5. OPTIMIZATION TOOL

As the last step in the Greenplan-IT application, the Optimization Tool was used to determine the optimal combinations of GI projects within the ESPS watershed 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 59 sub-basins were generated as a reference point from which the effectiveness of any GI scenarios were estimated.

GI Types and Design Specifications

Two GI types, bioretention and tree well (proprietary media), were included for optimization. Each GI type was assigned typical size and design configurations (Table 5-1) that were reviewed and approved by the Technical Advisory Committee. These design specifications remained unchanged during the optimization process. Thus, the decision variable was the number of each GI type within each sub-basin. 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 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	Y - Underdrain at drainage layer	4%	0.29
Tree Well	60 (10x6)	12	21	6	50	Y - Underdrain at bottom	0.4%	0.34

* 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 two 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. A unit cost approach was used to calculate the total cost associated with each GI scenario, in which cost per square feet 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.

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

GI Types	Surface Area of GI Feature (ft^2)	Cost per Unit (($/$ft^2$)
Bioretention	500	104
Tree Well	60	1312

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 sub-basin, 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 PCB load reduction at the watershed 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 sub-basins within the ESPS watershed. For each GI type, the decision variable values ranged 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 GIs within each sub-basin. 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 total treated area for each scenario (Table 5-1). During the optimization process, the numbers of GI units were adjusted when their combined treatment areas exceed the available area for treatment within each sub-basin.

5.3 Optimization Results

5.3.1 Cost-effectiveness Curve

The optimization process generates 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 watershed and their associated relative cost[2]. Figure 5-1 illustrates the relationship between project relative cost 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 edge of the curve). Each point along the cost-effectiveness curve represents a unique combination of the number of bioretention units and Tree Wells across the study area.

[2] 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.

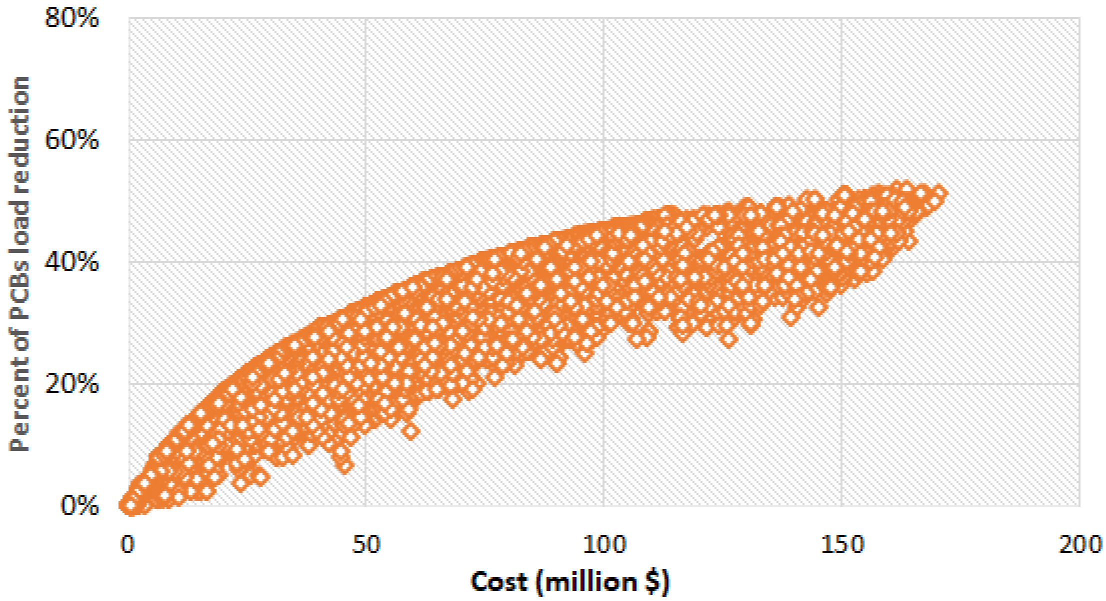

Figure 5-1. PCB cost-effectiveness curve: the relative cost of each implementation scenario in relation to the load reduction from the estimated baseline.

Figure 5-1 shows a wide spread of GI solutions for PCB load reductions. At the same level of cost, the percentage removal could vary by as much as 20%, while for the same level of pollutant reduction, the difference in total relative cost could be well over tens of millions 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, a 20% PCB removal can be achieved at a relative cost of about $20 million dollars, but an additional 20% removal can be expected for the next $50 million dollar investment. This makes sense given the heterogeneous nature of PCB sources across this urban landscape (McKee et al., 2015; Gilbreath et al., 2017). After treating the most polluted areas, subsequent implementation of treatment measures will need to be placed in areas having lower baseline yields of PCB, and therefore the load available for treatment will be less, resulting in a gradual increase in cost per unit mass treated[3]. The maximum reduction achievable appears around 50% for the ESPS watershed, 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 will become less desirable as the marginal benefit decreases.

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

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 in the study area. The model results show that spatial variability in runoff production is only about 2-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 65% (Figure 5-2), at which point the impervious areas were mostly captured and treated. Note that these solutions are optimized for PCB reduction and therefore not necessarily optimal for runoff reduction.

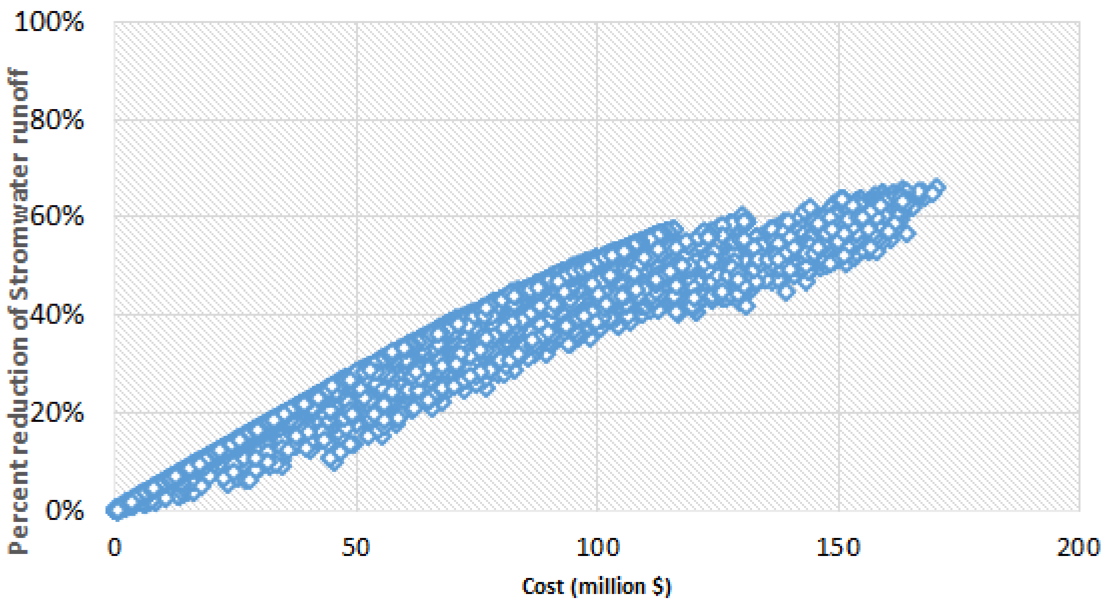

Figure 5-2. Runoff cost-effectiveness curve: the relative cost of each implementation scenario in relation to the flow reduction from the estimated baseline.

The Optimization Tool performs iterative searches to identify cost-effective solutions based on specific problem formulations, model assumptions, GI cost, design specifications, and constraints unique to this case study. Therefore, it is important to emphasize that the optimization results should be interpreted in the context of these factors. The cost-effective solutions from the optimization process would very much depend on the user-defined goals and assumptions and should be interpreted within the context that defines each specific application. If one or more assumptions are changed, the optimization procedure 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. 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.

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. 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 418 GI features, all of them are bioretention units. This selection makes sense because the unit cost for tree well is about 10 times higher than it is for bioretention. Collectively, once implemented, these GI features would treat 120 acres of impervious area or 10% of the watershed.

GI utilization results can be mapped by sub-basin to gain insight into the optimal spatial placement of these practices derived under the defined objective and constraints. Figure 5-3 shows the number of GI units identified in each sub-basin for the 20% PCB load reduction scenario. Ten sub-basins were identified as high leverage watersheds for reducing PCBs within the Ettie Street Pump Station watershed. In general, the optimization process identified more GI units in areas with high PCBs, where GI can be most efficient.

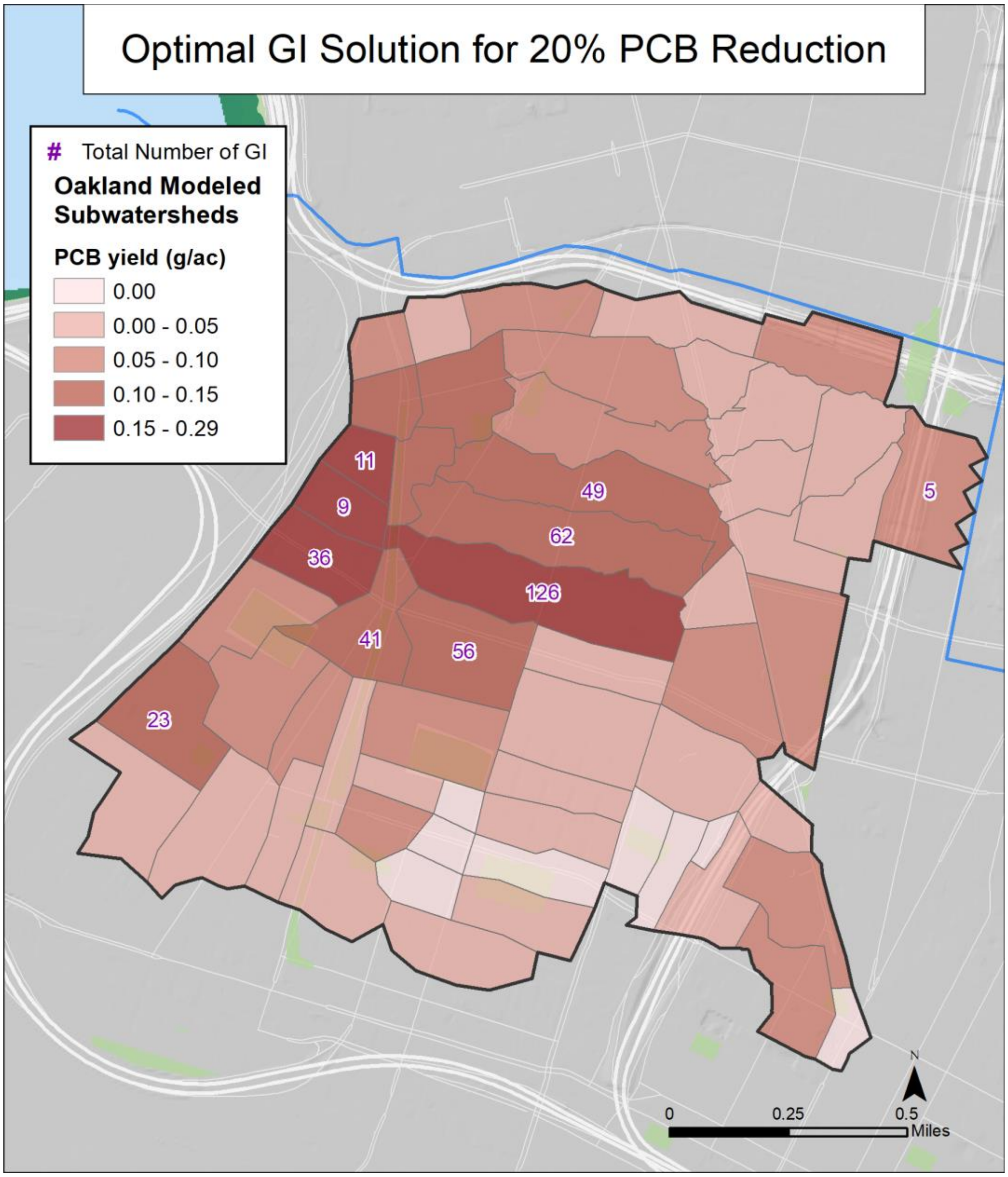

Figure. 5-3 The number of GI units identified in each sub-basin for the optimal scenario that achieved a 20% PCB load reduction.

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 watershed-wide GI master plan. Since GreenPlan-IT is a planning tool, it identifies the number of GI features at a sub-basin level without specifying the actual locations of implementation. To help prioritize management actions, one can work at a 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.

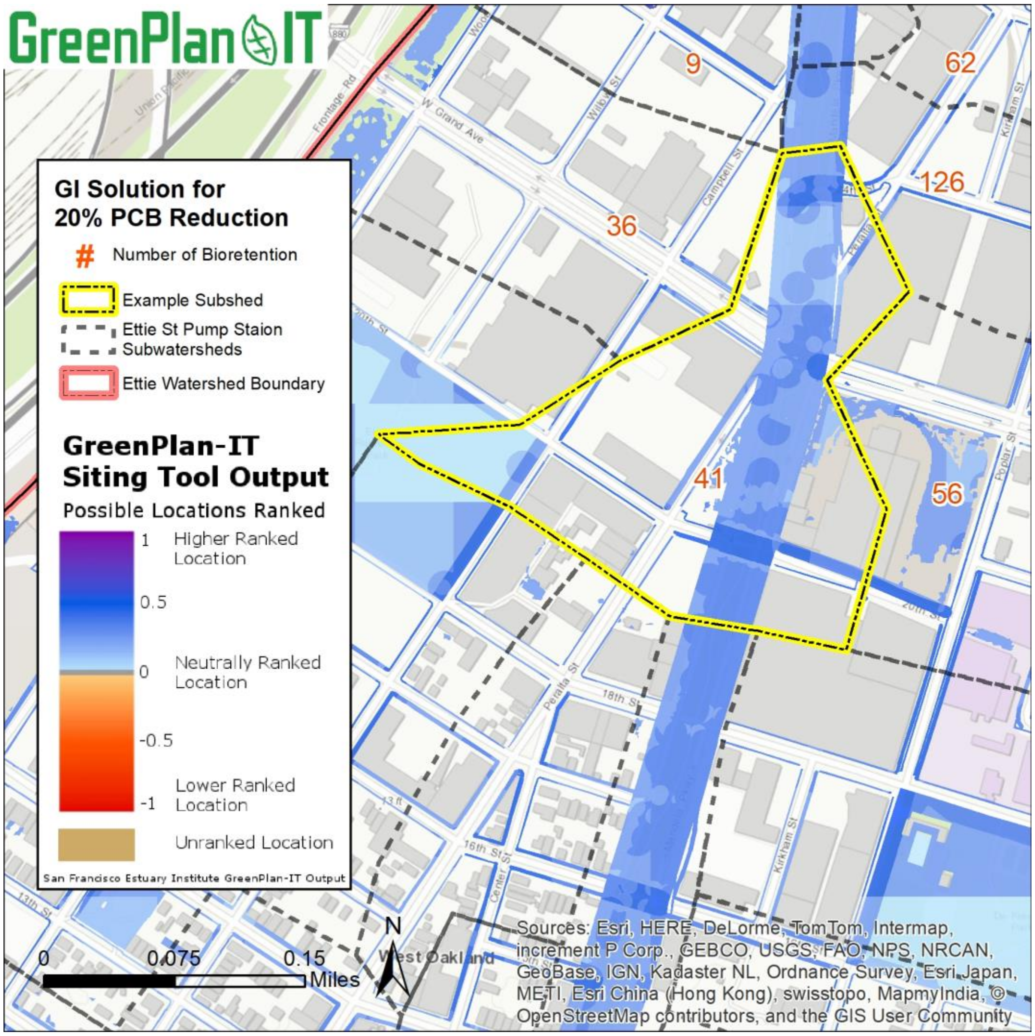

Fig. 5-4 The number of bioretention units identified within the optimization analysis for 20% PCB reduction in an example sub-basin

As an example, the optimization output shows a sub-basin where 41 bioretention units were identified for a 20% PCB reduction goal (Figure 5-4). Within this sub-basin, there are 4734 potential sites identified from the SLT, each with its own ranking. Managers could begin by exploring the highest ranked potential sites to evaluate the suitability of implementing a bioretention unit on each site. If one potential location is not suitable, City staff could continue down the ranked list, until the best 41 locations are selected. A similar process could be applied for selecting the best locations in other sub-basins.

In addition to the rankings, other factors that were not included in the GreenPlan-IT for GIS and cost benefit 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. 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 level 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 list of feasible locations for the City of Oakland. 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 of the Ettie Street Pump Station Watershed, the area of focus for this study, 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 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, 6200 acres of public locations within the City of Oakland were identified as potential locations for bioretention (with underdrain) and for tree wells. Of this area, 150 acres (2%) suitable for bioretention and 137 acres (2%) suitable for tree wells was highly ranked. The highest ranked sites should be considered first as implementation locations.
- The Site Locator Tool also identified 2000 acres of private property as potential locations for bioretention and for tree wells. Of this area, 50 acres (3%) suitable for bioretention and 53 acres (3%) for tree wells were highly ranked.

- For the Ettie Street pump station watershed, the estimated baseline PCB load is 98.4 g/year. This translates to PCB yields of 0.08 g/acre on average for the whole watershed.
- For a 20% reduction in PCB loads from this watershed, it was identified that 418 bioretention units would be needed to treat 120 acres of impervious areas, with an estimated relative cost of 21.7 million dollars.
- 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 bioretention implementation should be focused in 10 of the subwatersheds with the highest PCB loads.

7. REFERENCES

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