Green Infrastructure Planning for North Richmond Pump Station Watershed with GreenPlan-IT

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EXECUTIVE SUMMARY

Contra Costa County and the City of Richmond, via the San Francisco Municipal Regional Stormwater Permit (MRP), are required to develop and implement a Green Infrastructure (GI) Master Plan to reduce mercury and PCB loads in stormwater runoff from each jurisdiction. 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 North Richmond Pump Station watershed (an unincorporated community of Contra Costa County and partial jurisdiction of the City of Richmond) 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 North Richmond Pump Station watershed. 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 43.1 g/year for the NRPS watershed which translates to an average PCB yield of 0.09 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 93 bioretention units and 1 flow-through planter, which would treat 27 acres of impervious area. Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in seven of the subwatersheds with the highest PCB loads.

The outputs of the GreenPlan-IT application provided the County 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 County needs. Results from the application of GreenPlan-IT can be used to: 1) identify specific GI projects; 2) support the County's current and future planning efforts, including GI plans and Stormwater Resource Plans; and 3) 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 feasibility and cost-effectiveness of the implementation of GI within the watershed of the North Richmond Pump Station (NRPS), North Richmond (an unincorporated community of Contra Costa County), 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 and County’s current and future planning efforts, including GI Master Plans and Stormwater Resource 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 number 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 GreenPlan-IT in the North Richmond Pump Station watershed. 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 watershed of NRPS is located in North Richmond, an unincorporated community of Contra Costa County and partial jurisdiction of the City of Richmond located in northwest corner of District 1 of the County. North Richmond has an estimated population of around 3,715 people (2010 census) and is surrounded by the city of Richmond (Figure 2-1). Like many county unincorporated areas in the Bay Area with a legacy of industrial land uses, North Richmond is regulated by the MRP, and stormwater management is a driver for a number of County activities and area-wide programs. Within the County, there are a number of watersheds that have been identified as having elevated concentrations of PCBs, mostly in historical industrial areas where PCBs were used. This watershed is targeted for management actions and was selected by the County staff for this case study.

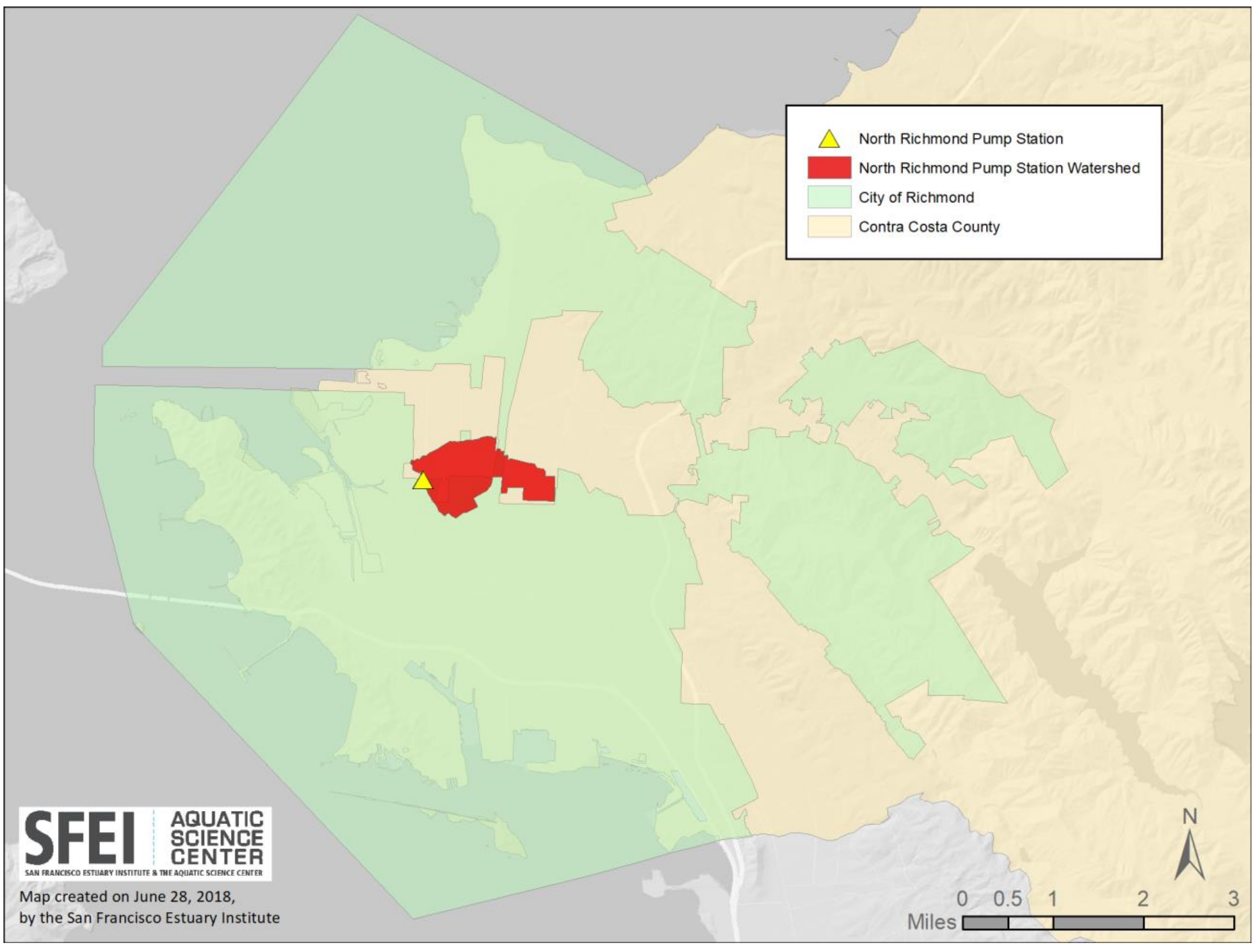

Figure 2-1. The North Richmond Pump Station, it's corresponding watershed, City of Richmond, and Contra Costa County.

2.1 Study Area

The NRPS is a Contra Costa County Public Works facility that discharges stormwater runoff into a slough that feeds into the lower portion of Wildcat Creek on the southeastern portion of San Pablo Bay. The NRPS services an area of 497 acres (2.01 km^2) and watershed land uses are primarily industrial, transportation, and residential with some percentage of the developed watershed being old industrial. 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.

2.2 Project Objectives

The goal of this project was to use GreenPlan-IT to identify feasible locations for four GI feature types within the NRPS watershed, as well as cost-effective solutions for the NRPS watershed where management action is planned. This application and its outputs can support the development of GI plan for PCBs and mercury reduction, as well as other County planning efforts associated with the C3 (New and redevelopment), C11 (Mercury controls) and C12 (PCB controls) provisions in the MRP.

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. The City of Richmond and Contra Costa County staff selected four GI feature types for this application: bioretention with underdrain, permeable pavement, flow-through planter, and tree well. A standard size of each feature type was specified and used. Details on design specifications 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 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 Richmond and Contra Costa County due to the shared jurisdiction. Full coverage and availability of the study area were also critical in choosing what data to use. Often data layers would be applicable, but only provided coverage for the City of Richmond or the Contra Costa County portions of the study area, and thus had to be left out. 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 North Richmond Pump Station watershed.

Layers:	Analysis:
North Richmond Pump Station On Street Parking Estimate	Locations
Vacant Parcels (using parcel codes)	Locations
Parks	Locations Local Opportunities and Constraints Analysis
Publicly owned Parcels (using parcel tax code)	Locations Local Opportunities and Constraints Analysis Ownership
Storm Network (from city and county sources)	Local Opportunities and Constraints Analysis
Fire Hydrants	Local Opportunities and Constraints Analysis
Truck Routes	Local Opportunities and Constraints Analysis
County 2020 Planned Pavement Improvement Projects	Local Opportunities and Constraints Analysis
Undeveloped Lots	Local Opportunities and Constraints Analysis
Priority Development Areas	Local Opportunities and Constraints Analysis
Capital Improvement Projects	Local Opportunities and Constraints Analysis
CalEnviroScreen 3.0 Disadvantaged Communities	Local Opportunities and Constraints Analysis
Existing Bikeways	Local Opportunities and Constraints Analysis
Planned Bikeways	Local Opportunities and Constraints Analysis
Schools	Local Opportunities and Constraints Analysis
Community Centers	Local Opportunities and Constraints Analysis
Baseline land Use - Old Industrial	Local Opportunities and Constraints Analysis
Baseline Land Use - Old Urban	Local Opportunities and Constraints Analysis
Trash Generation	Local Opportunities and Constraints Analysis
SFEI Green Infrastructure Specific Regional Suitability Layer	Local Opportunities and Constraints Analysis

3.2 Custom Ranking

The custom ranking was determined by a nested, weighted overlay of the GIS layers based on six factors that were identified as important to the City and County. The weighting was conducted by consulting with City and County staff through an iterative process. Each of the six factors was assigned a weight based on the City's and County'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 Richmond and Contra Costa County.

The primary focus or priority for the City and County's ranking was PCB, mercury, and trash reduction, and this was reflected in the factor weighting in the custom ranking. In addition, other priorities considered for this study included installation feasibility in relation to existing infrastructure, existing funding opportunities, benefiting the community through proximity to community hubs and pathways, 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 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
PCBs/Hg	0.25	Baseline land Use - Old Industrial	0.67	None	0	1
PCBs/Hg	0.25	Baseline Land Use - Old Urban	0.33	None	0	1
Trash	0.25	Trash Generation - low to high	0.33	None	0	1
Trash	0.25	Trash Generation - medium to high*	0.33	None	0	1
Trash	0.25	Trash Generation - high*	0.33	None	0	1
Regional Suitability	0.125	SFEI GI Specific Regional Suitability Layer	1	None	0	1
Install Feasibility	0.125	Storm Network	0.27	Full	60	1

Factor	Factor Weight	Layer name	Layer Weight	Buffer Type	Buffer (ft)	Rank
Install Feasibility	0.125	Fire Hydrants	0.27	Full	35	-1
Install Feasibility	0.125	Truck Routes	0.27	Full	160	-1
Install Feasibility	0.125	County 2020 Planned Pavement Improvement Projects	0.18	Full	60	1
Funding Opportunity	0.125	Publicly owned Parcels	0.15	None	0	1
Funding Opportunity	0.125	Undeveloped Lots	0.15	None	0	1
Funding Opportunity	0.125	Priority Development Areas	0.23	None	0	1
Funding Opportunity	0.125	Capital Improvement Projects (lines)	0.23	Full	160	1
Funding Opportunity	0.125	CalEnviroScreen 3.0 - Disadvantaged Community > 66%	0.08	None	0	1
Funding Opportunity	0.125	CalEnviroScreen 3.0 - Disadvantaged Community > 81%*	0.08	None	0	1
Funding Opportunity	0.125	CalEnviroScreen 3.0 - Disadvantaged Community > 91%*	0.08	None	0	1
Community Benefit	0.125	Existing Bikeways	0.23	Full	160	1
Community Benefit	0.125	Planned Bikeways	0.23	Full	160	1
Community Benefit	0.125	Parks	0.15	Full	200	1
Community Benefit	0.125	Schools	0.23	Full	200	1
Community Benefit	0.125	Community Centers	0.15	Full	200	1

*Overlap between layers was intentional in order to boost the ranking for areas with higher disadvantage community scoring and higher levels of trash generation.

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 North Richmond Pump Station Watershed was an iterative and interactive process of adding and subtracting data layers and adjusting weights as City and County staff reviewed the preliminary results against their needs. After three iterations of ranking and adjustment were made, 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 21% of the 497 acre watershed and 14% of the public right-of-way were identified for consideration. These potential locations provide a starting point for the City and County'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 map of the SLT outputs below (Figure 3-1), 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.

The SLT identified thousands of feasible GI locations for potential implementation. As an example, 72 acres of public locations within the NRPS watershed were identified as potential locations for bioretention (with underdrain). Of this area, 44 acres (61%) were highly ranked (rank of 0.3 or higher). The SLT also identified 33 acres of private property as potential locations for bioretention (with underdrain). Of this area, 6 acres (18%) 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 municipal 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 municipal staff are looking for implementation locations. These locations provide a starting point for the GI planning and implementation effort for the NRPS watershed. 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 the next sections.

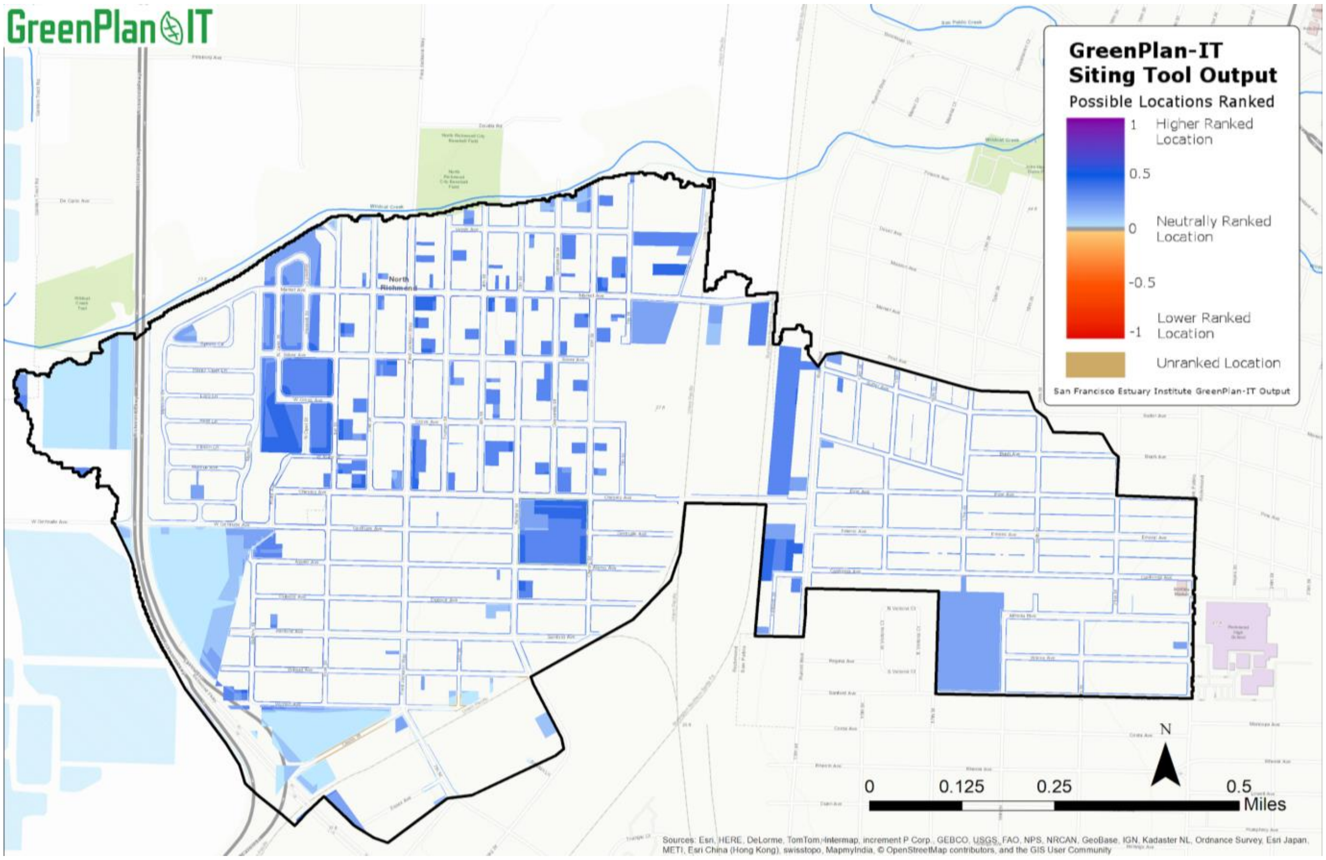

Figure 3-1 Ranked potential locations for bioretention within the North Richmond Pump Station watershed.

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.

4.1 Watershed Delineation

The first step in setting up the Modeling Tool for the NRPS watershed was to delineate the watershed into smaller, homogeneous sub-basins (model segments). Storm drainage data provided by City of Richmond and Contra Costa County Public Works Department were used to delineate the watershed into 49 sub-basins based on their connections and flow direction. These sub-basins range from 3.9 to 21.9 acres (Figure 4-1).

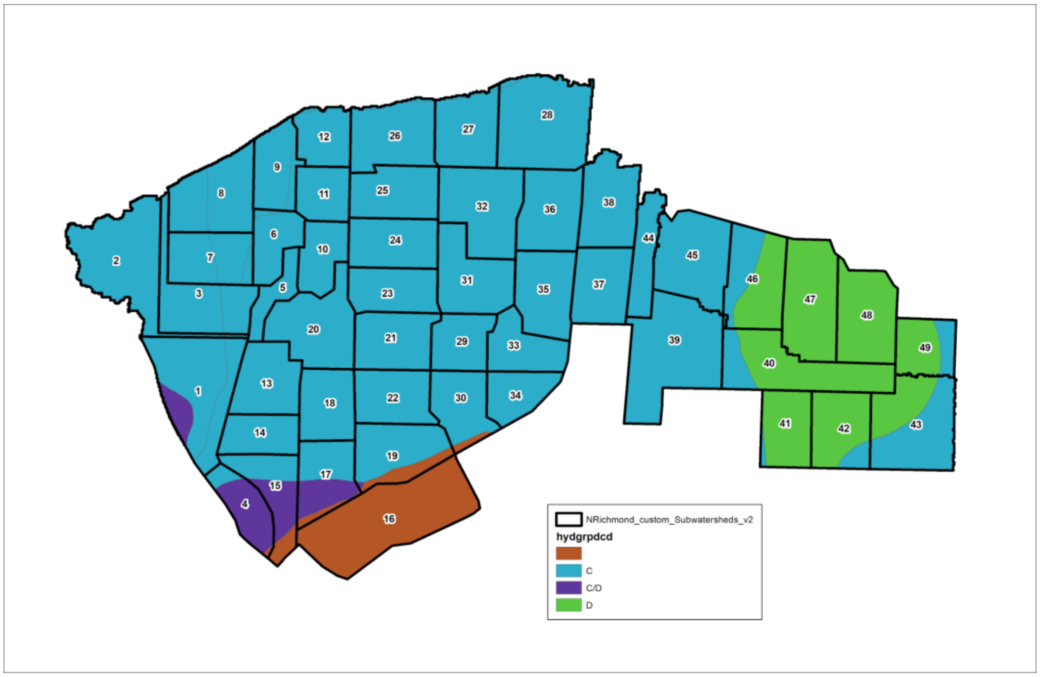

Figure 4-1. Delineated sub-basins for North Richmond Pump Station watershed.

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 NRPS watershed are described below.

Precipitation Data

High-resolution precipitation data (hourly intervals) for Water Years (WY) 2011 to 2014 were downloaded from the California Data Exchange Center (CDEC) for station code RHL (Richmond City Hall) and used for model calibration for which multiple storms were sampled for PCB concentrations. The average rainfall for WYs 2011-2014 was 20.6 inches (82% of the 1981-2010 average).

Evaporation Data

Monthly evaporation data for the NRPS watershed was obtained from California Irrigation Management Information System (CIMIS) reference evapotranspiration map, where Richmond falls into ETo Zone 2 (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). Monthly data are adequate for use in the model since evaporation is only a small component of rainfall driven runoff events.

Table 4-1. Monthly evaporation for North Richmond Pump Station watershed.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference evapotranspiration	1.2	1.7	3.1	3.9	4.7	5.1	5.0	4.7	3.9	2.8	1.8	1.2
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	0.7	1.2	2.2	2.9	3.5	4.1	4.0	3.7	2.9	2.1	1.3	0.8

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

Table 4-2. Land use distribution in North Richmond Pump Station watershed (acres).

Category	Commercial	Industrial	Open	Residential	Transportation	Total
Area	44	90	51	188	123	496
Percent	25%	38%	10%	18%	9%	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 by 30m pixels (http://www.mrlc.gov/nlcd2011.php). Average imperviousness in the watershed is estimated at 63%.

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 NRPS watershed is composed of 78% type C soils, 14% of type D soils, 3% a mix of C and D, and 5% unknown. Type C and D soils have low infiltration rates and high runoff rates. The unknown areas were assigned the soil types of neighboring areas.

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 model calibration was done for NRPS watershed, where monitored flow and PCB concentration data from 2011 to 2014 were available (Hunt et al., 2012; Gilbreath et al., 2015). In this instance, flow was based on the combination of pump runtime and the mechanical specifications of the pumps. Quality assurance and testing of these data has been previously performed and flow data were deemed reliable (Hunt et al., 2012; Gilbreath et al., 2015). Model calibration preceded by iteratively adjusting flow parameters within reasonable ranges and comparing the modeled flow to the pump runtime based flow. The modeled flow shows a typical flow pattern in relation to rainfall (Figure 4-2) but does not correlate well with the pump run time based flow which is regulated by pumps. But overall, the modeled flow matched the magnitude of observed data well, providing a reasonable assurance check of model performance.

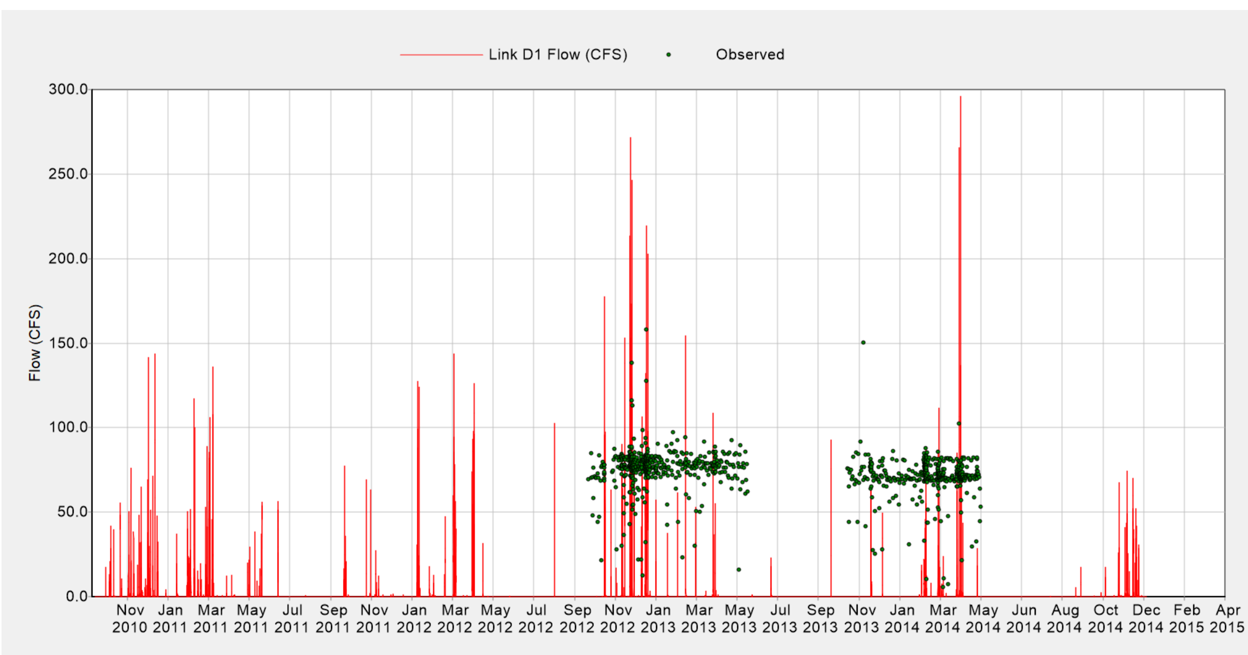

Figure 4-2. Flow calibration of SWMM5 for the North Richmond Pump Station watershed.

PCB data were collected during base flow in September 2010 and from May to September 2011 (Hunt et al., 2012) and during storms in the winters of WYs 2011, 2012 (Hunt et al., 2012) and 2013 and 2014 (Gilbreath et al., 2015). 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 4-3). 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.

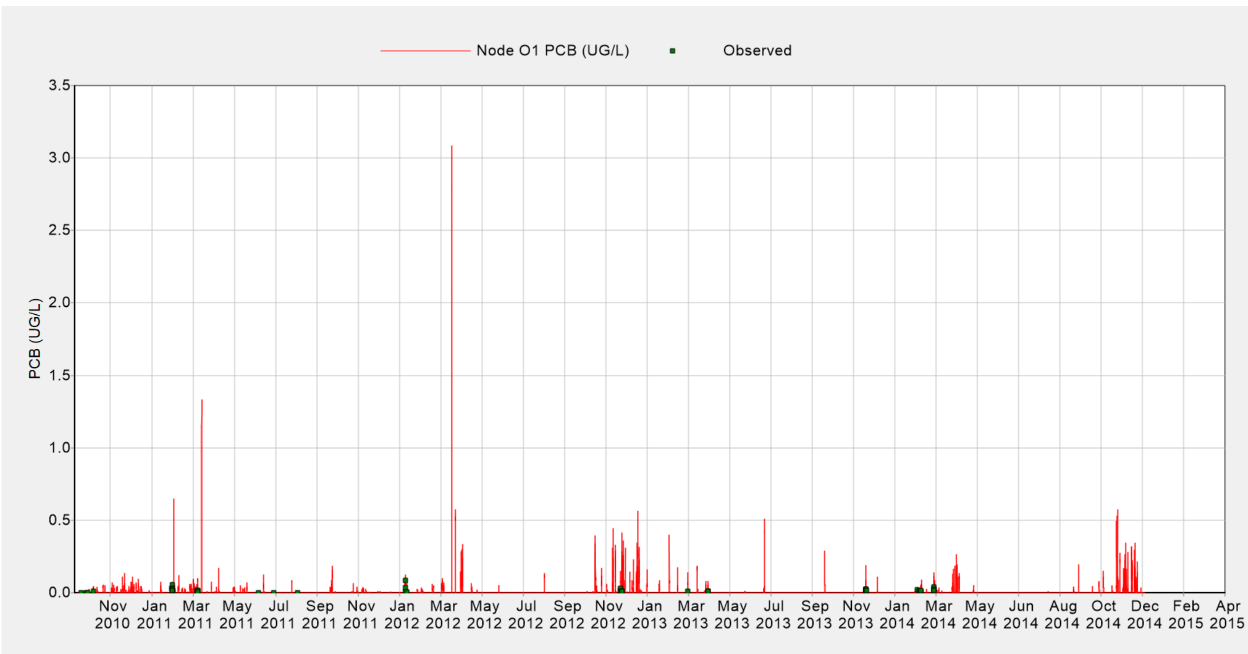

Figure 4-3. Modeled and observed PCB concentrations at North Richmond Pump Station watershed.

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 baseline flow and PCB loads were calculated to serve as the basis for the comparison of various GI solutions in the optimization. WY 2002 was chosen to establish a baseline condition for the NRPS watershed based on the recommendation of BASMAA's RAA guidance (BASMAA, 2017), which considers WY 2002 as representative of average condition. Hourly rainfall data for WY 2002 from Contra Costa County Flood Control District for Richmond City Hall station (http://www.ccflood.us/raintable.html, Station 21) were used to estimate baseline stormwater runoff and PCB loads. Prior to use, a basic quality assurance assessment was completed and indicated that the temporal distribution of the hourly data was reliable but the overall magnitude of monthly summations was low, necessitating the adjustment of the data by 1.4 to match the Richmond NOAA coop (074414). The adjusted total annual rainfall for the Richmond City Hall station was 25.5 inches. The monthly distribution of adjusted WY 2002 precipitation is shown in Table 4-4.

Table 4-4. Monthly distribution of precipitation for WY 2002 for North Richmond Pump Station watershed.

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Rainfall (in)	0.7	6.1	9.9	2.0	1.5	3.5	0.3	1.2	0	0	0	0

Annual PCB loads for WY 2002 from the NRPS watershed were estimated to be 43.1 grams. The average pollutant yields, expressed as load per unit area, were also calculated as 0.09 g/acre with a range from 0.03 to 0.6 g/acre. The distribution of stormwater runoff and PCB yield is shown in Figure 4-4.

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 NRPS 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 WY 2002 for each of 49 sub-basins were generated as a reference point from which the effectiveness of the GI scenarios were estimated.

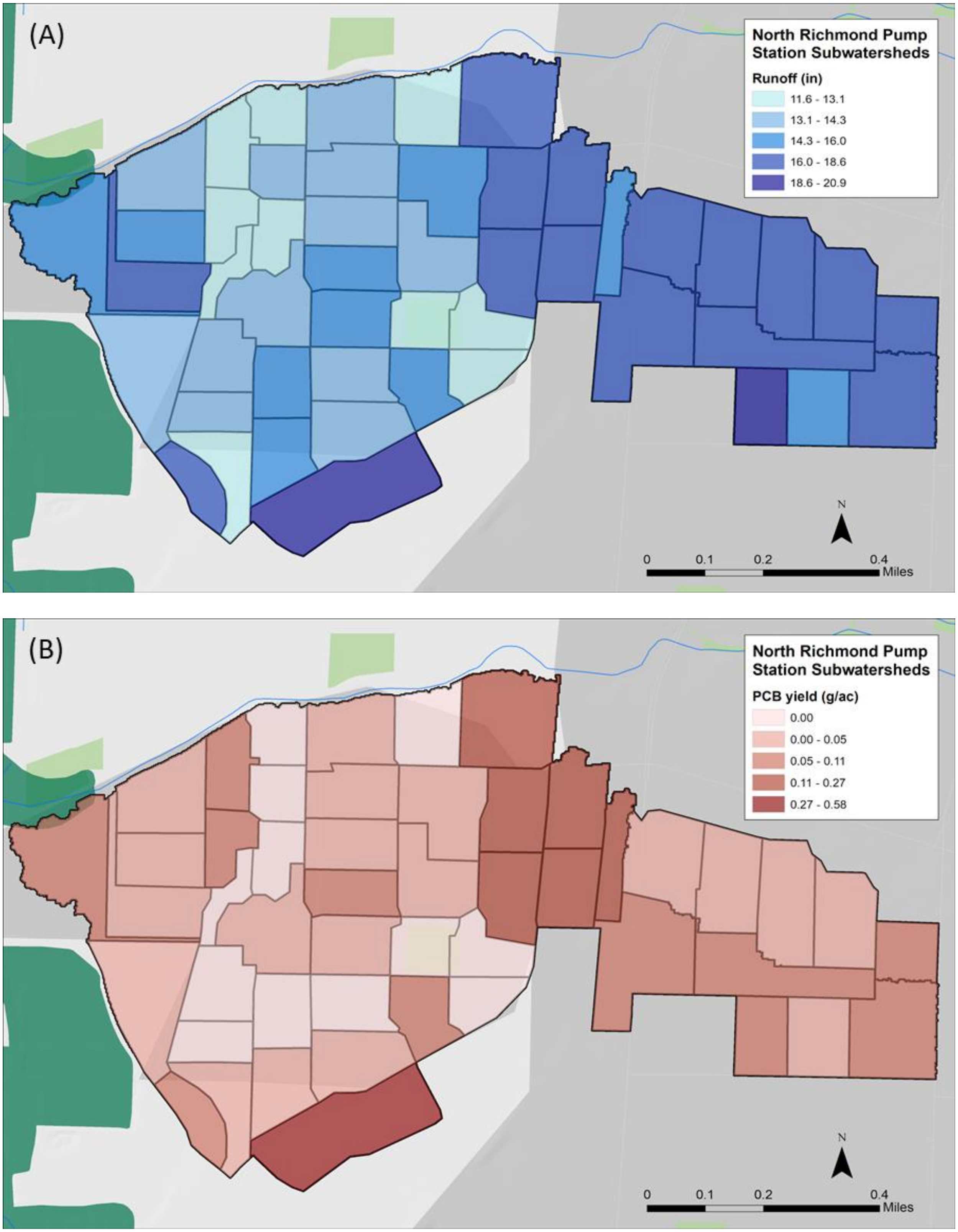

Figure 4-4. Annual runoff (A) and PCB yield (B) for North Richmond Pump Station watershed for WY 2002.

GI Types and Design Specifications

Four GI types (bioretention, permeable pavement, tree well, and flow-through planter) were included for optimization. Each GI type was assigned a typical size and design configuration (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 implicitly 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	Y - Underdrain at drainage layer	4%	0.29
Permeable Pavement	5000 (100X50)		0	24	100	Y - 8 inch for underdrain	50%	0.23
Tree Well	60 (10x6)	12	21	6	50	Y - Underdrain at bottom	0.4%	0.34
Flow-through Planter	300 (60x5)	9	18	12	5	Y - 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. 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.

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 sub-basin 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 NRPS 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 the 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[1]. 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, permeable pavement, tree wells, and flow-through planters across the study area.

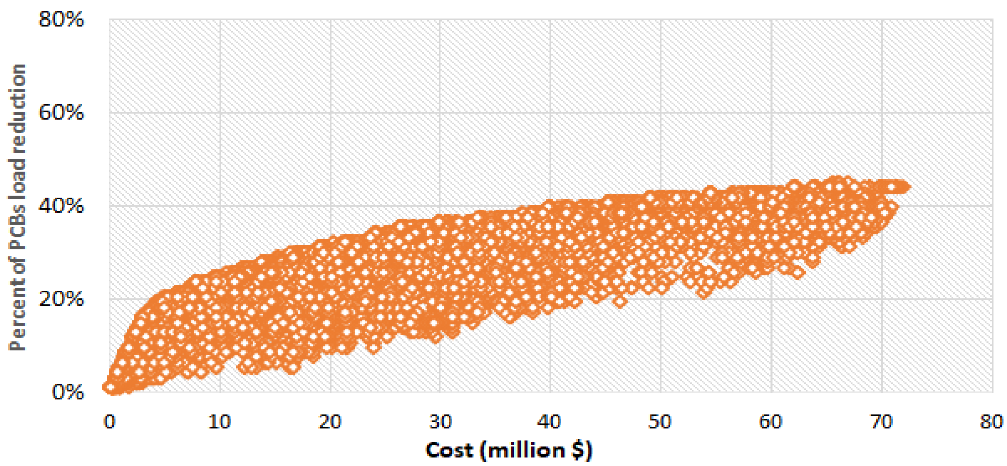

Figure 5-1 PCBs cost-effectiveness curve: the relative cost of each implementation scenario in relation to the load reduction from the estimated baseline.

[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.

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 $4.9 million dollars, but additional 20% PCB load reduction is estimated to require another $34 million dollars of investment. This makes sense given the heterogeneous nature of PCB sources across this urban landscape (McKee et al., 2015; Gilbreath et al., 2015).

After treating the most polluted areas, subsequent implementation of treatment measures will need to be placed in areas having lower baseline yields of PCBs, and therefore the load available for treatment will be less, resulting in a gradual increasing in cost per unit mass treated[2]. The maximum reduction achievable appears around 45% for the NRPS watershed, after which the curve starts to level off and little reduction can be achieved with additional investment. With this information, County and 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.

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 60% (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.

The Optimization Tool performs iterative searches to identify cost-effective solutions based on specific problem formulation, model assumptions, GI cost, design specifications, and constraints unique to this case study. Therefore, it is important to emphasize that the optimization results must be interpreted in the context of these factors. The cost-effective solutions from the

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

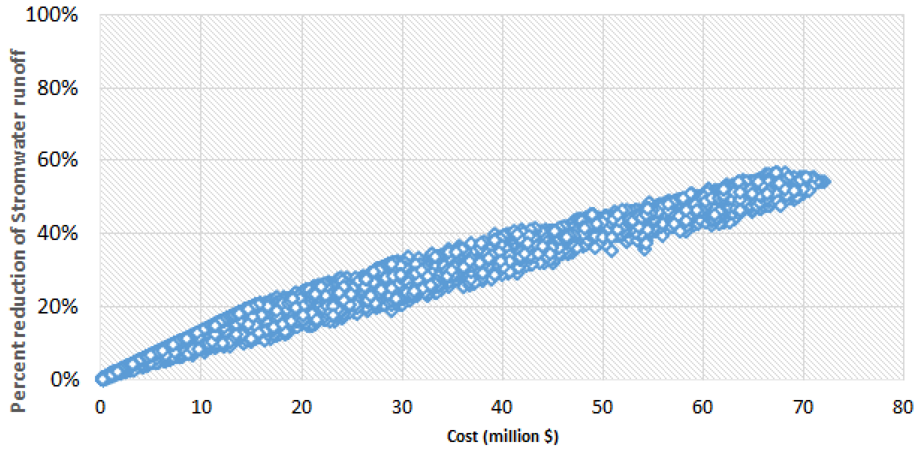

Figure 5-2. Runoff cost-effectiveness curve: the relative cost of each implementation scenario in relation to the flow reduction from the estimate baseline.

optimization process very much depend on the user-defined goals and assumptions and must 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 must 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 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 94 GI features, all but 1 of them are bioretention units. Another type of GI selected was flow-through planter (1 selected). This selection makes sense because the unit cost for tree well is about 10 times higher than it is for bioretention. Collectively, these GI features would treat 27 acres of impervious area or 5% of the watershed.

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 5-3 shows the number of GI features identified at each sub-basin for the 20% PCB load reduction scenario. Seven sub-basins were identified as high leverage watersheds for reducing PCBs within the NSPS watershed. In general, the optimization process identified more GI units in areas with high PCB loads, where GI can be most efficient.

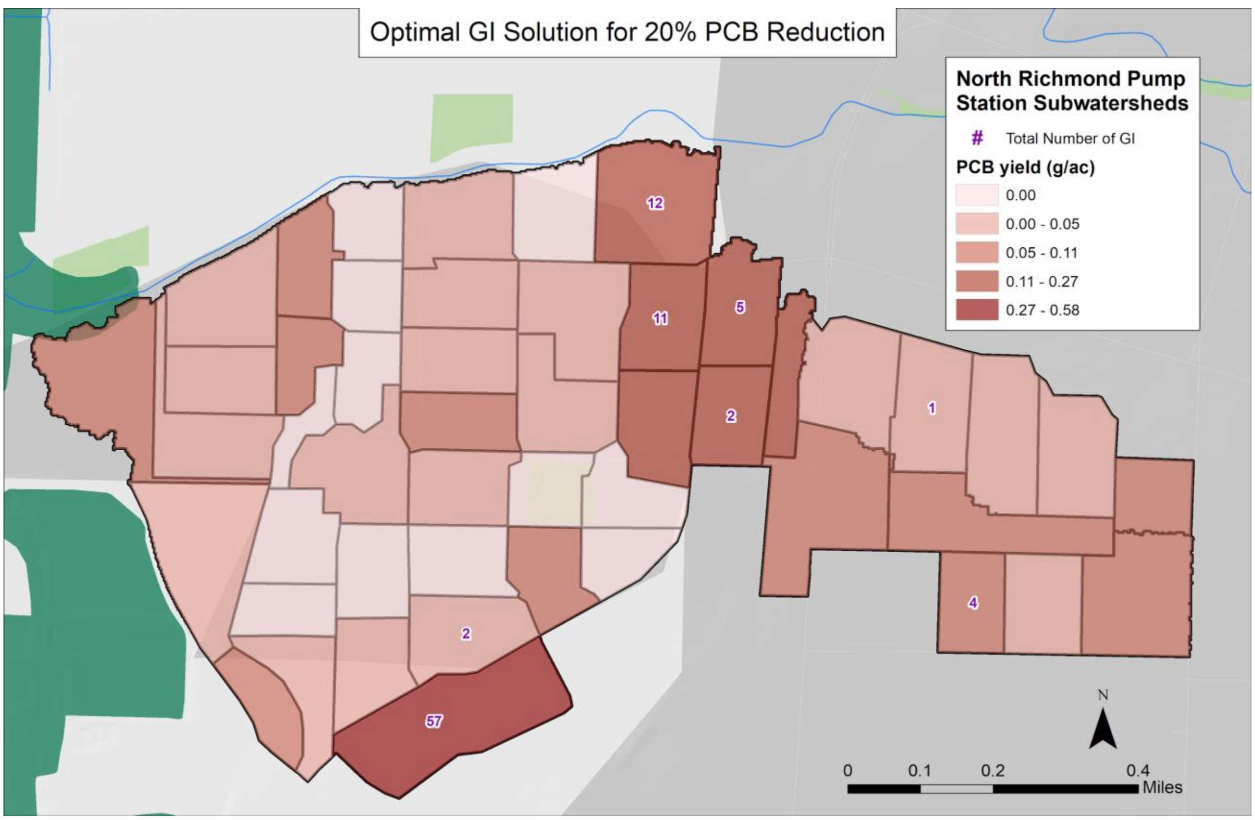

Figure 5-3. The number of GI units identified in each sub-basin for the optimal scenario that achieved a 20% PCB load reduction.

5.4 Incorporating GreenPlan-IT Results into Planning Documents

The optimal solutions identified through the Greenplan-IT application 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 SLT, once a reduction goal is set.

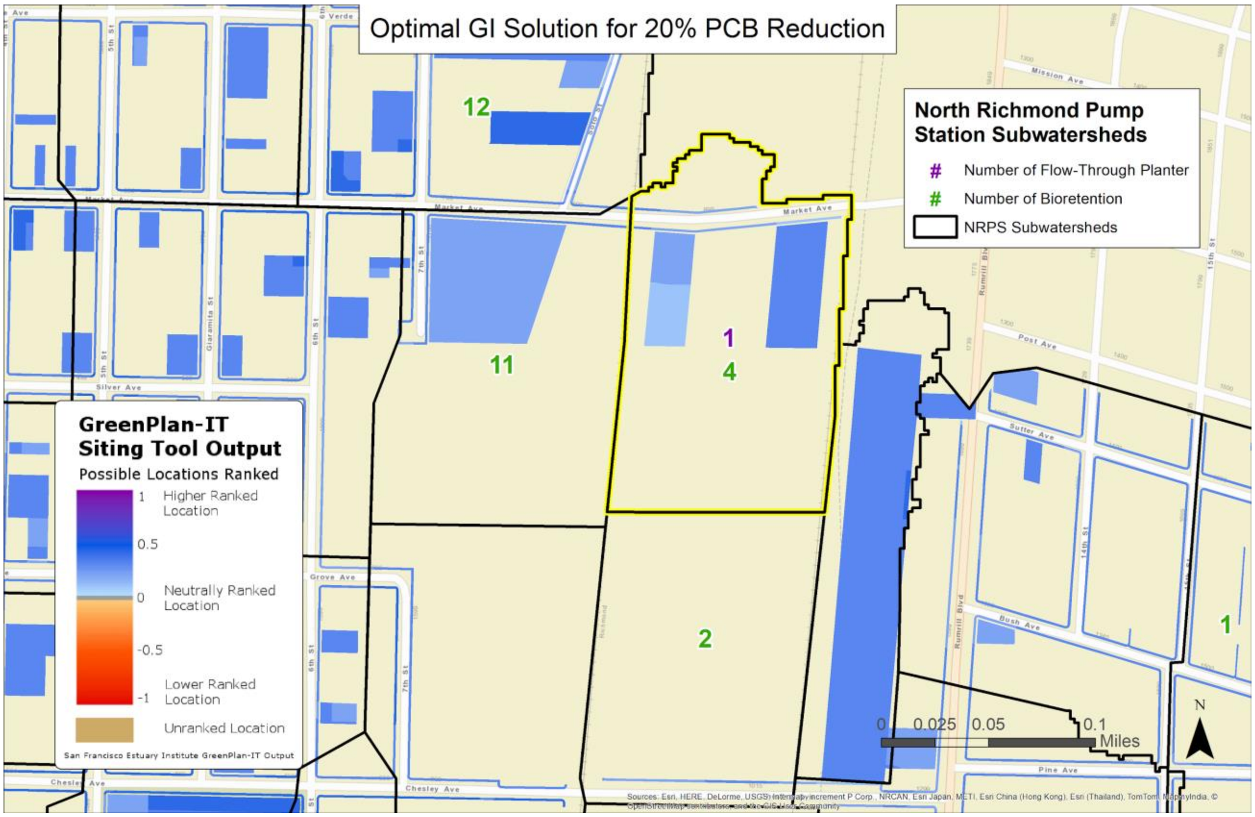

Figure 5-4. The number of bioretention and flow-through planter units identified for the optimal scenario that achieved a 20% PCB load reduction in an example sub-basin

Take for example a sub-basin where four bioretention units and one flow-through planter were identified for a 20% PCB reduction goal (Figure 5-4). Within this sub-basin, there is a combination of 143 potential sites for bioretention and/or 238 for flow-through planter identified from the SLT, each with its own ranking. County staff could begin by exploring the highest ranked potential sites to evaluate the suitability of implementing a bioretention unit on each site. This can be done within GIS software (such as ArcGIS or Google Earth) by selecting and considering the highest ranked locations within this sub-basin (perhaps starting with the top 10%

ranked locations). If one potential location is not suitable, County staff could continue down the ranked list, until the best five (4 bioretention and 1 flow-through planter) 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 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 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 North Richmond Pump Station watershed. This provided the County and City with a list of feasible locations identified based on landscape and GI characteristics and ranked based on local priorities. The Modeling Tool was then used to quantify the baseline flow and PCB loads from the watershed, 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 provide the County and 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 County and City needs. This kind of systematic approach has been found to be important for providing municipal 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, 72 acres of public locations within the North Richmond Pump Station watershed were identified as potential locations for bioretention (with underdrain). Of this area, 44 acres (61%) were highly ranked (ranked 0.3 or higher). The highest ranked sites should be considered first as implementation locations.

- The Site Locator Tool also identified 33 acres of private property as potential locations for bioretention and for tree wells. Of this area, 6 acres (18%) were highly ranked.
- For the North Richmond Pump Station watershed, the estimated baseline PCB loads are 43.1 g/year. This translates to PCB yields of 0.09 g/acre on average for the whole watershed.
- For a 20% reduction in PCB loads from this watershed, it was identified that 93 bioretention units and 1 flow-through planter features would be needed to treat 27 acres of impervious areas.
- 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 7 of the sub-basins with the highest PCB loads.

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