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

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EXECUTIVE SUMMARY

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

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

GreenPlan-IT was applied at the City scale. 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 was used to estimate a baseline PCB load, which for this city area, was 7,865 g/year; a result that appears to be biased high due to the use of parameterization from the North Richmond Pump Station model calibration. This translates to a PCB yield of 0.34 g/acre on average (which is a high yield) but a distribution among land uses and model subwatersheds appears reasonable. Thus, even if the loads appear biased high, the outcomes of the optimization are likely unaffected. The Optimization Tool was used to identify the best combinations of feasible GI locations for achieving a range of management goals at minimal cost. For a 20% reduction in PCB loads from the City, the optimal, most cost-effective solution consisted of 8,143 GI projects that include 3,115 bioretention units, 140 permeable pavement, 1,172 tree well, and 3,716 flow-through planters. The number of GI features required for this solution is high due to some of the highly polluted areas having steep topography, resulting in less efficient GI performance. If implemented, these features would treat an estimated 1,969 acres of impervious area. Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in just 30 of the 193 subwatersheds delineated within the model for the City of Richmond. These 30 subwatersheds are those that have the highest PCB loads and comprise just 29% of the City Area.

The outputs of the GreenPlan-IT applications can provide 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 biphenyls (PCBs) 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 should 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 the boundary of the City of Richmond, 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 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/or load reduction goals; and (d) a tracker tool that tracks GI implementation and report 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 Toolkit in the City of Richmond for all watersheds within the City boundary. 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 Richmond is located in the north San Francisco Bay Area, within Contra Costa County, and has an area of 29.8 square miles (19,087 acres) and population in 2016 of over 100,000 people. Like many cities in the Bay Area, the City of Richmond 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 a large portion of urbanized areas with elevated concentrations of PCBs in sediment in mostly historical, industrial areas where PCBs were used. These areas are targeted for management actions (Figure 2-1).

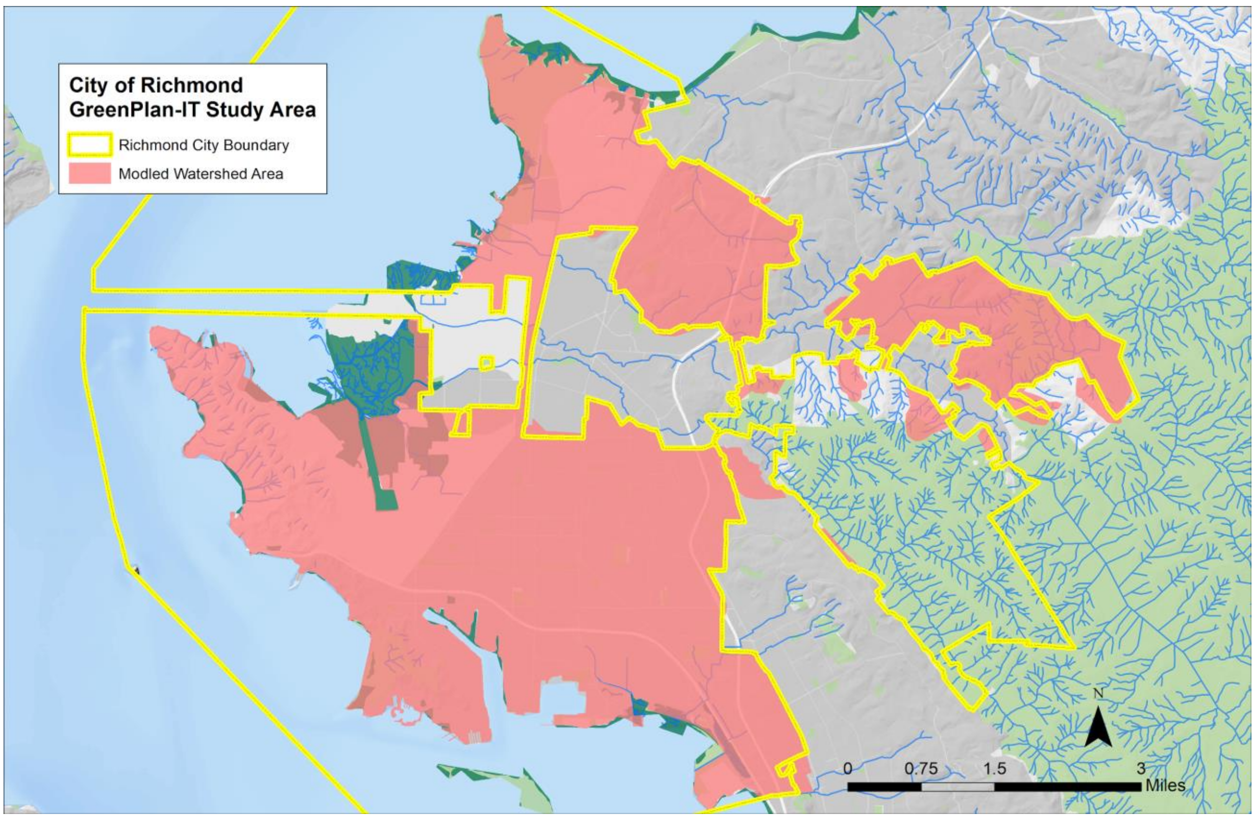

Figure 2-1. Map of the City of Richmond.

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 urbanized areas (Figure 2-1). The city consists of diverse land use areas, primarily industrial, transportation, open space, and residential with some percentage of the developed watershed being legacy industrial areas likely with historic PCB use. The watersheds within the City of Richmond drain into San Pablo Bay. The 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 potential GI locations within the City boundary, as well as cost-effective solutions for the urbanized watersheds where management action is planned. In addition, the City of Richmond is required by the MRP to develop a GI plan for PCB and mercury 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 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 Richmond 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. This section provides an overview of the use of the SLT in the City of Richmond.

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. Full coverage and availability of the study area were also critical in choosing what data to use. 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).

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. These weights were determined by consulting with City staff through an iterative process that occurred when determining ranking priorities for the City (Table 3-2). Each of the six factors was assigned a weight based on the City's priorities, and each data layer within the factors was assigned a weight that summed up to 1 within each factor. Higher weights were given to the data layers that were deemed more important within each factor. Through this process, the weights were customized and adjusted to reflect local priorities and management goals of the City.

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

Layers	Analysis
City of Richmond On Street Parking Estimate	Locations
Open Street Maps Parking	Location
Parks	Locations Local Opportunities and Constraints Analysis
Underdeveloped Parcels	Locations Local Opportunities and Constraints Analysis
Publicly owned Parcels (using parcel tax code)	Locations Local Opportunities and Constraints Analysis Ownership
Storm Network	Local Opportunities and Constraints Analysis
Fire Hydrants	Local Opportunities and Constraints Analysis
Truck Routes	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 and 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

Layers	Analysis
Existing Trash Capture Device Drainage Areas	Local Opportunities and Constraints Analysis
Existing Richmond Trees	Local Opportunities and Constraints Analysis
Tree Opportunity Sites	Local Opportunities and Constraints Analysis
SFEI Green Infrastructure Specific Regional Suitability Layer	Local Opportunities and Constraints Analysis
OpenStreetMap Building Footprints	Knockout
Bay Area Aquatic Resource Inventory Wetlands	Knockout
Bay Area Aquatic Resource Inventory Baylands	Knockout
California Protected Areas Database: Large Rural/Permeable Areas (custom)	Knockout

The primary focus or priority for the City's ranking was PCB and mercury reductions and trash reductions, which is reflected in the factor weighting in the custom ranking. In addition to these priorities, 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)”.

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 SLT for the City of Richmond was based

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
Regional Suitability	0.125	SFEI GI Specific Regional Suitability Layer	1	None	0	1
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	0.14	None	0	1
Trash	0.25	Trash Generation - medium to high*	0.29	None	0	1
Trash	0.25	Trash Generation - high*	0.43	None	0	1
Trash	0.25	Existing Trash Capture Device Drainage Areas	0.14	None	0	-1
Install Feasibility	0.125	Storm Network	0.18	Full	60	1
Install Feasibility	0.125	Existing Richmond Trees	0.18	Full	20	-1
Install Feasibility	0.125	Tree Opportunity Sites	0.27	Full	20	1
Install Feasibility	0.125	Fire Hydrants	0.18	Full	35	-1
Install Feasibility	0.125	Truck Routes	0.18	Full	160	-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

Factor	Factor Weight	Layer Name	Layer weight	Buffer type	Buffer (ft)	Rank
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 disadvantaged community scoring and higher levels of trash generation.

on an iterative and interactive process conducted with City staff when determining priorities for the ranking of the City's watersheds. This process included adding and subtracting data layers and adjusting weights as City staff reviewed the preliminary results against their own needs. Three iterations of ranking and adjustment were made for applying the tool to the North Richmond Pump Station drainage area, which was then used, with a few additions of layers of interest to the City, for the City of Richmond extent. Based on the ranking and weighting of the GIS layers, 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 21.7% of the 29.8 square mile City footprint were identified for consideration. These potential locations provide a starting point for the City's GI planning and implementation effort, but further planning work was then carried out 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 on the map. 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, 2600 acres of public locations within the City of Richmond were identified as potential locations for bioretention (with underdrain). Of this area, ~ 340 acres (13%) suitable for bioretention was ranked higher (rank of 0.3 or higher). The SLT also identified 1500 acres of private property as potential locations for bioretention. Of this area, ~ 80 acres of the area suitable for bioretention were ranked 0.3 or higher. 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.

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 City. But further planning work was done to determine which of these may be optimal by using the Modeling and Optimization tools, as described in the next sections.

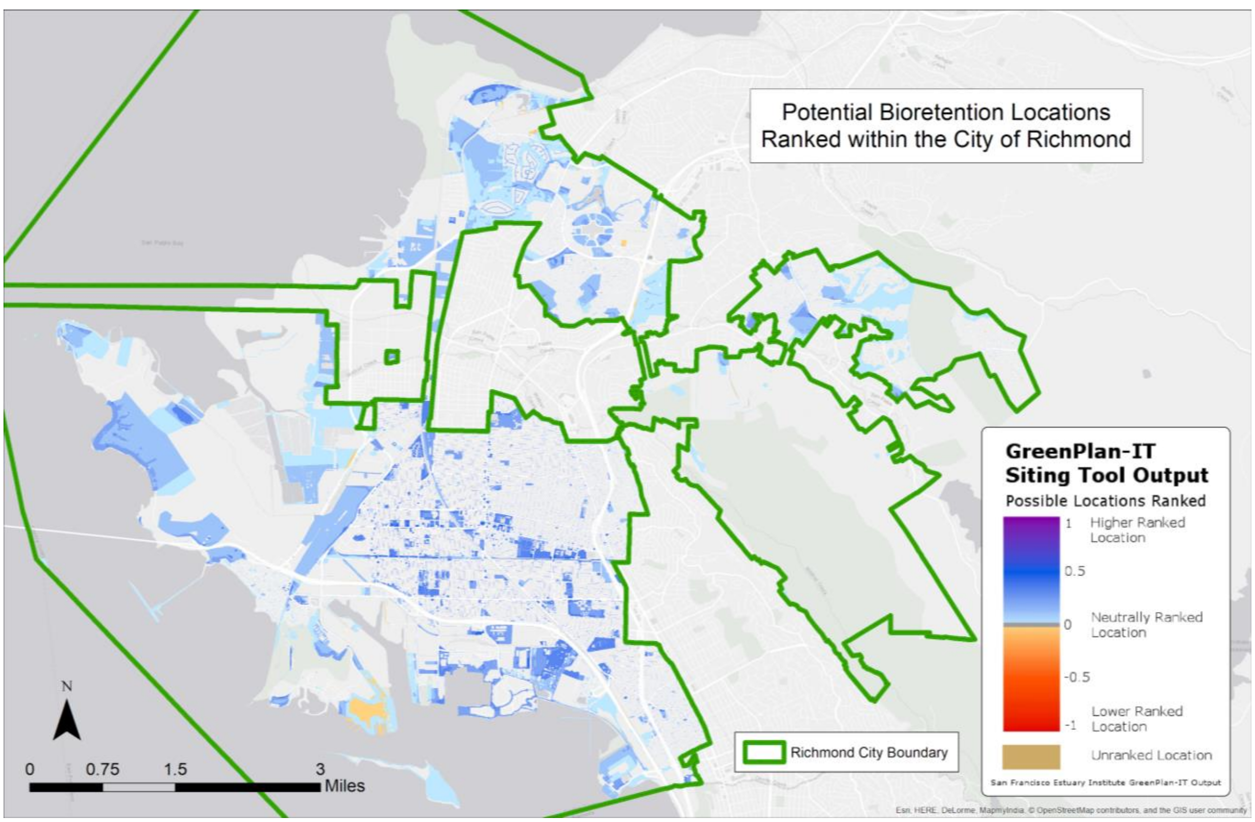

Figure 3-1. Ranked potential locations for bioretention within the City of Richmond.

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. For the City of Richmond, there is no model calibration because of lacking monitoring data. Instead, the calibrated model parameters from North Richmond Pump Station watershed (see parallel report: Wu, et. al., 2018) were extrapolated to other watersheds within the city boundary, which is a standard modeling practice for watersheds without data that have characteristics similar to the calibrated watershed. The extrapolation was done by assigning model parameters such as PCB washoff coefficients on a land use basis. The modeling effort was thus focused on simulating baseline conditions.

4.1 Watershed Delineation

The first step in setting up the Modeling Tool for the City of Richmond was to delineate the watershed into smaller, homogeneous sub-basins (model segments). Storm drain data provided by the City of Richmond were used to delineate the watershed into 193 sub-basins based on storm sewer connections and flow directions. These sub-basins range from 6.5 to 286.5 acres (Figure 4-1).

4.2 Input Data

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

Precipitation Data

High-resolution precipitation data (hourly intervals) for Water Year (WY) 2002 were obtained from Contra Costa County Flood Control District at Richmond City Hall station (http://www.ccflood.us/raintable.html, Station 21). WY 2002 was chosen in accordance with recommendations for use as a representative year for the Bay Area in the RAA guidance document (BASMAA, 2017). 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 an 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 WY 2002 precipitation is shown in Table 4-1.

Evaporation Data

Monthly evaporation data for the City of Richmond were 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.

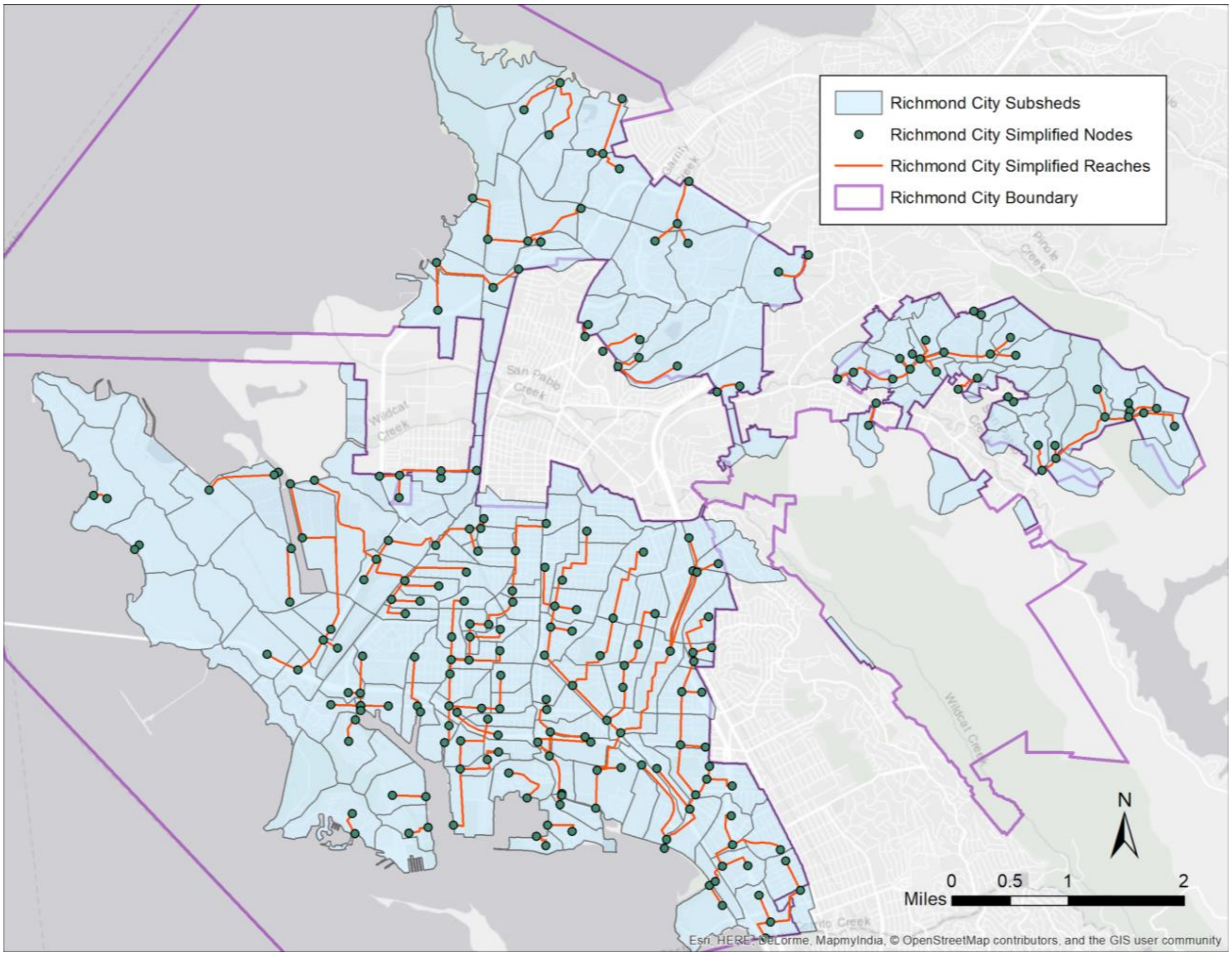

Figure 4-1. Delineated sub-basins within the City of Richmond.

Table 4-1. Monthly distribution of precipitation for WY 2002 for City of Richmond.

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

The monthly evaporation data were then converted to monthly average in inches/day as required by SWMM5 (Table 4-2). Monthly data are adequate for use in the model since evaporation is only a small component of rainfall-driven runoff events.

Table 4-2. Monthly evaporation for the City of Richmond.

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 City of Richmond are listed in Table 4-3.

Table 4-3. Land use distribution in the City of Richmond modeling area (acres).

Category	Commercial	Industrial	Open	Residential	Transportation	Total
Area	1,156	4,643	2,987	3,484	2,944	15,213
Percent	8%	30%	20%	23%	19%	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).

Soil Data

Soil data were obtained from the State Soil Geographic Database (STATSGO) and intersected with the subbasin boundary layer to determine the percentages of each soil group for each model segment. The City of Richmond is composed of 52% of type C soils and 48% of type D soils, which have low infiltration rates and high runoff rates.

Slope

The average surface slope of each sub-basin, expressed as percentage, was calculated from USGS's 10m resolution National Elevation Dataset (NED) The estimated slopes range from 0.1% to 38.4%. Of 193 sub-basins, 104 have a slope <4%, 22 have slopes between 4% and 10%, and 67 have a slope >10%.

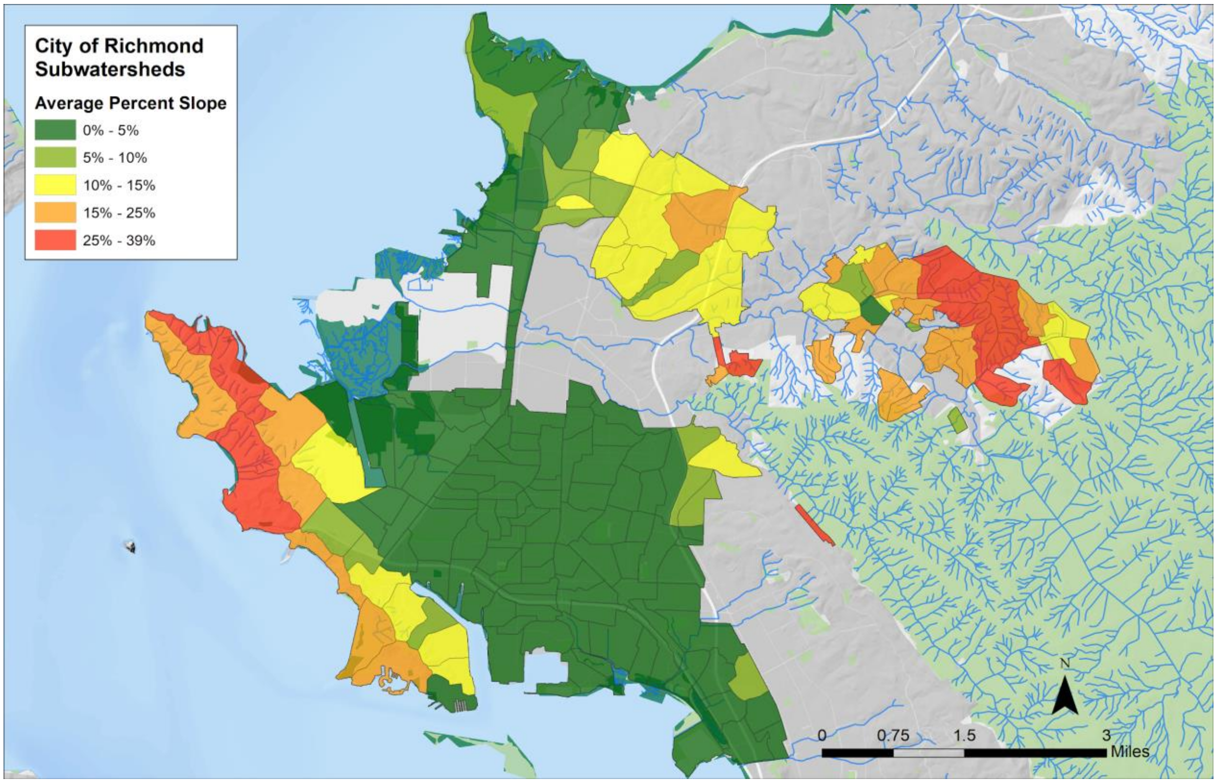

Figure 4-3. Average surface slopes for the City of Richmond modeled watersheds.

4.3 Baseline Flow and PCB Loads

The baseline flow and PCB loads were calculated to serve as the basis for the comparison of various GI solutions in the optimization. The estimated annual PCB load for WY 2002 from the City of Richmond is 7,865 grams, which may be biased high as a result of extrapolating the model parameters, in particular PCB washoff coefficients, from the NRPS watershed. While both City of Richmond and NRPS watersheds use the same land use groups in the Modeling Tool, the industrial areas in the NRPS watershed is mostly (over 90%) 'Old' industrial (prior to 1974) while only about 70% in the City of Richmond. As such, the PCB washoff coefficients from NRPS watershed for this land use may be high for some of the industrial areas in the City, resulting in higher estimated PCB loads within the City of Richmond. The modeled PCB loads could be refined in the future when monitoring data are available for model calibration. The average pollutant yields, expressed as load per unit area, were calculated as 0.34 g/acre for City of Richmond and with a range from 0.02 to 3.58 g/acre. The distribution of stormwater runoff and PCB yield is shown in Figure 4-4. Since the distribution among land uses and model subwatersheds is deemed reasonable, even if the loads are biased high, the outcomes of the optimization should be unaffected and reasonable, because it is the differences in PCB loads, not the absolute values, that drive cost-effective solutions (more GIs in more polluted areas).

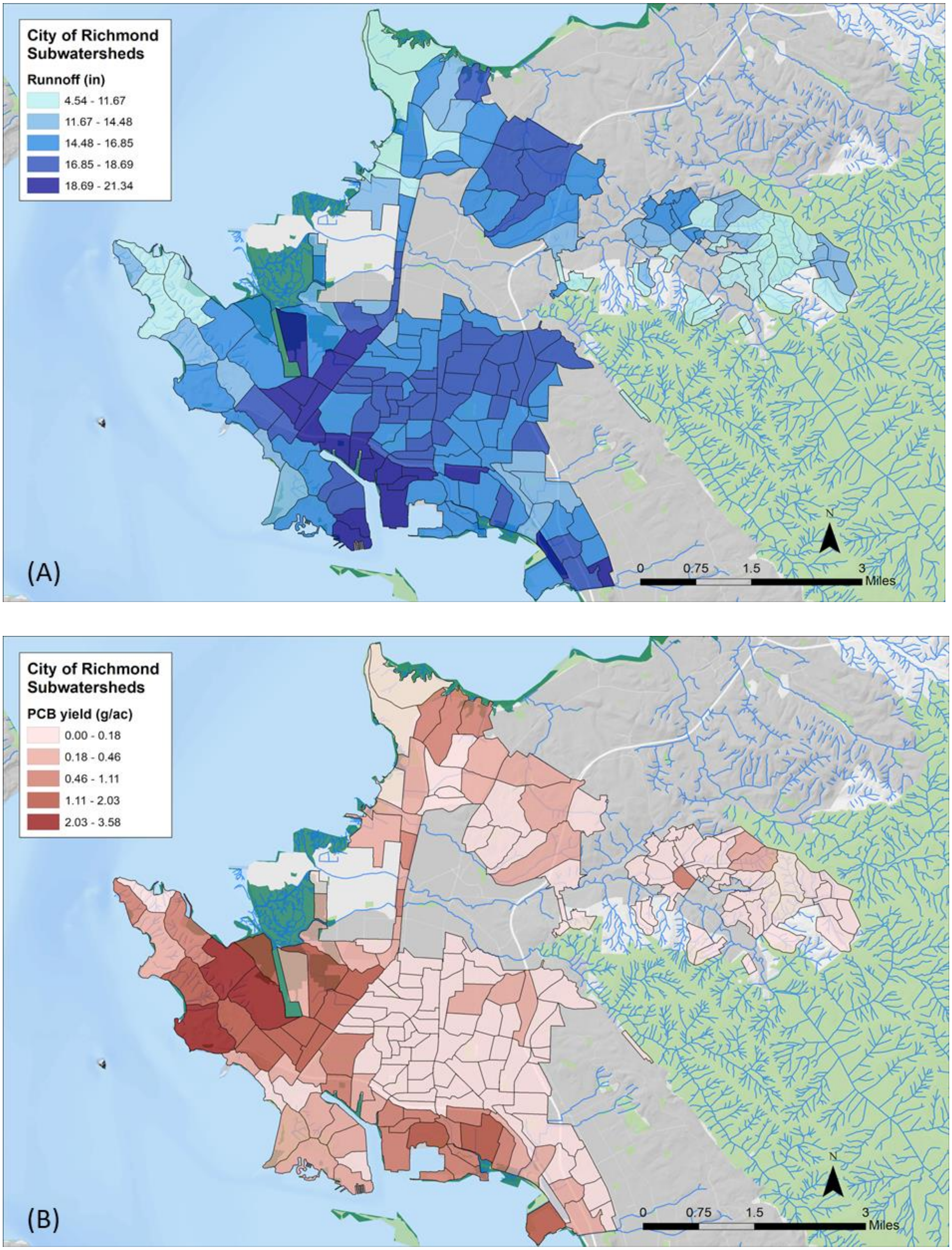

Figure 4-4. Annual runoff (A) and PCB yield (B) for the City of Richmond modeled watersheds for WY 2002.

5. OPTIMIZATION TOOL APPLICATION

As the last step in the GreenPlan-IT application, the Optimization Tool was used to determine the optimal combinations of GI projects within the City of Richmond 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 193 sub-basins were generated as a reference point from which the effectiveness of any GI scenarios were estimated.

GI Types and Design Specifications

Four GI types, bioretention, permeable pavement, tree well (proprietary media), and flow-through planter, were included for optimization. Each GI type was assigned typical size and design configurations (Table 5-1) that were reviewed and approved by the TAC. 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 GI 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.

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 differences 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

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.

Table 5-2. GI 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

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.

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 SLT. 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 City scale. In the optimization, since GI design specifications were user specified and remained constant, the decision variables were therefore the number of units of each of the GI types in each of the sub-basins within the City of Richmond. 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 TAC, 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 a number of bioretention units, permeable pavement, tree wells, and flow-through planters across the study area.

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 10%, 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

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[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.

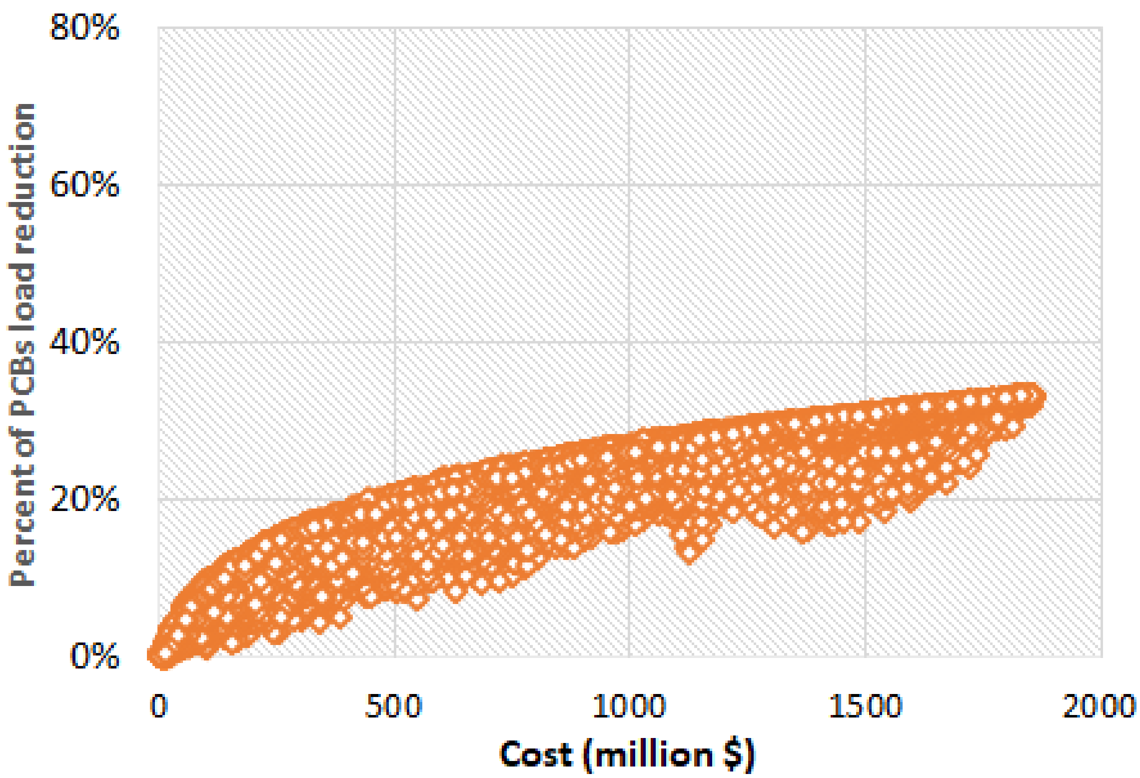

Figure 5-1. PCB cost-effectiveness curve: the relative cost of each implementation scenario in relation to the load reduction from the estimated baseline.

load reduction goals with limited budgets. 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 features. For example, a 10% PCB removal can be achieved at a relative cost of about $4 million dollars, while an additional 10% removal can be expected for the next $400-million-dollar investment. This makes sense given the heterogeneous nature of PCB sources across urbanized landscapes (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[2]. The maximum reduction achievable appears around 35% for the City of Richmond, 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

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

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 about 5-fold in this study area where most 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 50% (Figure 5-2), at which point the impervious areas were mostly captured and treated. Note that these solutions were optimized for PCB reduction and therefore not necessarily optimal for runoff reduction.

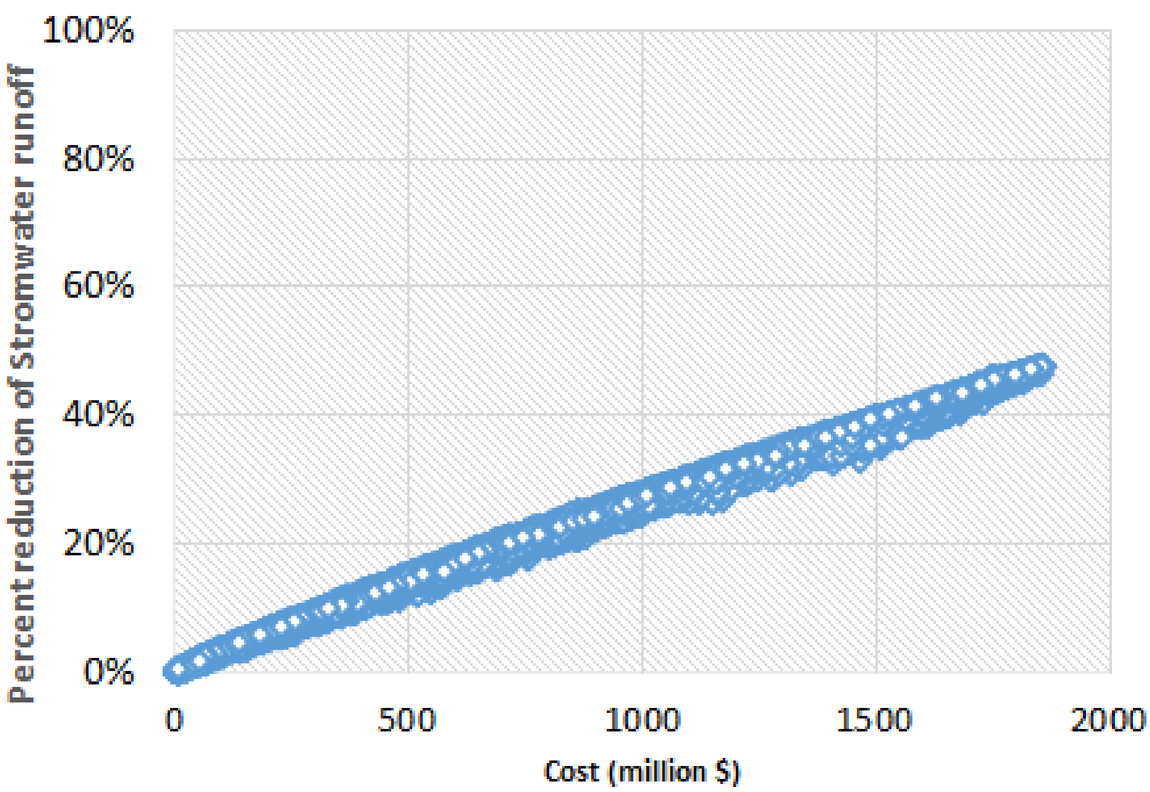

Figure 5-2. Runoff cost-effectiveness curve: the relative cost of each implementation scenario in relation to the runoff reduction from the estimated baseline.

The maximum 35% of PCB reduction and 50% of runoff reduction are considerably lower than what were estimated for other Greenplan-IT case studies in the Bay Area (65% PCB reduction for City of Sunnyvale, 50% for Ettie Street Pump Station watershed in Oakland, and 45% for the North Richmond Pump Station watershed) and may be explained by the City's topography. For the City of Richmond, 67 of 193 sub-basins have a slope >10%, which is very steep for GI implementation (Fig 4-3). These sub-basins account for 39% of the modeled area and contribute 49% of total PCB loads. GI features are less effective if they are built on steeper areas because runoff runs faster thereby leaving a shorter time for infiltration within the GI features. Therefore, the optimization routine either must assign more GI features in steeper areas to achieve the same load reduction or need to implement the GI features in other flatter but less polluted areas. The result in a cityscape that includes a larger area of steeper terrain, either way, is a higher cost per every additional unit of PCB load reduction than the same array of land uses on flatter terrain. During implementation, the City can target some of the highly polluted yet steep areas, with careful design and engineering to ensure GI features are properly built to maximize their performance.

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 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 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 8,143 GI projects, including 3,115 bioretention units, 140 permeable pavement features, 1,172 tree wells, and 3,716 flow-through planters. The numbers of GI required for this solution is fairly high, due to some of the highly polluted areas being very steep, resulting in GI under-performance. Collectively, these features would treat 1,969 acres of impervious area, accounting for 26% of total impervious area in the study area. The percent utilization of each GI type is quantified for the selected solution (Figure 5-3a). Flow-through planters account for 46% of total GIs identified, followed by bioretention at 38%. Permeable pavement is least utilized because of lack of feasible locations. The percent utilization of each GI type can also be viewed in terms of area treated (Figure 5-3b). While flow-through planters account for 46% of the total, it treats 32% of impervious area because of the inclusion of lining in the design specification (thus less efficient than bioretention). Bioretention treats 45% of impervious area because it both stores and infiltrates water. Tree wells are estimated to treat about 14% of impervious area while permeable pavement is estimated to treat only 2% of the area. Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 30 of the subwatersheds, those with the highest PCB loads.

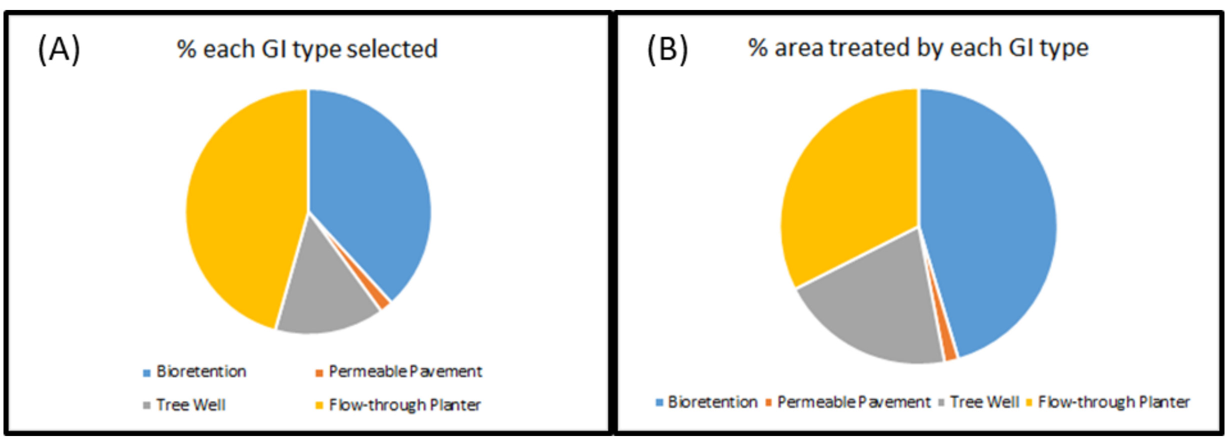

Figure 5-3. Percentage of each GI type selected and area treated by each type.

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

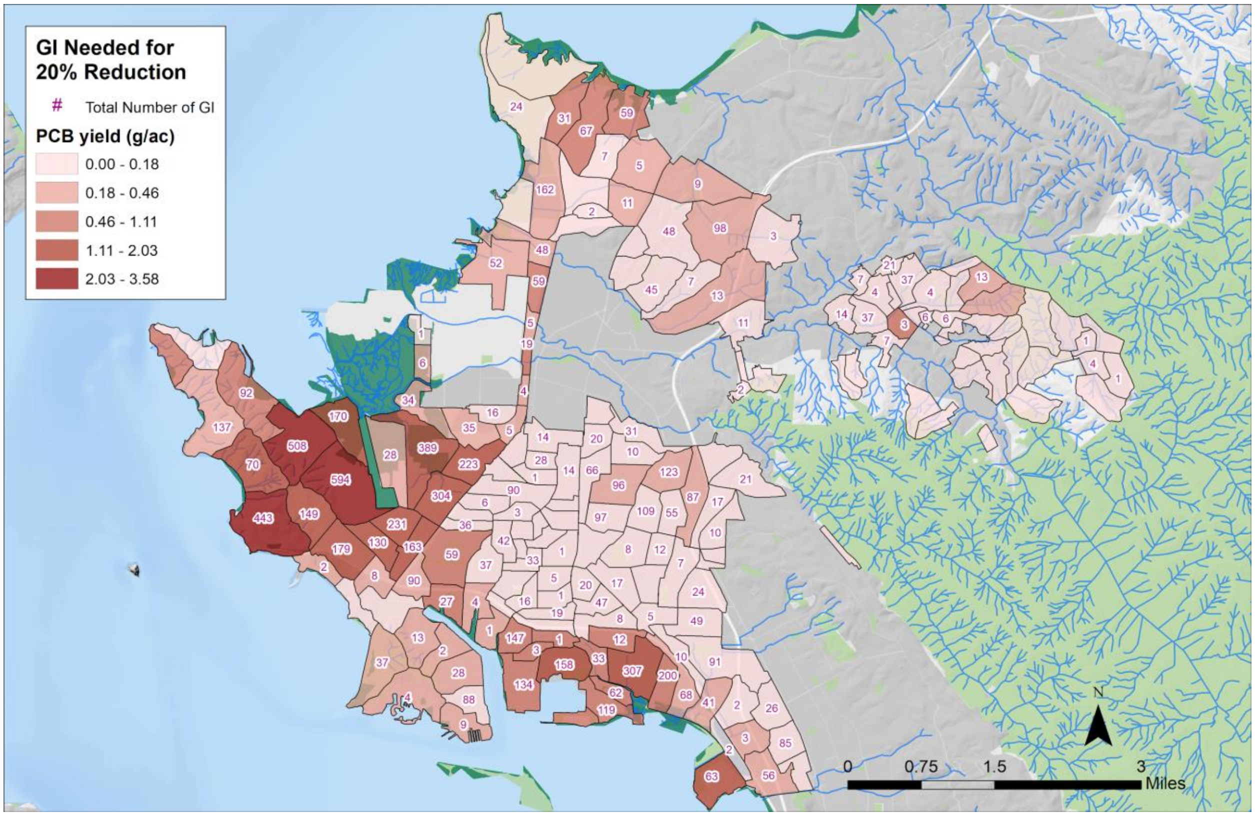

Figure 5-3. The number of GI features identified in each sub-basin for the optimal scenario that achieved a 20% PCB load reduction.

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 city-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.

Take the example of a sub-basin where 61 bioretention units, 15 permeable pavement units, 7 tree wells, and 7 flow-through planters were identified through the optimization for a 20% PCB reduction goal (Figure 5-4). Within this sub-basin, there are a combination of 143 potential sites for bioretention and/or 238 potential sites for flow-through planter 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. This can be done within

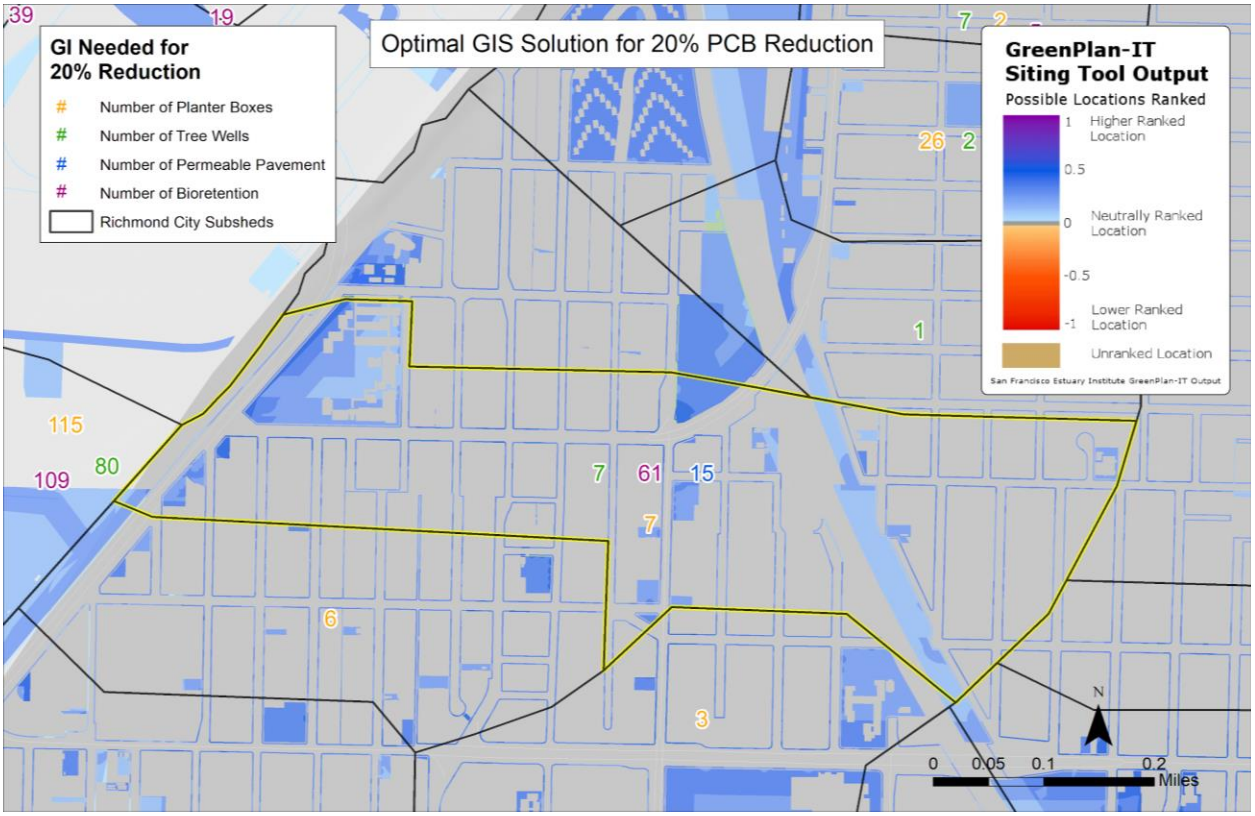

Figure 5-4. The number of bioretention and flow-through planter units identified within the optimization analysis for 20% PCB reduction in an example sub-basin.

a GIS (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, City staff could continue down the ranked list, until the best 90 locations are selected. A similar process could be applied for selecting the best locations in other sub-basins within the City boundary.

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 soils data on PCB and Hg concentrations or other indications of pollution source problem 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 ranked list of feasible locations for the City of Richmond. This provided the City with a list of feasible locations identified based on landscape and GI characteristics and ranked based on local priorities. The Modeling Tool was used to quantify the baseline flow and PCB loads from the City landscape, and to estimate flow and PCB loading reductions associated with implementing GI, thereby providing quantitative information on water quality and quantity benefits. The Optimization Tool was then used to identify the best combinations of feasible GI locations (among tens of thousands of options) for achieving management goals at minimal cost.

The results of the GreenPlan-IT application are maps and tables of feasible locations and a range of optimal solutions for different reduction goals. These potential locations can be compared and overlaid with maps of flooding, pollution source areas, 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, 2600 acres of public locations were identified as potential locations for bioretention (with underdrain) and 1500 acres of private property were also identified. The highest ranked sites should be considered as implementation locations.
- For the City of Richmond, the estimated baseline PCB load is 7,865 g/year. This translates to PCB yields of 0.34 g/acre on average for the City which is likely biased high due to the use of parameters from the North Richmond Pump Station model calibration. However, since the distribution of runoff and PCB yield among land uses and model subwatersheds appears reasonable, even if the loads are biased high, the outcomes of the optimization are likely unaffected.
- To achieve an example of 20% reduction in PCB loads from the City landscape, the optimal, most cost effective solution consists of 8,143 GI projects that include 3,115 bioretention units, 140 permeable pavement, 1,172 tree wells, and 3,716 flow-through

planters. Together they are estimated to treat 1,969 acres of impervious area. Similarly, optimal solutions and GI composition are available for other reduction goals of management interest.

- Some of the highly polluted areas have very steep slopes. Proper design and engineering are needed to ensure GI implementation and performance. This could help reduce the numbers of GI features required and therefore lower the overall implementation cost and achieve a higher level of runoff and load reductions.
- Based on the results of the modeling and optimization, it is suggested that GI implementation should be focused in 30 of the subwatersheds with the highest PCB loads.

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