

APPENDIX H

CCCWP RAA Modeling Report & Peer Review



REASONABLE ASSURANCE ANALYSIS PEER REVIEW PACKAGE

Alameda Countywide Clean Water Program and Contra Costa Clean Water Program

**Municipal Regional Stormwater Permit
NPDES Permit No. CAS612008
Order No. R2-2015-0049**

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Project Numbers: LA0542 and LA0540

December 11, 2019

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Peer Review Matrix: Attached File:

RAA_PeerReviewMatrix_ACCWP_CCCWP_120419_RTC.xlsx

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PR-1: Peer Review Component Descriptions

0. INTRODUCTION

This Peer Review package is intended to provide descriptions and back-up references associated with each model component identified for review in the Peer Review for SF Bay PCBs and Mercury Reasonable Assurance Analyses (RAAs) for Green (Stormwater) Infrastructure Instructions/Guidance to Peer Reviewers (Peer Review Instructions) and “FINAL_RAA_PeerReviewMatrix_Template_8_1_19.xlsx” (Peer Review Matrix), provided by BASMAA (2019). The descriptions herein are repeated or expanded from those included in the Peer Review Matrix, which includes fields that are requested to be populated by the peer reviewer. The descriptions provide summary information regarding the model inputs and/or reference other reports and documentation attached to this Peer Review Package that provide more extensive detail.

The Alameda Countywide Clean Water Program Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions Report (ACCWP, 2018) [PR-2] and the Contra Costa Clean Water Program Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions Report (CCCWP, 2018) [PR-3] (i.e., GI Quantitative Relationship Reports) are frequently referenced throughout this Peer Review package. Note that both GI Quantitative Relationship Reports are very similar, as the same RAA modeling methodology was used for both Counties; often reading one of the two reports will provide the referenced information.

1. BASELINE CONDITION MODELING

1.A Model Selection

Refer to Section 2.1 and 2.2 of the GI Quantitative Relationship Reports [PR-2; PR-3] for an overview of the model selected for the CCCWP and ACCWP RAA baseline condition models.

Rationale: The approach used for modeling hydrology is to use a hydrologic response unit (HRU) approach. An HRU is a unique combination of land surface features (imperviousness, underlying soil characteristics, slope, etc.) which is expected to give a consistent runoff response to rainfall, no matter where that unique combination is found. The HRU approach involves modeling thousands of combinations of land surface features present within the area of analysis, for a generic unit area drainage catchment, and then storing these results in a database. These HRU results can be scaled geospatially across the entire area of analysis without developing a detailed hydrologic model and this method is appropriate for estimating average annual runoff and pollutant loading. This method is consistent with the *Bay Area RAA Guidance Document* (BASMAA, 2017).

Spatial/Temporal Resolution: Generic HRUs, characterized by varying the values of specific identified parameters within a defined range, are modeled using USEPA’s Stormwater Management Model (SWMM). Continuous simulation HRU models are run on an hourly timestep for the identified baseline period of record (water year [WY] 2000 – 2009). An average annual runoff volume per acre is obtained for each HRU. The average annual runoff volume per acre

associated with a specific HRU can then be multiplied by the area represented by that HRU within the entire area for analysis. The resulting volumes associated with each represented HRU within the area of analysis can then be added together to estimate the total average annual runoff volume.

Alignment with Information/Needs/Data Available: The HRU approach is consistent with the *Bay Area RAA Guidance Document* and the precision of the methods used to develop the TMDLs. As the TMDL WLA and MRP requirements are in terms of annual load reduction, event-specific modeling results are not needed. Additionally, long-term continuous simulation modeling allows for effects such as those relating to antecedent conditions (e.g., soil saturation resulting from back-to-back storms) to be incorporated into the results. Finally, detailed storm drain information is not currently available for all areas within the area of analysis, so it is not possible to develop a detailed routing model at this time.

A flow chart representing the Baseline Loading Model is provided:

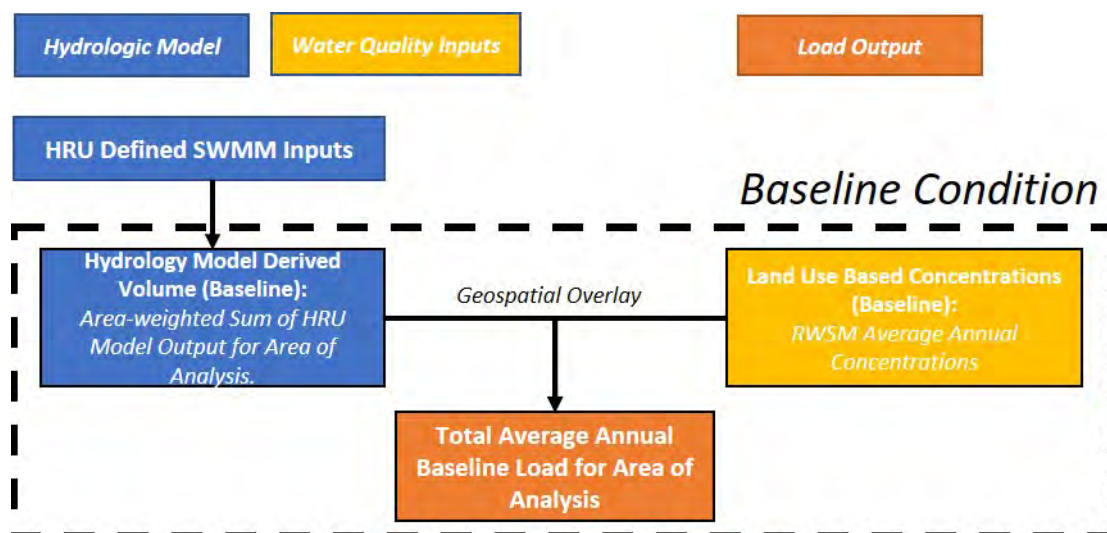


Figure 1-1: Baseline Condition Model Flow Chart

1.B Geographic Area of Analysis

The geographic area of analysis includes the entire area within Contra Costa and Alameda Counties, as shown in Exhibits 1 through 6 of the GI Quantitative Relationship Reports [PR-2; PR-3]. Note that the Counties are not labeled in PR-2 and PR-3; Contra Costa County is north of Alameda County. While the entire area is modeled, baseline results are ultimately subdivided based on regulatory (i.e., MRP covered areas vs. Phase II and Industrial General Permit covered areas) and jurisdictional boundaries. Modeled areas and jurisdictional boundaries are shown in Figure PR-1A and Figure PR-1B for Alameda and Contra Costa Counties, respectively.

1.C Period of Time

Baseline period of record is WY 2000 – 2009 (i.e., October 1, 1999 through September 30, 2009), as documented in the GI Quantitative Relationship Reports [PR-2; PR-3], see section 3.1.1. As included in the RAA Guidance Document (BASMAA, 2017), “For the purposes of RAA analyses, the baseline period for both PCBs and mercury analyses is recommended to be water years 2000

– 2009 (for long-term continuous simulation), or water year 2002 (for representative year simulation). These baseline period options are generally representative of the period during which much of the data were collected for mercury and PCBs.” Also see additional detail in item 1.I “Meteorology”.

1.D Flows and Pollutant Load Simulation

Section 2.2 of the GI Quantitative Relationship Reports [PR-2; PR-3] describes flow and pollutant load simulation. Refer to Section 2.2.2. of the GI Quantitative Relationship Reports [PR-2; PR-3] specifically for information regarding the water quality model.

1.E Rainfall/Runoff Processes

Rainfall/runoff processes are modeled using USEPA SWMM Version 5.1. A summary of the computational methods employed within SWMM to simulate runoff is provided in Section 3.4 of the USEPA SWMM Manual (USEPA, 2015) [PR-4].

1.F Pollutant Loading Variability

Land use variability is accounted for using SFEI’s Regional Watershed Spreadsheet Model (RWSM) output, as described in the “Regional Watershed Spreadsheet Model Version 1.0 Results Summary” memo (Geosyntec, 2019a), provided by BASMAA. The results were developed using Wu et al (2017). Also refer to Section 2.2.2. of the GI Quantitative Relationship Reports [PR-2; PR-3] specifically for information regarding the water quality model.

1.G Watershed Characteristics

See Section 3.1.1 and Table 3 of the GI Quantitative Relationship Reports [PR-2; PR-3] for the watershed characteristics that were varied and the ranges of inputs; also see Table 1.H-1 below, which summarizes SWMM parameter input values.

1.H Watershed Hydrology Parameterization

The output of each uniquely parameterized HRU is matched to those geospatial areas with the unique combination of parameter values, as identified with geospatial data. The geospatial data used to develop the ranges of parameters and match geospatial area to the unique HRUs are shown in Exhibits 1 through 6 of the GI Quantitative Relationship Reports [PR-2; PR-3]. Geospatial data sources associated with each parameter are provided within the text of Section 3.1.1 of the reports (also refer to footnotes). Table 1.H-1 below provides SWMM input values not summarized in Table 3 of the GI Quantitative Relationship Reports [PR-2; PR-3].

Table 1.H-1: SWMM Parameter Input Values

Parameter	Description & Source ¹	Unit	Value
Infiltration Model	Controls how infiltration of rainfall into the upper soil zone of subcatchments is modeled in SWMM.	--	Green Ampt, see parameters in Table 1.H-2
Routing Method	Determines the method used to route flows through the system in SWMM.	--	Kinematic Wave
Reporting Time Step	<i>Model time step input.</i>	Minutes	5
Dry Weather Time Step	<i>Model time step input.</i>	Minutes	240
Wet Weather Time Step	<i>Model time step input.</i>	Minutes	5
Routing Time Step	<i>Model time step input.</i>	Seconds	30
Flow Path Length	Overland flow path length assumed for sheet flow runoff. Selected default inputs represent typical overland sheet flow path lengths for undeveloped/open space areas and developed/urban areas, respectively.	Feet	500 (Existing non-developed condition; development footprint)
			250 (Proposed developed condition; development footprint)
N-Imperv	Manning's roughness for impervious or pervious surfaces.	--	0.012 (corresponds to smooth concrete)
N-Perv		--	0.25 (corresponds to dense grass)
Dstore-Imperv	Depth of depression storage (i.e., the maximum surface storage provided by ponding, surface wetting, and interception) for impervious and pervious surfaces.	Inches	0.1, 0.075, and 0.05 for slopes of 3%, 7.5%, and 15%, respectively
Dstore-Perv		Inches	0.2, 0.15, and 0.1 for slopes of 3%, 7.5%, and 15%, respectively
%Zero-Imperv	Percent of the impervious area with no depression storage.	%	25
Groundwater	--	-	Not simulated
Snowmelt	--	-	Not simulated

¹ Source of description and selected model input values obtained from USEPA, 2015 unless otherwise indicated.

Soil parameter model input values are provided in Table 1.H-2.

Table 1.H-2: Green-Ampt Soil Parameters

Hydrologic Soil Group	Prevalent Soil Texture Class	Saturated Soil Conductivity (in/hr)		Suction Head ¹ (in)	IMD ¹ (in/in)
		Existing Condition ¹	Developed Condition ²		
A	Sand, Loamy Sand	2.5	1.88	2.61	0.34
B	Sandy Loam	0.3	0.23	6.02	0.22
C	Loam	0.15	0.11	10.4	0.13
D	Clay	0.1	0.08	7.4	0.17

¹ HSG A and B estimated based on texture class from Rawls, et al., (1983); HSG C and D estimated through calibration, see the “Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation” Memo [PR-5].

² Determined based on an assumption of 25% reduction of conductivity due to compaction.

The varied input characteristics resulted in a total of 586 unique pervious HRU models, which are defined by the combinations of rainfall zone, ET zone, HSG, and slope. Additionally, a total of 74 impervious HRU types were modeled, defined by the combinations of rainfall zone, ET zone, and slope. The top 15 most dominant pervious HRU’s account for about 50% of the study area. The two most dominant pervious HRU types represent 14% of the total study area, and are both <1% developed (developed includes urbanized and agricultural areas).

1.I Meteorology

Rainfall files used for hydrologic model are documented in Table 1 and Evaporation data inputs are documented in Table 2 of the GI Quantitative Relationship Reports [PR-2; PR-3].

1.J Drainage System Representation

Storm drain system routing was not modeled, as an HRU approach was used, as described above. However, large-scale drainage routing was accounted for when conducting model calibration and validation. Model calibration and validation is further described in the “Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation Memo” (Geosyntec, 2019b) [PR-5].

1.K Model Calibration

Refer to the “Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation Memo” (Geosyntec, 2019b) [PR-5].

1.L Model Validation

Refer to the “Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation Memo” (Geosyntec, 2019b) [PR-5].

2. GREEN INFRASTRUCTURE LOAD REDUCTION MODELING

A flow chart showing the development and components of the future condition model is provided.

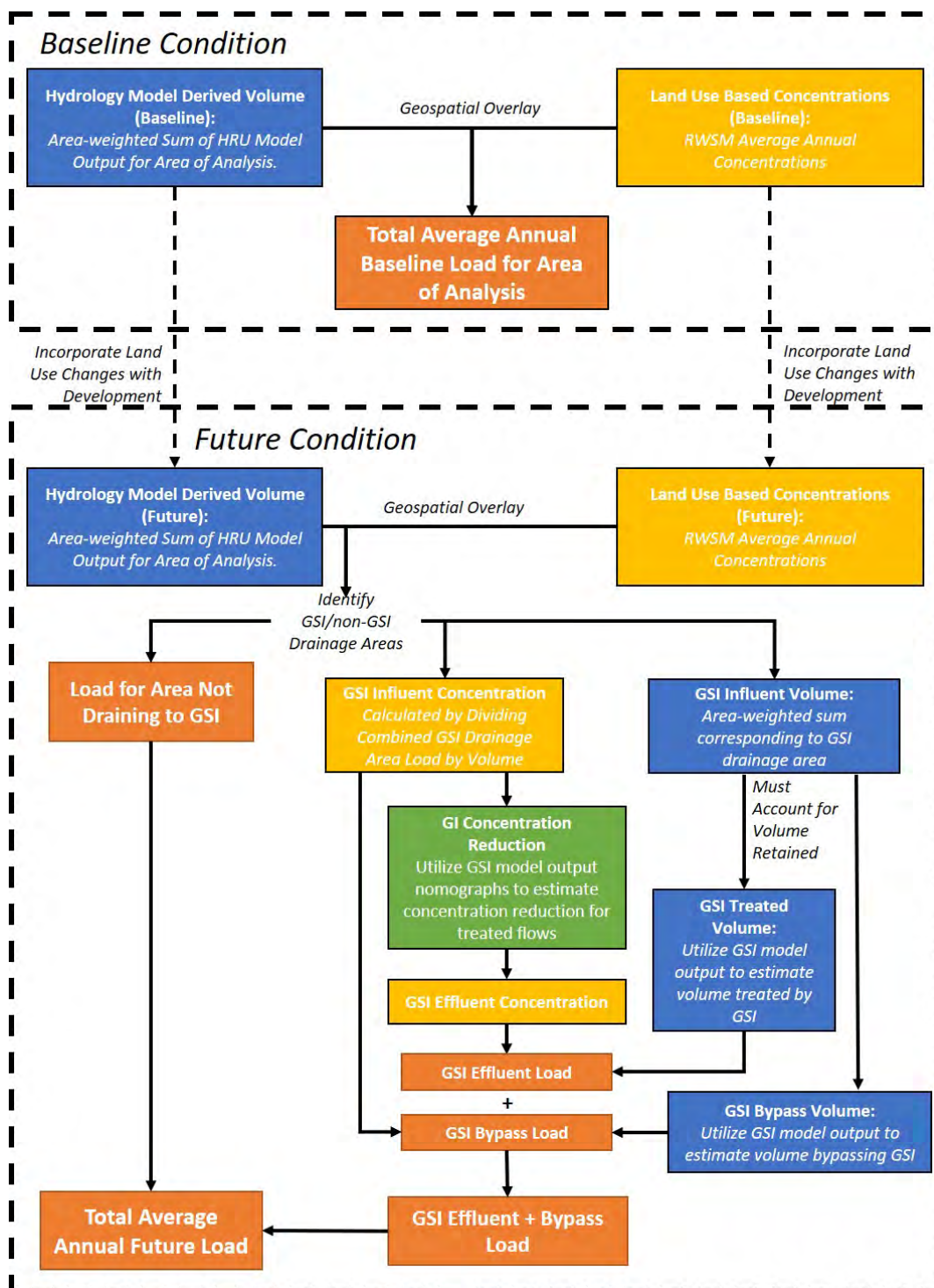


Figure 2-1: Future Condition Model Flow Chart

2.A Load Reduction Goal

The mercury load reduction required to be achieved through GI by 2040 per the MRP is 10 kg/yr MRP area-wide, or 3.1 kg/yr for Alameda County, and 1.7 kg/yr for Contra Costa County.

Calculations were conducted to develop the PCBs load reduction goals as described in the *Bay Area RAA Guidance Document* (BASMAA, 2017). The calculation methodology is summarized below.

2.A.1 TMDL Attainment Load Reduction (2030)

$$LR_{\text{goal}} = \text{Baseline} - \text{WLA (kg/yr)}$$

Where:

$$LR_{\text{goal}} = \text{The load reduction goal (kg/yr)}$$

$$\text{Baseline} = \text{The baseline pollutant loading as calculated through the RAA}$$

$$\text{WLA} = \text{The population-based wasteload allocation}$$

The TMDL population-based wasteload allocations for Alameda County and Contra Costa County are provided Table 2.A-1.

Table 2.A-1: TMDL Population-Based Wasteload Allocations for Alameda County and Contra Costa County

Stormwater Improvement Goal	PCBs (kg/yr)
Alameda County	0.5
Contra Costa County	0.3

2.A.2 RAA Calculated Baseline Load - PCBs

The results of the RAA baseline modeling are presented for Alameda County and for Contra Costa County in Table 2.A-2, below. The baseline countywide load used to establish the PCBs load reduction goal for the Permittee area is shown in bold. Refer to the RAA Guidance Document Section 2 and Section 3.5 (BASMAA, 2017) for details on the calculation methodology.

Table 2.A-2: RAA Model Baseline Loading Estimates – PCBs

RWQCB Region	Above/Below Dam	Permit	Baseline Load Alameda County (kg/yr)	Baseline Load Contra Costa County (kg/yr)
Region 2	Below Dam	MRP	3.6	1.6
		NPDES	0.2	0.8
		Phase 2	0.5	<0.1
	Above Dam	MRP	<0.1	<0.1
		NPDES	0.0	<0.1
		Phase 2	0.0	0.0
Region 5	Below Dam	MRP	<0.1	0.1
		NPDES	0.0	<0.1
		Phase 2	0.0	<0.1
	Above Dam	MRP	0.0	<0.1
		NPDES	0.0	0.0
		Phase 2	0.0	0.0
		Total	4.3	2.6

Using the preliminary RAA-calculated baseline load¹ of PCBs for each County, the load reduction goal is estimated to be 3.1 kg/yr for Alameda County and 1.3 kg/yr for Contra Costa County.

2.A.3 MRP Load Reduction through GI by 2040

The PCBs load reduction required to be achieved through GI by 2040 (i.e., 3 kg/yr MRP area-wide or 0.9 kg/yr for Alameda County and 0.5 kg/yr for Contra Costa County) must be adjusted to reflect the RAA-calculated baseline load (i.e., 3.6 kg/yr and 1.6 kg/yr for Alameda and Contra Costa Counties, respectively). The MRP load reduction requirement for GI for all permittees (3 kg/yr) represents 20.8% of the overall required TMDL load reduction. Therefore, the adjusted countywide load reduction through GI can be calculated as:

$$LR_{MRP, GI, 2040} = LR_{goal} * 20.8\%$$

The adjusted countywide PCBs load reduction goal through GI by 2040 are calculated as summarized in Table 2.A-3.

Table 2.A-3: Adjusted Countywide PCBs Load Reduction Goals through GI by 2040

County	PCBs Load Reduction Goal through GI (kg/yr)
Alameda County	0.6
Contra Costa County	0.3

2.B Overall Methodology to Account for GI Load Reductions

Refer to Sections 2.3, 3.2, and 3.3 of the GI Quantitative Relationship Reports [PR-2; PR-3].

¹ As of the May 2019 draft model run; the final baseline load is subject to change per peer review comments

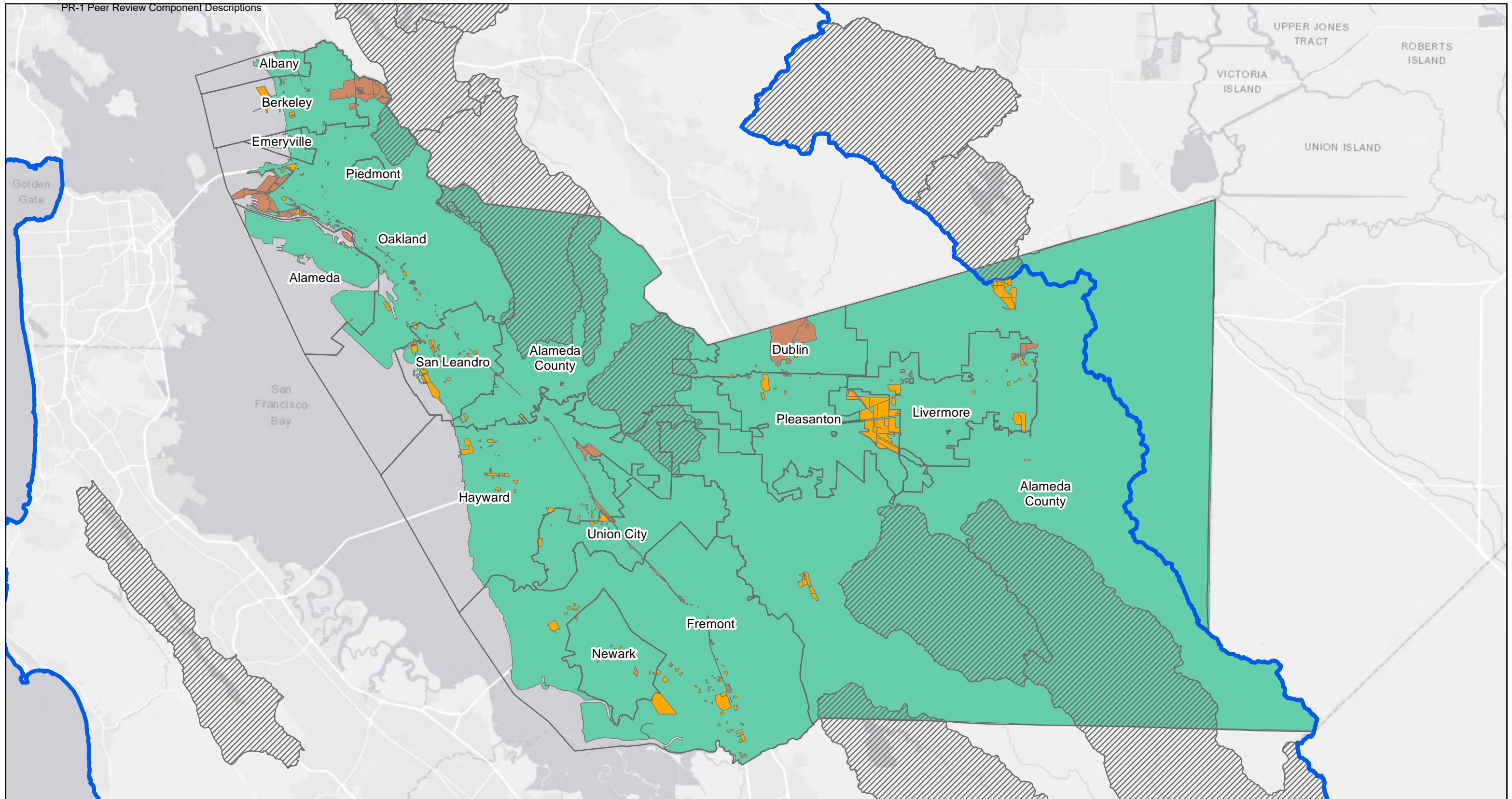
2.C Load Reduction Calculation Method

The load reduction is calculated based on the difference between the baseline PCBs and mercury load and the PCBs and mercury load accounting for GI. The baseline model produces a PCBs and mercury load for each County, along with a “load production” GIS layer that estimates the load corresponding with each parcel and ROW segment within each County (note that individual parcel loadings should be considered representative of the ‘average tendency’ of loading for similar parcels). This “load production” layer is revised for the future condition based on land use changes, then combined in GIS with planned green infrastructure projects to estimate the resulting parcel load, assuming standard bioretention treatment. The estimated load reduced per acre using this approach is calculated and presented in Sections 4 and 5 of the GI Quantitative Relationship Reports [PR-2; PR-3].

The sum of the revised and treated parcel loads, across each County, provides the load under the future estimated condition. This future estimated load is then subtracted from the baseline estimated load to estimate loads reduced.

3. REFERENCES

- ACCWP, 2018. Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions. September 28.
- BASMAA, 2017. Bay Area Reasonable Assurance Analysis Guidance Document. Prepared by Geosyntec Consultants and Paradigm Environmental. June.
- BASMAA, 2019. Peer Review for SF Bay PCBs and Mercury Reasonable Assurance Analyses (RAAs) for Green (Stormwater) Infrastructure Instructions/Guidance to Peer Reviewers. August.
- CCCWP, 2018. Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions. August 22.
- Geosyntec Consultants, 2019a. Regional Watershed Spreadsheet Model Version 1.0 Results Summary Memorandum. April 30.
- Geosyntec Consultants, 2019b. Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation Memorandum. August 7.
- USEPA, 2015. Storm Water Management Model User’s Manual Version 5.1. September.
- Wu, J., Gilbreath, A.N., McKee, L.J., 2017. Regional Watershed Spreadsheet Model (RWSM): Year 6 Progress Report. A technical report prepared for the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP), Sources, Pathways and Loadings Workgroup (SPLWG), Small Tributaries Loading Strategy (STLS). Contribution No. 811. San Francisco Estuary Institute, Richmond, California.



Legend

- Municipalities
- Area Above Dams¹
- RWQCB Region 2 Boundary
- RWQCB Region 5

Stormwater Permit Coverage

- Individual Stormwater NPDES Permit
- Phase II General Stormwater Permit Water Quality Order 2013-0001-DWQ
- MS4

Notes:

1. Areas above Dams are not included in baseline load estimated for Municipal Regional Stormwater Permittees. Areas covered under different stormwater permits (i.e., individual NPDES permits, Phase II permit) are not included in baseline load estimates for Municipal Regional Stormwater Permittees.



0 20,000 Feet

**Alameda County RAA
Baseline Loading Analysis Area**

Alameda County
California

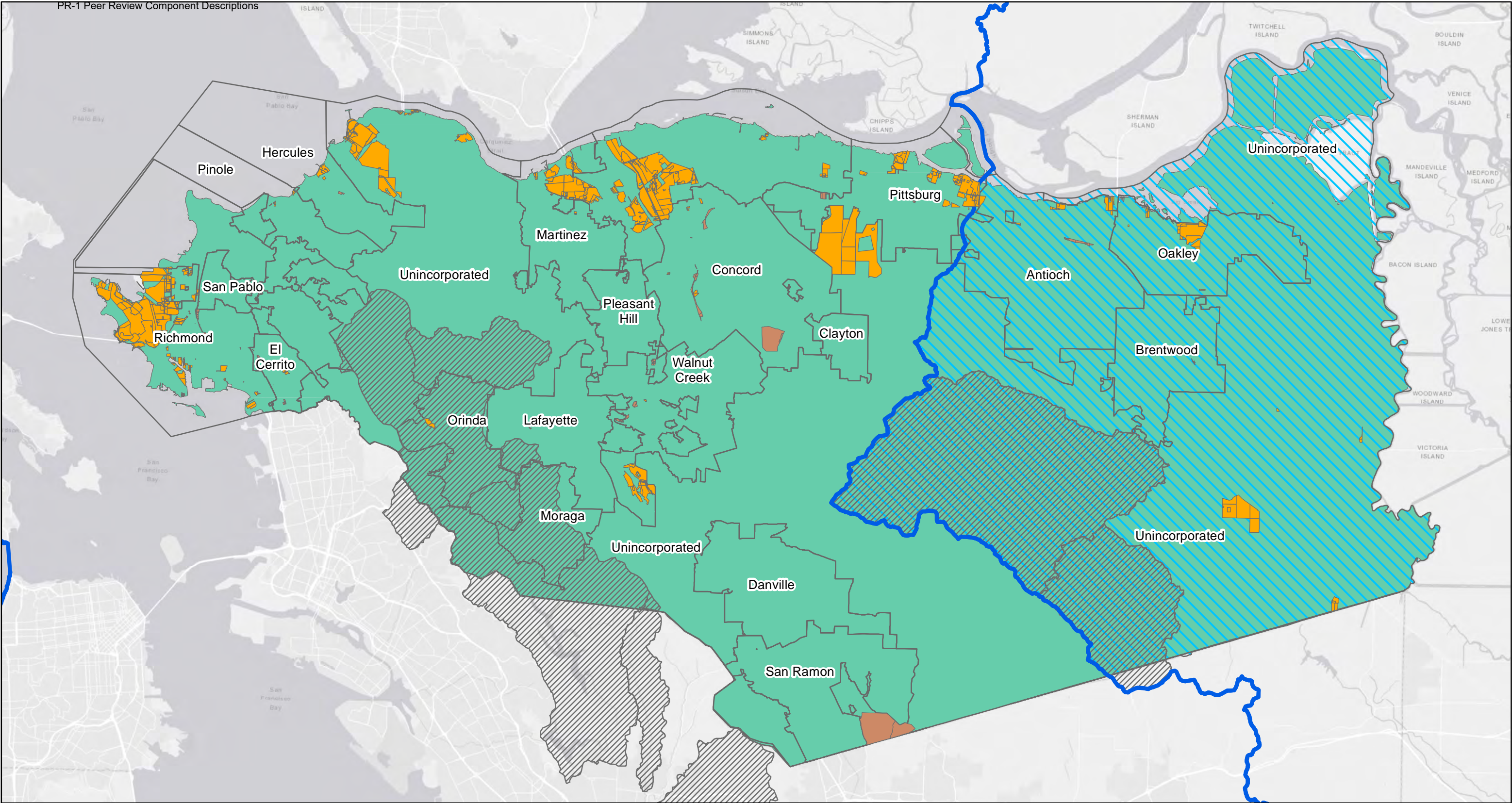
Geosyntec
consultants

Figure

1A

Oakland

October 2019



Legend

□ Municipalities

▨ Area Above Dams¹

▬ RWQCB Region 2 Boundary

▨ RWQCB Region 5

Stormwater Permit Coverage

■ Individual Stormwater NPDES Permit

■ Phase II General Stormwater Permit Water Quality Order 2013-0001-DWQ

■ MS4

Notes:

1. Areas above Dams are not included in baseline load estimated for Municipal Regional Stormwater Permittees. Areas covered under different stormwater permits (i.e., individual NPDES permits, Phase II permit) are not included in baseline load estimates for Municipal Regional Stormwater Permittees.



0 18,000 Feet

**Contra Costa County RAA
Baseline Loading Analysis Area**

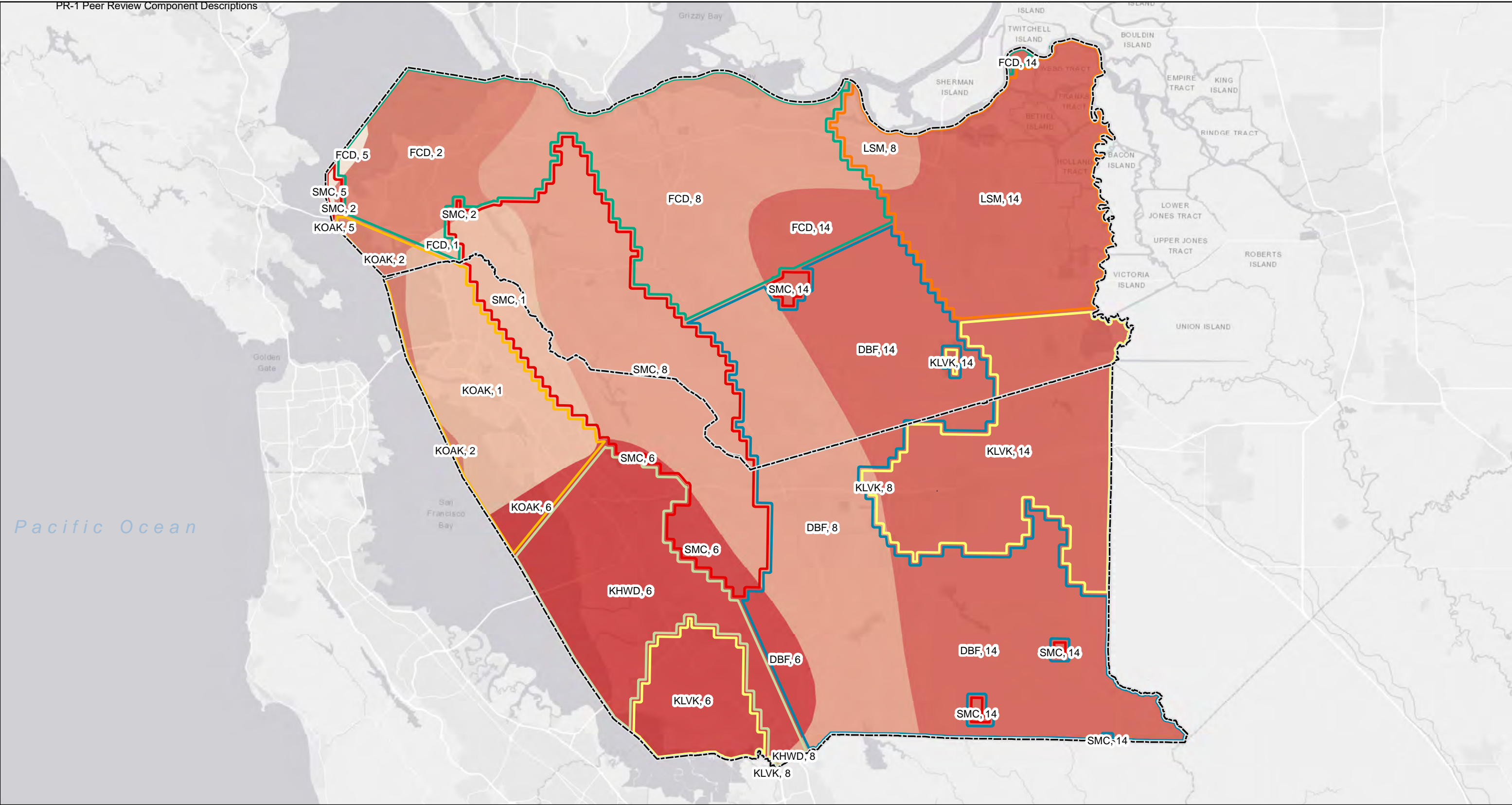
Contra Costa County
California

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Oakland

October 2019

**Figure
1B**



County Boundary

Rain Gauge Zones

DBF

FCD

KHW

KLV

KOAK

LSM

SMC

CIMIS ET Zone

1

2

5

6

8

14

Climate Zones are created by overlapping precipitation zones and ET zones. In Contra Costa County and Alameda County, unique climate zones are labeled as "Gauge ID, ET Zone".



RAA Climate Zones

Alameda County and Contra Costa County
California

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Oakland

Figure
PR-1C

November 2019

PR-2 Alameda Countywide Clean Water Program GI Quantitative Relationship Report



MEMBER AGENCIES:

Alameda
Albany
Berkeley
Dublin
Emeryville
Fremont
Hayward
Livermore
Newark
Oakland
Piedmont
Pleasanton
San Leandro
Union City
County of Alameda
Alameda County Flood
Control and Water
Conservation District
Zone 7 Water Agency

ALAMEDA COUNTYWIDE CLEAN WATER PROGRAM

QUANTITATIVE RELATIONSHIP BETWEEN GREEN INFRASTRUCTURE IMPLEMENTATION AND PCBS/MERCURY LOAD REDUCTIONS

Report prepared by:

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Submitted to:

California Regional Water Quality
Control Board, San Francisco Bay Region

September 28, 2018

Acknowledgements

This report was prepared in cooperation with the Contra Costa County Clean Water Program. Geosyntec Consultants contributed substantially to the writing and preparation of this report.

Preface

This *Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions* was prepared by the Alameda Countywide Clean Water Program (ACCWP) per the Municipal Regional Permit (MRP; NPDES Permit No. CAS612008; Order No. R2-2015-0049) for urban stormwater issued by the San Francisco Bay Regional Water Quality Control Board. This report fulfills the requirements of MRP Provisions C.11.b.iii.(3), C.11.c.iii.(1), C.12.b.iii.(3), and C.12.c.iii.(1) to submit refinements to the measurement and estimation methodologies for assessing mercury and PCBs load reductions in the next permit term and the quantitative relationship between green infrastructure implementation and mercury and PCBs load reductions that will be used for the reasonable assurance analyses.

This report is submitted by ACCWP on behalf of the following Permittees:

- The cities of Alameda, Albany, Berkeley, Dublin, Emeryville, Fremont, Hayward, Livermore, Newark, Oakland, Piedmont, Pleasanton, San Leandro, and Union City;
- Alameda County;
- Alameda County Flood Control and Water Conservation District; and
- Zone 7 of the Alameda County Flood Control and Water Conservation District (Zone 7 Water Agency).

LIST OF ACRONYMS

ASOS	Automated Surface Observation System
BASMAA	Bay Area Stormwater Management Agencies Association
BMP	Best Management Practices
CCCWP	Contra Costa Clean Water Program
CIMIS	California Irrigation Management Information System
GI	Green Infrastructure
GIS	Geographic Information System
HRU	Hydrologic Response Unit
KTRL	Kendall-Theil Robust Line
MAD	Median Absolute Deviation
MRP	Municipal Regional Permit
MS4	Municipal Separate Storm Sewer System
ng/kg	nanogram per kilogram
NPDES	National Pollutant Discharge Elimination System
PCBs	Polychlorinated Biphenyls
RAA	Reasonable Assurance Analysis
RMSE	Root Mean Square Error
ROW	Right-of-Way
RWSM	Regional Watershed Spreadsheet Model
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SFEI	San Francisco Estuary Institute
SWMM	Stormwater Management Model
TMDL	Total Maximum Daily Load
USEPA	United States Environmental Protection Agency
USGS	United States Geologic Survey
WY	Water Year

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1. INTRODUCTION

1.1 Purpose

This *Quantitative Relationship between Green Infrastructure Implementation and PCBs/Mercury Load Reductions* report was prepared by the Alameda Countywide Clean Water Program (ACCWP) per the Municipal Regional Permit (MRP) for urban stormwater issued by the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB; Order No. R2-2015-0049). This report fulfills the requirements of MRP Provisions C.11.b.iii.(3), C.11.c.iii.(1), C.12.b.iii.(3), and C.12.c.iii.(1) for submitting the quantitative relationship between green infrastructure (GI) implementation and PCBs load reductions that will be used for the Reasonable Assurance Analysis (RAA) required by MRP Provisions C.11.c.ii.(2), C.11.d.ii, C.12.c.ii.(2), and C.12.d.ii.

This report was prepared in cooperation with the Contra Costa Clean Water Program. The RAA modeling described herein will be conducted for both countywide programs and will use data inputs from both Alameda County and Contra Costa County.

1.2 Background

1.1.1 PCBs and Mercury Total Maximum Daily Loads

Fish tissue monitoring in San Francisco Bay has revealed bioaccumulation of PCBs, mercury, and other pollutants. The levels found are thought to pose a health risk to people consuming fish caught in the Bay. As a result of these findings, California has issued an interim advisory on the consumption of fish from the Bay. The advisory led to the Bay being designated as an impaired water body on the Clean Water Act "Section 303(d) list" due to PCBs and mercury. In response, the SFBRWQCB has developed Total Maximum Daily Load (TMDL) water quality restoration programs targeting PCBs and mercury in the Bay. The general goals of the TMDLs are to identify sources of PCBs and mercury to the Bay and implement actions to control the sources and restore water quality.

Municipal separate storm sewer systems (MS4s) are one of the PCBs and mercury source/pathways identified in the TMDL plans. Local public agencies (i.e., Permittees) subject to requirements via National Pollutant Discharge Elimination System (NPDES) permits are required to implement control measures in an attempt to reduce PCBs and mercury from entering stormwater runoff and the Bay. These control measures, also referred to as Best Management Practices (BMPs), are the tools that Permittees can use to assist in restoring water quality in the Bay.

1.1.2 Municipal Regional Permit

NPDES permit requirements associated with Phase I municipal stormwater programs and Permittees in the Bay area are included in the MRP, which was issued to 76 cities, counties and flood control districts in 2009 and revised in 2015. The MRP includes provisions to reduce loads of mercury and PCBs consistent with the TMDL implementation timeframe (Provisions C.11 and C.12, respectively) through implementation of GI projects (Provisions C.3.j, C.11.c, and C.12.c) and source controls (Provisions C.11.d and C.12.d).

The Permittees are reporting load reductions achieved before and during the current MRP term (2014 – 2020) using the approved Interim Accounting Methodology (BASMAA, 2017). MRP Provisions C.11.b.iii.(3) and C.12.b.iii.(3) requires the Permittees to report in the 2018 and subsequent Annual Reports any refinements to the Interim Accounting Methodology to be used in subsequent Permit terms. As part of this reporting requirement, Provision C.11.c.iii.(3) and C.12.c.iii.(1) requires the Permittees to report on the quantitative relationship between GI implementation and PCBs and mercury load reductions, including all data used and a full description of models and model inputs relied on to establish this relationship.

Green Infrastructure Planning and RAA

MRP Provision C.3.j requires the Permittees to develop a Green Infrastructure Plan for inclusion in the 2019 Annual Report. The Green Infrastructure Plan must be developed using a mechanism to prioritize and map areas for potential and planned GI projects, both public and private, on a drainage-area-specific basis, for implementation by 2020, 2030, and 2040.

MRP Provisions C.11.c and C.12.c require the Permittees to prepare an RAA for inclusion in the 2020 Annual Report that quantitatively demonstrates that specified mercury and PCBs load reductions will be achieved by 2040 through implementation of GI.

This RAA should do the following:

1. Quantify the relationship between the areal extent of GI implementation (e.g., acres treated) and mercury and PCBs load reductions. This quantification should take into consideration the scale of contamination of the treated area as well as the pollutant removal effectiveness of GI strategies likely to be implemented.
2. Estimate the amount and characteristics of land area that will be treated by GI by 2020, 2030, and 2040.
3. Estimate the amount of mercury and PCBs load reductions that will result from GI implementation by 2020, 2030, and 2040.

4. Ensure that the calculation methods, models, model inputs, and modeling assumptions used have been validated through a peer review process.

Additionally, MRP Provisions C.11.d. and C.12.d. require the Permittees to prepare plans and implementation schedules for mercury and PCBs control measures and an RAA demonstrating that sufficient control measures will be implemented to attain the mercury TMDL wasteload allocations by 2028 and the PCBs TMDL wasteload allocations by 2030. The implementation plans, which will also be included in the 2020 Annual Report, along with the GI-based RAA outlined above, must:

1. Identify all technically and economically feasible mercury or PCBs control measures (including GI projects, but also other control measures such as source property identification and abatement, managing PCBs in building materials during demolition, enhanced operations and maintenance, and other source controls) to be implemented;
2. Include a schedule according to which technically and economically feasible control measures will be fully implemented; and
3. Provide an evaluation and quantification of the mercury and PCBs load reduction of such measures as well as an evaluation of costs, control measure efficiency, and significant environmental impacts resulting from their implementation.

This report presents the quantitative relationship between GI implementation and PCBs and mercury load reductions, including the data used and a full description of models and model inputs relied on to establish this relationship. This relationship will be used to predict loads reduced through GI implementation for the RAAs described above and to report loads reduced through GI implementation in the subsequent Permit term.

2. DESCRIPTION OF RAA MODEL

This section provides an overview of the RAA modeling framework and describes the output of each component.

2.1 RAA Model Overview

The approach used to estimate the load reductions resulting from implementation of GI includes the model components listed below, which are described in further detail in the following sections:

- **Baseline Pollutant Loading Model** – the baseline pollutant loading model is a continuous simulation¹ hydrology model combined with pollutant loading inputs to obtain the average annual loading of mercury and PCBs across the county during the TMDL baseline period (i.e., 2003 – 2005).
 - **Hydrology** – this model component produces average annual runoff across each county for the period of record using a hydrologic response unit (HRU) approach. The HRU approach involves modeling various combinations of land surface features (i.e., imperviousness, underlying soil characteristics, slope, etc.) present within each county for a unit area drainage catchment. See Section 2.2.1.
 - **Water Quality** – the hydrology output is combined with average annual concentrations estimated by the Regional Monitoring Program’s Regional Watershed Spreadsheet Model (RWSM; Wu et al, 2017) developed by the San Francisco Estuary Institute (SFEI) to produce average annual PCBs and mercury loading for the period of record. See Section 2.2.2.
- **GI Performance Models** – the GI performance models are developed to represent load reductions resulting from implementation of GI. See Section 2.3.
- **Future Condition (RAA Scenario) Models** – the RAA scenario models are conducted to represent future land use changes and control measure implementation that could result in pollutant load reduction. Both GI and source controls are considered, depending on the time frame of interest. See Section 2.4 for a description of load reduction calculations.

2.2 Baseline Loading Model

2.2.1 Hydrologic Model

As introduced above, the proposed approach for modeling hydrology is to use a hydrologic response unit (HRU) approach. An HRU is a unique combination of land surface features (imperviousness, underlying soil characteristics, slope, etc.) which is expected to give a consistent runoff response to rainfall, no matter where that unique combination is found. The HRU approach involves modeling all possible combinations of land surface features present within each county for a unit area drainage catchment and then storing these results in a database. These HRU results can be scaled geospatially across the entire county without developing

¹ Continuous simulation models calculate outputs (e.g., runoff) “continuously”, i.e., for many time steps over a long-term period of record (e.g., every 10 minutes for 10 years). Long-term “continuous” input data (e.g., hourly rainfall) is required. This is contrasted with design-event simulations which model a single rainfall event, e.g., a 24-hour storm with a 10-year recurrence frequency.

a detailed hydrologic model. This method is consistent with the *Bay Area RAA Guidance Document* (BASMAA, 2017b).

The generic HRUs are modeled using USEPA's Stormwater Management Model (SWMM) to obtain an average annual runoff volume per acre for the identified baseline period of record (water year [WY] 2000 – 2009) for each HRU. Certain HRU inputs (imperviousness, soil parameters) are adjusted as needed to calibrate the HRUs on an average annual basis to identified flow gauges in the counties.

The average annual runoff volume per acre associated with a specific HRU can then be multiplied by the area represented by that HRU across each county (or a selected smaller planning area, such as a watershed or jurisdictional boundary). The resulting volumes associated with each represented HRU within the specified geospatial area can then be summed for the identified area to obtain the estimated total average annual runoff volume.

2.2.2 Water Quality Model

Identified HRUs across each county are combined with the RWSM land use classifications layer to determine pollutant loading rates. The RWSM provides average annual concentrations of PCBs and mercury that wash off from various land use categories. On an average annual basis, this approach approximates the total load.

Average annual runoff volume associated with the geospatial HRUs is multiplied by the PCBs and mercury average annual concentration (based on the RWSM land use categories for the identified area) to obtain average annual pollutant load using the following equation:

$$Load_{Baseline} = \sum(\sum Unit\ Runoff_{HRU} \times Area_{LU,HRU}) \times Concentration_{LU} \times 0.00123 \quad \text{Eqn. 1}$$

Where:

- Load_{Baseline} = The total average annual baseline pollutant load for the identified area for calculation [grams/year]
- Unit Runoff_{HRU} = The average annual runoff per acre for a given HRU within the identified area for calculation [ac-ft/acre/yr]
- Area_{LU,HRU} = The total area of the HRU within the RWSM land use category within the identified area for calculation [acres]
- Concentration_{LU} = The average annual pollutant concentration associated with the RWSM land use category [ng/L]

0.00123 = Conversion factor $[(L/ac-ft)*(g/ng)]$

2.3 Green Infrastructure Performance Model

Volume reduction (via retention in the green infrastructure facility) and pollutant load reduction (via filtration through media and discharge through an underdrain) are modeled utilizing a combination of hydraulic modeling in SWMM and currently available empirical GI performance data.

2.3.1 Hydraulic GI Models

GI control measure hydraulic performance is modeled in SWMM with a 100% impervious tributary area for three GI facility types: (1) bioretention² with a raised underdrain, (2) bioretention with no underdrain, and (3) lined bioretention. The model is run with varying footprint sizes and varying underlying infiltration rates (i.e., the rate at which treated runoff infiltrates into native soils underlying the BMP facility). Average annual volume retained, volume treated, and volume bypassed by the GI measure are recorded for each GI model run.

Volume-based performance³ corresponding to the generic 100% impervious tributary area can be applied to the effective area in GI drainage areas made up of identified HRUs. The effective area is also known as the “runoff generating area” and is calculated as the tributary area multiplied by the long-term or average annual runoff coefficient.

2.3.2 Green Infrastructure Pollutant Reduction Calculations

To calculate pollutant load reduction associated with GI implementation, the hydraulic model results are combined with water quality performance data. The annual estimate of pollutant load reduction from the modeled drainage area is equivalent to the difference between the influent load and the sum of the pollutant load that bypasses the GI measure and the effluent load (Eqn. 2). Equations corresponding to the pollutant reduction calculation are provided below and the water balance is illustrated in Figure 1. In summary, influent load is calculated as the pollutant load produced by the 100% impervious tributary area for each RWSM land use category using Eqn. 3. The pollutant load that bypasses the facility is calculated as the proportion of runoff that bypasses the facility per the hydraulic GI model output, multiplied by the influent concentration

² The bioretention is assumed to include: 6-inch or 12-inch ponding depth, 1.5 ft of filter media with a 5 in/hr flow through rate, and 1 ft of gravel beneath the media.

³ Volume-based performance refers to how much runoff volume the GI facility captures and retains or treats and discharges through the underdrain, typically represented as a percentage of the average annual runoff volume.

(Eqn. 4). The effluent load is calculated as the proportion of runoff that is captured by the facility per the hydraulic GI model output, combined with an effluent concentration (Eqn. 5 and Eqn. 6).

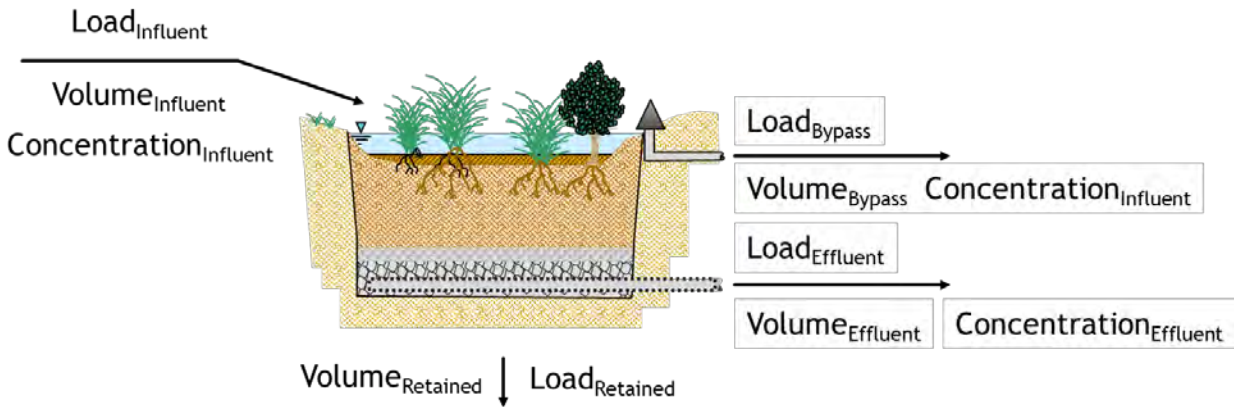


Figure 1: Illustration of GI Facility Pollutant Load Reduction Calculations

$$Load_{Reduced} = Load_{Influent} - Load_{Bypass} - Load_{Effluent} \quad \text{Eqn. 2}$$

$$Load_{Influent} = Volume_{Influent} \times Concentration_{Influent} \times C \quad \text{Eqn. 3}$$

$$Load_{Bypass} = Volume_{Bypass} \times Concentration_{Influent} \times C \quad \text{Eqn. 4}$$

$$Load_{Effluent} = (Volume_{Captured} - Volume_{Retained}) \times Concentration_{Effluent} \times C \quad \text{Eqn. 5}$$

$$Volume_{Captured} = Volume_{Influent} - Volume_{Bypass} \quad \text{Eqn. 6}$$

Where:

$Load_{Reduced}$ = The total average annual pollutant load reduced by the GI facility [g/year]

$Load_{Influent}$ = The total average annual pollutant load produced by the facility drainage area [g/year]

$Load_{Bypass}$ = The pollutant load that bypasses the facility [g/year]

$Load_{Effluent}$ = The pollutant load discharged from the facility after treatment [g/year]

$Volume_{Influent}$ = The runoff produced by the drainage area to the GI facility [ac-ft/year]

$Volume_{Bypass}$ = The proportion of influent runoff that bypasses the facility [ac-ft/year]

$\text{Volume}_{\text{Captured}}$	=	The proportion of influent runoff that is captured by the facility [ac-ft/year]
$\text{Volume}_{\text{Retained}}$	=	The proportion of captured runoff that is retained by the facility through infiltration and/or evapotranspiration [ac-ft/year]
$\text{Concentration}_{\text{Influent}}$	=	The pollutant concentration associated with the GI drainage area [ng/L]
$\text{Concentration}_{\text{Effluent}}$	=	The concentration discharged from the facility after treatment [ng/L]
C	=	Conversion factor constant = 0.00123 [(L/ac-ft)*(g/ng)]

2.4 RAA Scenario Loading Model

The loading corresponding with RAA future condition scenarios (2020, 2030, 2040) will be developed using the same volume and concentration combination approach used for the baseline condition. HRU outputs developed for the baseline model will scaled across the county corresponding to anticipated land use and development changes for each of the future conditions. Similarly, the RWSM land use classifications layer will be updated corresponding to each future condition scenario.

The outputs of the future hydrology scaling combined with the concentrations corresponding with future RWSM land use classification provides the land use-based loading estimated for each of the future conditions. To obtain the discharged load corresponding to each future GI scenario, load reductions associated with anticipated GI (developed as described above) will be subtracted from the land use-based load.

3. MODEL INPUTS AND DATA USED

This section describes the inputs to each component of the model and the data used.

3.1 Baseline Loading Model

3.1.1 Hydrologic Model

Generic HRU models are developed in SWMM to estimate average annual runoff volume per acre values that can be applied to all land surfaces within each county. The land surface feature inputs that will be varied to model the generic HRUs are described in the sections below and summarized in Table 3.

Climate Inputs

HRU climate inputs provide the total amount of precipitation that falls on the land surface and the amount of precipitation that is lost to the atmosphere via evapotranspiration before running off the land surface. Multiple gauges from across Alameda and Contra Costa counties that had continuous hourly precipitation data were chosen to represent distinct rainfall regions within both counties. For precipitation, these regions are based on 30-year annual rainfall regimes as identified by PRISM⁴. For evapotranspiration rates, the California Irrigation Management Information System (CIMIS) evapotranspiration zones were used within each county. The combination of the identified precipitation regions and evapotranspiration regions were combined to yield “climate zones” used for generic HRU models. Precipitation zones, evapotranspiration zones, and climate zones are shown in Exhibit 1 through Exhibit 3 (see Appendix A). Table 1 provides a summary of precipitation gauges used and average annual rainfall corresponding to the entire period of record and WY 2000 - 2009. Table 2 provides a summary of the CIMIS data used for the daily reference evapotranspiration rate for each evapotranspiration zone.

Table 1: HRU Precipitation Gauges WY2000-2009

Gauge ID	Gauge Name	Average Annual Precipitation (inches) WY 2000 - 2009	Gauge Source
KHWD	Hayward Air Terminal (ASOS)	16.3	ASOS ¹
KLVK	Livermore Municipal Airport (ASOS)	14.6	ASOS
KOAK	Oakland Airport (ASOS)	19.0	ASOS
DBF	Dublin Fire Station, San Ramon	17.3	CCCFC ²
FCD	Flood Control District, Martinez	16.2	CCCFC
LSM	Los Medanos, Pittsburg	11.8	CCCFC
SMC	Saint Mary's College, Moraga	28.9	CCCFC

1. Automated Surface Observation System (ASOS) data were used for Alameda County gauge sites for the period of WY2000-2009 since NCDC gauge data was not available for the baseline period. ASOS sites sometimes co-occur with NCDC gauge sites (e.g., airports), but are maintained and delivered by separate government entities.
2. Contra Costa County gauge data is collected by the Flood Control District but was provided to Geosyntec by Dubin Engineering.

⁴ Parameter-elevation Relationships on Independent Slopes Model (PRISM), developed and managed by the PRISM Climate Group, Oregon State University <http://prism.oregonstate.edu/>.

Table 2: CIMIS Reference Evapotranspiration

ET Zone	Monthly Evapotranspiration (in/day) ¹											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.03	0.05	0.08	0.11	0.13	0.15	0.15	0.13	0.11	0.08	0.04	0.02
2	0.04	0.06	0.1	0.13	0.15	0.17	0.16	0.15	0.13	0.09	0.06	0.04
3	0.06	0.08	0.12	0.16	0.17	0.19	0.18	0.17	0.14	0.11	0.08	0.06
6	0.06	0.08	0.11	0.16	0.18	0.21	0.21	0.2	0.16	0.12	0.08	0.06
8	0.04	0.06	0.11	0.16	0.2	0.23	0.24	0.21	0.17	0.11	0.06	0.03
14	0.05	0.08	0.12	0.17	0.22	0.26	0.28	0.25	0.19	0.13	0.07	0.05

1. CIMIS reference evapotranspiration, which is based on irrigated turf grass, was scaled by 0.6 to represent the local mix of vegetated cover including urban vegetation, native xeric adapted plants, and unirrigated vegetated open space areas.

Slope

Slope affects how quickly rainfall will run off a modeled land surface and therefore how much is able to be infiltrated into the subsurface. The available digital elevation model (DEM)⁵ for the counties was analyzed to obtain percent slope values for each ~30m by ~30m square of land surface. These percent slope values were classified into three distinct slope zones as summarized in Table 3 and shown in Exhibit 4 (see Appendix A).

Underlying Soil Inputs

Physical characteristics of the soil underlying the land surface affect the amount of rainfall that may be infiltrated into the subsurface. Infiltration was simulated in SWMM using the Green-Ampt infiltration model option. The physical soil input parameters for the Green-Ampt infiltration model were varied based on hydrologic soil group (HSG) as identified by the National Resource Conservation Service (NRCS⁶) soil survey and were modified as described below for developed areas. Soil parameters used as model inputs include suction head, hydraulic conductivity, and initial moisture deficit. Developed areas that are assumed to have been compacted and therefore result in less infiltration to the subsurface are modeled using 75 percent of the HSG hydraulic conductivity value. Soil parameters are not reported here, as this input is adjusted as part of baseline model calibration. Details about soil inputs are provided in Table 3. A map of hydrologic soil group is provided as Exhibit 5 (see Appendix A).

⁵ U.S. Geological Survey. National Elevation Dataset (NED) 1/3 arc-second. 2013

⁶ Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. link: <https://websoilsurvey.sc.egov.usda.gov/>

Areas of development were identified based on the land use of the surface. Soils within urban and agricultural use areas were considered to have been compacted by the site preparation and activities.

Imperviousness

Imperviousness (i.e., the percentage of impervious area) affects area on the land surface where rainfall may be infiltrated and therefore the quantity of runoff produced. The runoff from a range of land use imperviousness values is modeled by area-weighting the results of a pervious surface runoff result (i.e., pervious HRU output) with a corresponding impervious surface runoff result (i.e., impervious HRU output) (see Table 3 and Exhibit 6 (see Appendix A)).

The baseline model HRU imperviousness is developed by geospatially combining the land uses identified by the Association of Bay Area Governments (ABAG, 2005) with the National Land Cover Dataset (NLCD, 2006) data. Each feature of the ABAG dataset is assigned a single imperviousness value that is used to determine the average hydrologic response of that land surface. A lookup-table containing NLCD-based imperviousness for each ABAG land use code was used as a starting value for HRU calibration. Imperviousness may be adjusted within an appropriate range as part of baseline model calibration.

3.1.2 Developing HRUs across each County

Each identified combination of land surface features is modeled for a generic unit-acre drainage area in SWMM for the baseline period of record (i.e., WY 2000 – 2009), utilizing a batch-processing method (which allows for inputs to be altered, model files run, and results extracted for many models automatically). The average annual runoff volume per acre is then extracted for each generic HRU modeled.

Table 3: Land Surface Feature Inputs for Generic HRU Hydrologic Models

Variables	Description	Number of Varying Features	Feature Representations	Source
Hourly Annual Precipitation	Rainfall Gauge and Rainfall Zone	7	Contra Costa County Gauges: DBF, FCD, LSM, SMC Alameda County ASOS Gauges: KHWD, KLVK, KOAK	PRISM ¹ , NCDC/County-maintained rainfall gauges
Daily Evapotranspiration Rate	Evapotranspiration Zone	5	Zones 1, 2, 3, 6, 8, 14	CIMIS ²
Slope Zone	Representation of Slope	3	<5%, 5-15%, 15%+	USGS ³
Developed/Undeveloped Areas	Representation of Compaction of Underlying Soils (Pervious Areas Only)	2	Undeveloped (Ksat * 1) Developed (Ksat * 0.75)	ABAG Land Use 2005 ⁴
Hydrologic Soil Group	Representation of Underlying Soil Type (pervious areas only)	6	HSG A, B, C, D ⁵ , Rock, Water	NRCS ⁶
Imperviousness	Representation of Imperviousness	2	0% and 100%	NLCD and ABAG 2005

1. PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>, 30-year normal mean annual precipitation
2. California Irrigation Management Information System (CIMIS) Reference Evapotranspiration; digitized from http://www.cimis.water.ca.gov/App_Themes/images/etozonemap.jpg
3. U.S. Geological Survey. National Elevation Dataset (NED) 1/3 arc-second. 2013
4. ABAG land use features are proposed to be used for identifying developed and undeveloped condition and will have an imperviousness value assigned based on a geospatial analysis of the NLCD Imperviousness layer. The impervious value for each ABAG land use feature will then be carried into the HRU model calibration and adjusted accordingly.
5. "Urban" representation will be re-classified based on the dominant adjacent HSG.
6. U.S. Department of Agriculture, Natural Resources Conservation Service. Soil Survey Geographic (SSURGO) database. 2016

HRUs are determined geospatially based on the climate zone, slope zone, developed/undeveloped areas, and HSG, along with land use-based imperviousness. Exhibits 1 through 5 (see Appendix A) display the data used to develop climate zones, county slope zones, and the HSG distribution across each county. Imperviousness designations will occur based on

land use at the parcel, by combining the geospatial ABAG land use layer⁷ with the other hydrologic input regions. This results in a “patchwork” of HRUs across the counties⁸.

The resulting patchwork of HRUs can be combined at the scale of choice to provide total runoff volumes for a specific area, such as a watershed or jurisdictional boundary. To estimate the total runoff for the identified area, the total acreage of each designated HRU present within a watershed or jurisdiction will be multiplied by the average annual runoff per acre associated with each HRU and then summed (i.e., area-weighting the average annual runoff volume per acre for all HRUs present).

3.1.3 HRU Input Calibration

Calibration of hydrologic models is required by the *Bay Area RAA Guidance Document*. Calibration of the generic HRU models will be conducted utilizing available stream flow records and based solely upon the annual discharge volume between WY 2000-2009. This annual calibration means that the HRU runoff estimates are representative of the approximate annual runoff volume but will not be used to estimate or compare discharge rates at smaller timesteps, such as the hourly or daily runoff hydrograph.

The list of candidate gauge sites within the counties was developed based on an assessment of the representativeness of the gauged watersheds and the mitigation of confounding factors that interfere with calibration such as missing data and upstream impoundments. For the purposes of calibration, the candidate gauge sites that were selected included stream depth rating curves and at least daily mean records for the historical period of interest. The USGS flow gauges considered for calibration are provided in Table 4 and shown in Exhibit 8 (see Appendix A).

Table 4: Flow Gauge Considered for RAA Model Calibration

Gauge ID	Gauge Name	Location	County	Data Frequency
11337600	Marsh Creek	Brentwood	Contra Costa	Daily
11182500	San Ramon Creek	San Ramon	Contra Costa	Daily
11181390	Wildcat Creek	Richmond / San Pablo	Contra Costa	Daily
11181040	Lan Lorenzo Creek	San Lorenzo	Alameda	Daily
11181008	Castro Valley Creek	Hayward	Alameda	Daily

⁷ ABAG land use features will be used to aggregate the imperviousness for the land surface. The relationship between ABAG feature and its imperviousness will be developed based upon other local sources (SMCWPPP, 2017) and analysis of national public data sets such as the National Land Cover Dataset (NLCD).

⁸ This will be done once all the HRU input files are finalized, including the imperviousness layers.

Gauge ID	Gauge Name	Location	County	Data Frequency
11181000	San Lorenzo Creek	Hayward	Alameda	Daily
11180700	Alameda Creek Flood Channel	Union City	Alameda	Daily
11179000	Alameda Creek	Fremont	Alameda	Daily
11176900	Arroyo de la Laguna	Verona	Alameda	Daily
11173575	Alameda Creek Below Welch Creek	Sunol	Alameda	Daily
11173510	Alameda Creek Below Calaveras Creek	Sunol	Alameda	Daily

The effective area tributary to each flow gauge is used to calibrate the HRUs to the stream gauge records. Annual flow predicted by area-weighting HRU runoff output for the watersheds draining to the stream gauges was compared to annual flow in the stream records for the identified period of record.

Calibration of land surface runoff hydrology to stream gauge records requires that baseflow be computed and accounted for throughout the period of record. A variety of methods exist for separating baseflow from runoff, including the fixed-interval method and the local-minimum method (Sloto and Crouse, 1996). The most appropriate method for separating baseflow is determined on a gauge by gauge basis depending on the variability in the flow record, and the occurrence of confounding factors that affect baseflow such as dam releases and other dry weather inflows.

The average percent difference between the area-weighted HRU total average annual runoff volume for the watershed and the average annual flow (converted to volume) measured for the WY 2000 – 2009 period will be calculated. The acceptable ranges included in the RAA Guidance document are provided in Table 5 below.

Table 5: Allowable Difference between Simulated and Observed Annual Volumes

Model parameters	Average % difference between simulated annual results and observed data		
	Very Good	Good	Fair (lower bound, upper bound)
Hydrology/Flow	<10	10-15	15-25

If the average percent difference between simulated and measured annual storm flow volumes is greater than 25%, HRU model parameters are adjusted until the percent difference is within the acceptable range. The primary model parameters adjusted include underlying soil hydraulic conductivity and land use imperviousness, but other hydrologic model parameters, such as depression storage, may be adjusted as appropriate.

Once average percent differences in all identified watersheds are within the acceptable range, the HRU model parameters are finalized and the HRU results database will be regenerated. HRUs and resulting average annual baseline volume will be applied across each county to obtain the baseline volume discharged by each county.

3.1.4 Water Quality Model

RWSM values used to develop pollutant loading estimates across each county are:

Table 6: Regional Watershed Spreadsheet Model PCBs and Mercury Concentrations in Runoff

Land Use Category	Total PCBs (ng/L)	Total mercury (ng/L)
Ag, Open	0.2	80
New Urban	0.2	3
Old Residential	4	63
Old Commercial/ Transportation	40	63
Old Industrial and Source Areas	204	40

Water quality calculations are also used to perform baseline pollutant loading validation. The calculated pollutant load draining to Regional Monitoring Program stations will be validated by calculating the volume-weighted watershed pollutant concentration using the modeling results and comparing it to the observed concentrations in the Regional Monitoring Program data. The equation used to calculate concentration (in ng/L) at an end-of-watershed location is as follows:

$$Concentration_{Baseline} = \frac{\sum Runoff_{HRU} \times Area_{HRU} \times Concentration_{LU,HRU}}{\sum Runoff_{HRU} \times Area_{HRU}} \quad \text{Eqn. 7}$$

Pollutant concentration and loading data from the Regional Monitoring Program will be compared to the result of Equation 7 for several watersheds for validation purposes.

3.2 **Green Infrastructure Performance Model**

3.2.1 Long-Term Green Infrastructure Simulations

Long term performance was assessed for each BMP configuration using continuous historical rainfall records. In Contra Costa County historical data was available at the same gauges that were used for the HRU runoff modeling between WY2000-2009, but for Alameda County other gauge sites with longer histories were used for long term BMP performance modeling. The rainfall gauges used to model BMP performance are shown in Table 7.

Table 7: Long Term GI Performance Precipitation Gauges

Gauge ID	Gauge Name	Period of Record	Average Annual Precipitation (inches)	Gauge Source ¹
040693	Berkeley (NCDC)	1948-1990	19.8	NCDC
041060	Brentwood (NCDC)	1950-1985	14.9	NCDC
043863	Hayward (NCDC)	1948-1988	24.3	NCDC
046335	Oakland Airport (NCDC)	1948-1985	16.4	NCDC
047821	San Jose Airport (NCDC)	1948-2010	13.6	NCDC
DBF	Dublin Fire Station, San Ramon	1973-2016	15.0	CCCFCF
FCD	Flood Control District, Martinez	1971-2016	16.5	CCCFCF
LSM	Los Medanos, Pittsburg	1974-2016	10.6	CCCFCF
SMC	Saint Mary's College, Moraga	1972-2016	26.8	CCCFCF

1. NCDC data was used for Alameda County and San Jose gauge sites. Contra Costa County gauge data is collected by the Flood Control District and was provided to Geosyntec by Dubin Engineering.

3.2.2 Hydraulic Green Infrastructure Model

Hydraulic GI models were developed in SWMM to estimate hydraulic performance for a 100% impervious tributary area. Hydraulic model inputs that were varied to model the GI facility performance for the counties are described below and summarized in Table 8.

1. BMP Configuration – three GI facility types were assumed: (1) bioretention with a raised underdrain, (2) bioretention with no underdrain, and (3) lined bioretention with an underdrain.
2. BMP Footprint Size – the BMP footprint size was varied as a percent of impervious area to model different levels of hydraulic capture performance depending on facility sizing.
3. BMP Underlying Infiltration Rate – the infiltration rate of the soils underneath the bioretention facility was varied for the bioretention with a raised underdrain and bioretention with no underdrain configurations (i.e., the unlined facility types).

Table 8: Land Surface Feature Inputs for Generic GI Performance Hydraulic Models

Variables	Description	Number of Varying Features	Feature Representations
Hourly Precipitation	Rainfall Gauge	9	NCDC: 040693 (Berkeley) 046335 (Oakland Airport) 043863 (Hayward) 047821 (San Jose) 041060 (Brentwood) Contra Costa County: DBF, FCD, LSM, SMC
Daily Evapotranspiration Rate	Evapotranspiration Zone	4	CIMIS Zones: 1, 6, 8, 14
BMP Configurations	BMP profiles and underdrain	3	Lined Bioretention with underdrain Unlined Bioretention with elevated underdrain Infiltration Basin without underdrain
BMP Surface Ponding Depth	Depth (feet)	2	0.5, 1
BMP Footprint Sizes	% of Impervious Area	12	0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6
BMP Infiltration Rates	Ksat of underlying soil (in/hr)	7	Unlined Bioretention: 0.024, 0.05, 0.1, 0.2, 0.24, 0.3, 0.4, 0.5
		3	Infiltration Basin: 0.5, 1, 2

The BMP cross-sections that were modeled each include:

- 6-inches or 12-inches ponding depth (both were modeled),
- 1.5 ft of filter media with 25% porosity with a 5 in/hr flow through rate, and
- 1 ft of gravel beneath the media with 40% porosity.

Two of the modeled BMP configurations include underdrains. In the lined bioretention facility, the underdrain is located at the bottom of the gravel layer. In the unlined bioretention facility, the underdrain was modeled at the top of the gravel layer. BMP configurations are shown in Exhibits 9 through 11 (see Appendix A).

3.2.3 Green Infrastructure Pollutant Reduction Calculations

As described in Section 2.3.2, pollutant load reduction associated with GI is calculated by combining the hydraulic model results with water quality performance data. The annual estimate

of pollutant load reduction from the modeled drainage area is equivalent to the difference between the influent load and the sum of the pollutant load that bypasses the GI measure and the effluent load. The effluent load is calculated as the proportion of runoff that is treated by the GI measure multiplied by an effluent concentration.

Water quality performance data from selected, representative studies were used to determine a method to predict effluent concentrations in stormwater following treatment through a biofiltration (bioretention or tree well filters) GI measure. The data used to develop the relationship came from three studies: a) 2011 monitoring study of the El Cerrito Rain Gardens (Gilbreath, Pearce, and McKee, 2012), b) Clean Watersheds for a Clean Bay (CW4CB)⁹ (Geosyntec and EOA, 2017), and c) a study at Echo Lake in King County, WA (King County, 2017). A summary of the paired influent-effluent data associated with each study is provided in table:

Table 9: Data used to Develop Effluent Concentrations

Project Name	Project Sponsor	Facility ID	Influent-Effluent Data Pairs (n pairs)	
			PCBs	Mercury
El Cerrito Green Streets – CW4CB	El Cerrito	ELC-B1	3	3
El Cerrito Green Streets – SFEI	SFEI	ELC-B1	4	4
PG&E Substation 1st and Cutting Bioretention Cells – CW4CB	Richmond	LAU-3	8	8
Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin Bioretention Planter Boxes – SAM Effectiveness Study	King County, Dept. of Natural Resources and Parks	BPB-1	4	0
		BPB-2	4	0
		BPB-3	4	0
		BPB-4	2	0
West Oakland Industrial Area Tree Wells – CW4CB	Oakland	ETT-TW2	4	4
		ETT-TW6	4	4
Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin Tree Well – SAM Effectiveness Study	King County, Dept. of Natural Resources and Parks	FLT-1	4	0
Total Data Pairs			41	23

⁹ The CW4CB study included additional monitoring of the El Cerrito rain gardens.

These data were statistically evaluated to identify an appropriate method for predicting effluent concentrations of PCBs and total mercury. The data analysis first evaluated whether available influent and effluent concentration data were significantly different and, if so, whether a monotonic relationship existed (i.e., effluent generally increased when influent increased).

A Wilcoxon non-parametric hypothesis test was run on the PCBs and total mercury paired influent-effluent data to determine if influent and effluent concentrations were statistically different at a 5% significance level. This difference was found to be significant for PCBs, and significant for total mercury when corresponding influent suspended solids concentration was greater than 20 mg/L.

Spearman's rho and Kendall's tau, which are non-parametric rank correlation coefficients, were used to identify the direction and strength of correlation between influent and effluent concentrations. As shown in Table 10, both correlation coefficients suggest that effluent concentrations are positively correlated with influent concentrations for both PCBs and mercury.

Table 10: Influent/Effluent Correlation Coefficients

Correlation Coefficient	Total PCBs	Total Mercury
Spearman's rho	0.725	0.547
Kendall's tau	0.527	0.396

The Kendall-Theil Robust Line (KTRL) method (Granato, 2006) was used to determine the best fit line between influent and effluent data. This non-parametric method uses the median of all possible pairwise slopes between points, which is more robust to outliers than a simple linear regression. Because stormwater data tend to be lognormal, the analysis was focused on linear and log-linear relationships. After the KTRL was generated, the lower portion of the curve was adjusted to assume that neither PCBs nor total mercury can be exported from biofilters under normal circumstances, i.e., that the maximum effluent concentration of PCBs or total mercury is equal to the influent concentration. The resulting KTRL for PCBs is shown Figure 2. The resulting KTRL for total mercury is shown in Figure 3. Each figure also includes a constant average effluent concentration line with data fit statistics: root mean square error (RMSE) and median absolute deviation (MAD). As indicated, the KTRL provide a better fit of the data. However, the resulting effluent concentrations are not much different between the two lines except when influent PCBs are low (<10 ng/L) and total mercury concentration are high (>50 ng/L). For total mercury, concentration reductions are only predicted to occur when influent concentrations are greater than about 30 ng/L. Due to observed export of total mercury for several events, particularly for the 1st and Cutting bioretention cell (LAU-3), the moderate concentration reductions assumed by the KTRL at higher influent concentrations is reasonably conservative.

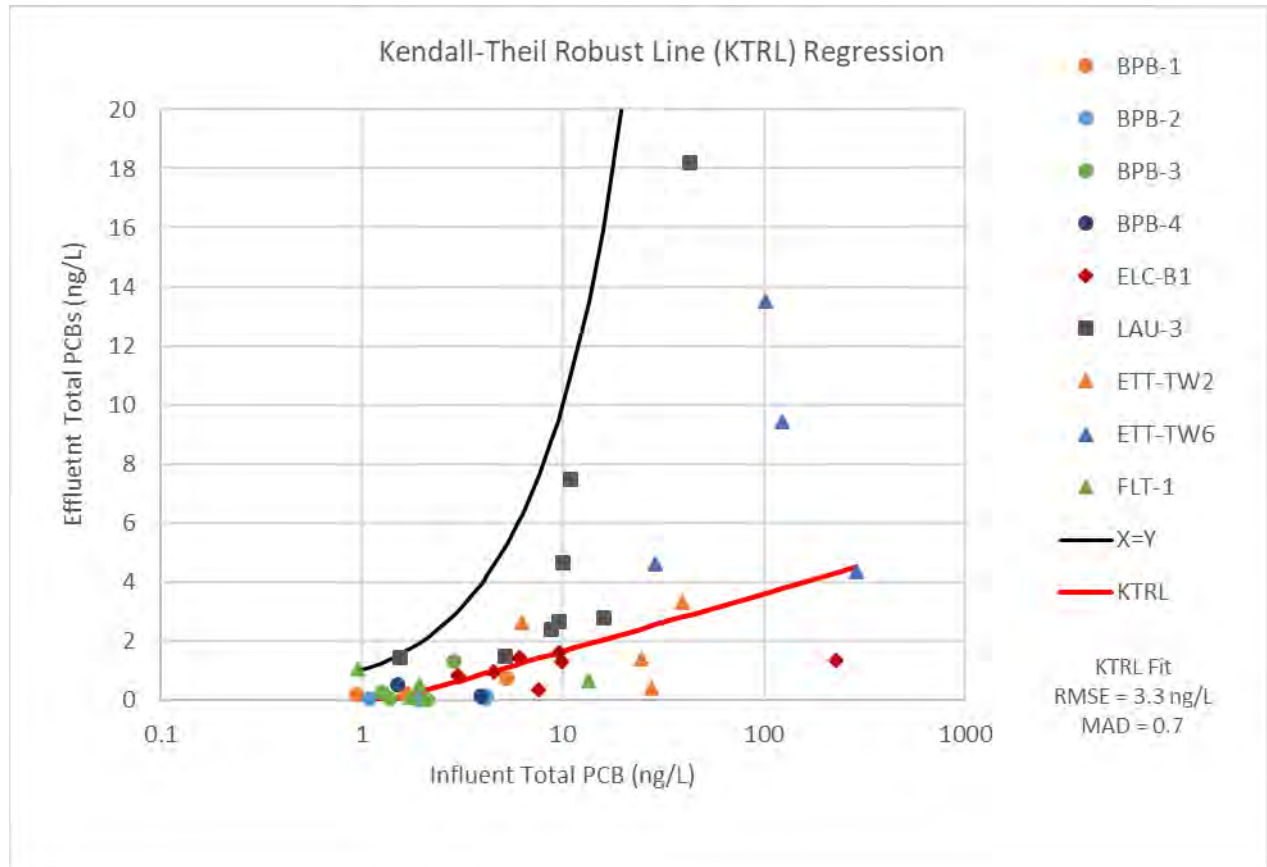


Figure 2: PCBs Influent vs Effluent Concentration Relationship Determined by KTRL Regression

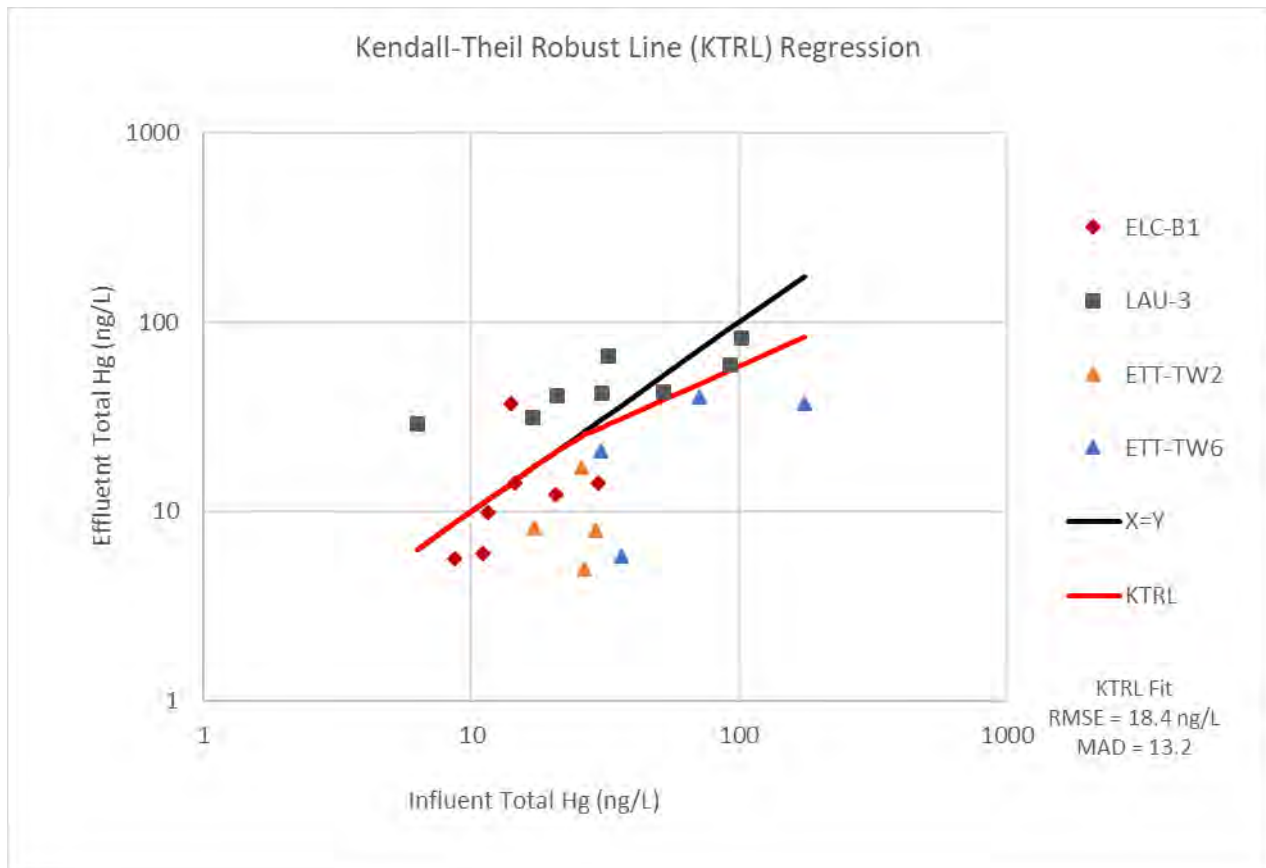


Figure 3: Mercury Influent vs Effluent Concentration Relationship Determined by KTRL Regression

3.3 RAA Scenario Loading Model

To model RAA future scenarios, future condition land use is needed. Future condition land use will be estimated using predictions of private parcel new development and redevelopment in combination with GI implementation on public parcels and rights-of-way.

Load reductions estimated for implementation of GI will be applied to future condition RAA scenario models based on estimated locations of GI and the tributary drainage areas to those GI. Effective area will be used to relate the HRUs, which can have a variety of imperviousness values, to the GI performance which will be based on a unit of effective area with 100% imperviousness. The GI performance curves can thus be applied to many different HRU types and/or combinations of HRUs that make up the tributary drainage areas for future GI measures.

4. QUANTITATIVE RELATIONSHIP BETWEEN GI IMPLEMENTATION AND PCBs LOADS REDUCED

The results of the hydraulic and pollutant reduction modeling of GI measures were used to develop a quantitative relationship between GI implementation and PCBs that can be applied to RAA future scenario models. An example quantitative relationship is provided for GI models run for the Berkeley gauge (040693). Utilizing output from hydraulic modeling, GI measure volumetric percent capture was calculated on an average annual basis. Volumetric model results for runs with GI measures sized to achieve 80%, 85%, 90%, and 95% capture were combined with water quality inputs to obtain pollutant load reduction for varying PCBs influent concentration.

The results of this analysis are shown in nomographs¹⁰ provided in Figure 4, Figure 5, and Figure 6, which correspond to infiltrating bioretention (i.e., with no underdrain), bioretention with a raised underdrain, and lined bioretention, respectively. All facilities shown in the figures below have a 6-inch ponding depth. For bioretention with a raised underdrain, the facility configuration with an underlying infiltration rate of 0.24 in/hr only is shown (see Table 8 for all modeled infiltration rates). Facilities sized to achieve 80%, 85%, 90%, and 95% capture from the 100% impervious tributary catchment are shown in series, with pollutant load reduction in grams per effective acre¹¹ displayed as a function of influent concentration. Constant influent lines corresponding with RWSM land use-based influent concentrations are shown.

¹⁰ A nomograph is a graphical relationship between two variables that can be used to quickly estimate one value from another.

¹¹ Effective area is calculated as the area multiplied by the runoff coefficient.

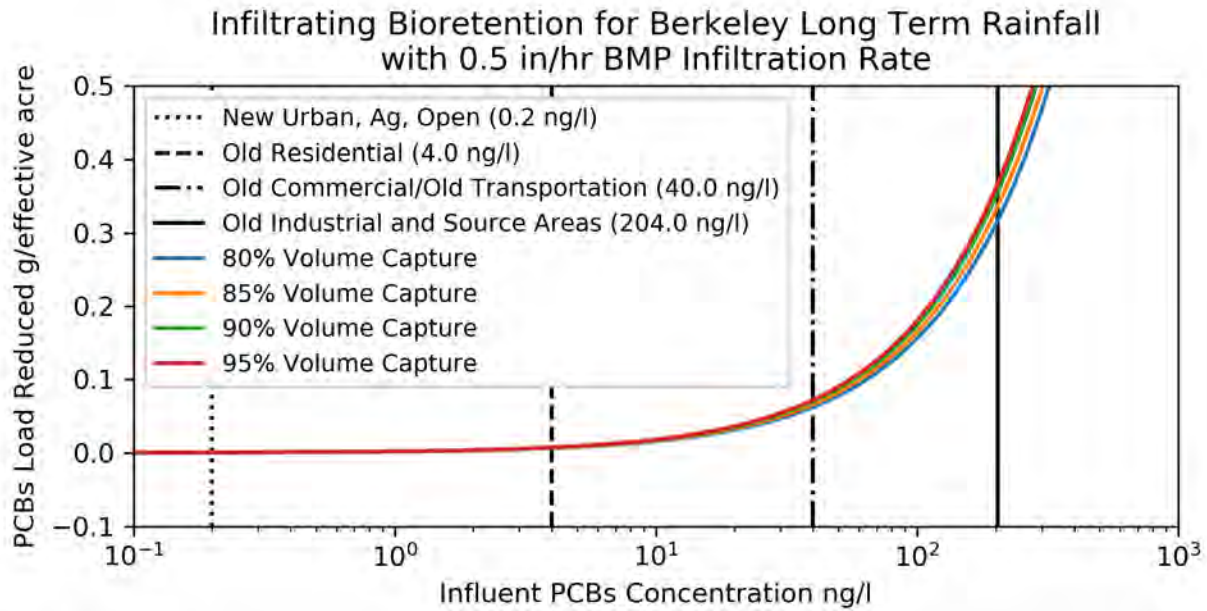


Figure 4: Modeled PCBs Load Removal Performance for Infiltrating Bioretention Basin

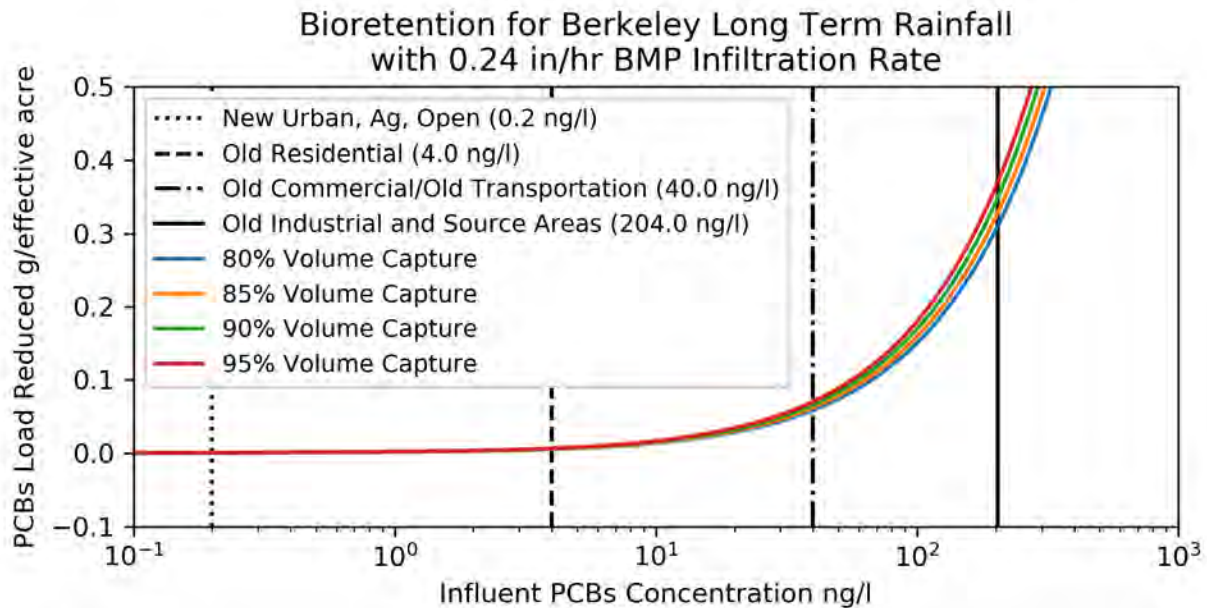


Figure 5: Modeled PCBs Load Removal Performance for Bioretention Basin with Elevated Underdrain

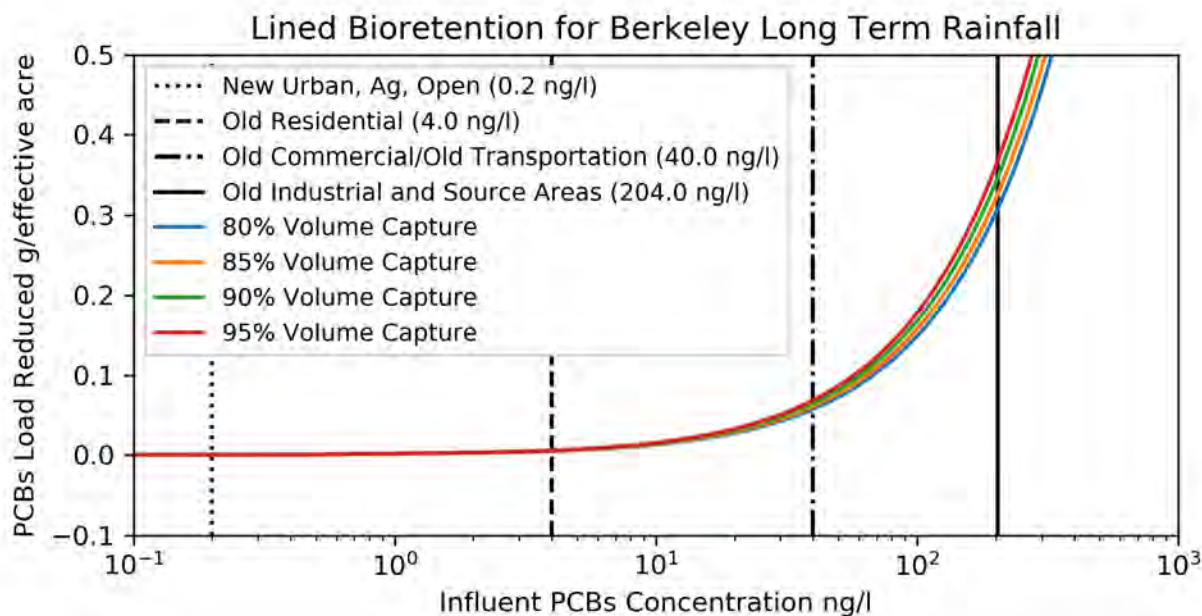


Figure 6: Modeled PCBs Load Removal Performance for Lined Bioretention Basin with Underdrain

The intersection points between the load reduction series and the constant influent lines represent the load reduced in grams per acre for each specific RWSM land use category. These intersection points are listed in Table 11.

Table 11: PCBs Load Reduction for RWSM Land Use Categories for Berkeley Gauge for Different BMP Percent Capture Values

Facility Configuration	Land Use Category	PCBs Load Reduced (g/effective ac)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Infiltrating Bioretention (0.5 underlying infiltration rate)	New Urban, Ag, Open	3.12E-04	3.30E-04	3.49E-04	3.61E-04
	Old Residential	0.00623	0.0066	0.00698	0.00722
	Old Commercial / Old Transportation	0.0623	0.066	0.0698	0.0722
	Old Industrial and Source Areas	0.318	0.337	0.356	0.368
Bioretention with Raised Underdrain (0.24 underlying infiltration rate)	New Urban, Ag, Open	3.08E-04	3.26E-04	3.47E-04	3.67E-04
	Old Residential	0.00518	0.0055	0.00589	0.00633
	Old Commercial / Old Transportation	0.0586	0.0621	0.0661	0.0703
	Old Industrial and Source Areas	0.311	0.329	0.350	0.371
Lined Bioretention	New Urban, Ag, Open	3.08E-04	3.26E-04	3.46E-04	3.67E-04
	Old Residential	0.00484	0.00513	0.00545	0.00577
	Old Commercial / Old Transportation	0.0574	0.0608	0.0647	0.0685
	Old Industrial and Source Areas	0.309	0.327	0.348	0.368

1. Average Annual Facility Volumetric Runoff Capture

5. QUANTITATIVE RELATIONSHIP BETWEEN GI IMPLEMENTATION AND MERCURY LOADS REDUCED

Mercury load reduction results for the Berkeley Gauge are shown in nomographs¹² in Figure 7, Figure 8, and Figure 9, which correspond to infiltrating bioretention (i.e., with no underdrain), bioretention with a raised underdrain, and lined bioretention, respectively. All facilities shown in the figures below have a 6-inch ponding depth. For bioretention with a raised underdrain, the facility configuration with an underlying infiltration rate of 0.24 in/hr only is shown (see Table 9 for all modeled infiltration rates). Facilities sized to achieve 80%, 85%, 90%, and 95% capture from the 100% impervious tributary catchment are shown in series, with pollutant load reduction in grams per acre displayed as a function of influent concentration. Constant influent lines corresponding with RWSM land use-based influent concentrations are shown.

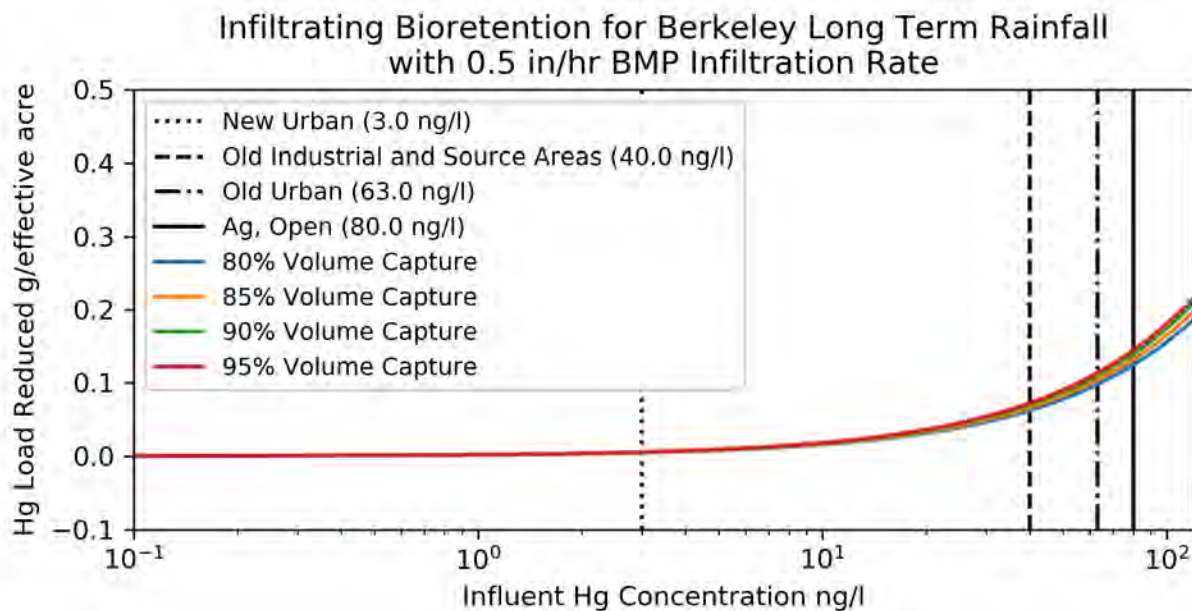


Figure 7: Modeled Mercury Load Removal Performance for Infiltrating Bioretention Basin

¹² A nomograph is a graphical relationship between two variables that can be used to quickly estimate one value from another.

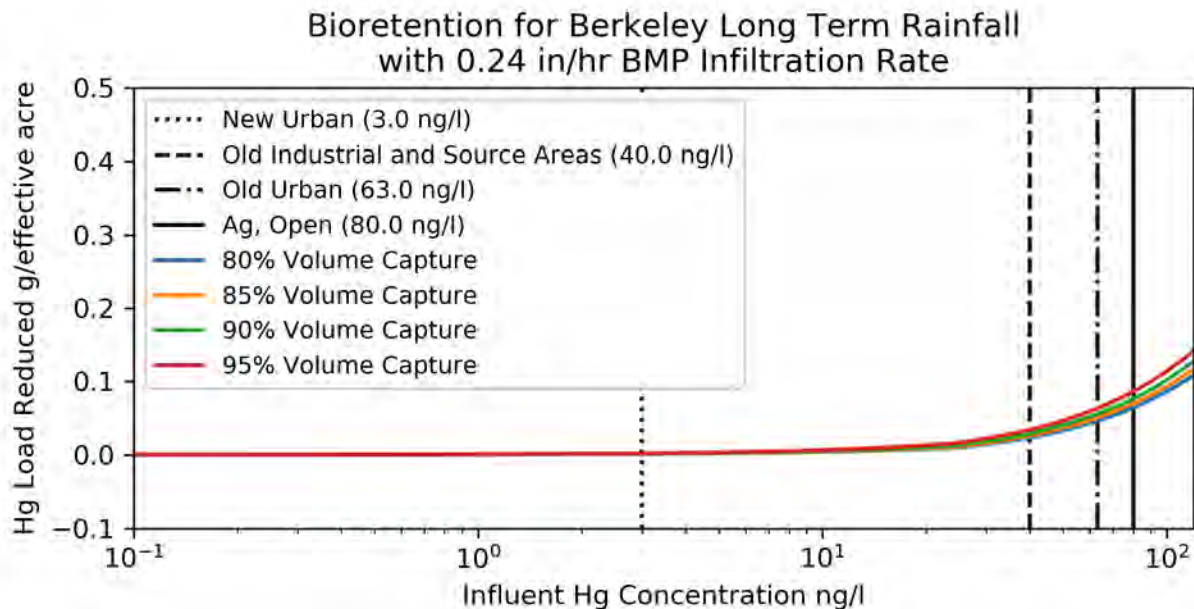


Figure 8: Modeled Mercury Load Removal Performance for Bioretention Basin with Elevated Underdrain

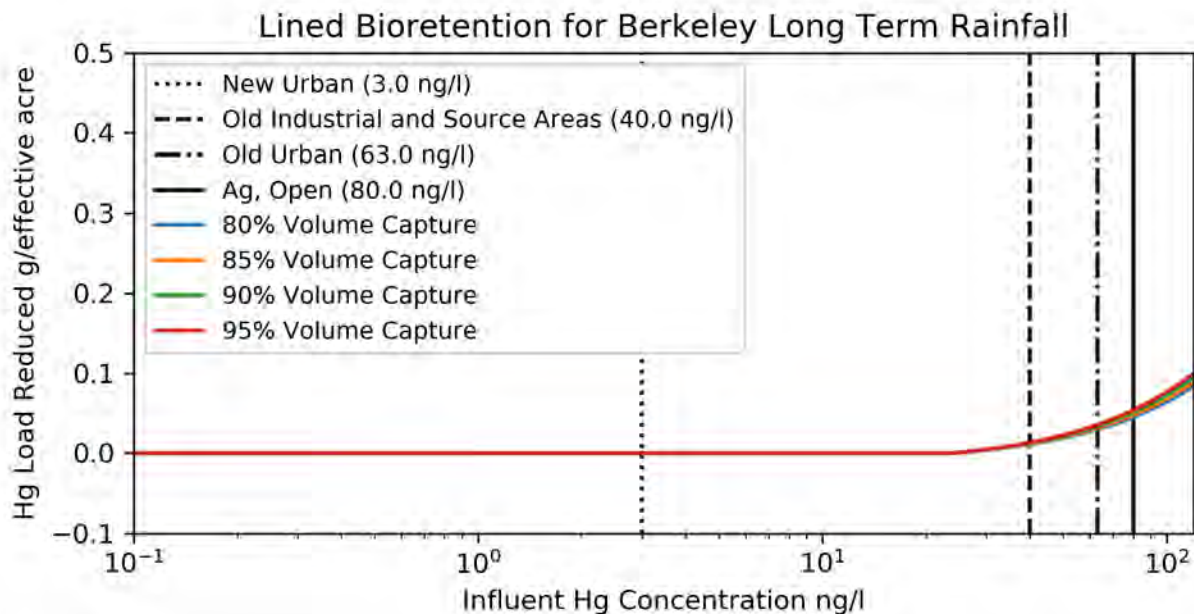


Figure 9: Modeled Mercury Load Removal Performance for Lined Bioretention Basin with Underdrain

The intersection points between the load reduction series and the constant influent lines represent the load reduced in grams per acre for each specific RWSM land use category. These intersection points are summarized in Table 12.

Table 12: Mercury Load Reduction for RWSM Land Use Categories for Berkeley Gauge for Different BMP Percent Capture Values

Facility Configuration	Land Use Category	Mercury Load Reduced (g/effective acre)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Infiltrating Bioretention (0.5 underlying infiltration rate)	New Urban	0.00467	0.00495	0.00524	0.00541
	Old Industrial and Source Areas	0.0623	0.066	0.0698	0.0722
	Old Urban	0.0981	0.104	0.110	0.114
	Ag, Open	0.125	0.132	0.140	0.144
Bioretention with Raised Underdrain (0.24 underlying infiltration rate)	New Urban	0.00113	0.0013	0.00153	0.00192
	Old Industrial and Source Areas	0.0234	0.0258	0.029	0.0341
	Old Urban	0.0462	0.0503	0.0556	0.0634
	Ag, Open	0.0643	0.0696	0.0765	0.0862
Lined Bioretention	New Urban	0	0	0	0
	Old Industrial and Source Areas	0.0108	0.0115	0.0123	0.0130
	Old Urban	0.0296	0.0314	0.0335	0.0353
	Ag, Open	0.0449	0.0476	0.0507	0.0536

¹ Average Annual Facility Volumetric Runoff Capture

6. REFERENCES

Bay Area Stormwater Management Agencies Association (BASMAA), 2017a. Interim Accounting Methodology for TMDL Loads Reduced, Version 1.1. Prepared by Geosyntec Consultants and EOA, Inc. for the Bay Area Stormwater Management Agencies Association (BASMAA). March 2017.

BASMAA, 2017b. Bay Area Reasonable Assurance Analysis Guidance Document. Prepared by Geosyntec Consultants and Paradigm Environmental. June.

Geosyntec Consultants and EOA, 2017. Clean Watersheds for a Clean Bay (CW4CB). Final Report. Prepared for Bay Area Stormwater Management Agencies Association
<http://basmaa.org/Clean-Watersheds-for-a-Clean-Bay-Project/CW4CB-Overall-Project-Report>

Gilbreath, A. N.; Pearce, S.; McKee, L. J., 2012. Monitoring and Results for El Cerrito Rain Gardens. San Francisco Estuary Institute: Richmond, CA.
<http://www.sfei.org/documents/monitoring-and-results-el-cerrito-rain-gardens>

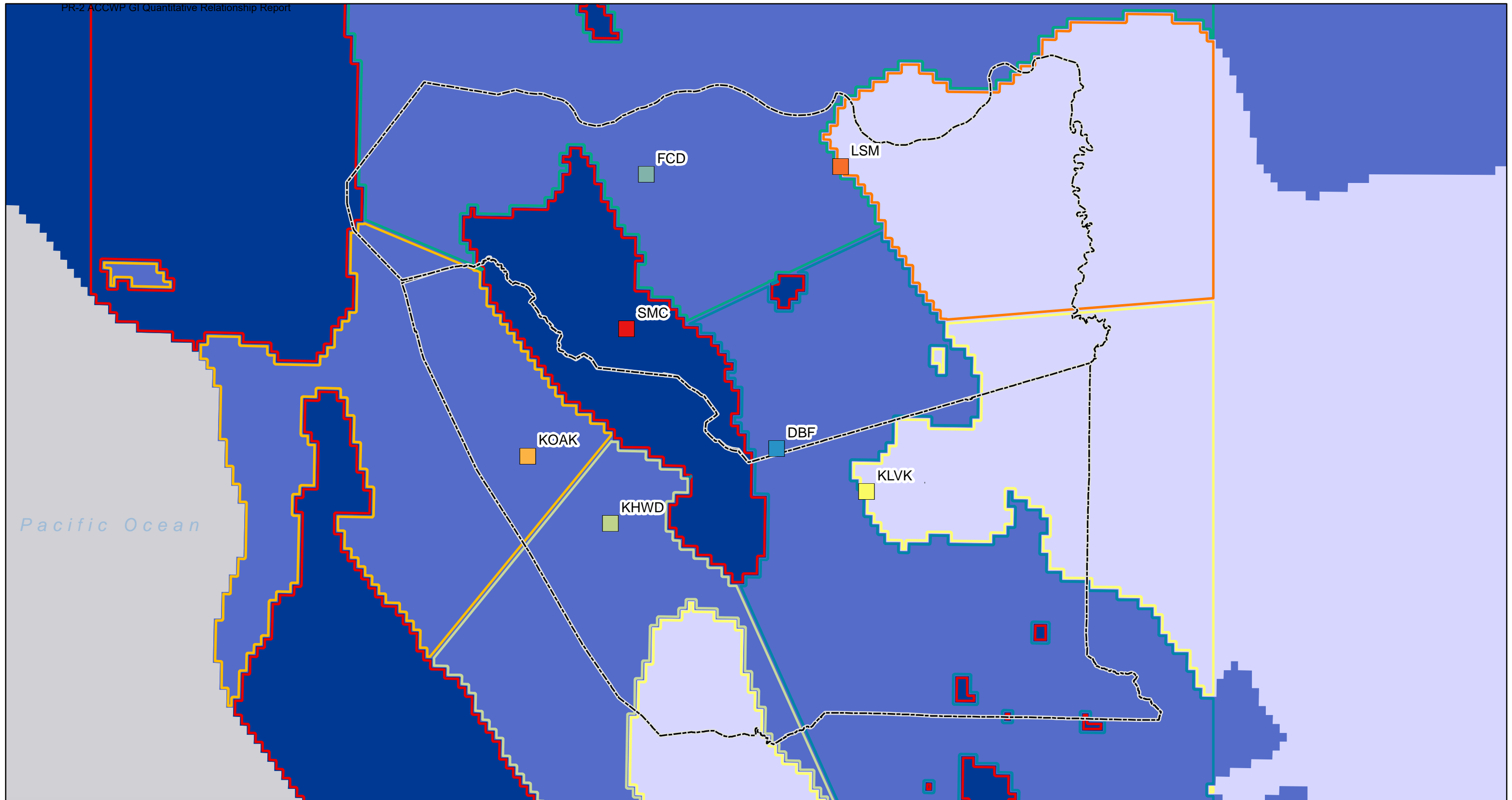
King County, 2017. Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin - SAM Effectiveness Study - Final Report. Prepared by Carly Greyell, Water and Land Resources Division. Seattle, WA. <https://www.kingcounty.gov/depts/dnrp/wlr/sections-programs/science-section/doing-science/echo-lake-study.aspx>














Granato, G.E., 2006, Kendall-Theil Robust Line (KTRLine—version 1.0)—A visual basic program for calculating and graphing robust nonparametric estimates of linear-regression coefficients between two continuous variables: Techniques and Methods of the U.S. Geological Survey, book 4, chap. A7, 31 p.: <https://pubs.usgs.gov/tm/2006/tm4a7/>

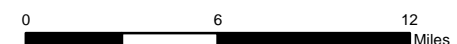
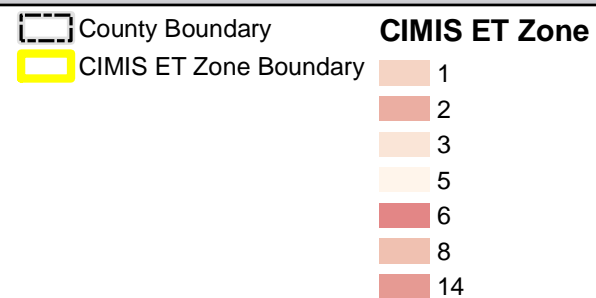
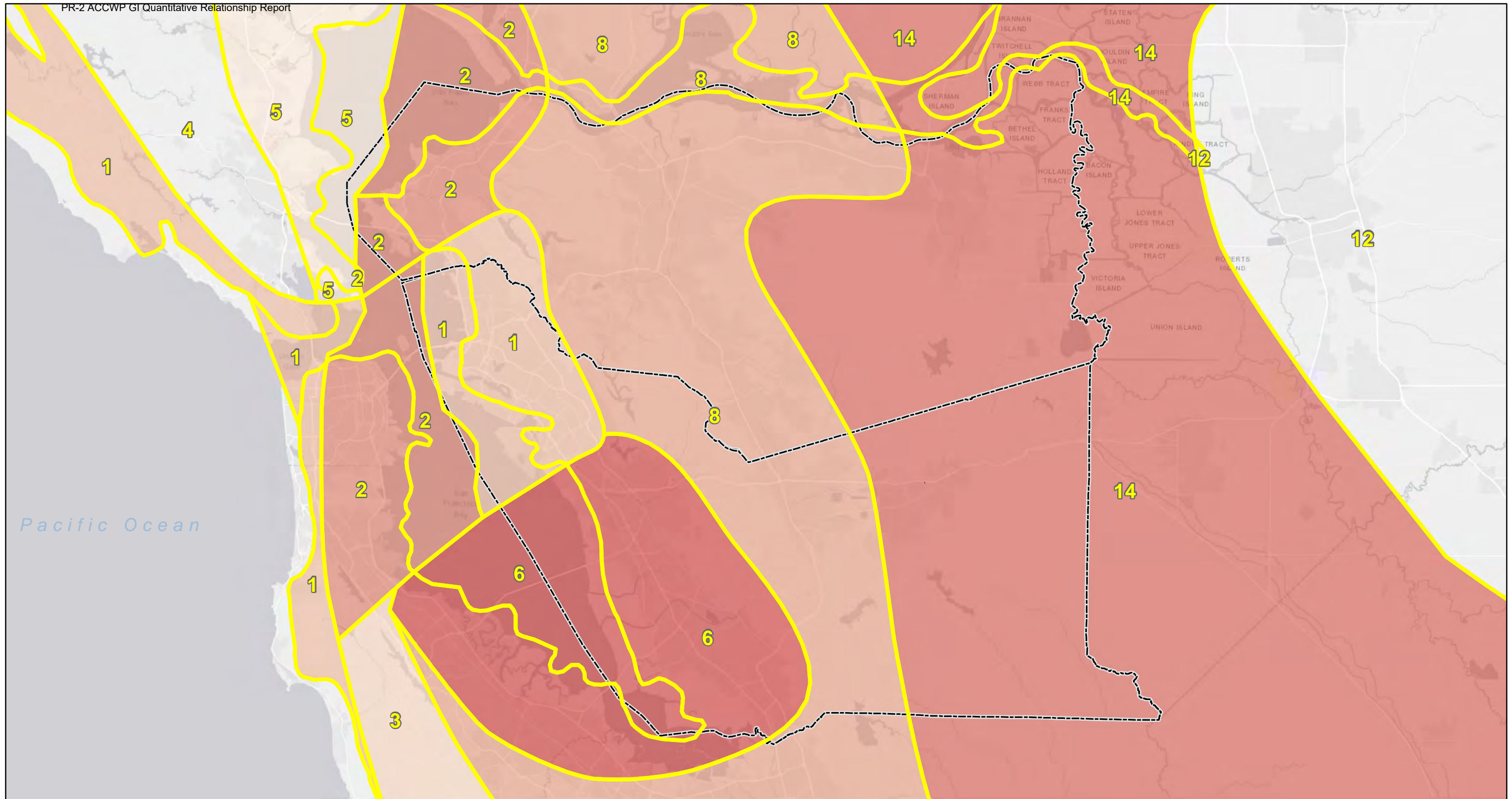
USEPA, 2017. Developing Reasonable Assurance: A Guide to Performing Model-Based Analysis to Support Municipal Stormwater Program Planning. Prepared by Paradigm Environmental. February.

APPENDIX A

Modeling Inputs and Data Exhibits



Rain Gauge ID  Rain Gauge ID  County Boundary	Mean Annual Precipitation (in)  < 16  16 - 25  > 25	Rain Gauge Zones  DBF  FCD  KHW  KLVK  KOAK  LSM  SMC	<div data-bbox="2526 1665 2915 1721">Precipitation Zones for Baseline Runoff Period (WY 2000-2009)</div> <div data-bbox="2526 1745 2915 1790">Alameda County and Contra Costa County California</div> <div data-bbox="2526 1806 2769 1891">  consultants </div> <div data-bbox="2495 1907 2573 1931">Oakland</div> <div data-bbox="2731 1907 2822 1931">July 2018</div> <div data-bbox="2915 1806 3017 1931"> Exhibit 1 </div>
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CIMIS Evapotranspiration Zones

Alameda County and Contra Costa County
California

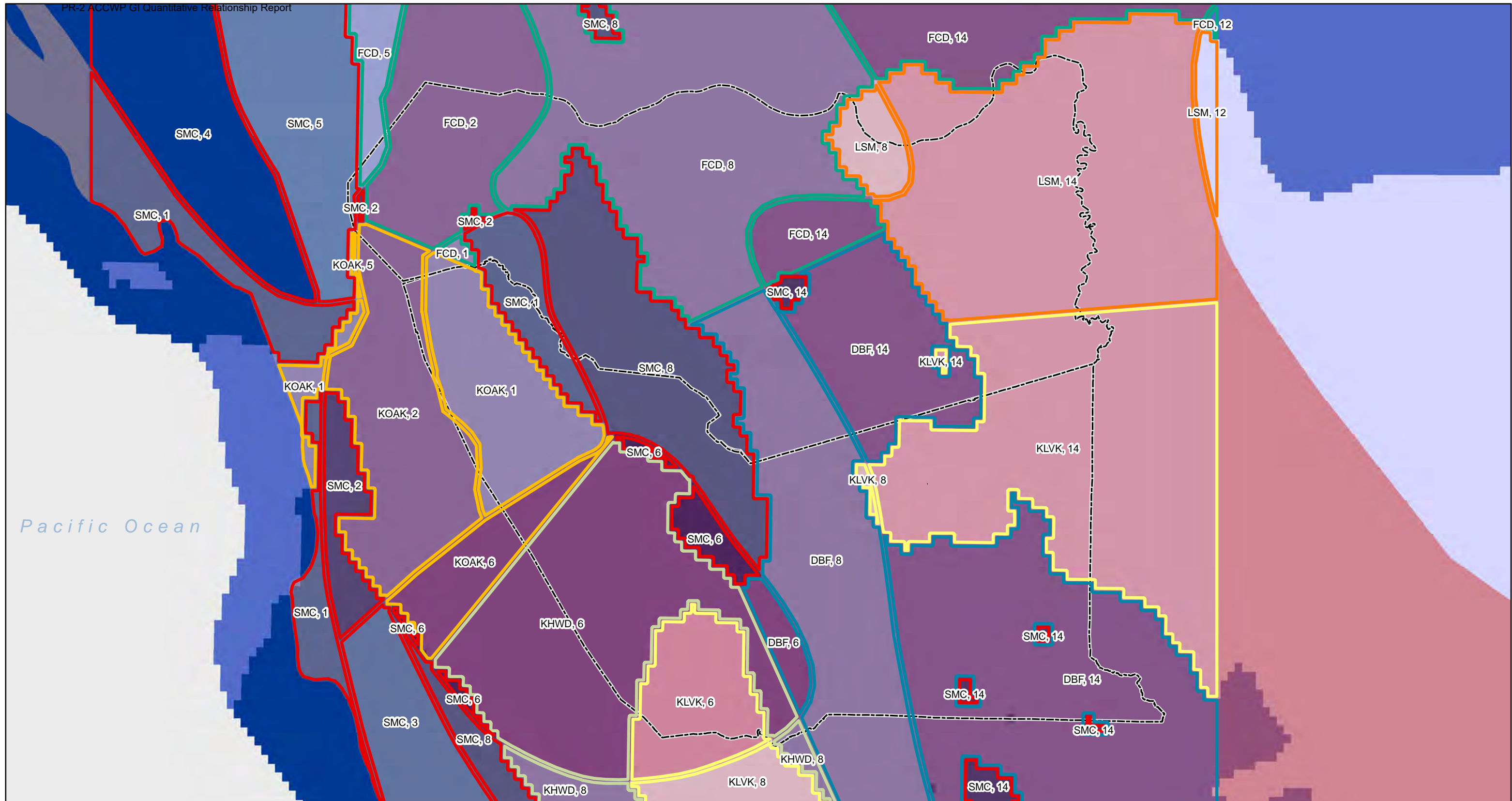
Geosyntec
consultants

Oakland

July 2018

Exhibit

2



County Boundary

Mean Annual Precipitation (in)

- < 16
- 16 - 25
- > 25

CIMIS ET Zone

1	5
2	6
3	8
	14

Climate Zones are created by overlapping precipitation zones and ET zones. The unique climate zones that occur in Contra Costa and Alameda County are labeled as "Gauge ID, ET Zone".



0 6 12 Miles

Climate Zones for Baseline Runoff Period (WY 2000-2009)

Alameda County and Contra Costa County
California

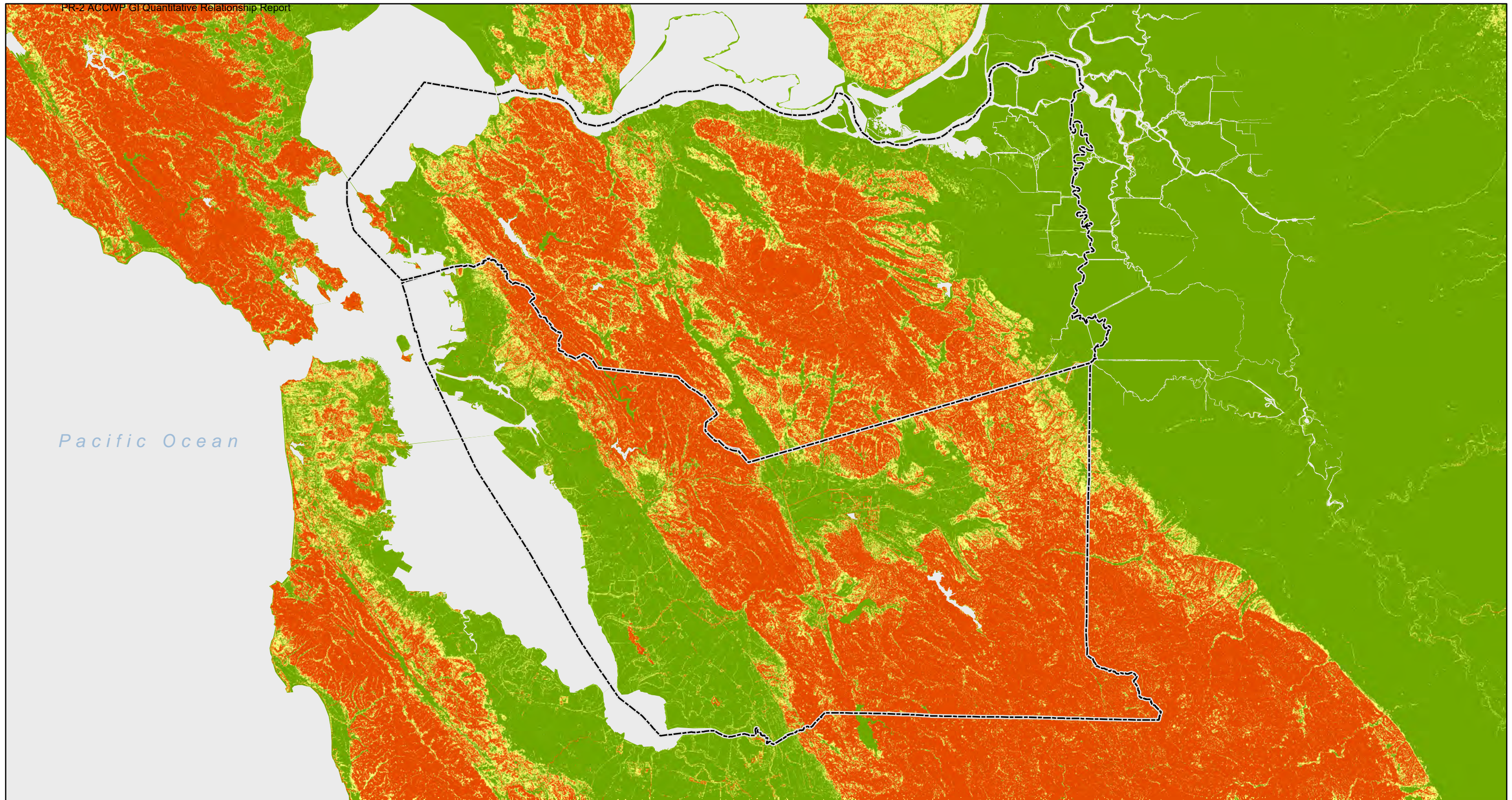
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consultants


Oakland

July 2018


Exhibit


3




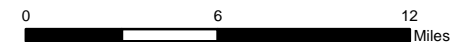
 County Boundary

% Slope

 < 5

 5-15

 > 15



Slope Zones

Alameda County and Contra Costa County
California

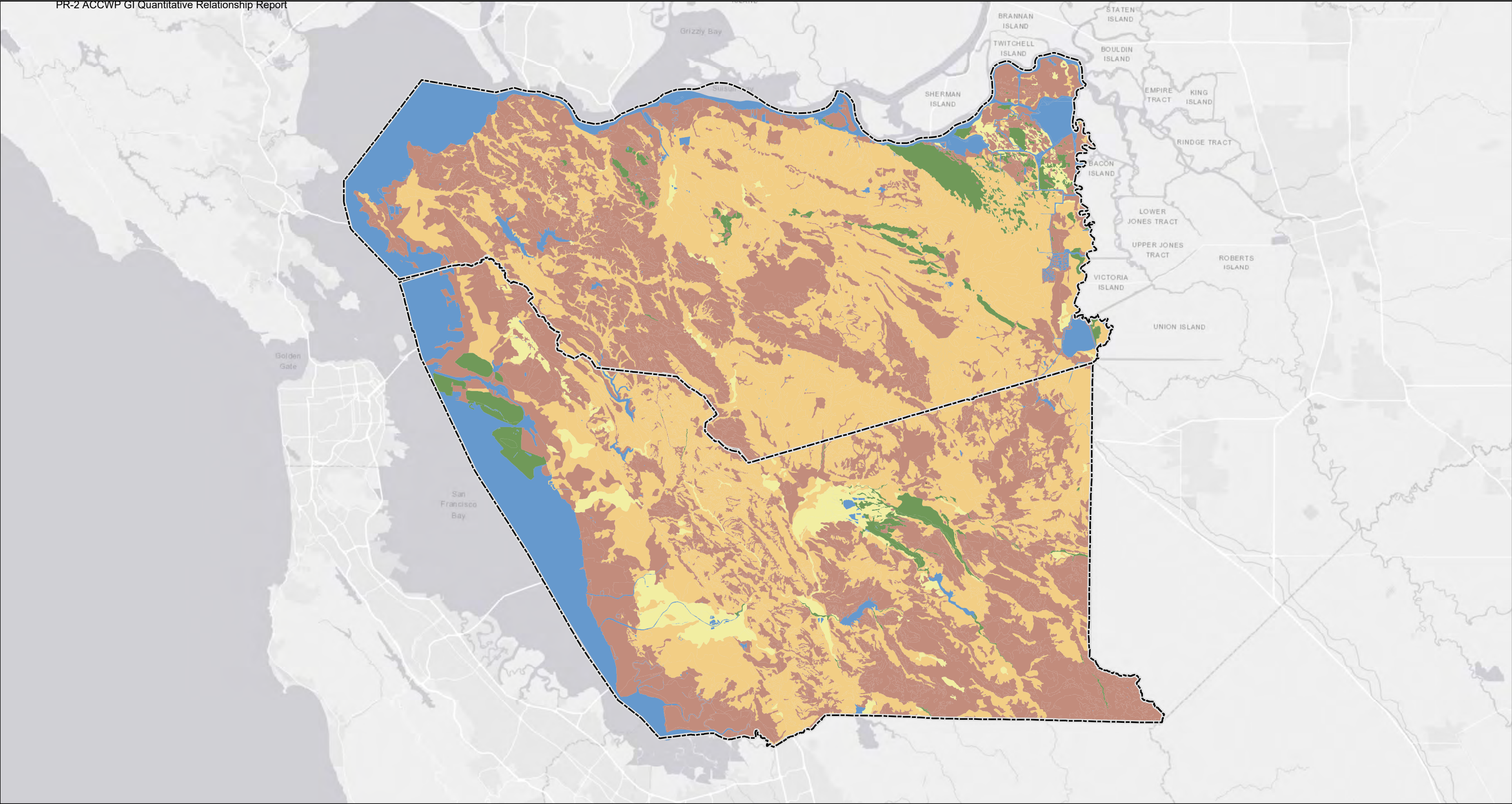


Oakland

July 2018

Exhibit

4



County Boundary

- HSG**
- A
 - B
 - C
 - D
 - W

Note: Area within the county with no HSG assignment was assigned the HSG of the most prominent adjacent soil group.

N

0 6 12 Miles

Hydrologic Soil Group

Alameda County and Contra Costa County
California

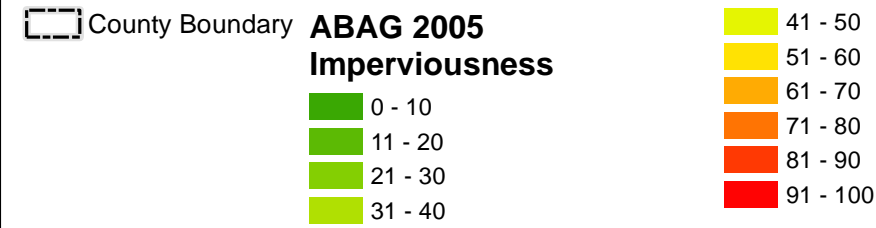
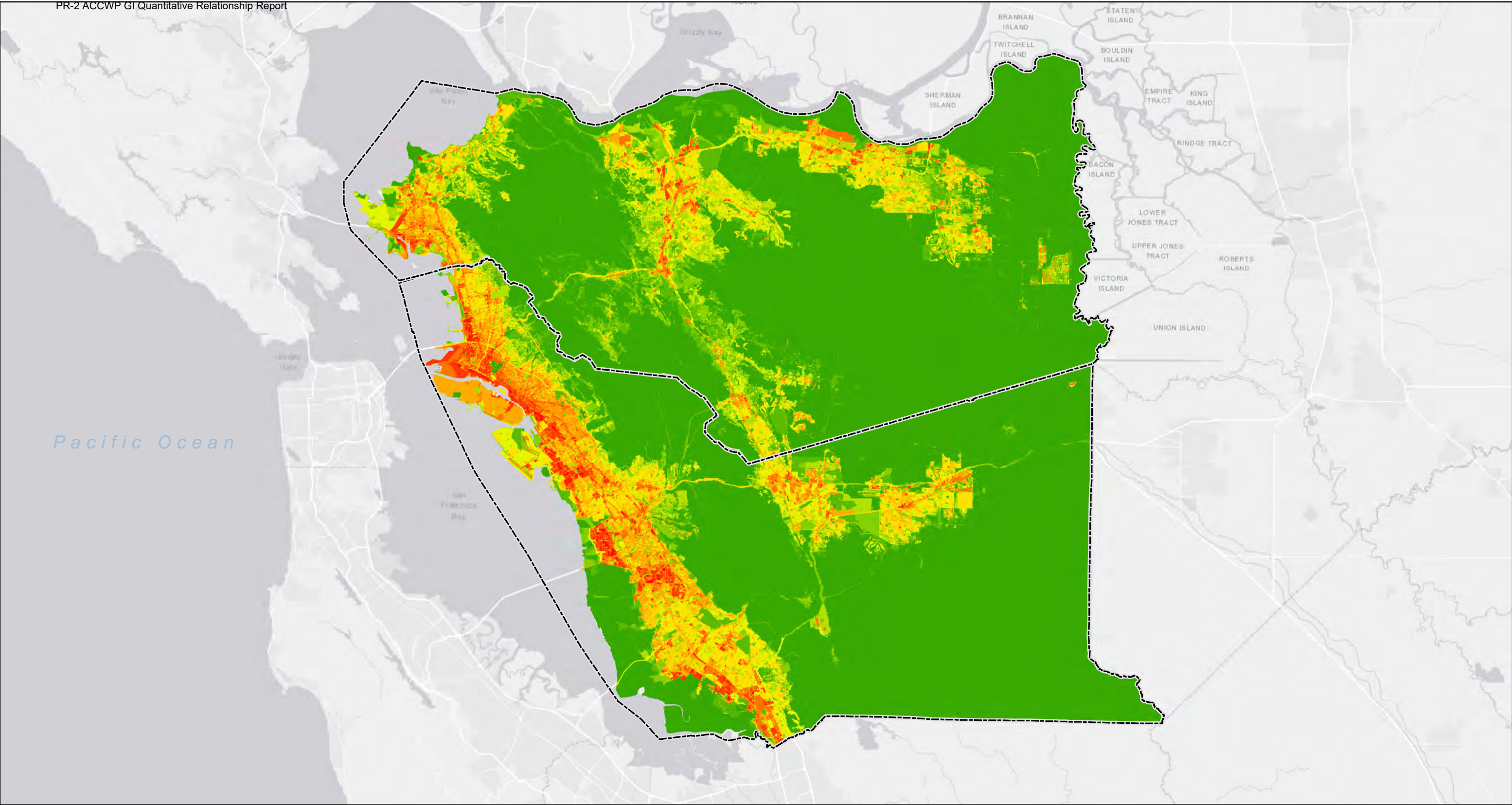
Geosyntec
consultants

Oakland

July 2018

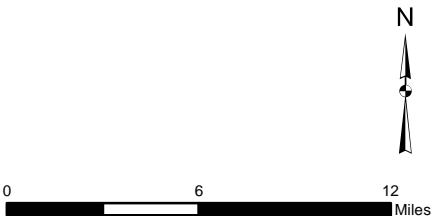
Exhibit

5



Note:
Imperviousness is assigned to ABAG 2005 landuse based on the NLCD 2006 Impervious Cover layer. These values may be adjusted during calibration for certain categories of ABAG landuse.

For purposes of calculating runoff from areas with compacted soil, developed areas and agricultural uses were assumed to be compacted to 0.75 times the underlying saturated soil conductivity (ksat). These areas generally have percent imperviousness > 20%.



Regional Imperviousness

Alameda County and Contra Costa County
California

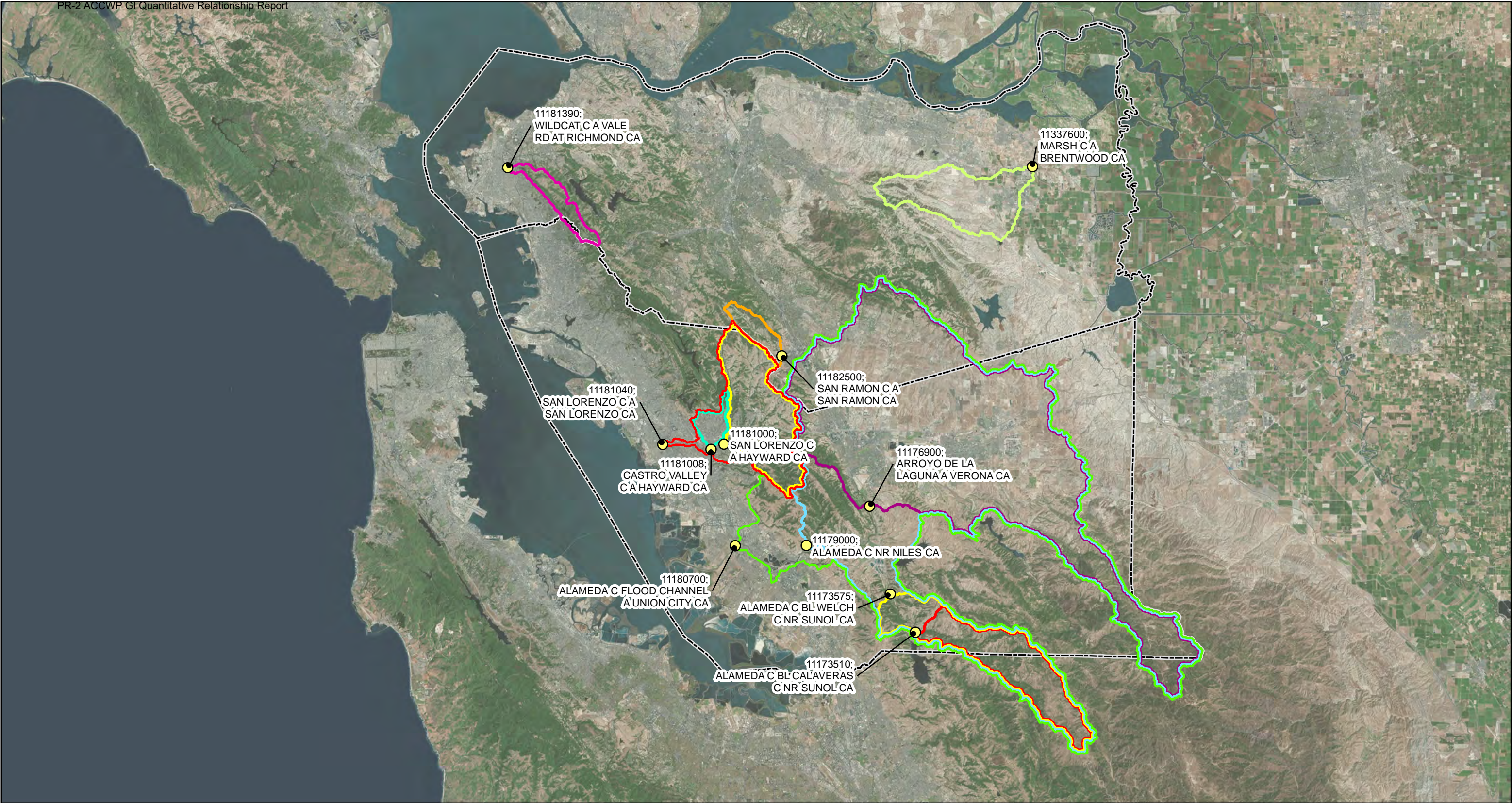
Geosyntec
consultants

Oakland

July 2018

Exhibit

6



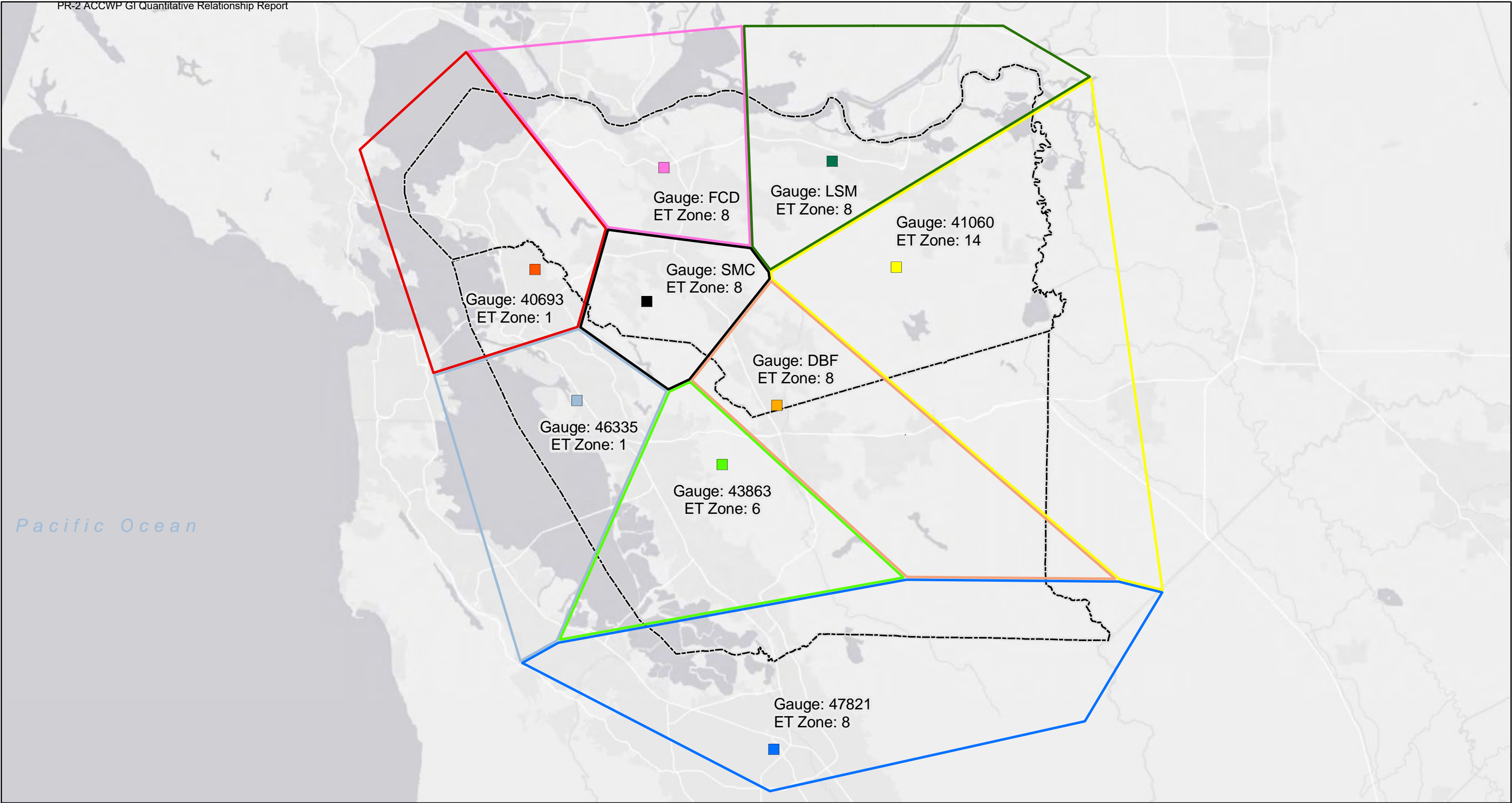
County Boundary		Group 1	Group 2	Group 3	Group 4	Group 4
	County Boundary					
	Gauge Location					

11181040; SAN LORENZO C A SAN LORENZO CA
11181000; SAN LORENZO C A HAYWARD CA
11181008; CASTRO VALLEY C A HAYWARD CA
11180700; ALAMEDA C FLOOD CHANNEL A UNION CITY CA
11182500; SAN RAMON C A SAN RAMON CA
11179000; ALAMEDA C NR NILES CA
11173575; ALAMEDA C BL WELCH C NR SUNOL CA
11173510; ALAMEDA C BL CALAVERAS C NR SUNOL CA
11176900; ARROYO DE LA LAGUNA A VERONA CA
11337600; MARSH C A BRENTWOOD CA
11181390; WILDCAT C A VALE RD AT RICHMOND CA

0 6 12 Miles

N

Candidate Calibration Watersheds	
Alameda County and Contra Costa County California	
	Exhibit
Oakland	7
July 2018	



County Boundary

Long-Term Rainfall Gauge Location

47821

DBF

40693

FCD

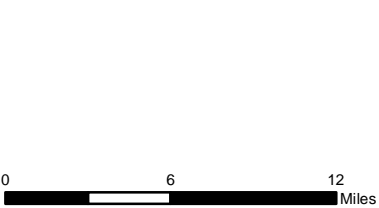
41060

LSM

43863

SMC

46335



Long-Term Rainfall Gauge Zones

Alameda County and Contra Costa County
California

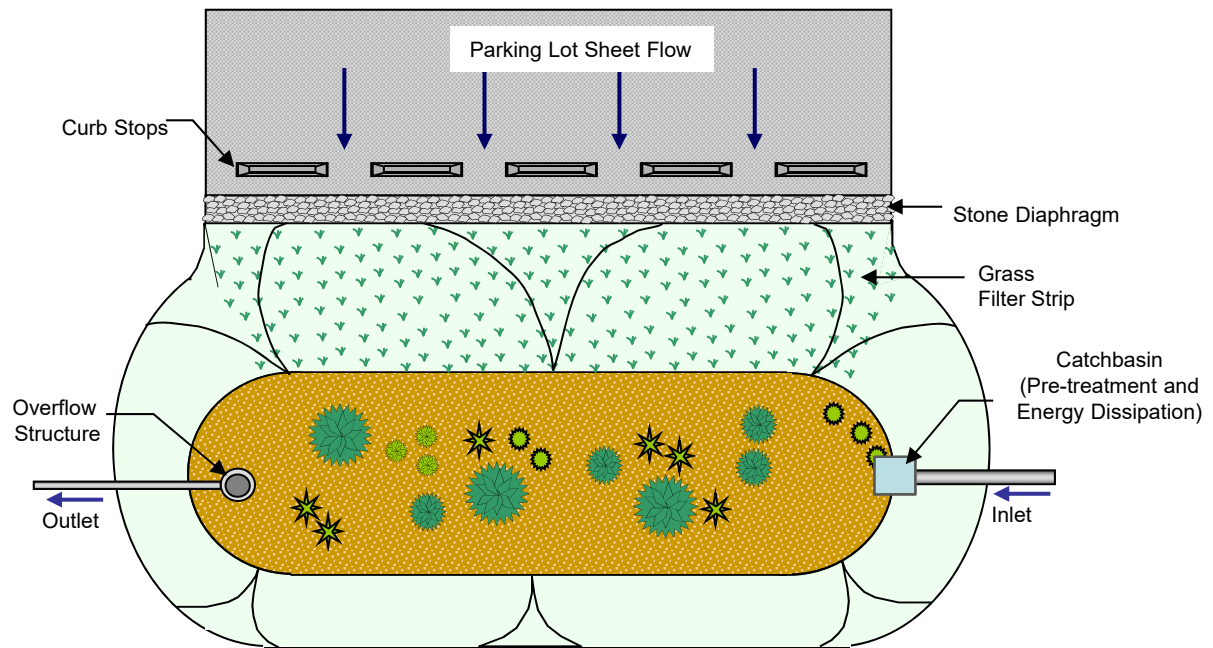
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consultants

Oakland

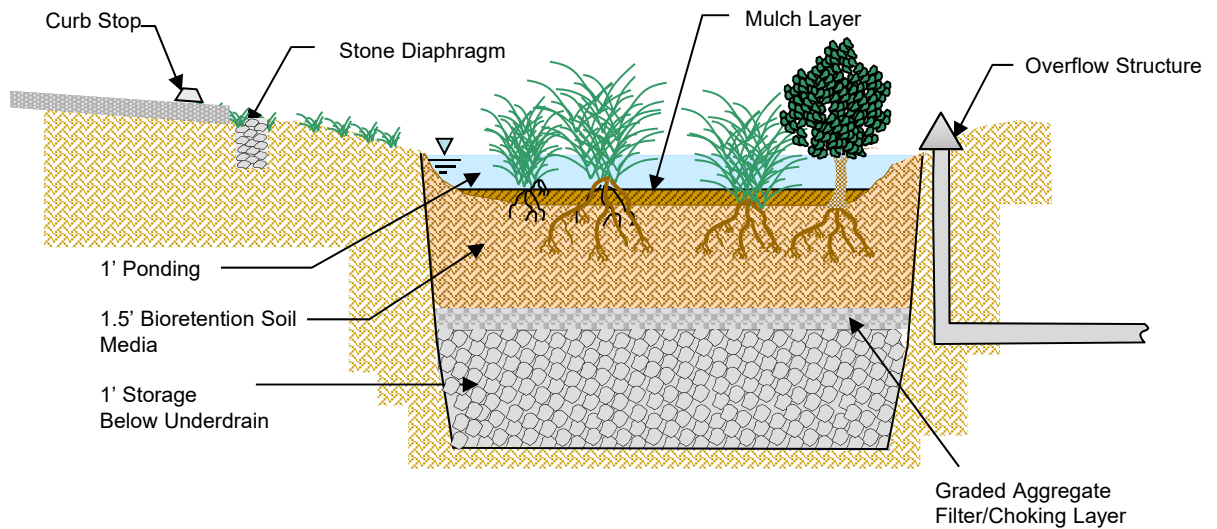
Exhibit
8

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of an Infiltration Facility

Geosyntec
consultants

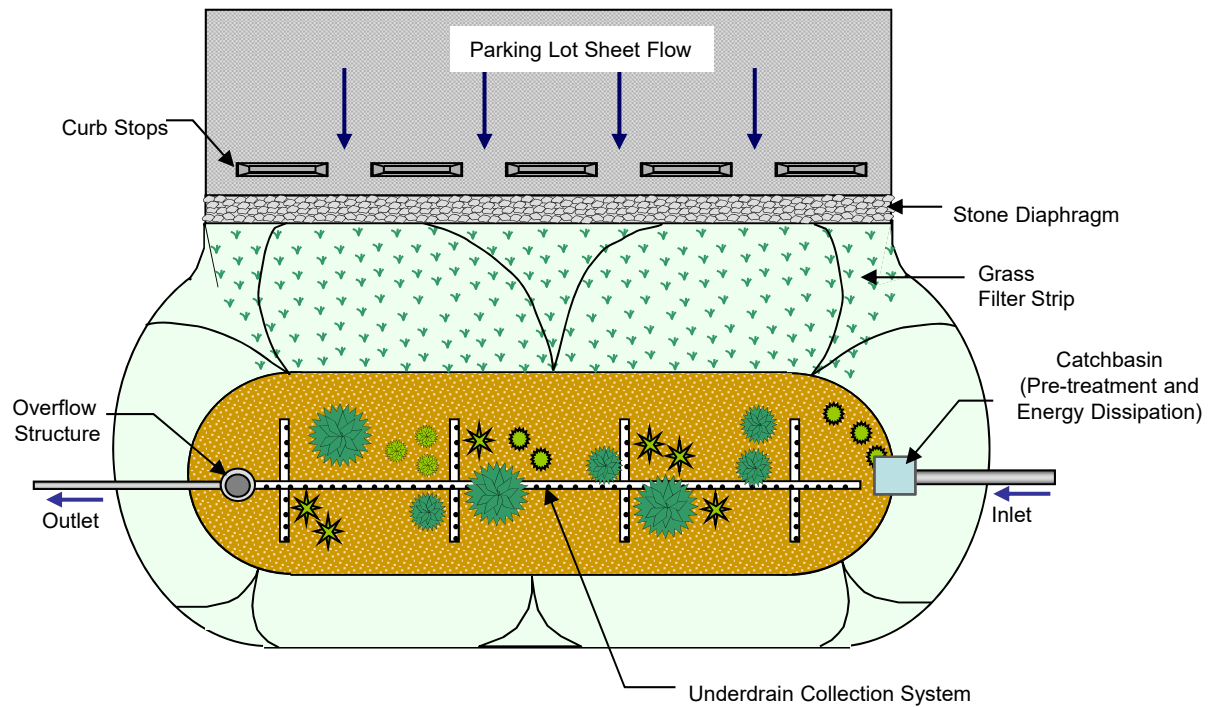
Exhibit

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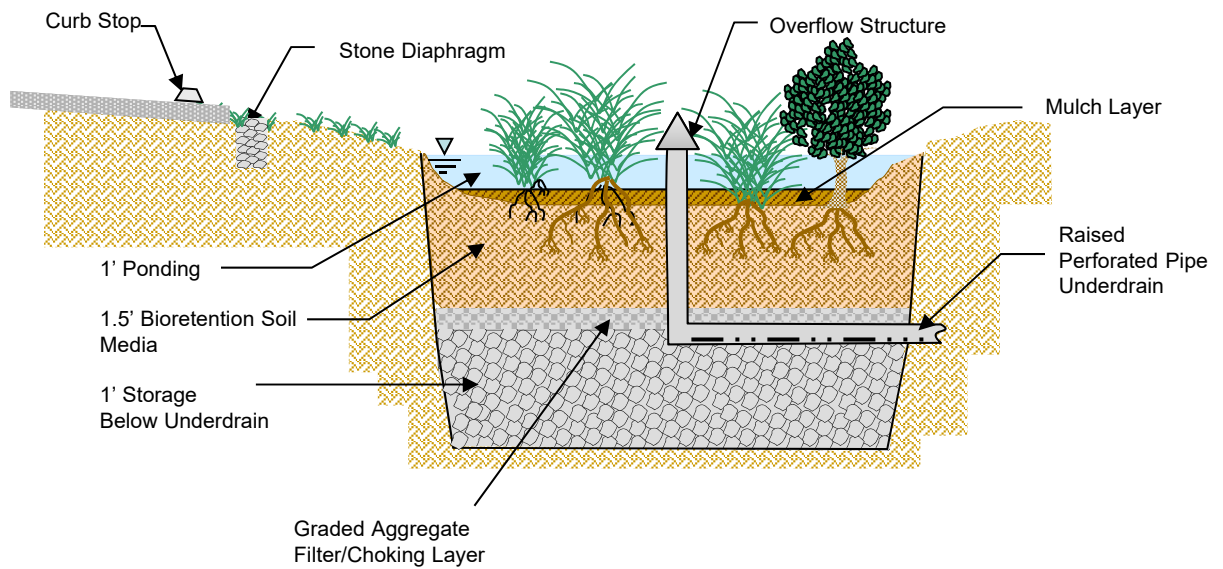
Oakland

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of a Bioretention/Bioinfiltration Facility

Geosyntec
consultants

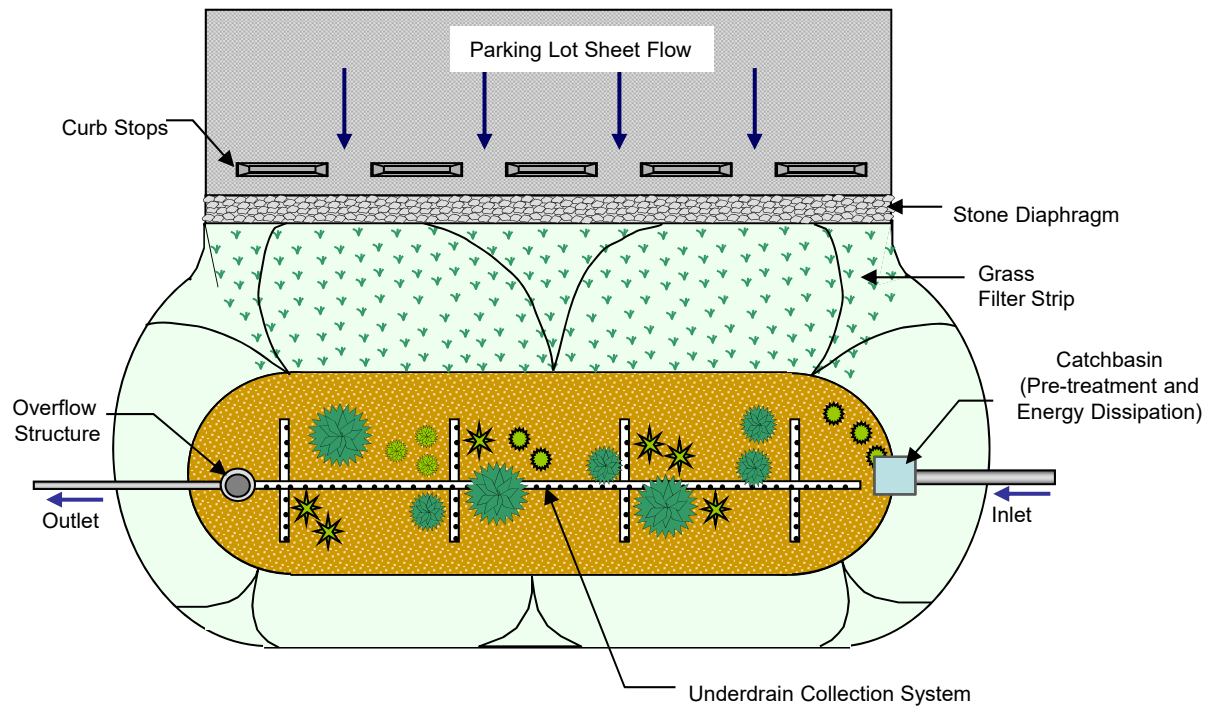
Exhibit

10

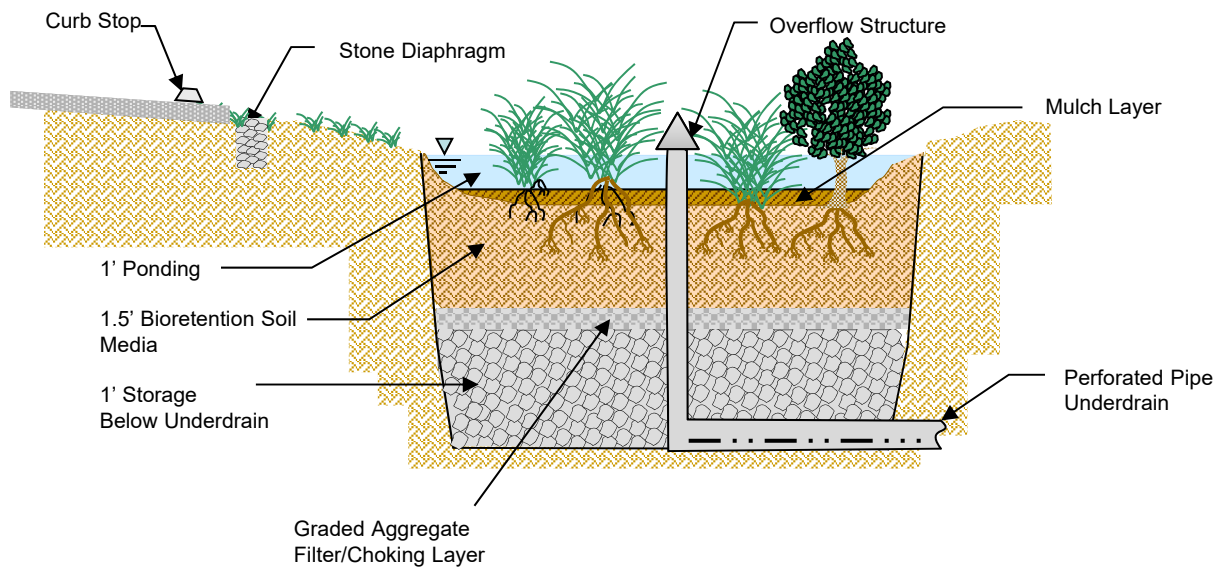
Oakland

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of a Biofiltration Facility

Geosyntec
consultants

Exhibit

11

Oakland

July 2018

PR-3 Contra Costa Clean Water Program GI Quantitative Relationship Report



QUANTITATIVE RELATIONSHIP BETWEEN GREEN INFRASTRUCTURE IMPLEMENTATION AND PCBs/MERCURY LOAD REDUCTIONS

***Submitted in Compliance with Provisions C.11.b.iii.(3), C.11.c.iii.(3),
C.12.b.iii.(3), and C.12.c.iii.(1)***

***Municipal Regional Stormwater Permit
NPDES Permit No. CAS612008
Order No. R2-2015-0049***

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***The Contra Costa Clean Water Program – A Municipal Stormwater Program consisting of
Contra Costa County, its 19 Incorporated Cities/Towns, and the
Contra Costa County Flood Control & Water Conservation District***

This report is submitted by the agencies of the



Program Participants:

- Cities of: Antioch, Brentwood, Clayton, Concord, Danville (Town), El Cerrito, Hercules, Lafayette, Martinez, Moraga (Town), Oakley, Orinda, Pinole, Pittsburg, Pleasant Hill, Richmond, San Pablo, San Ramon and Walnut Creek
- Contra Costa County
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LIST OF ACRONYMS

ASOS	Automated Surface Observation System
BASMAA	Bay Area Stormwater Management Agencies Association
BMP	Best Management Practices
CCCWP	Contra Costa Clean Water Program
CIMIS	California Irrigation Management Information System
GI	Green Infrastructure
GIS	Geographic Information System
HRU	Hydrologic Response Unit
KTRL	Kendall-Theil Robust Line
MAD	Median Absolute Deviation
MRP	Municipal Regional Permit
MS4	Municipal Separate Storm Sewer System
ng/kg	nanogram per kilogram
NPDES	National Pollutant Discharge Elimination System
PCBs	Polychlorinated Biphenyls
RAA	Reasonable Assurance Analysis
RMSE	Root Mean Square Error
ROW	Right-of-Way
RWSM	Regional Watershed Spreadsheet Model
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SFEI	San Francisco Estuary Institute
SWMM	Stormwater Management Model
TMDL	Total Maximum Daily Load
USEPA	United States Environmental Protection Agency
USGS	United States Geologic Survey
WY	Water Year

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1. INTRODUCTION

1.1 Purpose

This *Quantitative Relationship between Green Infrastructure Implementation and PCBs/Mercury Load Reductions* report was prepared by the Contra Costa Clean Water Program (CCCWP) per the Municipal Regional Permit (MRP) for urban stormwater issued by the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB; Order No. R2-2015-0049). This report fulfills the requirements of MRP Provisions C.11.b.iii.(3), C.11.c.iii.(3), C.12.b.iii.(3), and C.12.c.iii.(1) for submitting the quantitative relationship between green infrastructure (GI) implementation and PCBs load reductions that will be used for the Reasonable Assurance Analysis (RAA) required by MRP Provisions C.11.c.ii.(2), C.11.d.ii, C.12.c.ii.(2), and C.12.d.ii.

This report was prepared in cooperation with the Alameda Countywide Clean Water Program. The RAA modeling described herein will be conducted for both countywide programs and will use data inputs from both Contra Costa County and Alameda County.

1.2 Background

1.1.1 PCBs and Mercury Total Maximum Daily Loads

Fish tissue monitoring in San Francisco Bay has revealed bioaccumulation of PCBs, mercury, and other pollutants. The levels found are thought to pose a health risk to people consuming fish caught in the Bay. As a result of these findings, California has issued an interim advisory on the consumption of fish from the Bay. The advisory led to the Bay being designated as an impaired water body on the Clean Water Act "Section 303(d) list" due to PCBs and mercury. In response, the SFBRWQCB has developed Total Maximum Daily Load (TMDL) water quality restoration programs targeting PCBs and mercury in the Bay. The general goals of the TMDLs are to identify sources of PCBs and mercury to the Bay and implement actions to control the sources and restore water quality.

Municipal separate storm sewer systems (MS4s) are one of the PCBs and mercury source/pathways identified in the TMDL plans. Local public agencies (i.e., Permittees) subject to requirements via National Pollutant Discharge Elimination System (NPDES) permits are required to implement control measures in an attempt to reduce PCBs and mercury from entering stormwater runoff and the Bay. These control measures, also referred to as Best Management Practices (BMPs), are the tools that Permittees can use to assist in restoring water quality in the Bay.

1.1.2 Municipal Regional Permit

NPDES permit requirements associated with Phase I municipal stormwater programs and Permittees in the Bay area are included in the MRP, which was issued to 76 cities, counties and flood control districts in 2009 and revised in 2015¹. The MRP includes provisions to reduce loads of mercury and PCBs consistent with the TMDL implementation timeframe (Provisions C.11 and C.12, respectively) through implementation of GI projects (Provisions C.3.j, C.11.c, and C.12.c) and source controls (Provisions C.11.d and C.12.d).

The Permittees are reporting load reductions achieved before and during the current MRP term (2014 – 2020) using the approved Interim Accounting Methodology (BASMAA, 2017). MRP Provisions C.11.b.iii.(3) and C.12.b.iii.(3) requires the Permittees to report in the 2018 and subsequent Annual Reports any refinements to the Interim Accounting Methodology to be used in subsequent Permit terms. As part of this reporting requirement, Provision C.11.c.iii.(3) and C.12.c.iii.(1) requires the Permittees to report on the quantitative relationship between GI implementation and PCBs and mercury load reductions, including all data used and a full description of models and model inputs relied on to establish this relationship.

Green Infrastructure Planning and RAA

MRP Provision C.3.j requires the Permittees to develop a Green Infrastructure Plan for inclusion in the 2019 Annual Report. The Green Infrastructure Plan must be developed using a mechanism

¹ The cities of Antioch, Brentwood, and Oakley, and the eastern portions of unincorporated Contra Costa County and the Contra Costa County Flood Control & Water Conservation District (the East County Permittees) are located within the jurisdiction of the Central Valley Water Board and are covered under a separate Joint Municipal NPDES Permit titled “East Contra Costa County Municipal NPDES Permit” (East County Permit), which was last reissued in September 2010 (NPDES Permit No. CAS083313, Order No. R5-2010-0102). The East County Permit expired on September 1, 2015; however, it remains in force and effect until a new permit is reissued. In October 2016, the East County Permittees requested that the Central Valley Water Board designate the San Francisco Bay Water Board as the permitting authority for MS4 discharges in eastern Contra Costa County. In response to this request, the Central Valley Water Board provided a letter, dated January 6, 2017, that documents written agreement by both Water Boards to designate the San Francisco Bay Water Board to regulate MS4 discharges from the East County Permittees under MRP 2.0 and any successor orders. This East County Permittees are implementing PCBs and mercury control measures and this document reports those implementation efforts and the associated load reductions.

to prioritize and map areas for potential and planned GI projects, both public and private, on a drainage-area-specific basis, for implementation by 2020, 2030, and 2040.

MRP Provisions C.11.c and C.12.c require the Permittees to prepare an RAA for inclusion in the 2020 Annual Report that quantitatively demonstrates that specified mercury and PCBs load reductions will be achieved by 2040 through implementation of GI.

This RAA should do the following:

1. Quantify the relationship between the areal extent of GI implementation (e.g., acres treated) and mercury and PCBs load reductions. This quantification should take into consideration the scale of contamination of the treated area as well as the pollutant removal effectiveness of GI strategies likely to be implemented.
2. Estimate the amount and characteristics of land area that will be treated by GI by 2020, 2030, and 2040.
3. Estimate the amount of mercury and PCBs load reductions that will result from GI implementation by 2020, 2030, and 2040.
4. Ensure that the calculation methods, models, model inputs, and modeling assumptions used have been validated through a peer review process.

Additionally, MRP Provisions C.11.d. and C.12.d. require the Permittees to prepare plans and implementation schedules for mercury and PCBs control measures and an RAA demonstrating that sufficient control measures will be implemented to attain the mercury TMDL wasteload allocations by 2028 and the PCBs TMDL wasteload allocations by 2030. The implementation plans, which will also be included in the 2020 Annual Report, along with the GI-based RAA outlined above, must:

1. Identify all technically and economically feasible mercury or PCBs control measures (including GI projects, but also other control measures such as source property identification and abatement, managing PCBs in building materials during demolition, enhanced operations and maintenance, and other source controls) to be implemented;
2. Include a schedule according to which technically and economically feasible control measures will be fully implemented; and
3. Provide an evaluation and quantification of the mercury and PCBs load reduction of such measures as well as an evaluation of costs, control measure efficiency, and significant environmental impacts resulting from their implementation.

This report presents the quantitative relationship between GI implementation and PCBs and mercury load reductions, including the data used and a full description of models and model inputs relied on to establish this relationship. This relationship will be used to predict loads reduced through GI implementation for the RAAs described above and to report loads reduced through GI implementation in the subsequent Permit term.

2. DESCRIPTION OF RAA MODEL

This section provides an overview of the RAA modeling framework and describes the output of each component.

2.1 RAA Model Overview

The approach used to estimate the load reductions resulting from implementation of GI includes the model components listed below, which are described in further detail in the following sections:

- **Baseline Pollutant Loading Model** – the baseline pollutant loading model is a continuous simulation² hydrology model combined with pollutant loading inputs to obtain the average annual loading of mercury and PCBs across the county during the TMDL baseline period (i.e., 2003 – 2005).
 - **Hydrology** – this model component produces average annual runoff across each county for the period of record using a hydrologic response unit (HRU) approach. The HRU approach involves modeling various combinations of land surface features (i.e., imperviousness, underlying soil characteristics, slope, etc.) present within each county for a unit area drainage catchment. See Section 2.2.1.
 - **Water Quality** – the hydrology output is combined with average annual concentrations estimated by the Regional Monitoring Program’s Regional Watershed Spreadsheet Model (RWSM; Wu et al, 2017) developed by the San Francisco Estuary Institute (SFEI) to produce average annual PCBs and mercury loading for the period of record. See Section 2.2.2.

² Continuous simulation models calculate outputs (e.g., runoff) “continuously”, i.e., for many time steps over a long-term period of record (e.g., every 10 minutes for 10 years). Long-term “continuous” input data (e.g., hourly rainfall) is required. This is contrasted with design-event simulations which model a single rainfall event, e.g., a 24-hour storm with a 10-year recurrence frequency.

- GI Performance Models – the GI performance models are developed to represent load reductions resulting from implementation of GI. See Section 2.3.
- Future Condition (RAA Scenario) Models – the RAA scenario models are conducted to represent future land use changes and control measure implementation that could result in pollutant load reduction. Both GI and source controls are considered, depending on the time frame of interest. See Section 2.4 for a description of load reduction calculations.

2.2 Baseline Loading Model

2.2.1 Hydrologic Model

As introduced above, the proposed approach for modeling hydrology is to use a hydrologic response unit (HRU) approach. An HRU is a unique combination of land surface features (imperviousness, underlying soil characteristics, slope, etc.) which is expected to give a consistent runoff response to rainfall, no matter where that unique combination is found. The HRU approach involves modeling all possible combinations of land surface features present within each county for a unit area drainage catchment and then storing these results in a database. These HRU results can be scaled geospatially across the entire county without developing a detailed hydrologic model. This method is consistent with the *Bay Area RAA Guidance Document* (BASMAA, 2017b).

The generic HRUs are modeled using USEPA's Stormwater Management Model (SWMM) to obtain an average annual runoff volume per acre for the identified baseline period of record (water year [WY] 2000 – 2009) for each HRU. Certain HRU inputs (imperviousness, soil parameters) are adjusted as needed to calibrate the HRUs on an average annual basis to identified flow gauges in the counties.

The average annual runoff volume per acre associated with a specific HRU can then be multiplied by the area represented by that HRU across each county (or a selected smaller planning area, such as a watershed or jurisdictional boundary). The resulting volumes associated with each represented HRU within the specified geospatial area can then be summed for the identified area to obtain the estimated total average annual runoff volume.

2.2.2 Water Quality Model

Identified HRUs across each county are combined with the RWSM land use classifications layer to determine pollutant loading rates. The RWSM provides average annual concentrations of PCBs

and mercury that wash off from various land use categories. On an average annual basis, this approach approximates the total load.

Average annual runoff volume associated with the geospatial HRUs is multiplied by the PCBs and mercury average annual concentration (based on the RWSM land use categories for the identified area) to obtain average annual pollutant load using the following equation:

$$Load_{Baseline} = \sum(\sum Unit\ Runoff_{HRU} \times Area_{LU,HRU}) \times Concentration_{LU} \times 0.00123 \quad \text{Eqn. 1}$$

Where:

$Load_{Baseline}$ = The total average annual baseline pollutant load for the identified area for calculation [grams/year]

$Unit\ Runoff_{HRU}$ = The average annual runoff per acre for a given HRU within the identified area for calculation [ac-ft/acre/yr]

$Area_{LU,HRU}$ = The total area of the HRU within the RWSM land use category within the identified area for calculation [acres]

$Concentration_{LU}$ = The average annual pollutant concentration associated with the RWSM land use category [ng/L]

0.00123 = Conversion factor [(L/ac-ft)*(g/ng)]

2.3 Green Infrastructure Performance Model

Volume reduction (via retention in the green infrastructure facility) and pollutant load reduction (via filtration through media and discharge through an underdrain) are modeled utilizing a combination of hydraulic modeling in SWMM and currently available empirical GI performance data.

2.3.1 Hydraulic GI Models

GI control measure hydraulic performance is modeled in SWMM with a 100% impervious tributary area for three GI facility types: (1) bioretention³ with a raised underdrain, (2) bioretention with no underdrain, and (3) lined bioretention. The model is run with varying footprint sizes and varying underlying infiltration rates (i.e., the rate at which treated runoff infiltrates into native soils underlying the BMP facility). Average annual volume retained, volume treated, and volume bypassed by the GI measure are recorded for each GI model run.

Volume-based performance⁴ corresponding to the generic 100% impervious tributary area can be applied to the effective area in GI drainage areas made up of identified HRUs. The effective area is also known as the “runoff generating area” and is calculated as the tributary area multiplied by the long-term or average annual runoff coefficient.

2.3.2 Green Infrastructure Pollutant Reduction Calculations

To calculate pollutant load reduction associated with GI implementation, the hydraulic model results are combined with water quality performance data. The annual estimate of pollutant load reduction from the modeled drainage area is equivalent to the difference between the influent load and the sum of the pollutant load that bypasses the GI measure and the effluent load (Eqn. 2). Equations corresponding to the pollutant reduction calculation are provided below and the water balance is illustrated in Figure 1. In summary, influent load is calculated as the pollutant load produced by the 100% impervious tributary area for each RWSM land use category using Eqn. 3. The pollutant load that bypasses the facility is calculated as the proportion of runoff that bypasses the facility per the hydraulic GI model output, multiplied by the influent concentration (Eqn. 4). The effluent load is calculated as the proportion of runoff that is captured by the facility per the hydraulic GI model output, combined with an effluent concentration (Eqn. 5 and Eqn. 6).

³ The bioretention is assumed to include: 6-inch or 12-inch ponding depth, 1.5 ft of filter media with a 5 in/hr flow through rate, and 1 ft of gravel beneath the media.

⁴ Volume-based performance refers to how much runoff volume the GI facility captures and retains or treats and discharges through the underdrain, typically represented as a percentage of the average annual runoff volume.

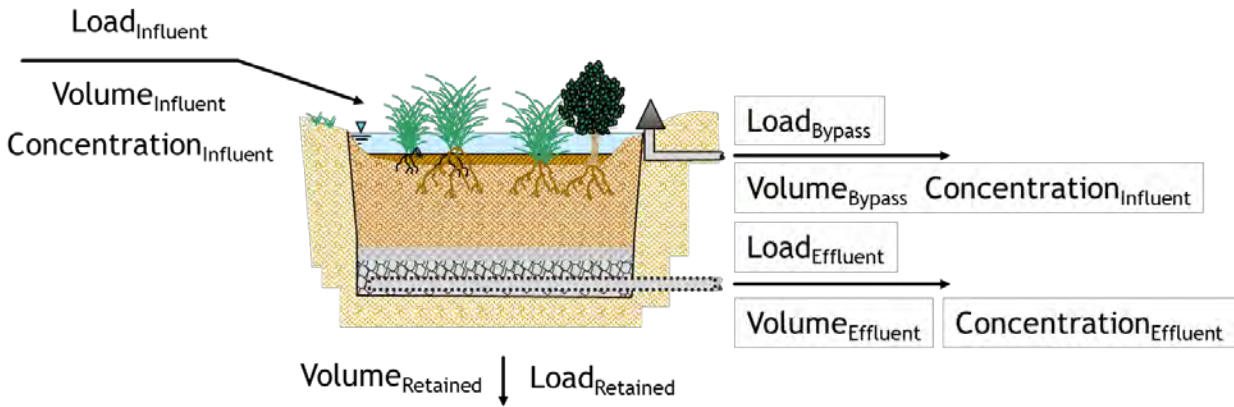


Figure 1: Illustration of GI Facility Pollutant Load Reduction Calculations

$$Load_{Reduced} = Load_{Influent} - Load_{Bypass} - Load_{Effluent} \quad \text{Eqn. 2}$$

$$Load_{Influent} = Volume_{Influent} \times Concentration_{Influent} \times C \quad \text{Eqn. 3}$$

$$Load_{Bypass} = Volume_{Bypass} \times Concentration_{Influent} \times C \quad \text{Eqn. 4}$$

$$Load_{Effluent} = (Volume_{Captured} - Volume_{Retained}) \times Concentration_{Effluent} \times C \quad \text{Eqn. 5}$$

$$Volume_{Captured} = Volume_{Influent} - Volume_{Bypass} \quad \text{Eqn. 6}$$

Where:

$Load_{Reduced}$ = The total average annual pollutant load reduced by the GI facility [g/year]

$Load_{Influent}$ = The total average annual pollutant load produced by the facility drainage area [g/year]

$Load_{Bypass}$ = The pollutant load that bypasses the facility [g/year]

$Load_{Effluent}$ = The pollutant load discharged from the facility after treatment [g/year]

$Volume_{Influent}$ = The runoff produced by the drainage area to the GI facility [ac-ft/year]

$Volume_{Bypass}$ = The proportion of influent runoff that bypasses the facility [ac-ft/year]

$\text{Volume}_{\text{Captured}}$	=	The proportion of influent runoff that is captured by the facility [ac-ft/year]
$\text{Volume}_{\text{Retained}}$	=	The proportion of captured runoff that is retained by the facility through infiltration and/or evapotranspiration [ac-ft/year]
$\text{Concentration}_{\text{Influent}}$	=	The pollutant concentration associated with the GI drainage area [ng/L]
$\text{Concentration}_{\text{Effluent}}$	=	The concentration discharged from the facility after treatment [ng/L]
C	=	Conversion factor constant = $0.00123 \text{ [(L/ac-ft)*(g/ng)]}$

2.4 RAA Scenario Loading Model

The loading corresponding with RAA future condition scenarios (2020, 2030, 2040) will be developed using the same volume and concentration combination approach used for the baseline condition. HRU outputs developed for the baseline model will be scaled across the county corresponding to anticipated land use and development changes for each of the future conditions. Similarly, the RWSM land use classifications layer will be updated corresponding to each future condition scenario.

The outputs of the future hydrology scaling combined with the concentrations corresponding with future RWSM land use classification provides the land use-based loading estimated for each of the future conditions. To obtain the discharged load corresponding to each future GI scenario, load reductions associated with anticipated GI (developed as described above) will be subtracted from the land use-based load.

3. MODEL INPUTS AND DATA USED

This section describes the inputs to each component of the model and the data used.

3.1 Baseline Loading Model

3.1.1 Hydrologic Model

Generic HRU models are developed in SWMM to estimate average annual runoff volume per acre values that can be applied to all land surfaces within each county. The land surface feature inputs that will be varied to model the generic HRUs are described in the sections below and summarized in Table 3.

Climate Inputs

HRU climate inputs provide the total amount of precipitation that falls on the land surface and the amount of precipitation that is lost to the atmosphere via evapotranspiration before running off the land surface. Multiple gauges from across Alameda and Contra Costa counties that had continuous hourly precipitation data were chosen to represent distinct rainfall regions within both counties. For precipitation, these regions are based on 30-year annual rainfall regimes as identified by PRISM⁵. For evapotranspiration rates, the California Irrigation Management Information System (CIMIS) evapotranspiration zones were used within each county. The combination of the identified precipitation regions and evapotranspiration regions were combined to yield “climate zones” used for generic HRU models. Precipitation zones, evapotranspiration zones, and climate zones are shown in Exhibit 1 through Exhibit 3 (see Appendix A). Table 1 provides a summary of precipitation gauges used and average annual rainfall corresponding to the entire period of record and WY 2000 - 2009. Table 2 provides a summary of the CIMIS data used for the daily reference evapotranspiration rate for each evapotranspiration zone.

Table 1: HRU Precipitation Gauges WY2000-2009

Gauge ID	Gauge Name	Average Annual Precipitation (inches) WY 2000 - 2009	Gauge Source
KHWD	Hayward Air Terminal (ASOS)	16.3	ASOS ¹
KLVK	Livermore Municipal Airport (ASOS)	14.6	ASOS
KOAK	Oakland Airport (ASOS)	19.0	ASOS
DBF	Dublin Fire Station, San Ramon	17.3	CCCFC ²
FCD	Flood Control District, Martinez	16.2	CCCFC
LSM	Los Medanos, Pittsburg	11.8	CCCFC
SMC	Saint Mary's College, Moraga	28.9	CCCFC

1. Automated Surface Observation System (ASOS) data were used for Alameda County gauge sites for the period of WY2000-2009 since NCDC gauge data was not available for the baseline period. ASOS sites sometimes co-occur with NCDC gauge sites (e.g., airports), but are maintained and delivered by separate government entities.
2. Contra Costa County gauge data is collected by the Flood Control District but was provided to Geosyntec by Dublin Engineering.

⁵ Parameter-elevation Relationships on Independent Slopes Model (PRISM), developed and managed by the PRISM Climate Group, Oregon State University <http://prism.oregonstate.edu/>.

Table 2: CIMIS Reference Evapotranspiration

ET Zone	Monthly Evapotranspiration (in/day) ¹											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.03	0.05	0.08	0.11	0.13	0.15	0.15	0.13	0.11	0.08	0.04	0.02
2	0.04	0.06	0.1	0.13	0.15	0.17	0.16	0.15	0.13	0.09	0.06	0.04
3	0.06	0.08	0.12	0.16	0.17	0.19	0.18	0.17	0.14	0.11	0.08	0.06
6	0.06	0.08	0.11	0.16	0.18	0.21	0.21	0.2	0.16	0.12	0.08	0.06
8	0.04	0.06	0.11	0.16	0.2	0.23	0.24	0.21	0.17	0.11	0.06	0.03
14	0.05	0.08	0.12	0.17	0.22	0.26	0.28	0.25	0.19	0.13	0.07	0.05

1. CIMIS reference evapotranspiration, which is based on irrigated turf grass, was scaled by 0.6 to represent the local mix of vegetated cover including urban vegetation, native xeric adapted plants, and unirrigated vegetated open space areas.

Slope

Slope affects how quickly rainfall will run off a modeled land surface and therefore how much is able to be infiltrated into the subsurface. The available digital elevation model (DEM)⁶ for the counties was analyzed to obtain percent slope values for each ~30m by ~30m square of land surface. These percent slope values were classified into three distinct slope zones as summarized in Table 3 and shown in Exhibit 4 (see Appendix A).

Underlying Soil Inputs

Physical characteristics of the soil underlying the land surface affect the amount of rainfall that may be infiltrated into the subsurface. Infiltration was simulated in SWMM using the Green-Ampt infiltration model option. The physical soil input parameters for the Green-Ampt infiltration model were varied based on hydrologic soil group (HSG) as identified by the National Resource Conservation Service (NRCS⁷) soil survey and were modified as described below for developed areas. Soil parameters used as model inputs include suction head, hydraulic conductivity, and initial moisture deficit. Developed areas that are assumed to have been compacted and therefore result in less infiltration to the subsurface are modeled using 75 percent of the HSG hydraulic conductivity value. Soil parameters are not reported here, as this input is adjusted as part of

⁶ U.S. Geological Survey. National Elevation Dataset (NED) 1/3 arc-second. 2013

⁷ Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. link: <https://websoilsurvey.sc.egov.usda.gov/>

baseline model calibration. Details about soil inputs are provided in Table 3. A map of hydrologic soil group is provided as Exhibit 5 (see Appendix A).

Areas of development were identified based on the land use of the surface. Soils within urban and agricultural use areas were considered to have been compacted by the site preparation and activities.

Imperviousness

Imperviousness (i.e., the percentage of impervious area) affects area on the land surface where rainfall may be infiltrated and therefore the quantity of runoff produced. The runoff from a range of land use imperviousness values is modeled by area-weighting the results of a pervious surface runoff result (i.e., pervious HRU output) with a corresponding impervious surface runoff result (i.e., impervious HRU output) (see Table 3 and Exhibit 6 (see Appendix A)).

The baseline model HRU imperviousness is developed by geospatially combining the land uses identified by Association of Bay Area Governments (ABAG, 2005) with the National Land Cover Dataset (NLCD, 2006) data. Each feature of the ABAG dataset is assigned a single imperviousness value that is used to determine the average hydrologic response of that land surface. A lookup-table containing NLCD based imperviousness for each ABAG land use code was used as a starting value for HRU calibration. These initial values may be adjusted within an appropriate range as part of baseline model calibration.

3.1.2 Developing HRUs across each County

Each identified combination of land surface features is modeled for a generic unit-acre drainage area in SWMM for the baseline period of record (i.e., WY 2000 – 2009), utilizing a batch-processing method (which allows for inputs to be altered, model files run, and results extracted for many models automatically). The average annual runoff volume per acre is then extracted for each generic HRU modeled.

Table 3: Land Surface Feature Inputs for Generic HRU Hydrologic Models

Variables	Description	Number of Varying Features	Feature Representations	Source
Hourly Annual Precipitation	Rainfall Gauge and Rainfall Zone	7	Contra Costa County Gauges: DBF, FCD, LSM, SMC Alameda County ASOS Gauges: KHWD, KLVK, KOAK	PRISM ¹ , NCDC/ County-maintained rainfall gauges
Daily Evapotranspiration Rate	Evapotranspiration Zone	5	Zones 1, 2, 3, 6, 8, 14	CIMIS ²
Slope Zone	Representation of Slope	3	<5%, 5-15%, 15%+	USGS ³
Developed/ Undeveloped Areas	Representation of Compaction of Underlying Soils (Pervious Areas Only)	2	Undeveloped (Ksat * 1) Developed (Ksat * 0.75)	ABAG Land Use 2005 ⁴
Hydrologic Soil Group	Representation of Underlying Soil Type (pervious areas only)	6	HSG A, B, C, D ⁵ , Rock, Water	NRCS ⁶
Imperviousness	Representation of Imperviousness	2	0% and 100%	NLCD and ABAG 2005

1. PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>, 30-year normal mean annual precipitation
2. California Irrigation Management Information System (CIMIS) Reference Evapotranspiration; digitized from http://www.cimis.water.ca.gov/App_Themes/images/etozonemap.jpg
3. U.S. Geological Survey. National Elevation Dataset (NED) 1/3 arc-second. 2013
4. ABAG land uses are proposed to be used for identifying developed and undeveloped condition and will have an imperviousness value assigned based on a geospatial analysis of the NLCD Imperviousness layer. The impervious value for each ABAG land use feature will then be carried into the HRU model calibration and adjusted accordingly.
5. "Urban" representation will be re-classified based on the dominant adjacent HSG.
6. U.S. Department of Agriculture, Natural Resources Conservation Service. Soil Survey Geographic (SSURGO) database. 2016

HRUs are determined geospatially based on the climate zone, slope zone, developed/undeveloped areas, and HSG, along with land use-based imperviousness. Exhibits 1 through 5 (see Appendix A) display the data used to develop climate zones, county slope zones, and the HSG distribution across each county. Imperviousness designations will occur based on

land use at the parcel level, by combining the geospatial ABAG land use layer⁸ with the other hydrologic input regions. This results in a “patchwork” of HRUs across the counties⁹.

The resulting patchwork of HRUs can be combined at the scale of choice to provide total runoff volumes for a specific area, such as a watershed or jurisdictional boundary. To estimate the total runoff for the identified area, the total acreage of each designated HRU present within a watershed or jurisdiction will be multiplied by the average annual runoff per acre associated with each HRU and then summed (i.e., area-weighting the average annual runoff volume per acre for all HRUs present).

3.1.3 HRU Input Calibration

Calibration of hydrologic models is required by the *Bay Area RAA Guidance Document*. Calibration of the generic HRU models will be conducted utilizing available stream flow records and based solely upon the annual discharge volume between WY 2000-2009. This annual calibration means that the HRU runoff estimates are representative of the approximate annual runoff volume but will not be used to estimate or compare discharge rates at smaller timesteps, such as the hourly or daily runoff hydrograph.

The list of candidate gauge sites within the counties was developed based on an assessment of the representativeness of the gauged watersheds and the mitigation of confounding factors that interfere with calibration such as missing data and upstream impoundments. For the purposes of calibration, the candidate gauge sites that were selected included stream depth rating curves and at least daily mean records for the historical period of interest. The USGS flow gauges considered for calibration are provided in Table 4 and shown in Exhibit 8 (see Appendix A).

⁸ ABAG land use features will be used to aggregate the imperviousness for the land surface. The relationship between ABAG feature and its imperviousness will be developed based upon other local sources (SMCWPPP, 2017) and analysis of national public data sets such as the National Land Cover Dataset (NLCD)

⁹ This will be done once all the HRU input files are finalized, including the imperviousness layers.

Table 4: Flow Gauge Considered for RAA Model Calibration

Gauge ID	Gauge Name	Location	County	Data Frequency
11337600	Marsh Creek	Brentwood	Contra Costa	Daily
11182500	San Ramon Creek	San Ramon	Contra Costa	Daily
11181390	Wildcat Creek	Richmond / San Pablo	Contra Costa	Daily
11181040	Lan Lorenzo Creek	San Lorenzo	Alameda	Daily
11181008	Castro Valley Creek	Hayward	Alameda	Daily
11181000	San Lorenzo Creek	Hayward	Alameda	Daily
11180700	Alameda Creek Flood Channel	Union City	Alameda	Daily
11179000	Alameda Creek	Fremont	Alameda	Daily
11176900	Arroyo de la Laguna	Verona	Alameda	Daily
11173575	Alameda Creek Below Welch Creek	Sunol	Alameda	Daily
11173510	Alameda Creek Below Calaveras Creek	Sunol	Alameda	Daily

The effective area tributary to each flow gauge is used to calibrate the HRUs to the stream gauge records. Annual flow predicted by area-weighting HRU runoff output for the watersheds draining to the stream gauges was compared to annual flow in the stream records for the identified period of record.

Calibration of land surface runoff hydrology to stream gauge records requires that baseflow be computed and accounted for throughout the period of record. A variety of methods exist for separating baseflow from runoff, including the fixed-interval method and the local-minimum method (Sloto and Crouse, 1996). The most appropriate method for separating baseflow is determined on a gauge by gauge basis depending on the variability in the flow record, and the occurrence of confounding factors that affect baseflow such as dam releases and other dry weather inflows.

The average percent difference between the area-weighted HRU total average annual runoff volume for the watershed and the average annual flow (converted to volume) measured for the WY 2000 – 2009 period will be calculated. The acceptable ranges included in the RAA Guidance document are provided in Table 5 below.

Table 5: Allowable Difference between Simulated and Observed Annual Volumes

Model parameters	Average % difference between simulated annual results and observed data		
	Very Good	Good	Fair (lower bound, upper bound)
Hydrology/Flow	<10	10-15	15-25

If the average percent difference between simulated and measured annual storm flow volumes is greater than 25%, HRU model parameters are adjusted until the percent difference is within the acceptable range. The primary model parameters adjusted include underlying soil hydraulic conductivity and land use imperviousness, but other hydrologic model parameters, such as depression storage, may be adjusted as appropriate.

Once average percent differences in all identified watersheds are within the acceptable range, the HRU model parameters are finalized and the HRU results database will be regenerated. HRUs and resulting average annual baseline volume will be applied across each county to obtain the baseline volume discharged by each county.

3.1.4 Water Quality Model

RWSM values used to develop pollutant loading estimates across each county are:

Table 6: Regional Watershed Spreadsheet Model PCBs and Mercury Concentrations in Runoff

Land Use Category	Total PCBs (ng/L)	Total mercury (ng/L)
Ag, Open	0.2	80
New Urban	0.2	3
Old Residential	4	63
Old Commercial/ Transportation	40	63
Old Industrial and Source Areas	204	40

Water quality calculations are also used to perform baseline pollutant loading validation. The calculated pollutant load draining to Regional Monitoring Program stations will be validated by calculating the volume-weighted watershed pollutant concentration using the modeling results and comparing it to the observed concentrations in the Regional Monitoring Program data. The equation used to calculate concentration (in ng/L) at an end-of-watershed location is as follows:

$$Concentration_{Baseline} = \frac{\sum Runoff_{HRU} \times Area_{HRU} \times Concentration_{LU,HRU}}{\sum Runoff_{HRU} \times Area_{HRU}} \quad \text{Eqn. 7}$$

Pollutant concentration and loading data from the Regional Monitoring Program will be compared to the result of Equation 7 for several watersheds for validation purposes.

3.2 Green Infrastructure Performance Model

3.2.1 Long-Term Green Infrastructure Simulations

Long term performance was assessed for each BMP configuration using continuous historical rainfall records. In Contra Costa County historical data was available at the same gauges that were used for the HRU runoff modeling between WY2000-2009, but for Alameda County other gauge sites with longer histories were used for long term BMP performance modeling. The rainfall gauges used to model BMP performance are shown in Table 7.

Table 7: Long Term GI Performance Precipitation Gauges

Gauge ID	Gauge Name	Period of Record	Average Annual Precipitation (inches)	Gauge Source ¹
040693	Berkeley (NCDC)	1948-1990	19.8	NCDC
041060	Brentwood (NCDC)	1950-1985	14.9	NCDC
043863	Hayward (NCDC)	1948-1988	24.3	NCDC
046335	Oakland Airport (NCDC)	1948-1985	16.4	NCDC
047821	San Jose Airport (NCDC)	1948-2010	13.6	NCDC
DBF	Dublin Fire Station, San Ramon	1973-2016	15.0	CCCFCFCD
FCD	Flood Control District, Martinez	1971-2016	16.5	CCCFCFCD
LSM	Los Medanos, Pittsburg	1974-2016	10.6	CCCFCFCD
SMC	Saint Mary's College, Moraga	1972-2016	26.8	CCCFCFCD

1. NCDC data was used for Alameda County and San Jose gauge sites. Contra Costa County gauge data is collected by the Flood Control District and was provided to Geosyntec by Dubin Engineering.

3.2.2 Hydraulic Green Infrastructure Model

Hydraulic GI models were developed in SWMM to estimate hydraulic performance for a 100% impervious tributary area. Hydraulic model inputs that were varied to model the GI facility performance for the counties are described below and summarized in Table 8.

1. BMP Configuration – three GI facility types were assumed: (1) bioretention with a raised underdrain, (2) bioretention with no underdrain, and (3) lined bioretention with an underdrain.

2. BMP Footprint Size – the BMP footprint size was varied as a percent of impervious area to model different levels of hydraulic capture performance depending on facility sizing.
3. BMP Underlying Infiltration Rate – the infiltration rate of the soils underneath the bioretention facility was varied for the bioretention with a raised underdrain and bioretention with no underdrain configurations (i.e., the unlined facility types).

Table 8: Land Surface Feature Inputs for Generic GI Performance Hydraulic Models

Variables	Description	Number of Varying Features	Feature Representations
Hourly Precipitation	Rainfall Gauge	9	NCDC: 040693 (Berkeley) 046335 (Oakland Airport) 043863 (Hayward) 047821 (San Jose) 041060 (Brentwood) Contra Costa County: DBF, FCD, LSM, SMC
Daily Evapotranspiration Rate	Evapotranspiration Zone	4	CIMIS Zones: 1, 6, 8, 14
BMP Configurations	BMP profiles and underdrain	3	Lined Bioretention with underdrain Unlined Bioretention with elevated underdrain Infiltration Basin without underdrain
BMP Surface Ponding Depth	Depth (feet)	2	0.5, 1
BMP Footprint Sizes	% of Impervious Area	12	0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6
BMP Infiltration Rates	Ksat of underlying soil (in/hr)	7	Unlined Bioretention: 0.024, 0.05, 0.1, 0.2, 0.24, 0.3, 0.4, 0.5
		3	Infiltration Basin: 0.5, 1, 2

The BMP cross-sections that were modeled each include:

- 6-inches or 12-inches ponding depth (both were modeled),
- 1.5 ft of filter media with 25% porosity with a 5 in/hr flow through rate, and

- 1 ft of gravel beneath the media with 40% porosity.

Two of the modeled BMP configurations include underdrains. In the lined bioretention facility, the underdrain is located at the bottom of the gravel layer. In the unlined bioretention facility, the underdrain was modeled at the top of the gravel layer. BMP configurations are shown in Exhibits 9 through 11 (see Appendix A).

3.2.3 Green Infrastructure Pollutant Reduction Calculations

As described in Section 2.3.2, pollutant load reduction associated with GI is calculated by combining the hydraulic model results with water quality performance data. The annual estimate of pollutant load reduction from the modeled drainage area is equivalent to the difference between the influent load and the sum of the pollutant load that bypasses the GI measure and the effluent load. The effluent load is calculated as the proportion of runoff that is treated by the GI measure multiplied by an effluent concentration.

Water quality performance data from selected, representative studies were used to determine a method to predict effluent concentrations in stormwater following treatment through a biofiltration (bioretention or tree well filters) GI measure. The data used to develop the relationship came from three studies: a) 2011 monitoring study of the El Cerrito Rain Gardens (Gilbreath, Pearce, and McKee, 2012), b) Clean Watersheds for a Clean Bay (CW4CB)¹⁰ (Geosyntec and EOA, 2017), and c) a study at Echo Lake in King County, WA (King County, 2017). A summary of the paired influent-effluent data associated with each study is provided in table:

Table 9: Data used to Develop Effluent Concentrations

Project Name	Project Sponsor	Facility ID	Influent-Effluent Data Pairs (n pairs)	
			PCBs	Mercury
El Cerrito Green Streets – CW4CB	El Cerrito	ELC-B1	3	3
El Cerrito Green Streets – SFEI	SFEI	ELC-B1	4	4
PG&E Substation 1st and Cutting Bioretention Cells – CW4CB	Richmond	LAU-3	8	8

¹⁰ The CW4CB study included additional monitoring of the El Cerrito rain gardens.

Project Name	Project Sponsor	Facility ID	Influent-Effluent Data Pairs (n pairs)	
			PCBs	Mercury
Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin Bioretention Planter Boxes – SAM Effectiveness Study	King County, Dept. of Natural Resources and Parks	BPB-1	4	0
		BPB-2	4	0
		BPB-3	4	0
		BPB-4	2	0
West Oakland Industrial Area Tree Wells – CW4CB	Oakland	ETT-TW2	4	4
		ETT-TW6	4	4
Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin Tree Well – SAM Effectiveness Study	King County, Dept. of Natural Resources and Parks	FLT-1	4	0
Total Data Pairs			41	23

These data were statistically evaluated to identify an appropriate method for predicting effluent concentrations of PCBs and total mercury. The data analysis first evaluated whether available influent and effluent concentration data were significantly different and, if so, whether a monotonic relationship existed (i.e., effluent generally increased when influent increased).

A Wilcoxon non-parametric hypothesis test was run on the PCBs and total mercury paired influent-effluent data to determine if influent and effluent concentrations were statistically different at a 5% significance level. This difference was found to be significant for PCBs, and significant for total mercury when corresponding influent suspended solids concentration was greater than 20 mg/L.

Spearman's rho and Kendall's tau, which are non-parametric rank correlation coefficients, were used to identify the direction and strength of correlation between influent and effluent concentrations. As shown in Table 10, both correlation coefficients suggest that effluent concentrations are positively correlated with influent concentrations for both PCBs and mercury.

Table 10: Influent/Effluent Correlation Coefficients.

Correlation Coefficient	Total PCBs	Total Mercury
Spearman's rho	0.725	0.547
Kendall's tau	0.527	0.396

The Kendall-Theil Robust Line (KTRL) method (Granato, 2006) was used to determine the best fit line between influent and effluent data. This non-parametric method uses the median of all possible pairwise slopes between points, which is more robust to outliers than a simple linear regression. Because stormwater data tend to be lognormal, the analysis was focused on linear and log-linear relationships. After the KTRL was generated, the lower portion of the curve was adjusted to assume that neither PCBs nor total mercury can be exported from biofilters under normal circumstances, i.e., that the maximum effluent concentration of PCBs or total mercury is equal to the influent concentration. The resulting KTRL for PCBs is shown Figure 2. The resulting KTRL for total mercury is shown in Figure 3. Each figure also includes a constant average effluent concentration line with data fit statistics: root mean square error (RMSE) and median absolute deviation (MAD). As indicated, the KTRL provide a better fit of the data. However, the resulting effluent concentrations are not much different between the two lines except when influent PCBs are low (<10 ng/L) and total mercury concentration are high (>50 ng/L). For total mercury, concentration reductions are only predicted to occur when influent concentrations are greater than about 30 ng/L. Due to observed export of total mercury for several events, particularly for the 1st and Cutting bioretention cell (LAU-3), the moderate concentration reductions assumed by the KTRL at higher influent concentrations is reasonably conservative.

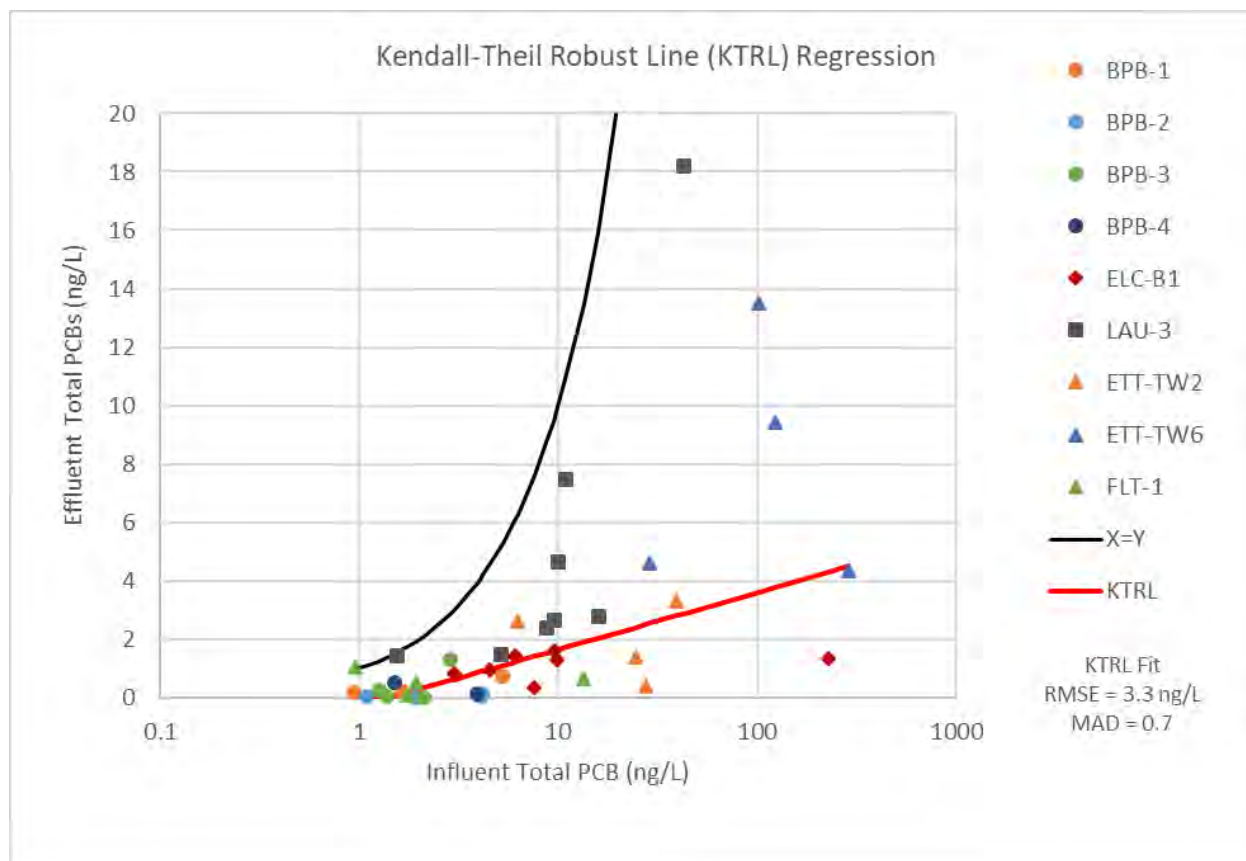


Figure 2: PCBs Influent vs Effluent Concentration Relationship Determined by KTRL Regression

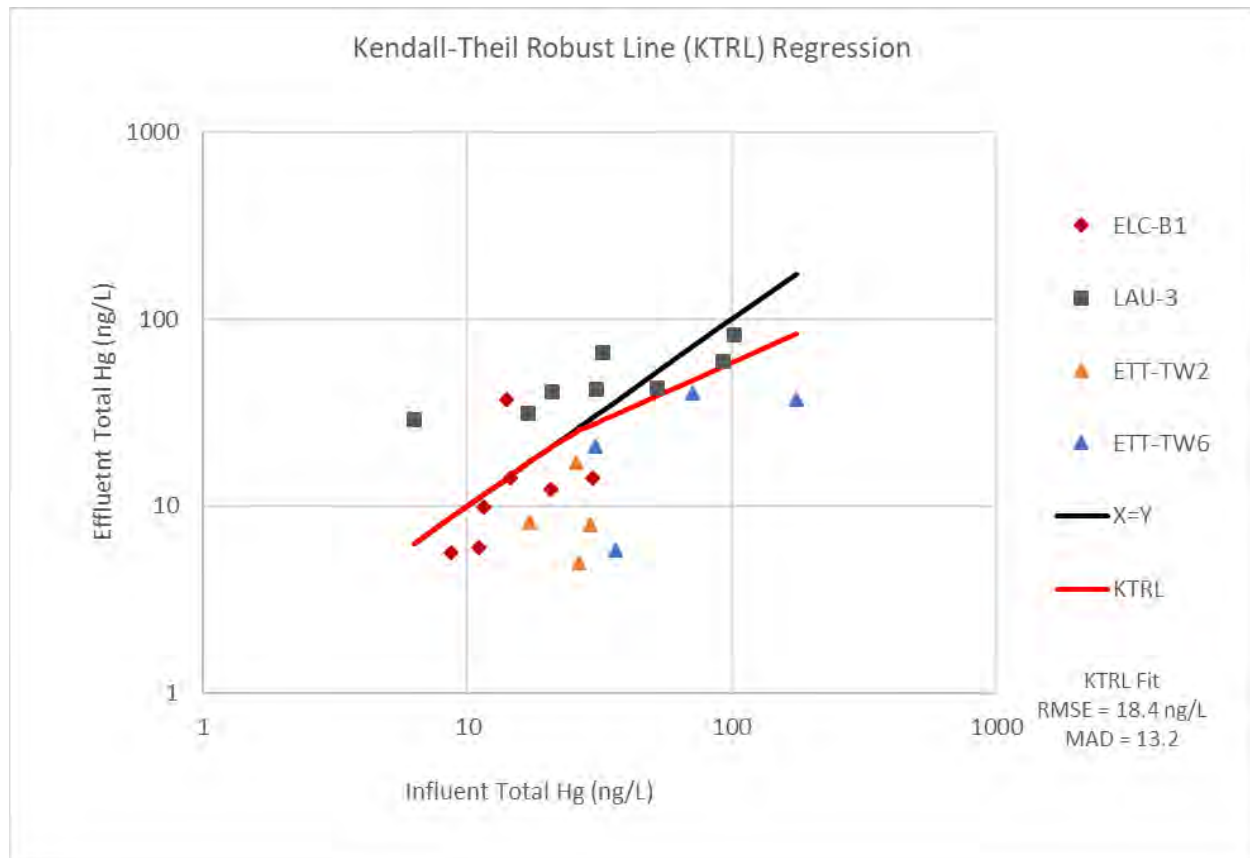


Figure 3: Mercury Influent vs Effluent Concentration Relationship Determined by KTRL Regression

3.3 RAA Scenario Loading Model

To model RAA future scenarios, future condition land use is needed. Future condition land use will be estimated using predictions of private parcel new development and redevelopment in combination with GI implementation on public parcels and rights-of-way.

Load reductions estimated for implementation of GI will be applied to future condition RAA scenario models based on estimated locations of GI and the tributary drainage areas to those GI. Effective area will be used to relate the HRUs, which can have a variety of imperviousness values, to the GI performance which will be based on a unit of effective area with 100% imperviousness. The GI performance curves can thus be applied to many different HRU types and/or combinations of HRUs that make up the tributary drainage areas for future GI measures.

4. QUANTITATIVE RELATIONSHIP BETWEEN GI IMPLEMENTATION AND PCBs LOADS REDUCED

The results of the hydraulic and pollutant reduction modeling of GI measures were used to develop a quantitative relationship between GI implementation and PCBs that can be applied to RAA future scenario models. An example quantitative relationship is provided for GI models run for the Berkeley gauge (040693). Utilizing output from hydraulic modeling, GI measure volumetric percent capture was calculated on an average annual basis. Volumetric model results for runs with GI measures sized to achieve 80%, 85%, 90%, and 95% capture were combined with water quality inputs to obtain pollutant load reduction for varying PCBs influent concentration.

The results of this analysis are shown in nomographs¹¹ provided in Figure 4, Figure 5, and Figure 6, which correspond to infiltrating bioretention (i.e., with no underdrain), bioretention with a raised underdrain, and lined bioretention, respectively. All facilities shown in the figures below have a 6-inch ponding depth. For bioretention with a raised underdrain, the facility configuration with an underlying infiltration rate of 0.24 in/hr only is shown (see Table 8 for all modeled infiltration rates). Facilities sized to achieve 80%, 85%, 90%, and 95% capture from the 100% impervious tributary catchment are shown in series, with pollutant load reduction in grams per effective acre¹² displayed as a function of influent concentration. Constant influent lines corresponding with RWSM land use-based influent concentrations are shown.

¹¹ A nomograph is a graphical relationship between two variables that can be used to quickly estimate one value from another.

¹² Effective area is calculated as the area multiplied by the runoff coefficient.

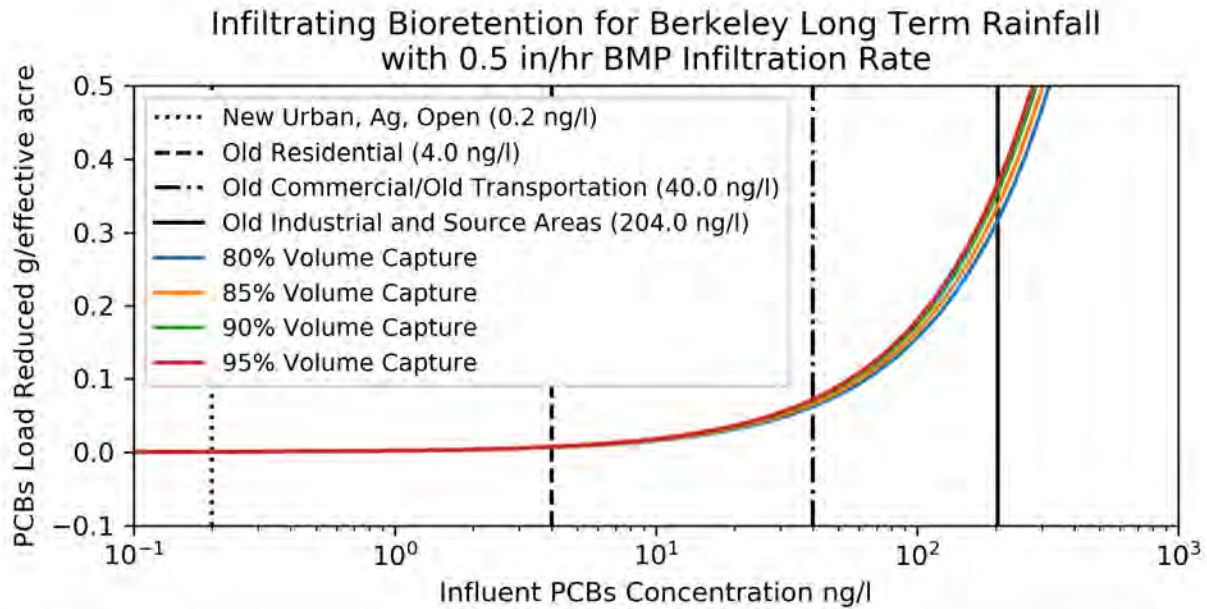


Figure 4: Modeled PCBs Load Removal Performance for Infiltrating Bioretention Basin

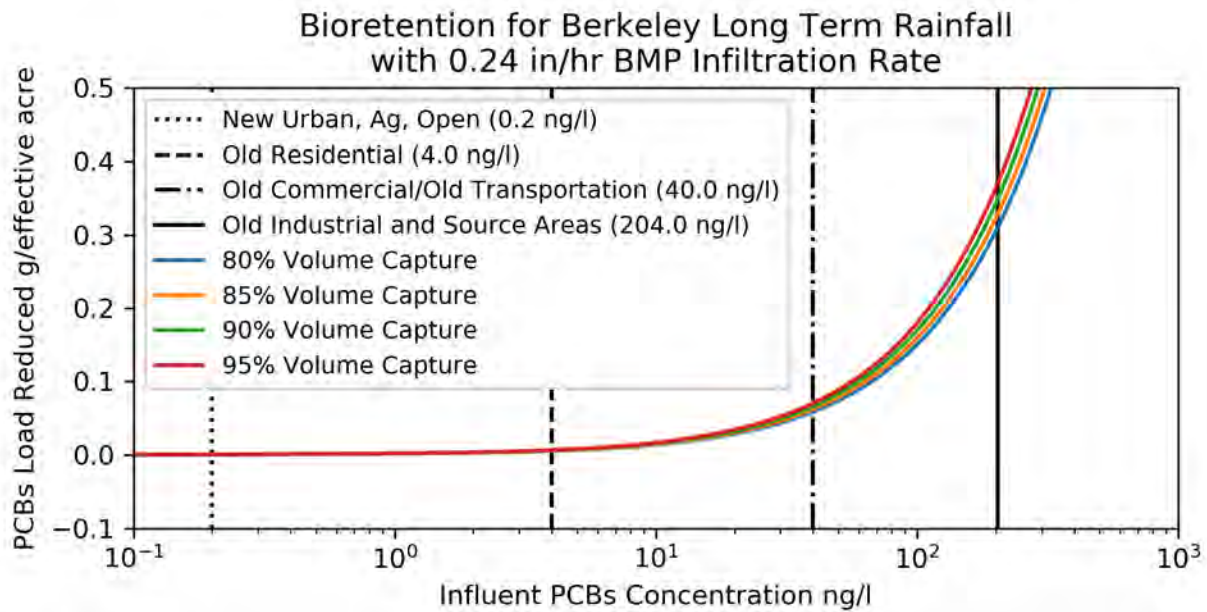


Figure 5: Modeled PCBs Load Removal Performance for Bioretention Basin with Elevated Underdrain

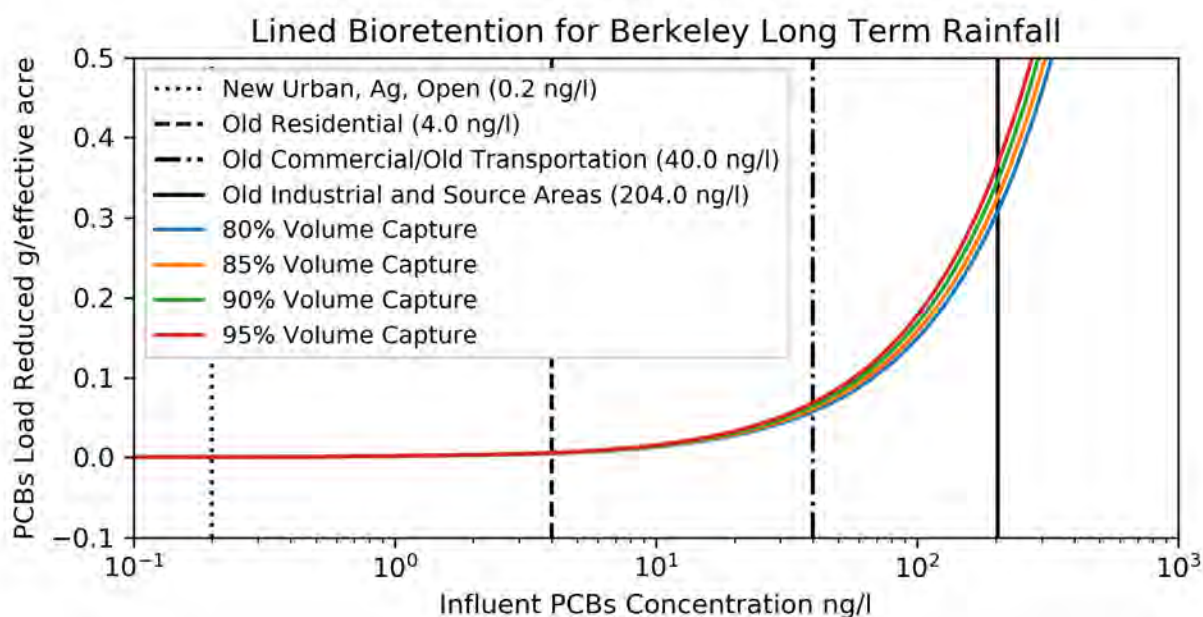


Figure 6: Modeled PCBs Load Removal Performance for Lined Bioretention Basin with Underdrain

The intersection points between the load reduction series and the constant influent lines represent the load reduced in grams per acre for each specific RWSM land use category. These intersection points are listed in Table 11.

Table 11: PCBs Load Reduction for RWSM Land Use Categories for Berkeley Gauge for Different BMP Percent Capture Values

Facility Configuration	Land Use Category	PCBs Load Reduced (g/effective ac)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Infiltrating Bioretention (0.5 underlying infiltration rate)	New Urban, Ag, Open	3.12E-04	3.30E-04	3.49E-04	3.61E-04
	Old Residential	0.00623	0.0066	0.00698	0.00722
	Old Commercial / Old Transportation	0.0623	0.066	0.0698	0.0722
	Old Industrial and Source Areas	0.318	0.337	0.356	0.368
Bioretention with Raised Underdrain (0.24 underlying infiltration rate)	New Urban, Ag, Open	3.08E-04	3.26E-04	3.47E-04	3.67E-04
	Old Residential	0.00518	0.0055	0.00589	0.00633
	Old Commercial / Old Transportation	0.0586	0.0621	0.0661	0.0703
	Old Industrial and Source Areas	0.311	0.329	0.350	0.371

Facility Configuration	Land Use Category	PCBs Load Reduced (g/effective ac)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Lined Bioretention	New Urban, Ag, Open	3.08E-04	3.26E-04	3.46E-04	3.67E-04
	Old Residential	0.00484	0.00513	0.00545	0.00577
	Old Commercial / Old Transportation	0.0574	0.0608	0.0647	0.0685
	Old Industrial and Source Areas	0.309	0.327	0.348	0.368

1. Average Annual Facility Volumetric Runoff Capture

5. QUANTITATIVE RELATIONSHIP BETWEEN GI IMPLEMENTATION AND MERCURY LOADS REDUCED

Mercury load reduction results for the Berkeley Gauge are shown in nomographs¹³ in Figure 7, Figure 8, and Figure 9, which correspond to infiltrating bioretention (i.e., with no underdrain), bioretention with a raised underdrain, and lined bioretention, respectively. All facilities shown in the figures below have a 6-inch ponding depth. For bioretention with a raised underdrain, the facility configuration with an underlying infiltration rate of 0.24 in/hr only is shown (see Table 9 for all modeled infiltration rates). Facilities sized to achieve 80%, 85%, 90%, and 95% capture from the 100% impervious tributary catchment are shown in series, with pollutant load reduction in grams per acre displayed as a function of influent concentration. Constant influent lines corresponding with RWSM land use-based influent concentrations are shown.

¹³ A nomograph is a graphical relationship between two variables that can be used to quickly estimate one value from another.

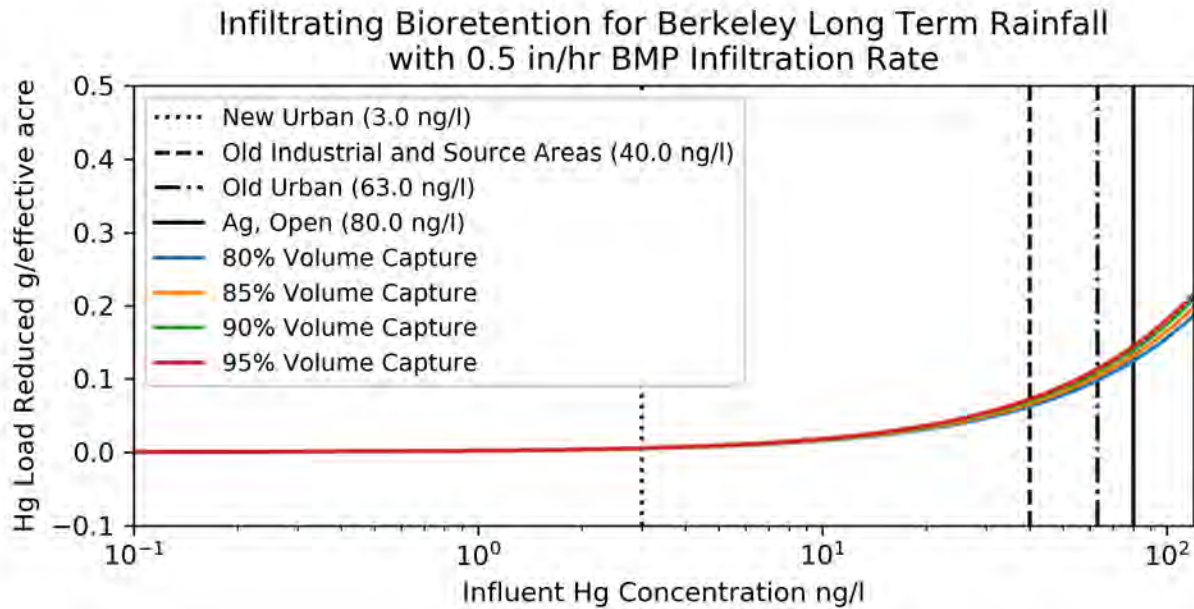


Figure 7: Modeled Mercury Load Removal Performance for Infiltrating Bioretention Basin

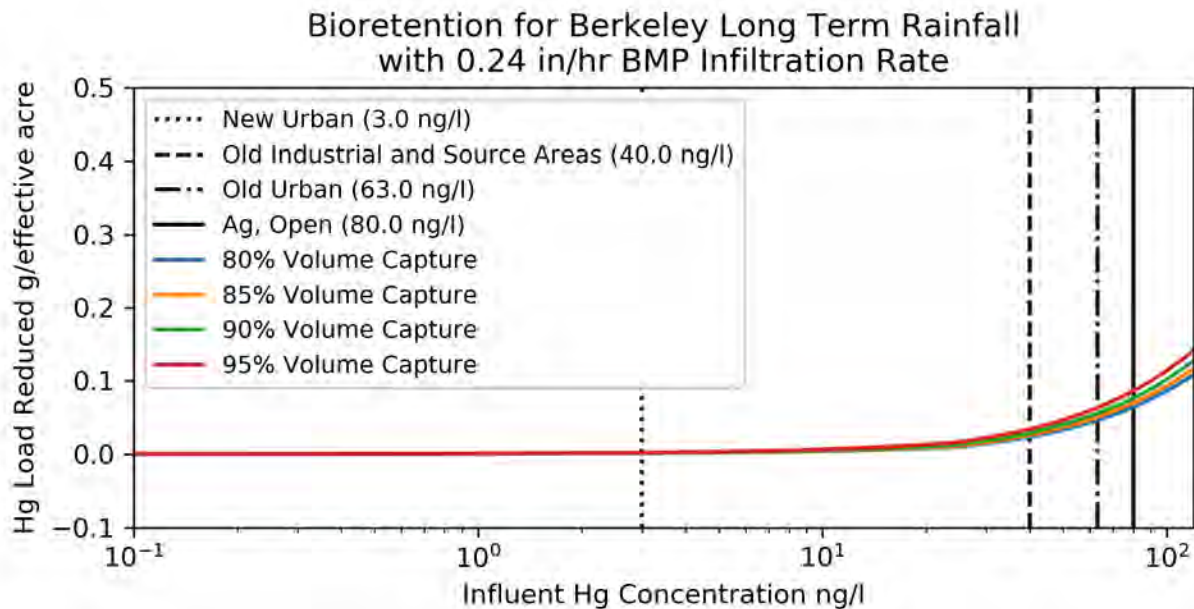


Figure 8: Modeled Mercury Load Removal Performance for Bioretention Basin with Elevated Underdrain

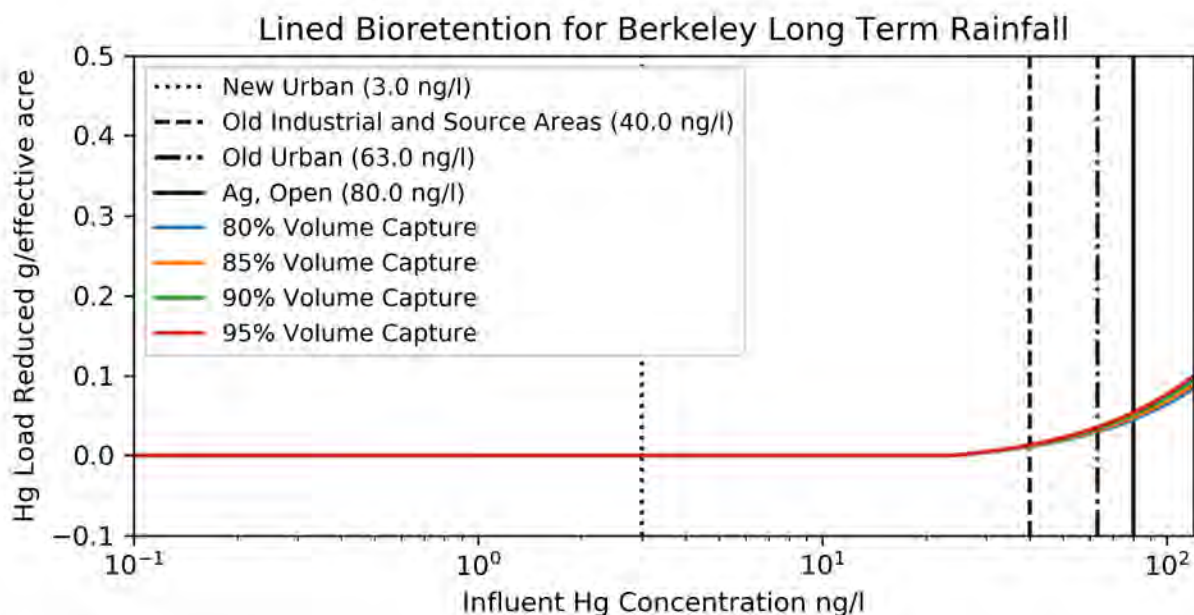


Figure 9: Modeled Mercury Load Removal Performance for Lined Bioretention Basin with Underdrain

The intersection points between the load reduction series and the constant influent lines represent the load reduced in grams per acre for each specific RWSM land use category. These intersection points are summarized in Table 12.

Table 12: Mercury Load Reduction for RWSM Land Use Categories for Berkeley Gauge for Different BMP Percent Capture Values

Facility Configuration	Land Use Category	Mercury Load Reduced (g/effective acre)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Infiltrating Bioretention (0.5 underlying infiltration rate)	New Urban	0.00467	0.00495	0.00524	0.00541
	Old Industrial and Source Areas	0.0623	0.066	0.0698	0.0722
	Old Urban	0.0981	0.104	0.110	0.114
	Ag, Open	0.125	0.132	0.140	0.144
Bioretention with Raised Underdrain (0.24 underlying infiltration rate)	New Urban	0.00113	0.0013	0.00153	0.00192
	Old Industrial and Source Areas	0.0234	0.0258	0.029	0.0341
	Old Urban	0.0462	0.0503	0.0556	0.0634
	Ag, Open	0.0643	0.0696	0.0765	0.0862

Facility Configuration	Land Use Category	Mercury Load Reduced (g/effective acre)			
		80% Capture ¹	85% Capture ¹	90% Capture ¹	95% Capture ¹
Lined Bioretention	New Urban	0	0	0	0
	Old Industrial and Source Areas	0.0108	0.0115	0.0123	0.0130
	Old Urban	0.0296	0.0314	0.0335	0.0353
	Ag, Open	0.0449	0.0476	0.0507	0.0536

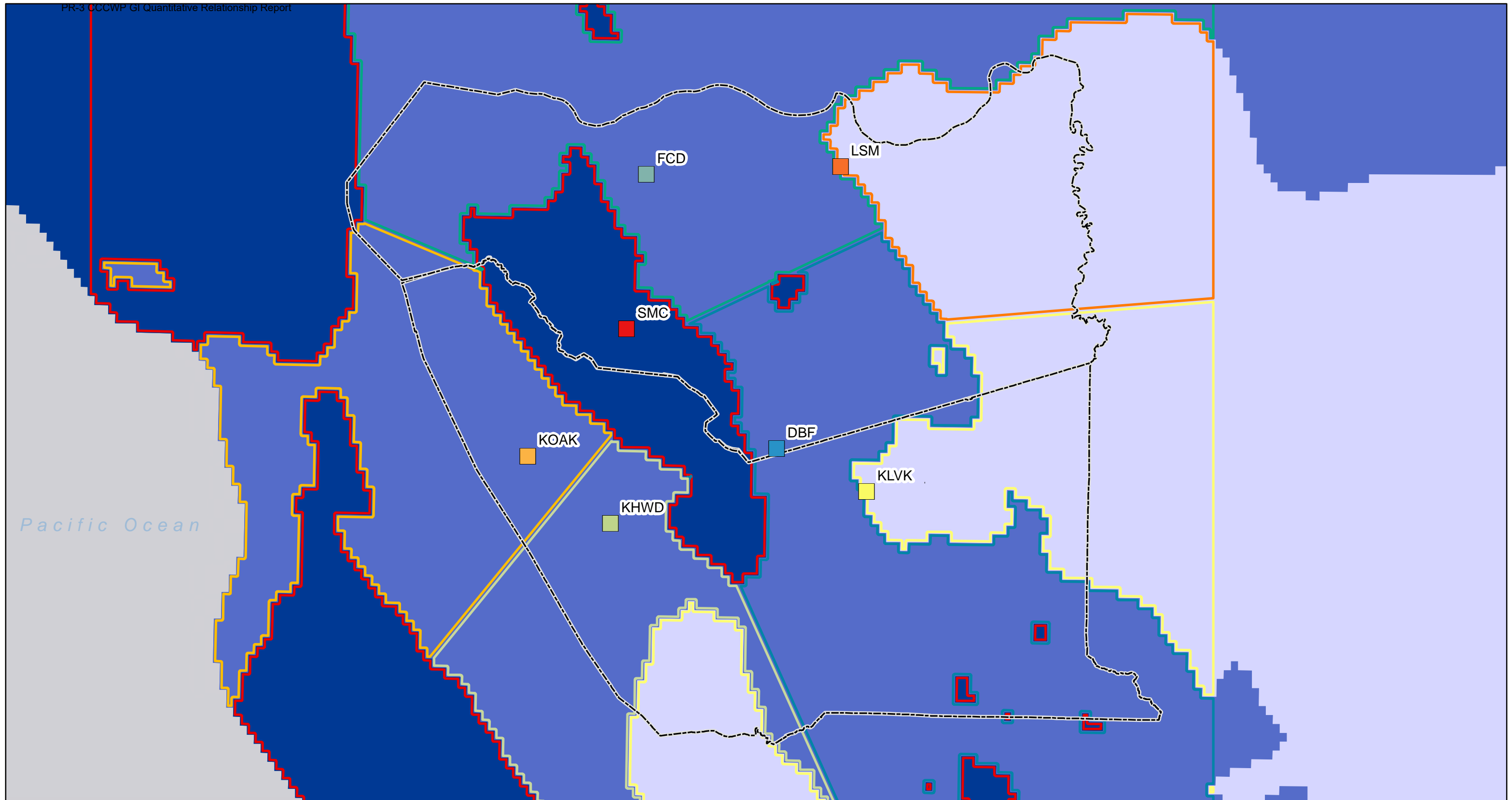
¹ Average Annual Facility Volumetric Runoff Capture














6. REFERENCES

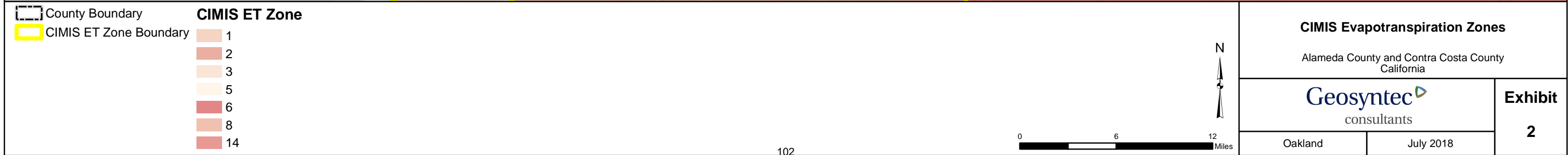
- Bay Area Stormwater Management Agencies Association (BASMAA), 2017a. Interim Accounting Methodology for TMDL Loads Reduced, Version 1.1. Prepared by Geosyntec Consultants and EOA, Inc. for the Bay Area Stormwater Management Agencies Association (BASMAA). March 2017.
- BASMAA, 2017b. Bay Area Reasonable Assurance Analysis Guidance Document. Prepared by Geosyntec Consultants and Paradigm Environmental. June.
- Geosyntec Consultants and EOA, 2017. Clean Watersheds for a Clean Bay (CW4CB). Final Report. Prepared for Bay Area Stormwater Management Agencies Association <http://basmaa.org/Clean-Watersheds-for-a-Clean-Bay-Project/CW4CB-Overall-Project-Report>
- Gilbreath, A. N.; Pearce, S.; McKee, L. J., 2012. Monitoring and Results for El Cerrito Rain Gardens. San Francisco Estuary Institute: Richmond, CA. <http://www.sfei.org/documents/monitoring-and-results-el-cerrito-rain-gardens>
- King County, 2017. Monitoring Stormwater Retrofits in the Echo Lake Drainage Basin - SAM Effectiveness Study - Final Report. Prepared by Carly Greyell, Water and Land Resources Division. Seattle, WA. <https://www.kingcounty.gov/depts/dnrp/wlr/sections-programs/science-section/doing-science/echo-lake-study.aspx>
- Granato, G.E., 2006, Kendall-Theil Robust Line (KTRLLine—version 1.0)—A visual basic program for calculating and graphing robust nonparametric estimates of linear-regression coefficients between two continuous variables: Techniques and Methods of the U.S. Geological Survey, book 4, chap. A7, 31 p.: <https://pubs.usgs.gov/tm/2006/tm4a7/>
- USEPA, 2017. Developing Reasonable Assurance: A Guide to Performing Model-Based Analysis to Support Municipal Stormwater Program Planning. Prepared by Paradigm Environmental. February.

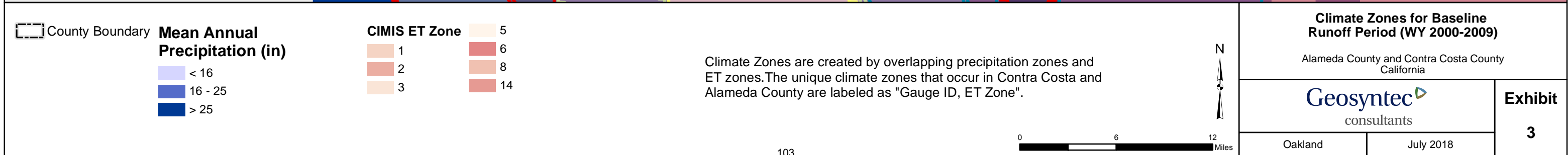
APPENDIX A

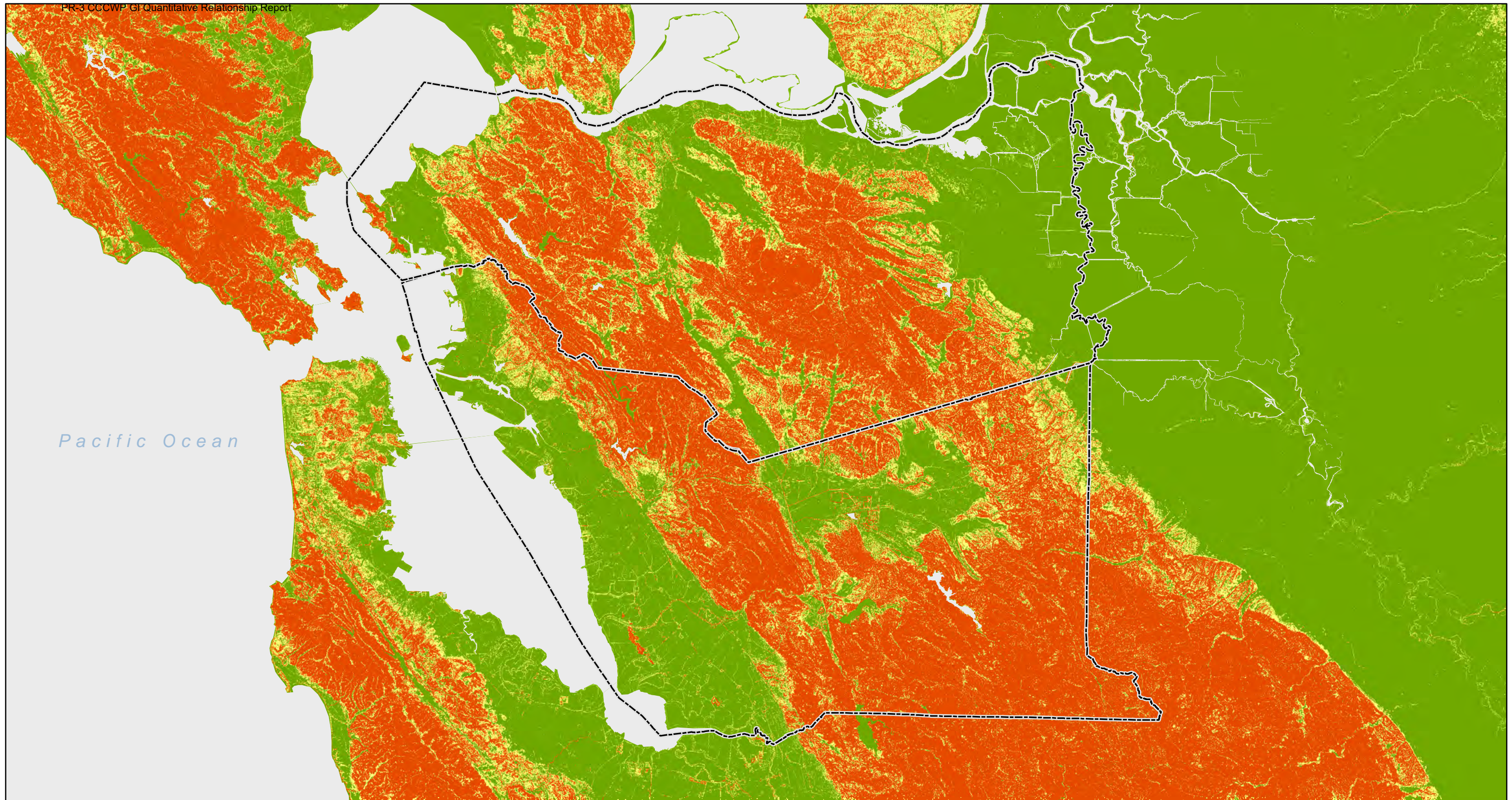
Modeling Inputs and Data Exhibits




Rain Gauge ID  Rain Gauge ID  County Boundary	Mean Annual Precipitation (in)  < 16  16 - 25  > 25	Rain Gauge Zones  DBF  FCD  KHW  KLV  KOA  LSM  SMC	<div data-bbox="2526 1665 2915 1721">Precipitation Zones for Baseline Runoff Period (WY 2000-2009)</div> <div data-bbox="2526 1743 2915 1790">Alameda County and Contra Costa County California</div> <div data-bbox="2526 1804 2915 1891">  </div> <div data-bbox="2495 1905 2822 1931"> <div data-bbox="2495 1905 2651 1931">Oakland</div> <div data-bbox="2728 1905 2822 1931">July 2018</div> </div> <div data-bbox="2915 1804 3017 1931"> <div data-bbox="2915 1804 3017 1850">Exhibit</div> <div data-bbox="2955 1880 2977 1907">1</div> </div>
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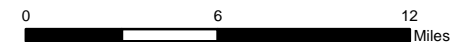
 County Boundary

% Slope

 < 5

 5-15

 > 15



Slope Zones

Alameda County and Contra Costa County
California

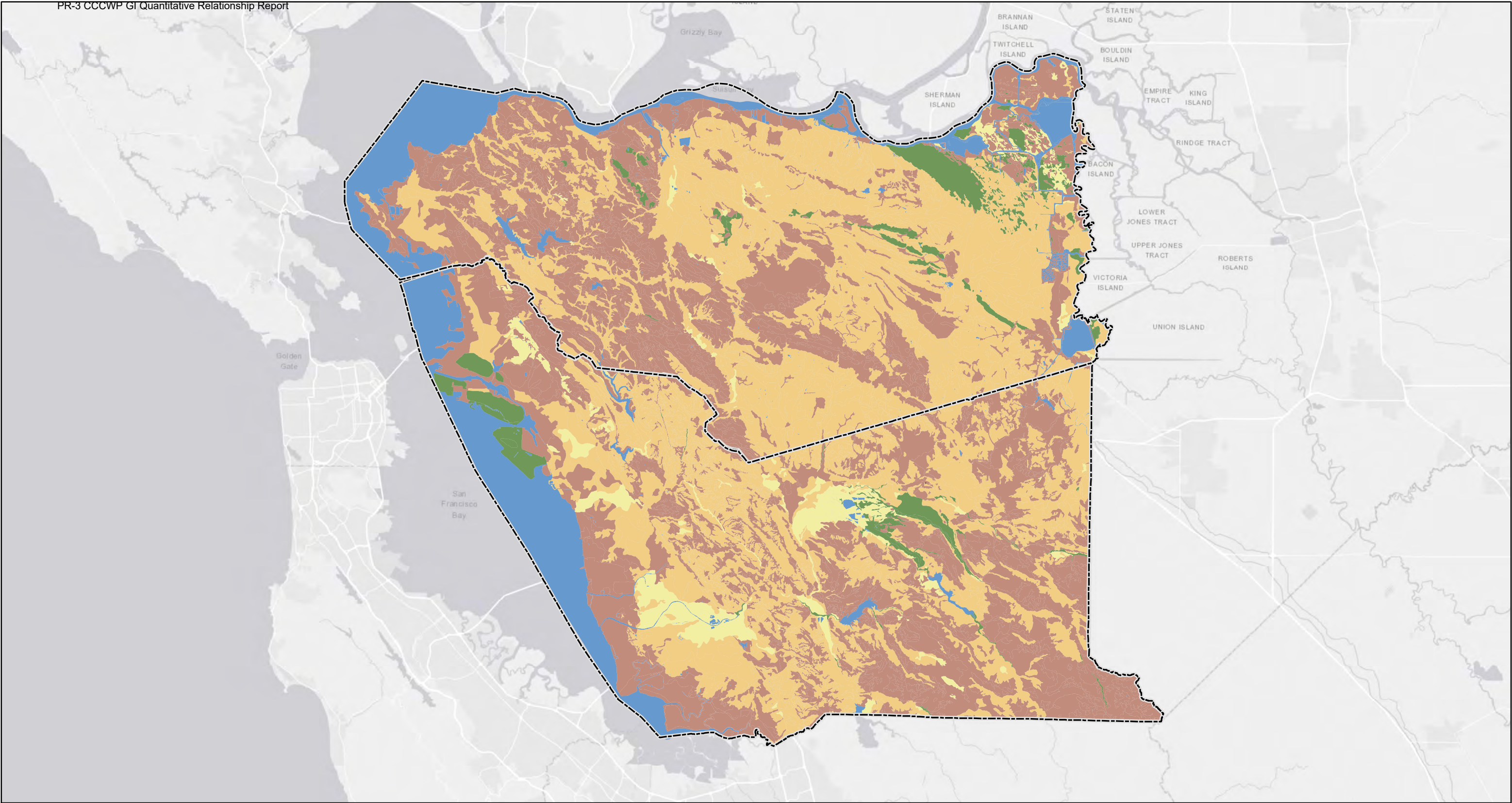


Exhibit

4

Oakland

July 2018



County Boundary

- HSG**
- A
 - B
 - C
 - D
 - W

Note: Area within the county with no HSG assignment was assigned the HSG of the most prominent adjacent soil group.

N

0 6 12 Miles

Hydrologic Soil Group

Alameda County and Contra Costa County
California

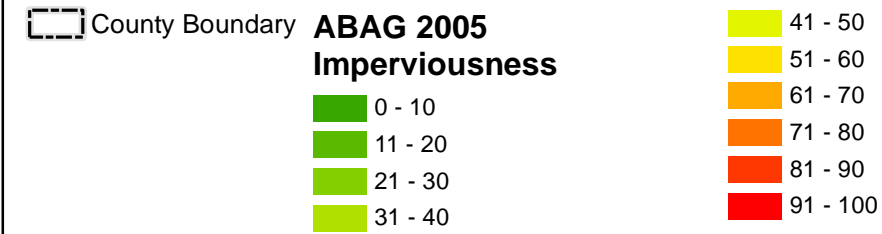
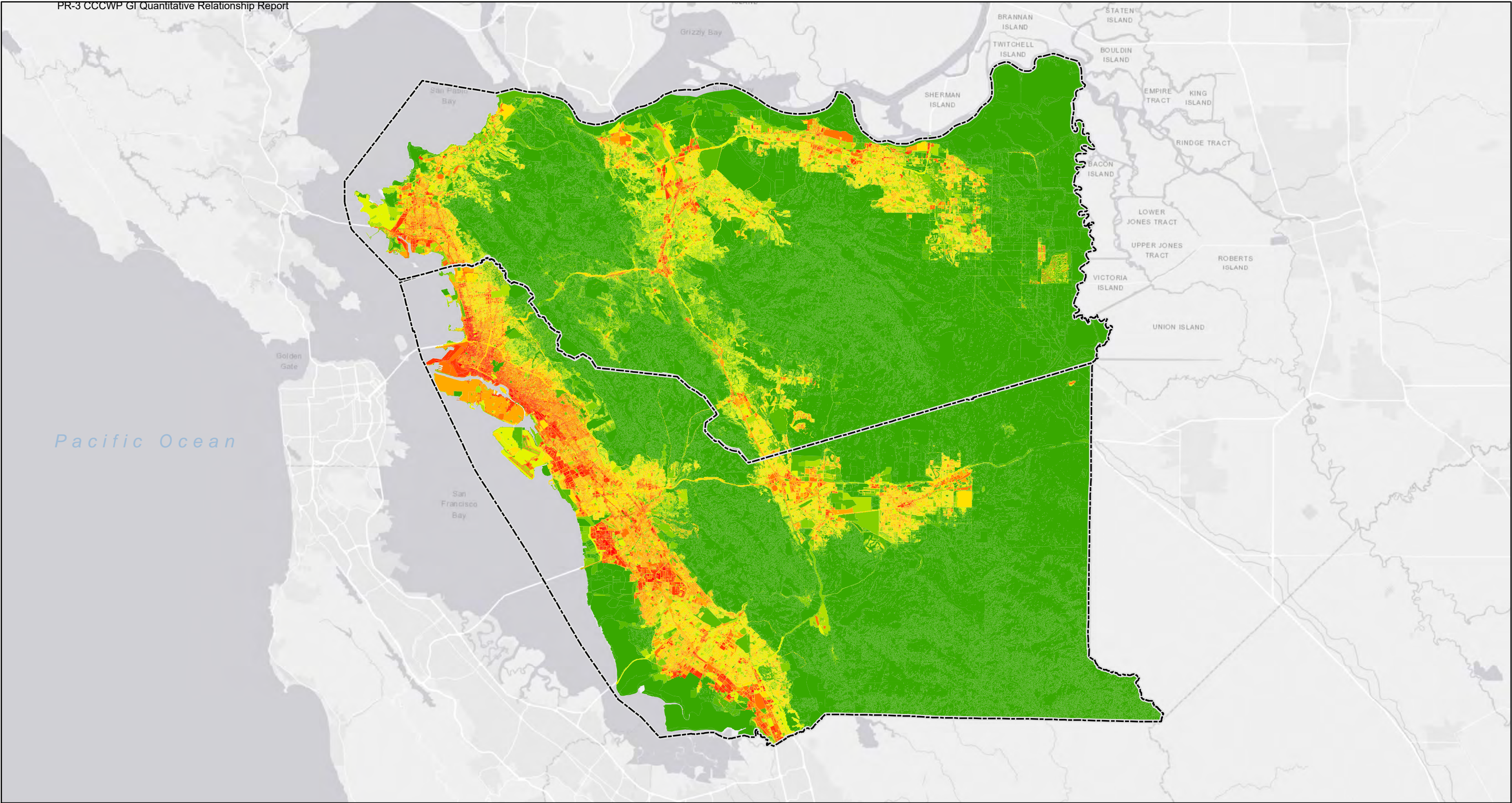
Geosyntec
consultants

Oakland

July 2018

Exhibit

5



Note:
Imperviousness is assigned to ABAG 2005 landuse based on the NLCD 2006 Impervious Cover layer. These values may be adjusted during calibration for certain categories of ABAG landuse.

For purposes of calculating runoff from areas with compacted soil, developed areas and agricultural uses were assumed to be compacted to 0.75 times the underlying saturated soil conductivity (ksat). These areas generally have percent imperviousness > 20%.



Regional Imperviousness

Alameda County and Contra Costa County
California

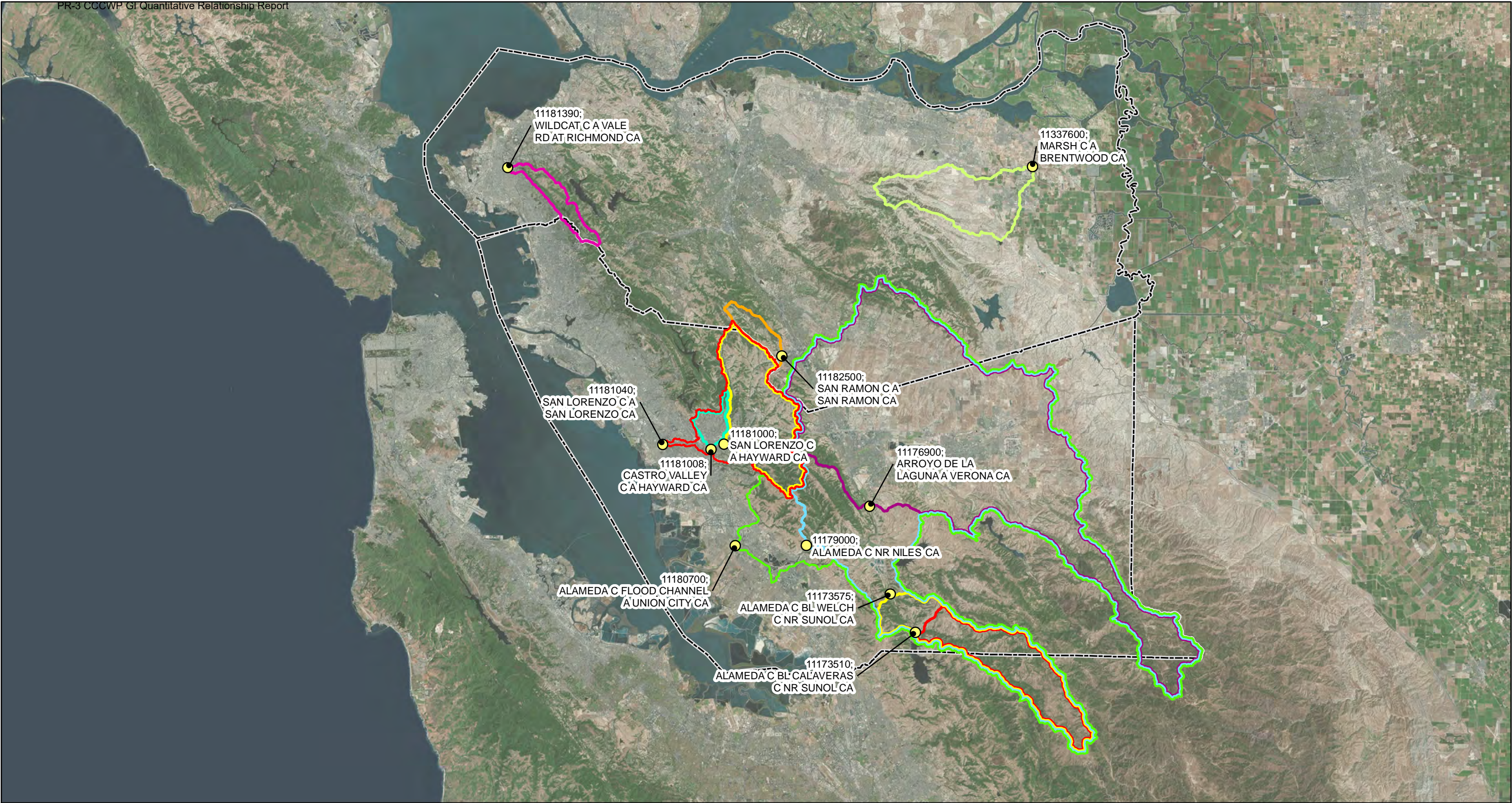
Geosyntec
consultants

Oakland

July 2018

Exhibit

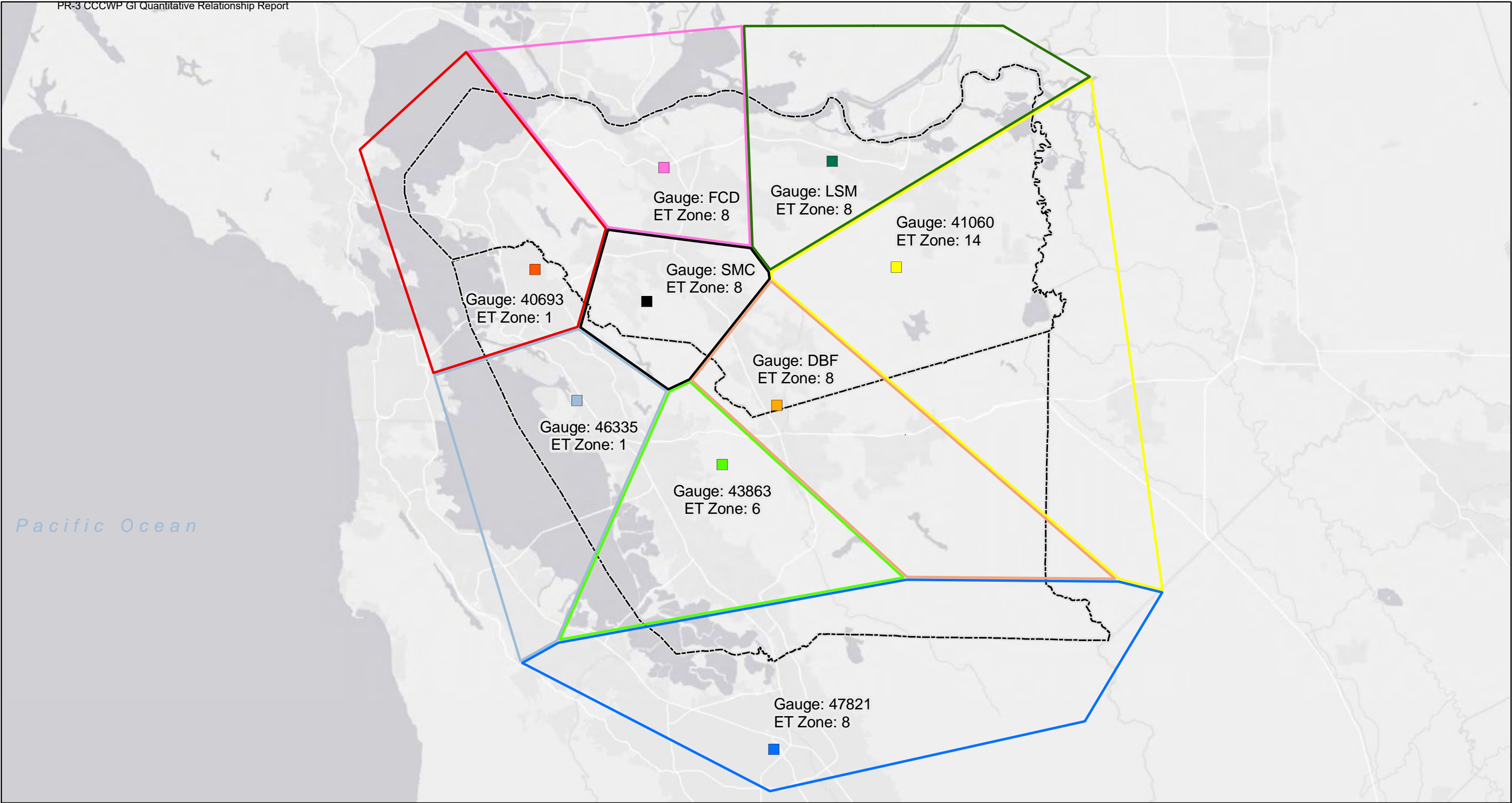
6



County Boundary Gauge Location	Group 1	Group 2	Group 3	Group 4	Group 4
	11181040	11180700	11182500	11337600	11181390
	11181000	11179000			
	11181008	11173575			
		11176900			
	11173510				

0 6 12 Miles

Candidate Calibration Watersheds Alameda County and Contra Costa County California	
 Geosyntec consultants	Exhibit 7
Oakland	July 2018



County Boundary

Long-Term Rainfall Gauge Location

47821

DBF

40693

FCD

41060

LSM

43863

SMC

46335

N

0 6 12 Miles

Long-Term Rainfall Gauge Zones

Alameda County and Contra Costa County
California

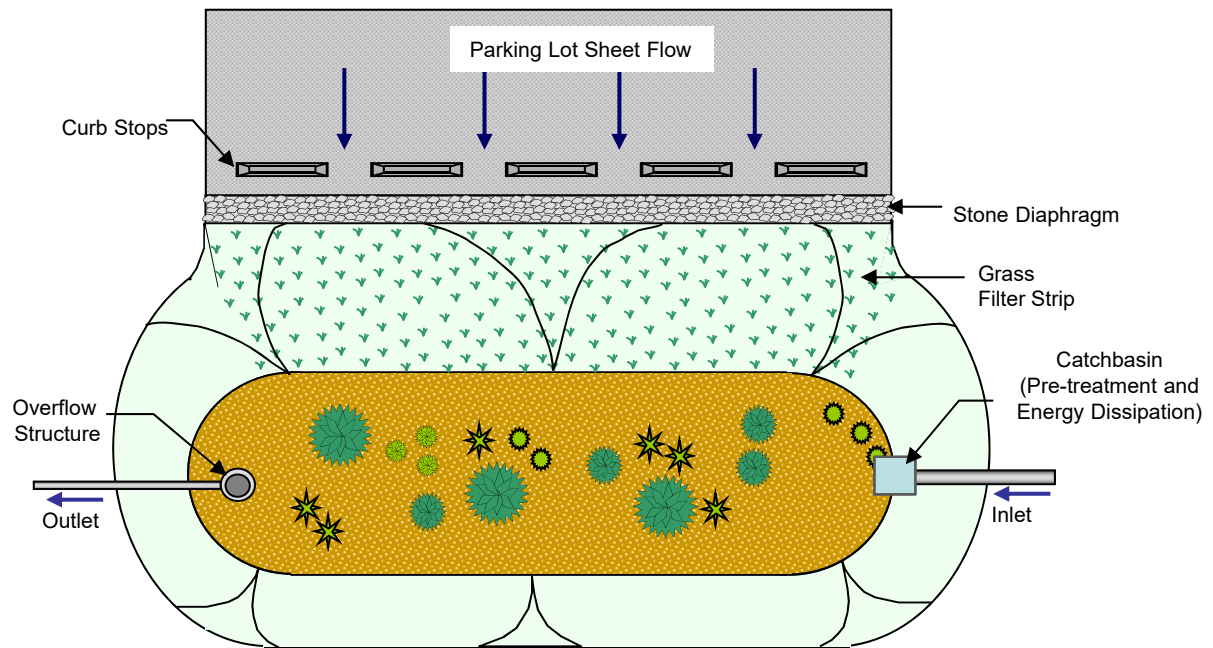
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consultants

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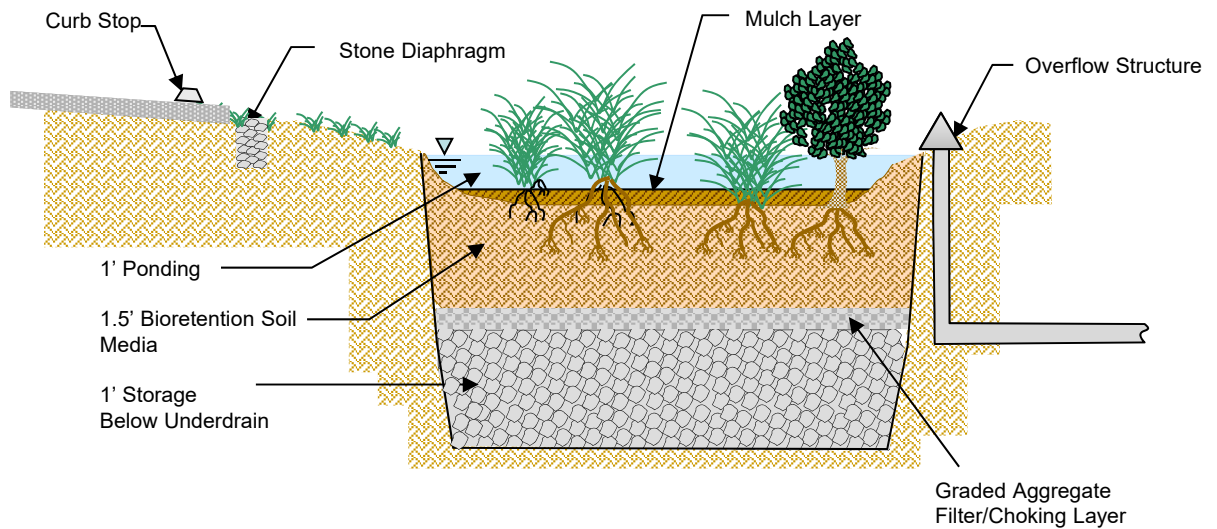
Exhibit
8

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of an Infiltration Facility

Geosyntec
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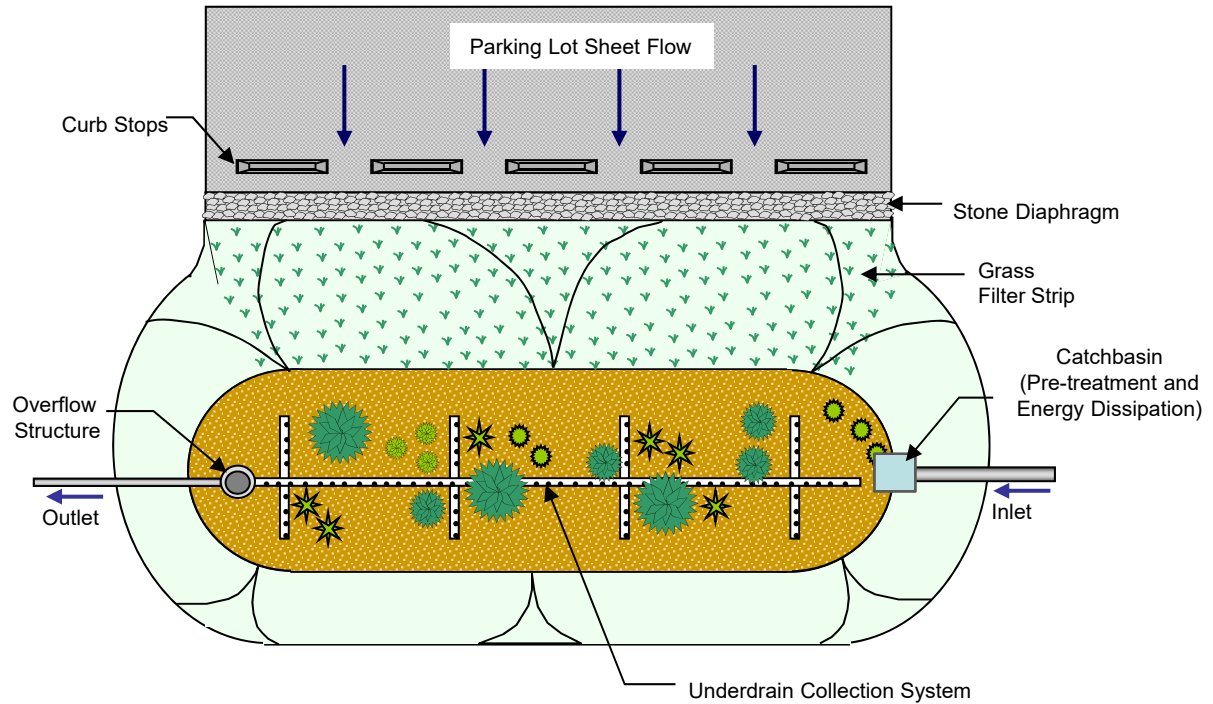
Exhibit

9

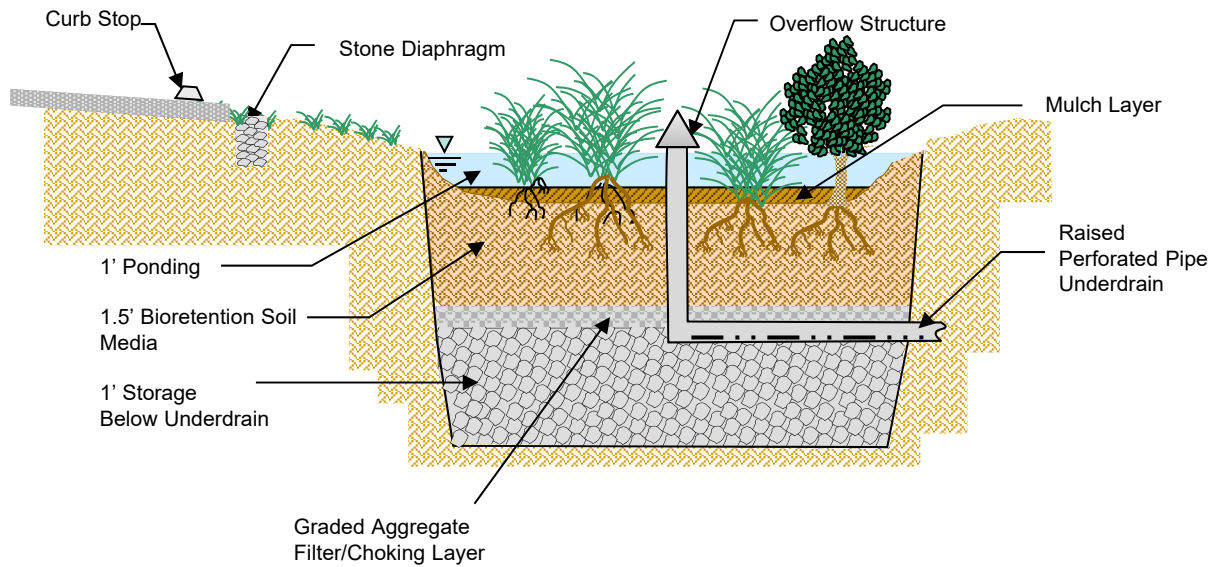
Oakland

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of a Bioretention/Bioinfiltration Facility

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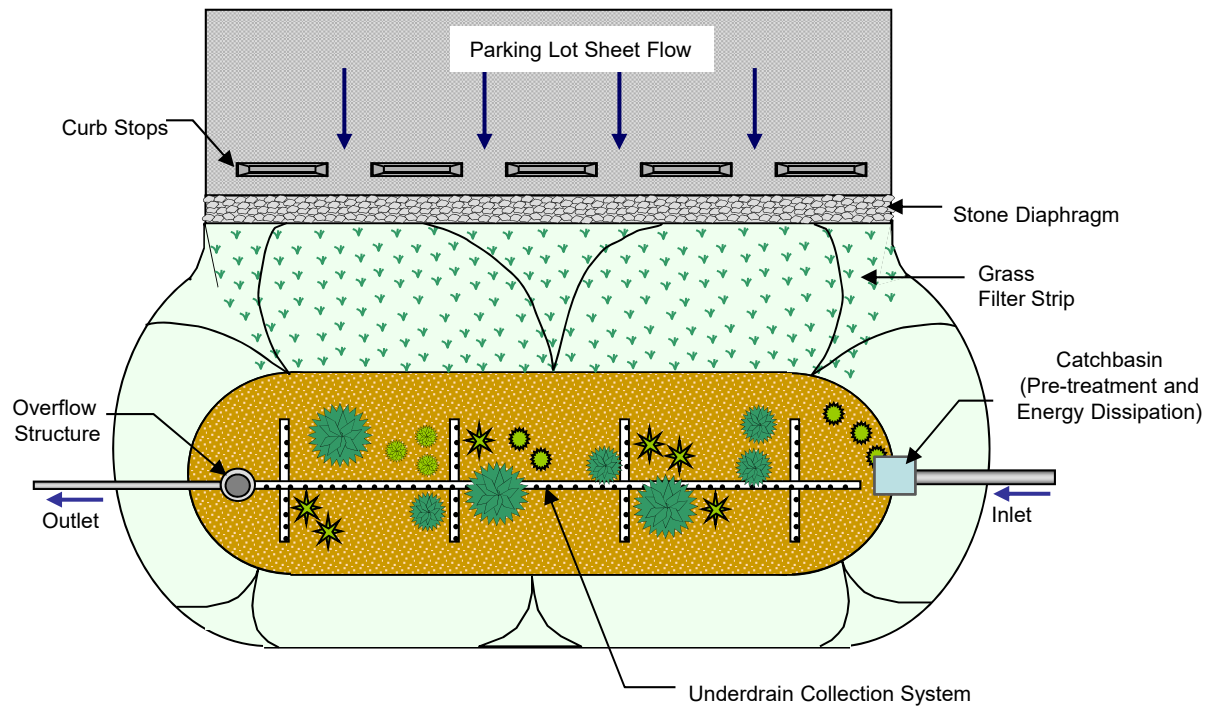
Exhibit

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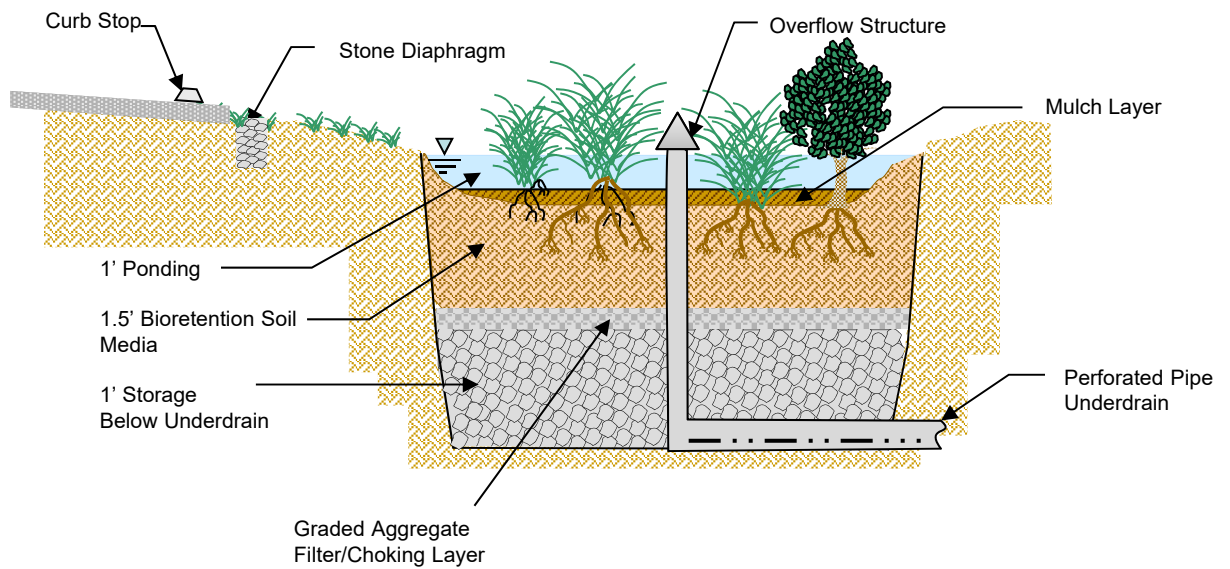
Oakland

July 2018

Plan View



Profile



Note: Plan and Profile views are not to scale

Conceptual Illustration of a Biofiltration Facility

Geosyntec
consultants

Exhibit

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Oakland

July 2018

PR-4 USEPA Stormwater Management Model Manual Excerpts

falls directly on them and do not capture runoff from other impervious areas in their subcatchment.

The second approach allows LID controls to be strung along in series and also allows runoff from several different upstream subcatchments to be routed onto the LID subcatchment. If these single-LID subcatchments are carved out of existing subcatchments, then once again some adjustment of the Percent Impervious, Width and also the Area properties of the latter may be necessary. In addition, whenever an LID occupies the entire subcatchment the values assigned to the subcatchment's standard surface properties (such as imperviousness, slope, roughness, etc.) are overridden by those that pertain to the LID unit.

Normally both surface and drain outflows from LID units are routed to the same outlet location assigned to the parent subcatchment. However one can choose to return all LID outflow to the pervious area of the parent subcatchment and/or route the drain outflow to a separate designated outlet. (When both of these options are chosen, only the surface outflow is returned to the pervious sub-area.)

3.4 Computational Methods

SWMM is a physically based, discrete-time simulation model. It employs principles of conservation of mass, energy, and momentum wherever appropriate. This section briefly describes the methods SWMM uses to model stormwater runoff quantity and quality through the following physical processes:

- Surface Runoff
- Groundwater
- Flow Routing
- Water Quality Routing
- Infiltration
- Snowmelt
- Surface Ponding

3.4.1 Surface Runoff

The conceptual view of surface runoff used by SWMM is illustrated in Figure 3-7 below. Each subcatchment surface is treated as a nonlinear reservoir. Inflow comes from precipitation and any designated upstream subcatchments. There are several outflows, including infiltration, evaporation, and surface runoff. The capacity of this "reservoir" is the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting, and interception. Surface runoff per unit area, Q , occurs only when the depth of water in the "reservoir" exceeds the maximum depression storage, d_s , in which case the outflow is given by Manning's equation. Depth of water over the subcatchment (d) is continuously updated with time by solving numerically a water balance equation over the subcatchment.

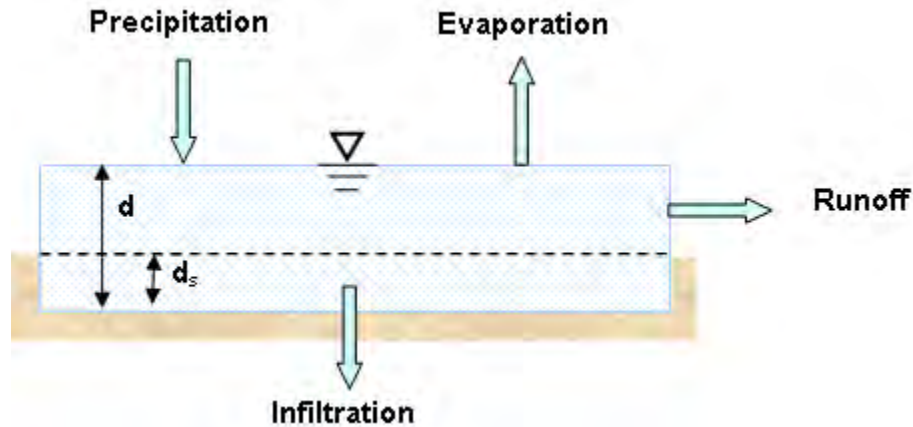


Figure 3-7 Conceptual view of surface runoff

3.4.2 Infiltration

Infiltration is the process of rainfall penetrating the ground surface into the unsaturated soil zone of pervious subcatchments areas. SWMM offers four choices for modeling infiltration:

Horton's Method

This method is based on empirical observations showing that infiltration decreases exponentially from an initial maximum rate to some minimum rate over the course of a long rainfall event. Input parameters required by this method include the maximum and minimum infiltration rates, a decay coefficient that describes how fast the rate decreases over time, and a time it takes a fully saturated soil to completely dry.

Modified Horton Method

This is a modified version of the classical Horton Method that uses the cumulative infiltration in excess of the minimum rate as its state variable (instead of time along the Horton curve), providing a more accurate infiltration estimate when low rainfall intensities occur. It uses the same input parameters as does the traditional Horton Method.

Green-Ampt Method

This method for modeling infiltration assumes that a sharp wetting front exists in the soil column, separating soil with some initial moisture content below from saturated soil above. The input parameters required are the initial moisture deficit of the soil, the soil's hydraulic conductivity, and the suction head at the wetting front. The recovery rate of moisture deficit during dry periods is empirically related to the hydraulic conductivity.

Modified Green-Ampt Method

This method modifies the original Green-Ampt procedure by not depleting moisture deficit in the top surface layer of soil during initial periods of low rainfall as was done in the original method. This change can produce more realistic infiltration behavior for storms with long initial periods where the rainfall intensity is below the soil's saturated hydraulic conductivity.

Curve Number Method

This approach is adopted from the NRCS (SCS) Curve Number method for estimating runoff. It assumes that the total infiltration capacity of a soil can be found from the soil's tabulated Curve Number. During a rain event this capacity is depleted as a function of cumulative rainfall and remaining capacity. The input parameters for this method are the curve number and the time it takes a fully saturated soil to completely dry.

SWMM also allows the infiltration recovery rate to be adjusted by a fixed amount on a monthly basis to account for seasonal variation in such factors as evaporation rates and groundwater levels. This optional monthly soil recovery pattern is specified as part of a project's Evaporation data.

3.4.3 Groundwater

Figure 3-8 is a definitional sketch of the two-zone groundwater model that is used in SWMM. The upper zone is unsaturated with a variable moisture content of θ . The lower zone is fully saturated and therefore its moisture content is fixed at the soil porosity ϕ . The fluxes shown in the figure, expressed as volume per unit area per unit time, consist of the following:

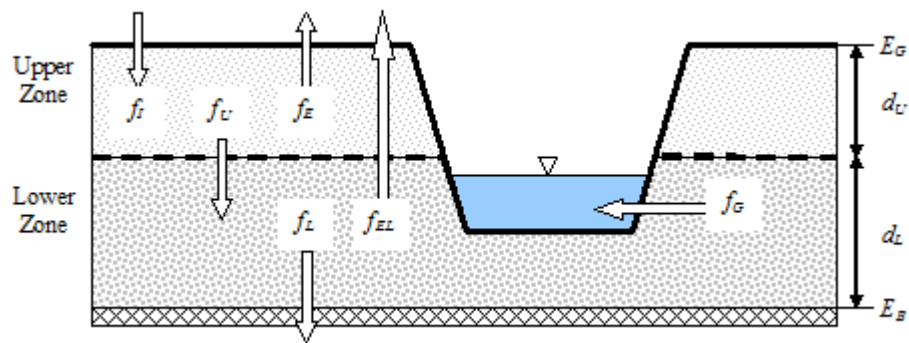


Figure 3-8 Two-zone groundwater model

- f_i infiltration from the surface
- f_{EU} evapotranspiration from the upper zone which is a fixed fraction of the un-used surface evaporation
- f_U percolation from the upper to lower zone which depends on the upper zone moisture content θ and depth d_U
- f_{EL} evapotranspiration from the lower zone, which is a function of the depth of the upper zone d_U
- f_L seepage from the lower zone to deep groundwater which depends on the lower zone depth d_L
- f_G lateral groundwater interflow to the drainage system, which depends on the lower zone depth d_L as well as the depth in the receiving channel or node.

where

$C = \text{IMD} \cdot S$, ft of water,
 t = time, sec, and
 $1,2$ = subscripts for start and end of time interval
 respectively.

This equation must be solved iteratively for F_2 , the cumulative infiltration at the end of the time step. A Newton-Raphson routine is used.

The infiltration volume during time step ($t_2 - t_1$) is thus $(t_2 - t_1) \times i$ if the surface does not saturate and $(F_2 - F_1)$ if saturation has previously occurred and a sufficient water supply is at the surface. If saturation occurs during the time interval, the infiltration volumes over each stage of the process within the time steps are calculated and summed. When rainfall ends (or falls below infiltration capacity) any water ponded on the surface is allowed to infiltrate and added to the cumulative infiltration volume.

Recovery of Infiltration Capacity (Redistribution)

Evaporation, subsurface drainage, and moisture redistribution between rainfall events decrease the soil moisture content in the upper soil zone and increase the infiltration capacity of the soil. The processes involved are complex and depend on many factors. In SWMM a simple empirical routine is used as outlined below; commonly used units are given in the equations to make the description easier to understand.

Infiltration is usually dominated by conditions in the uppermost layer of the soil. The thickness of this layer depends on the soil type; for a sandy soil it could be several inches, for a heavy clay it could be less. The equation used to determine the thickness of the layer is:

$$L = 4 \cdot \sqrt{K_s} \quad (20-73)$$

where

L = thickness of layer, in, and
 K_s = saturated hydraulic conductivity, in/hr.

Thus for a high K_s of 0.5 in/hr (12.7 mm/hr) the thickness is 2.83 inches (71.8 mm). For a soil with a low hydraulic conductivity, say $K_s = 0.1$ in/hr (2.5 mm/hr), the computed thickness is 1.26 inches (32.1 mm).

A depletion factor is applied to the soil moisture during all time steps for which there is no infiltration from rainfall or depression storage. This factor is indirectly related again to the saturated hydraulic conductivity of the soil and is calculated by:

$$DF = \frac{L}{300} \quad (20-74)$$

where

DF = depletion factor, hr^{-1} , and

L = depth of upper zone, in.

Hence, for $K_s = 0.5$ in/hr (12.7 mm/hr), $DF = 0.9\%$ per hour; for $K_s = 0.1$ in/hr (2.5 mm/hr) $DF = 0.4\%$ per hour. The depletion volume (DV) per time step is then:

$$DV = DF \cdot FU_{\max} \cdot \Delta t \quad (20-75)$$

where

$FU_{\max} = L \cdot \text{IMD}_{\max}$ = saturated moisture content of the
 upper zone, in,

IMD_{\max} = maximum initial moisture deficit, in/in, and

Δt = time step, hr.

The computations used are:

$$FU = FU - DV \quad \text{for } FU \geq 0 \quad (20-76)$$

$$F = F - DV \quad \text{for } F \geq 0 \quad (20-77)$$

where

FU = current moisture content of upper zone, in,
 and

F = cumulative infiltration volume for this event,
 in.

To use the Green-Ampt infiltration model in continuous SWMM, it is necessary to choose a time interval after which further rainfall will be considered as an independent event. This time is computed as:

$$T = \frac{6}{100 \cdot DF} \quad (20-78)$$

where

T = time interval for independent event, hr.

For example, when $K_s = 0.5$ in/hr (12.7 mm/hr) the time between independent events as given in the last equation is 6.4 hr; when $K_s = 0.1$ in/hr (2.5 mm/hr) the time is 14.3 hr. After time T has elapsed the variable F is set to zero, ready for the next event. The moisture remaining in the upper zone of the soil is then redistributed (diminished) at each time step by the two previous equations in order to update the current moisture deficit (IMD). The deficit is allowed to increase up to its maximum value (IMD_{\max} , an input parameter) over prolonged dry periods. The equation used is

$$\text{IMD} = \frac{FU_{\max} - FU}{L} \quad \text{for } \text{IMD} \leq \text{IMD}_{\max} \quad (20-79)$$

When light rainfall ($i \leq K_s$) occurs during the redistribution period, the upper zone moisture storage, FU , is increased by the infiltrated rainfall volume and IMD is again updated using the last equation.

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Guidelines for estimating parameter values for the Green-Ampt model are given elsewhere in this manual. As is also the case for the Horton equation, different soil types can be modelled for different subcatchments.

Program Variables

The infiltration computations are performed in subroutines WSHED and GAMP in the RUNOFF Module. Correspondence of program variables to those of this subsection is as follows:

$S = \text{SUCT}(J)$	$L = \text{UL}(J)$
$\text{IMD}_{\max} = \text{SMDMAX}(J)$	$\text{DF} = \text{DF}(J)$
$K_s = \text{HYDCON}(J)$	$i = \text{RI}$
$\text{FU}_{\max} = \text{FUMAX}(J)$	$t = \text{time}$
$\text{FU} = \text{FU}(J)$	$\Delta t = \text{DELT}$
$\text{IMD} = \text{SMD}(J)$	$\text{DV} = \text{DEP}$
$F = \text{F}(J)$	$F_s = \text{FS}$

20.5.4 Green-Ampt Infiltration Input Data

Although not as well known as the Horton equation, the Green-Ampt equation (1911) has the advantage of physically based parameters that, in principle, can be predicted a priori. The Mein-Larson (1973) formulation of the Green-Ampt equation is a two-stage model. The first step predicts the volume of water, F_s , which will infiltrate before the surface becomes saturated. From this point onward, infiltration capacity, f_p , is predicted directly by the Green-Ampt equation. Thus,

$$\text{For } F < F_s : f = i \text{ and } F_s = \frac{S_u \text{ IMD}}{i / K_s - 1} \text{ for } i > K_s; \quad (20-80)$$

No calculation of F_s for $i \leq K_s$.

$$\text{For } F \geq F_s : f = f_p \text{ and } f_p = K_s \left(1 + \frac{S_u \text{ IMD}}{F} \right) \quad (20-81)$$

where

- f = infiltration rate, ft/sec,
- f_p = infiltration capacity, ft/sec,
- i = rainfall intensity, ft/sec,
- F = cumulative infiltration volume, this event, ft,
- F_s = cumulative infiltration volume required to cause surface saturation, ft,
- S_u = average capillary suction at the wetting front (SUCT), ft water,
- IMD = initial moisture deficit for this event (SMDMAX), ft/ft, and

PR-5 Alameda Countywide Clean Water Program
and Contra Costa Clean Water Program
Reasonable Assurance Analysis Model
Calibration and Validation Memo



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Memorandum

Date: November 13, 2019

To: Jim Scanlin, Alameda Countywide Clean Water Program, and Courtney Riddle, Contra Costa Clean Water Program

Copy: Karin Graves and Lucile Paquette, Contra Costa Clean Water Program

From: Kelly Havens, Senior Engineer, Austin Orr, Engineer, Lisa Austin, Principal, and Marc Leisenring, Principal

Subject: Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation
Geosyntec Project Numbers: WW2127 and WW2407

1. INTRODUCTION

This memorandum provides an expanded description and summary results for the calibration and validation conducted as for the development of the Alameda Countywide Clean Water Program (ACCWP) and Contra Costa Clean Water Program (CCCWP) Reasonable Assurance Analysis (RAA) model. This memorandum provides additional information to that provided in the Alameda Countywide Clean Water Program Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions Report and the Contra Costa Clean Water Program Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions Report (i.e., “GI Quantitative Relationship Reports”; ACCWP, 2018 [PR-2] and CCCWP, 2018 [PR-3]) for the purpose of peer review. As such, this memorandum references information and sections in those reports.

2. CALIBRATION APPROACH AND PARAMETERS

As described in the GI Quantitative Relationship Reports [PR-2; PR-3], the baseline pollutant loading model utilized for the RAA is based on continuous simulation hydrology model run in EPA’s Stormwater Management Model (SWMM) version 5.1, combined with land use-based runoff concentrations to obtain the average annual loading of mercury and PCBs in stormwater runoff from Alameda and Contra Costa counties during the TMDL baseline period (i.e., 2003 – 2005). The hydrologic model utilizes generic hydrologic response units (HRUs), as described in Sections 2.2.1 and 3.1.1 of the GI Quantitative Relationship Reports [PR-2; PR-3]. Calibration of the generic HRU models was conducted on the average annual discharge volume for water years

ACCWP and CCCWP RAA Calibration and Validation Memo

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(WYs) 2000-2009, utilizing available stream flow records. The objective of the calibration was to reasonably match the average annual runoff volume for this 10-year period.

The acceptable percent difference between simulated and observed annual volumes included in the *Bay Area RAA Guidance Document* (BASMAA, 2017) are provided in Table 1 below. These ranges were used to verify model results and evaluate whether parameters have been adequately calibrated.

Table 1: Allowable Difference between Simulated and Observed Annual Volumes

Model parameters	Average % difference between simulated annual results and observed data		
	Very Good	Good	Fair (lower bound, upper bound)
Hydrology/Flow	<10	10-15	15-25

A summary of the observed data and the parameters used to conduct the calibration with the simulated (modeled) results are provided in the following subsections.

2.1 Observed Data

2.1.1 Flow Gauges Used for Calibration

A list of candidate flow gauge sites were identified for potential use in calibration in the GI Quantitative Relationship Reports [PR-2; PR-3]. For the purposes of calibration, the candidate gauge sites that were identified in the GI Quantitative Relationship Reports included stream depth rating curves and daily mean records for the WY 2000 – 2009 period, and all are USGS gauges. The flow gauges used in calibration are summarized in Table 2 and shown in Figure PR-5A (all figures are provided at the end of the memo).

Table 2: Flow Gauges Used for RAA Model Calibration

Gauge ID	Gauge Name	Location	County	Data Frequency
11182500	San Ramon Creek	San Ramon	Contra Costa	Daily
11181390	Wildcat Creek ¹	Richmond / San Pablo	Contra Costa	Daily
11181040	San Lorenzo Creek	San Lorenzo	Alameda	Daily
11181008	Castro Valley Creek	Hayward	Alameda	Daily
11181000	San Lorenzo Creek	Hayward	Alameda	Daily
11180700	Alameda Creek Flood Channel	Union City	Alameda	Daily
11179000	Alameda Creek	Fremont	Alameda	Daily
11176900	Arroyo de la Laguna	Verona	Alameda	Daily

1. The Wildcat Creek gauge record is incomplete and contains data only for the four-year period WY 2006-2009. Geosyntec used the available years of gauge data to inform the calibration effort, but it was not ultimately used to assess the overall fitness of the model at representing the RAA baseline period regional hydrology.

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Three other gauges were identified for potential use in calibration in the GI Quantitative Relationship Reports, but were ultimately not used for calibration, as described below. These included:

- Gauge number 11337600, Marsh Creek, which had considerable quantities of dry weather flows recorded with significant variability, such that baseflow removal techniques were not successful in isolating flows associated with rainfall;
- Gauge number 11173575, Alameda Creek Below Welch Creek, which contained significant data gaps in the record, as well as erratic stream flows likely caused by dam influence; and
- Gauge number 11173510, Alameda Creek Below Calaveras Creek, which contained significant data gaps in the record, as well as erratic stream flows likely caused by dam influence.

Given the data availability, calibration was conducted for both Alameda County and Contra Costa County areas simultaneously.

The area tributary to each flow gauge was delineated using the USGS StreamStats online tool (U.S. Geological Survey, 2016). These delineations were intersected with the HRU layer to select generic HRU's from across the two counties for use in the calibration, including multiple different rainfall and climate zones, soil classifications, surface slopes, and land uses. The watershed areas tributary to the gauges used are shown in Figure PR-5A and summarized in Table 3.

Table 3: Calibration Watershed Tributary Area Characteristics

Gauge ID	Gauge Name	Area (acres)	Percent Developed	Percent Impervious
11182500	San Ramon Creek	3,878	21%	2%
11181390	Wildcat Creek	4,999	22%	5%
11181040	San Lorenzo Creek	29,989	38%	12%
11181008	Castro Valley Creek	3,531	93%	44%
11181000	San Lorenzo Creek	24,203	24%	5%
11180700	Alameda Creek Flood Channel	237,946	29%	10%
11179000	Alameda Creek	224,072	28%	9%
11176900	Arroyo de la Laguna	164,679	35%	12%

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2.1.2 Baseflow Removal Process

Calibration of land surface runoff hydrology to stream gauge records requires that baseflow be computed and accounted for throughout the period of record, as the RAA model does not include storm flow routing, groundwater inflow/outflow, diversions, or reservoirs. Where baseflow constitutes a large percentage of total flow, baseflow accounting allows for isolation and calibration of just the flow gauge runoff response to a rainfall event, which is dependent on land surface features. A variety of methods exist for separating baseflow from runoff. For those flow gauges requiring baseflow separation, two methods were identified as appropriate for the flow gauges used for Alameda County and Contra Costa County RAA model calibration. The methods and gauge characteristics corresponding to the use of the method include:

1. Base-Flow Index (BFI) modified: BFI modified is a timeseries analysis which locates minimum values in the hydrograph over five-day increments. For each identified minimum, if 90% of its value is less than both adjacent minimums, it is identified as a hydrograph ‘turning point’. The baseflow hydrograph is established by connecting the turning points with straight lines (Barlow et., al, 2015). This method was used to remove baseflow from calibration watersheds with appreciable development.
2. PART (short for partitioning): PART is an iterative timeseries analysis that identifies daily streamflow values that are not affected by surface runoff, assigns these values as baseflow, then removes baseflow from all days to compile the baseflow-corrected record used for surface runoff calibration. Daily streamflow values are identified as baseflow if they are preceded by N days of continuous streamflow recession (Barlow et., al, 2015); N is identified through the pattern of recession of streamflow measurements. This method was used to remove baseflow from large calibration watersheds influenced by significant impoundments.

The gauges for which no baseflow separation was conducted were estimated to have very little or no potential for baseflow to influence the calibration to mean annual volume since the streams are largely undeveloped, aren’t actively managed with significant impoundments, and typically run dry in the month of September. The most appropriate method for separating baseflow was determined on a gauge-specific basis, depending on the variability in the flow record and the occurrence of confounding factors that affect baseflow such as dam releases and other dry weather inflows.

A summary of the baseflow separation method used for each flow gauge is provided in Table 4.

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Table 4: Calibration Flow Gauge Baseflow Removal Methods Used

Gauge ID	Gauge Name	Baseflow Separation and Removal Method	Notes	Total Watershed Area Including Impoundments (acres)	Impounded Area in Watershed (acres)
11182500	San Ramon Creek	No Baseflow Removal	Small, mostly undeveloped, typically dry in August or September	3,878	None
11181390 ¹	Wildcat Creek	No Baseflow Removal	Small, mostly undeveloped, typically dry in August or September. Data only available for WY 2006-2009	4,999	None
11181040	San Lorenzo Creek	BFI Modified	Contains significant urban development	29,989	None
11181008	Castro Valley Creek	BFI Modified	Contains significant urban development	3,531	None
11181000	San Lorenzo Creek	No Baseflow Removal	Small, mostly undeveloped, typically dry in August or September	24,203	None
11180700	Alameda Creek Flood Channel	PART	Used only WY 2002, 2003, and 2005 – 2009 due to missing and erroneous data in other WYs. Large watershed with impoundments.	418,788	180,809
11179000	Alameda Creek	PART	Large watershed with impoundments.	404,913	180,809
11176900	Arroyo de la Laguna	BFI Modified	Contains significant urban development	258,121	93,419

1. The USGS does not report discharge for this gauge more recently than 1996. Balance Hydrologics began recording measurements for this gauge in 2005; this record was used for WY2006-2009.

2.2 Modeled Results - Model Calibration Parameters

To conduct the calibration, modeled annual storm flow produced from the delineated watersheds draining to the stream gauges (see Figure PR-5A) was compared to annual flow in the stream gauge records, with baseflow separated as described in Section 2.1.2, for WYs 2000 – 2009. Modeled annual storm flow was predicted by area-weighting the runoff output from generic HRU models in proportion to the areas of those generic HRUs within the watersheds draining to the stream gauges.

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HRU calibration parameters were adjusted in three phases. The first phase entailed establishing the general range and sensitivity of the hydrologic model to saturated soil hydraulic conductivity (Ksat) for HSG C and D type soils for the generic HRUs within the three undeveloped watersheds tributary to identified calibration flow gauges (see Tables 2, 3, and 4). The second phase involved exploring sensitivity to changes in soil infiltration recovery time for the identified range of Ksat values. The third phase incorporated soil parameter value combinations identified in the first two phases in models for all eight calibration watersheds. National Land Cover Dataset (NLCD) imperviousness data were initially considered as a calibration parameter but were not ultimately used (see further discussion in Section 2.2.3 below).

Identified model parameters were adjusted for each phase until the average percent difference between modeled and measured average annual storm flow volumes (with baseflow removed as described in Table 4) was less than 25% - the acceptable range as summarized in Table 1. Once the average percent difference for all the calibration watersheds were within the acceptable range, the HRU model parameters were finalized.

2.2.1 Soil Hydraulic Conductivity

Soil Ksat was primarily calibrated in the watersheds draining to flow gauges 11182500 (San Ramon Creek), 11181390 (Wildcat Creek), and 11181000 (San Lorenzo Creek) because these watersheds are primarily undeveloped and thus provide greater isolation of the pervious area runoff and loss response to rainfall. Given the percent total area of hydrologic soil group (HSG) C and D type soils in these watersheds, soil Ksat was adjusted only for HSG types C and D. The Ksat for soil groups A and B were assigned by area-weighting literature values corresponding with the texture classes that are present within Alameda County and Contra Costa County. It was found that adjusting HSG A and B Ksat model input values resulted in minimal changes to average annual volume in the watersheds given that A and B type soils each cover less than 5% of the Alameda County and Contra Costa County areas modeled.

2.2.2 Soil Recovery Pattern

The same three watersheds used for Ksat calibration were also used to calibrate soil recovery time. This parameter is associated with the soil drying effects caused by evapotranspiration and determines how many days it takes for a soil to recover its full infiltrative capacity during the dry period following a rainfall event. In SWMM, this parameter is a function of both the subbasin's Ksat and expected soil recovery time and can be defined on a monthly basis as part of the climatological parameters. See SWMM5 Users Guide 13th Edition pg. 462-463 (James et., al, 2010; provided in PR-4) for information on the Green Ampt Equation and the Recovery of Infiltration Capacity.

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2.2.3 Calibration for Developed Watersheds

Imperviousness (associated with specific Association of Bay Area Governments [ABAG] land use types, see Section 3.1.1. of the GI Quantitative Relationship Reports [PR-2; PR-3]) was considered as a parameter for calibration, but NLCD-derived imperviousness was found to produce modeled results within the acceptable range, so no adjustment to imperviousness was applied as part of calibration. Imperviousness values were assigned for each individual polygon in the ABAG 2005 Geospatial Information System (GIS) dataset by area-weighting the NLCD 2006 imperviousness values associated with the polygon. Each parcel and right-of-way (ROW) segment had roughly the same spatial resolution.

Soil parameters calibrated to undeveloped watersheds were adjusted for soil compaction assumed to occur during development (see Section 3.1.1 of the GI Quantitative Relationship Reports [PR-2; PR-3]) and were used to develop area-weighted average annual HRU runoff output for the other more developed and impervious watersheds associated with identified flow gauges. Coupled with the NLCD-derived imperviousness method for identifying representative HRUs for the watersheds, these calibrated soil parameters were found to produce results within the acceptable calibration range for the more developed and impervious watersheds used for calibration.

3. CALIBRATION RESULTS

3.1 Parameter Adjustment

To identify the region of best fit between modeled and measured average annual runoff for the identified calibration parameters, a large range of values were input into the generic HRU models representative of the areas within the calibration watersheds.

3.1.1 Soil Hydraulic Conductivity and Recovery Time

Soil Ksat values between 0.025 – 0.35 inches per hour (in/hr) for HSG C and D soils were examined as part of the first phase of calibration. Varying combinations of Ksat values for the two soil types were tested for the undeveloped calibration watersheds. Each pair of parameters represent hundreds of individual continuous HRU SWMM models. This calibration exercise revealed that the best fit values for HSG C and D type soil in the three undeveloped calibration watersheds likely falls between 0.1 and 0.2 in/hr for HSG C soils, and between 0.05 and 0.125 in/hr for HSG D type soils.

This range of parameters was explored further in the second phase of calibration, in which soil recovery time was adjusted for three different values: 7 days, 14 days, and 18 days. The calibration percent difference results corresponding to the combinations of HSG C and D soil Ksat values and soil recovery times are shown in Figure PR-5B. Darker blue areas indicate a lower percent difference between modeled runoff volume and measured total discharge volume

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(with baseflow removed per Table 4) in the three undeveloped calibration watersheds. Over 11,800 continuous simulation HRU model runs were evaluated in order to create the grid of values, shown in Figure PR-5B.

The darkest blue areas of the three plots in Figure PR-5B indicate the least percentage difference between modeled and measured average annual runoff volume for all three undeveloped stream gauge records during the period from WY 2000 - 2009. The percentage difference in total annual average runoff volume is quite sensitive to changes in HSG C and D type soils for the range of Ksat values searched during this exercise, but the model is not very sensitive to soil recovery time as indicated by the small differences in the three plots.

From this calibration phase two investigation, it was identified that the most appropriate soil Ksat values ranged from 0.125 – 0.15 in/hr for HSG C soils, 0.075 – 0.1 in/hr for HSG D soils. A soil recovery pattern equivalent to a 14-day soil recovery time for HSG C soils was also identified to be the most appropriate for the calibration watersheds.

Phase three of the calibration used this tighter range of HSG C and D soil Ksat values to evaluate percent difference between average annual modeled runoff and measured discharge at all of the calibration gauges (as corrected for baseflow removal per Table 4). The best-fit soil Ksat parameters for all eight of the calibration gauges are shown in Table 5 below.

Table 5: Final Soil Ksat Values for the Eight Calibration Gauge Tributary Watersheds

HSG	Undeveloped Soil Ksat (in/hr)	Developed Soil Ksat ¹ (in/hr)
A ²	2.5	1.875
B ²	0.3	0.225
C	0.15	0.1125
D	0.1	0.075

¹ Ksat is decreased by 25% to account for soil compaction expected to occur during development.

² Ksat assigned by area-weighting literature values corresponding with soil texture classes present in the areas modeled.

3.2 Resulting Percent Difference between Modeled and Measured Average Annual Runoff

Utilizing the calibrated parameter values described in Section 3.1 and summarized in Table 5, the percent difference between average annual modeled runoff and average annual measured runoff for the period of record (WY 2000 – 2009) was found to be within the required threshold (Table 1) for most of the watersheds examined, with the exception of the Wildcat Creek gauge (gauge number 11181390). This gauge has an incomplete record and contains data for only four years, from WY 2006-2009. The available data from this gauge was used to inform the calibration parameters, but given the incomplete record, the percent difference between measured and modeled average annual runoff volume was not ultimately used to assess the overall fitness of the RAA hydrologic model for the full baseline time period (WY 2000-2009).

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The percent difference between average annual modeled runoff and measured runoff (accounting for baseflow corrections per Table 4) for the RAA baseline period from WY 2000-2009 for each calibration gauge is shown in Figure PR-5C. Since the entire decade was modeled, some individual years within the period of record varied more than the 25% threshold; however, these percent differences are offset between wet years and dry years to provide an acceptable percent difference between average annual modeled and measured values.

4. VALIDATION

Following completion of baseline hydrologic calibration, baseline loads were validated using pollutant monitoring data collected as part of the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP; specifically, the Small Tributary Loading Strategy project) and the Surface Water Ambient Monitoring Program (SWAMP). Pollutant concentration data were obtained from the California Environmental Data Exchange Network (CEDEN). The validation analysis included 206 total PCBs and 291 total mercury results from various monitoring locations in Alameda and Contra Costa Counties with sample dates ranging from 2001 to 2014.

Samples were taken at load monitoring stations, mostly during wet weather. These stations are shown on Figures PR-5D (PCBs) and PR-5E (mercury) along with their respective watershed delineations. Where not provided by SFEI, watershed delineations were developed using the USGS StreamStats delineation tool (USGS, 2016). The land use composition of the validation watersheds is provided in Attachment A to this memo.

The validation exercise conducted combines the calibrated Contra Costa and Alameda County regional hydrology with the Regional Watershed Spreadsheet Model (RWSM) PCBs and mercury values estimated by SFEI (see section 2.1 and 2.2.2 of the GI Quantitative Relationship Reports [PR-2; PR-3] and Regional Watershed Spreadsheet Model Version 1.0 Results Summary Memorandum (Geosyntec, 2019). Because the RWSM concentrations used for the RAA water quality model are not modifiable for the regional RAA Modeling approaches, this validation exercise is purely qualitative, and is not expected to result in changes to the hydrologic or water quality model input parameters.

The validation process includes computing the area-weighted average annual runoff volume for each land use category within the validation watersheds and combining these results with the associated RWSM average annual pollutant concentration. The resulting land use-based pollutant loads are added together over all land uses to obtain the estimated average annual pollutant load for each validation watershed. This average annual pollutant load is divided by the average annual runoff volume for the validation watershed to obtain an average annual pollutant discharge concentration for each validation watershed. The values calculated from the model output were compared to monitoring data collected at the associated validation monitoring

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locations. Statistical summaries and the number of samples for PCBs and mercury concentrations measured at each validation monitoring location are shown in box plot format in Figure PR-5F and Figure PR-5G, respectively. The resulting average annual pollutant discharge concentration for each validation watershed is superimposed on the box plots of the measured values for comparison.

The modeled PCBs concentrations are within the expected ranges for the validation watersheds examined (see Figure PR-5F). In some cases, the model slightly overpredicts the PCBs concentration in runoff, notably in the Ettie Street and Zone 5 Line M watersheds, and in other cases, underpredicts, such as in the Santa Fe Channel watershed. This is expected given the highly variable spatial distribution of PCBs contamination and storm-to-storm variability in runoff characteristics. The differences are largely attributable to the use of the regionally-characteristic land use-based RWSM values for modeling PCBs runoff concentrations and comparing average annual concentrations computed from annualized loads and volumes.

The validation exercise for mercury included many more watersheds than for PCBs. In general, the modeled values for mercury concentration are significantly higher than the measured values (see Figure PR-5G). The present RWSM land use-based concentration values for mercury appear to overestimate the observed concentration of mercury in the monitored watersheds within Alameda County and Contra Costa County.

5. REFERENCES

- ACCWP, 2018. Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions. September 28.
- Barlow, P.M., Cunningham, W.L., Zhai, Tong, and Gray, Mark, 2015, U.S. Geological Survey groundwater toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods 3-B10, 27 p., <https://dx.doi.org/10.3133/tm3B10>.
- BASMAA, 2017. Bay Area Reasonable Assurance Analysis Guidance Document. Prepared by Geosyntec Consultants and Paradigm Environmental. June.
- CCCWP, 2018. Quantitative Relationship Between Green Infrastructure Implementation and PCBs/Mercury Load Reductions. August 22.
- California Environmental Data Exchange Network (CEDEN) [Internet]. Sacramento, CA. 2010. Accessed July 2018. Available from: <http://www.ceden.org>

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Geosyntec Consultants, 2019. Regional Watershed Spreadsheet Model Version 1.0 Results Summary Memorandum. April 30.

James, William, Rossman, Lewis A. and James, W. R. C. 2010 User's guide to SWMM 5, 13th edition. CHI, Guelph, Ontario, Canada.

U.S. Geological Survey, 2016. The StreamStats program. Accessed July 2018. Available from: <http://streamstats.usgs.gov>

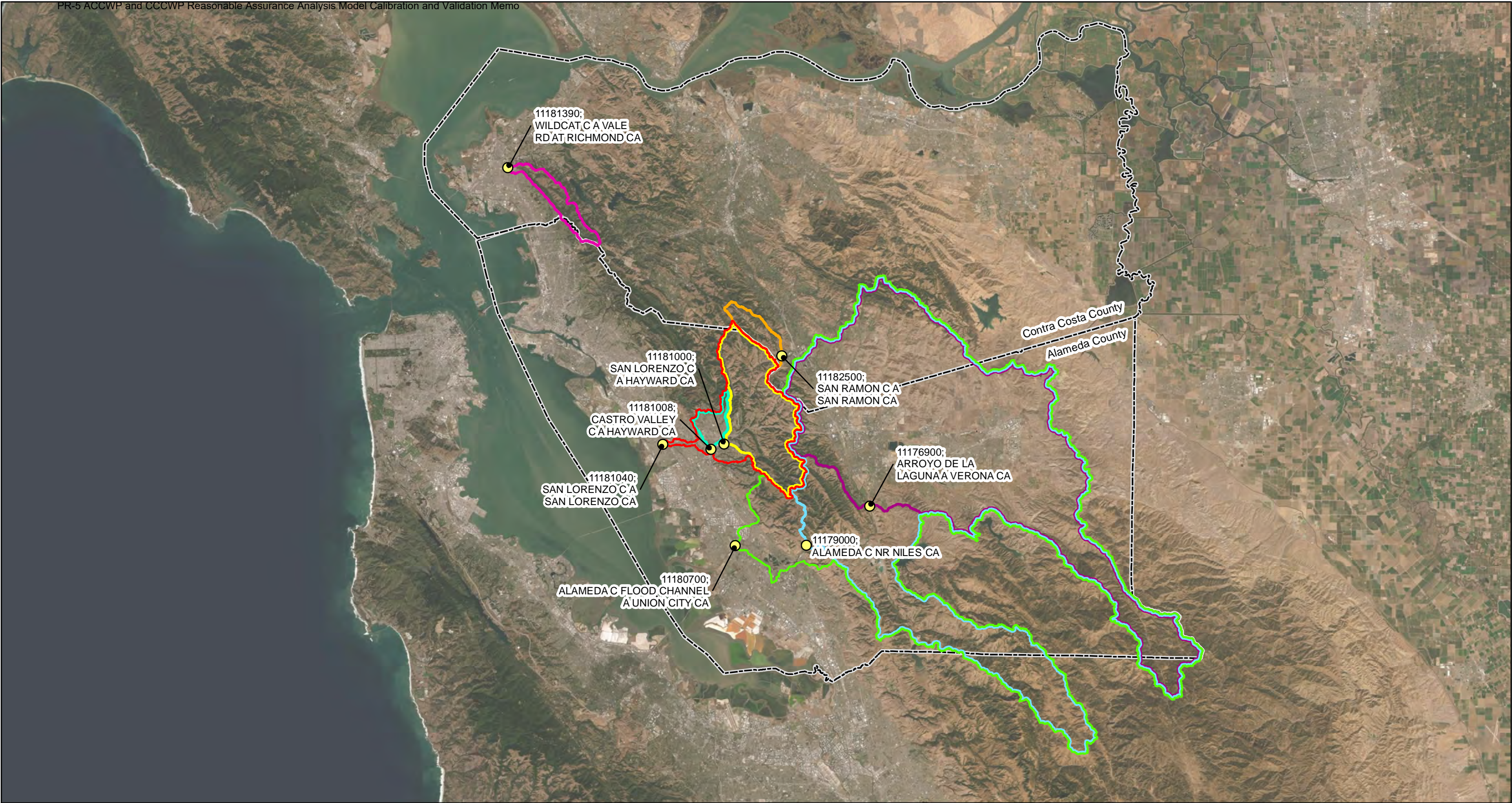
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Attachment

PR-5 ACCWP and CCCWP Reasonable Assurance Analysis Model Calibration and Validation
Alameda Countywide Clean Water Program and Contra Costa Clean Water Program Reasonable Assurance Analysis Model Calibration and Validation Memo
Attachment A: Land Use Breakdown, Validation Watersheds
November 8, 2019

Validation Watershed	POC	Total Acres by Land Use					Total Acres	Percent Area by Land Use				
		Old Industrial	Old Commercial/ Old Transportation	Old Residential	New Urban	Open Space		Old Industrial	Old Commercial/ Old Transportation	Old Residential	New Urban	Open Space
Ettie Street Pump Station_A	PCBs and Hg	356	187	580	47	13	1,183	30%	16%	49%	4%	1%
Santa Fe Channel-SFeCh	PCBs and Hg	197	240	1,012	43	35	1,527	13%	16%	66%	3%	2%
Zone 5 Line M-Z5LM	PCBs and Hg	162	79	645	100	858	1,843	9%	4%	35%	5%	47%
Hayward Ind Stdrrn	PCBs and Hg	82	312	495	118	14	1,021	8%	31%	48%	12%	1%
Meeker Slough	PCBs and Hg	9	74	415	3	5	507	2%	15%	82%	<1%	<1%
San Leandro Creek	PCBs and Hg	49	243	4,750	617	23,052	28,710	<1%	<1%	17%	2%	80%
San Lorenzo Creek	PCBs and Hg	50	842	5,619	2,781	20,694	29,986	<1%	3%	19%	9%	69%
Lower Marsh Creek	PCBs and Hg	125		1,113	6,034	67,837	75,109	<1%	0%	1%	8%	90%
Walnut Creek	PCBs and Hg	88	2,284	18,655	5,558	28,004	54,590	<1%	4%	34%	10%	51%
Glen Echo Creek-GECr	PCBs and Hg		90	400	3	223	716	0%	13%	56%	<1%	31%
Port Chicago Highway	Hg Only	1,650	268	1,801	1,021	14,229	18,968	9%	1%	9%	5%	75%
Codornices at 2nd Street	Hg Only	61	24	893	3	2	983	6%	2%	91%	<1%	<1%
Kirker Creek at Floodway	Hg Only	23		204	99	105	431	5%	0%	47%	23%	24%
El Charro	Hg Only	981	1,027	2,792	4,653	44,201	53,654	2%	2%	5%	9%	82%
Cerrito at Creekside Park	Hg Only	27	119	1,626	17	89	1,879	1%	6%	87%	<1%	5%
Richmond Parkway	Hg Only	36	165	868	47	4,382	5,497	<1%	3%	16%	<1%	80%
3rd St. Bridge	Hg Only	123	339	6,804	911	18,576	26,753	<1%	1%	25%	3%	69%
Baxter at Booker	Hg Only	1	65	541	2	83	692	<1%	9%	78%	<1%	12%
Above Vulcan Bridge Zone 7	Hg Only	28	96	1,078	414	26,592	28,209	<1%	<1%	4%	1%	94%
Arroyo Viejo Rec. Center	Hg Only	2	130	1,841	64	1,400	3,438	<1%	4%	54%	2%	41%
Cesar Chavez Park	Hg Only	0	116	1,287	2	56	1,461	0%	8%	88%	<1%	4%
Strawberry Creek Park	Hg Only		98	822	75	454	1,448	0%	7%	57%	5%	31%
Sausal at E.22nd	Hg Only		140	1,822	6	545	2,513	0%	6%	73%	<1%	22%
Above Lake Temescal	Hg Only		37	817	49	202	1,105	0%	3%	74%	4%	18%
Kirker Creek Apartments	Hg Only		50		10	3,497	3,558	0%	1%	0%	<1%	98%
Mitchell on Oak St	Hg Only			97	0	2,729	2,826	0%	0%	3%	0%	97%

Figures



Legend County Boundaries Flow Gauge Location	San Lorenzo Ck.	Alameda Ck.	San Ramon Ck.	Wildcat Ck.
	11181040	11180700	11182500	11181390
	11181000	11179000		
	11181008	11176900		

0 6 12 Miles

N

RAA Hydrologic Model Calibration

Watersheds Tributary to Flow Gauges Used for Comparison

Alameda County and Contra Costa County

California

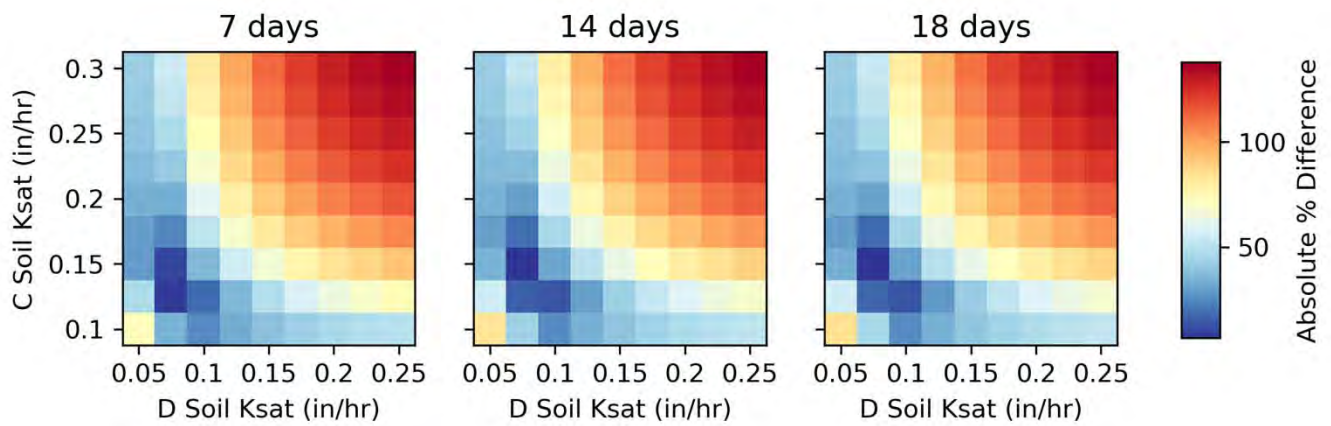
Geosyntec
consultants

Figure

PR-5A

Oakland

August 2019



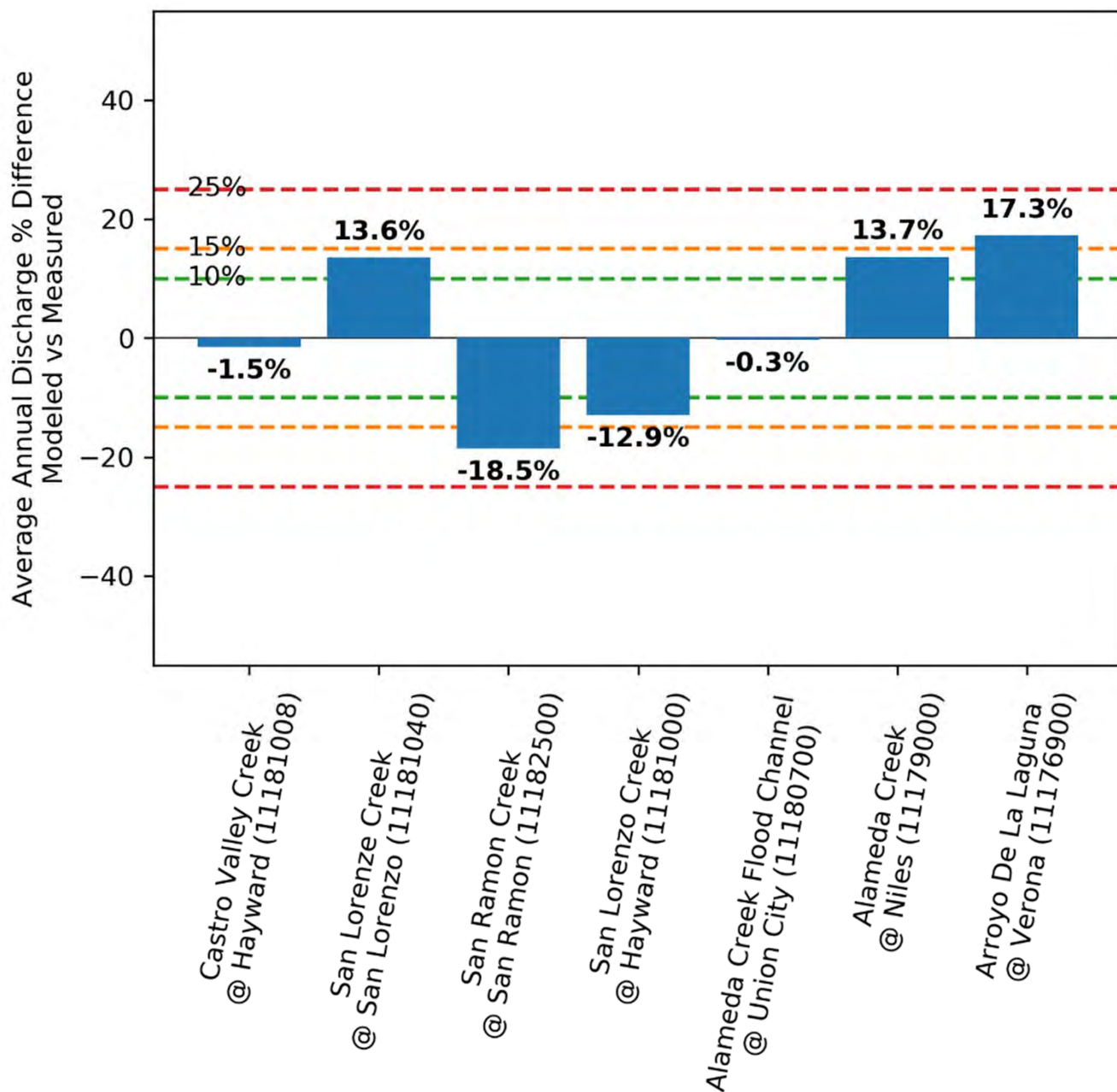
**Calibration Matrix for HSG C and D Soils and
Soil Recovery Time**

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**Figure
PR-5B**

Oakland

August 2019



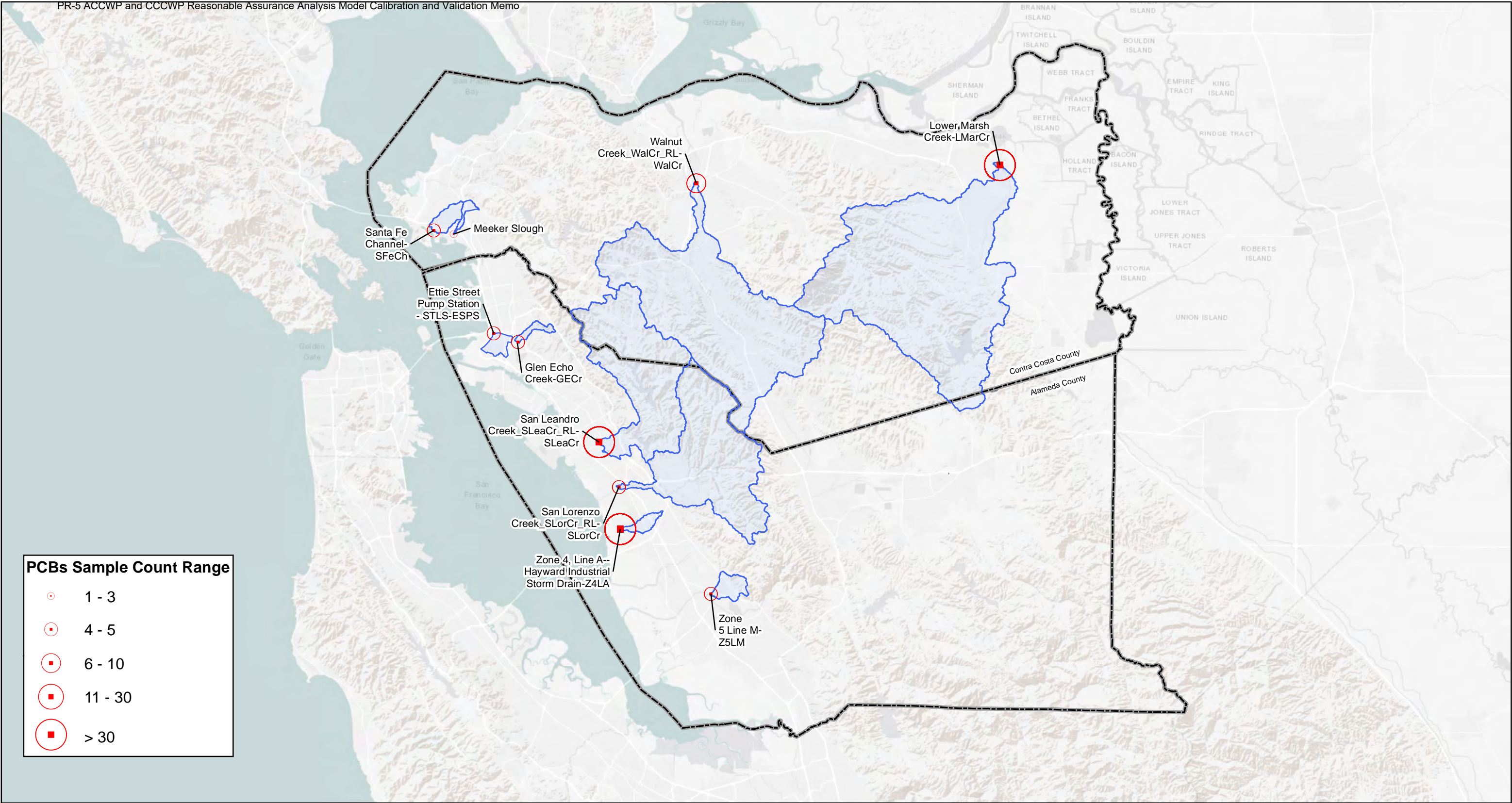
Percent Difference Between Modeled and Measured Average Annual Runoff Volume for Each Calibration Watershed

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Figure
PR-5C

Oakland

August 2019



PCBs Sample Count Range

- 1 - 3
- 4 - 5
- 6 - 10
- 11 - 30
- > 30

Legend

- County Boundary
- Validation Watershed
- Monitoring Location



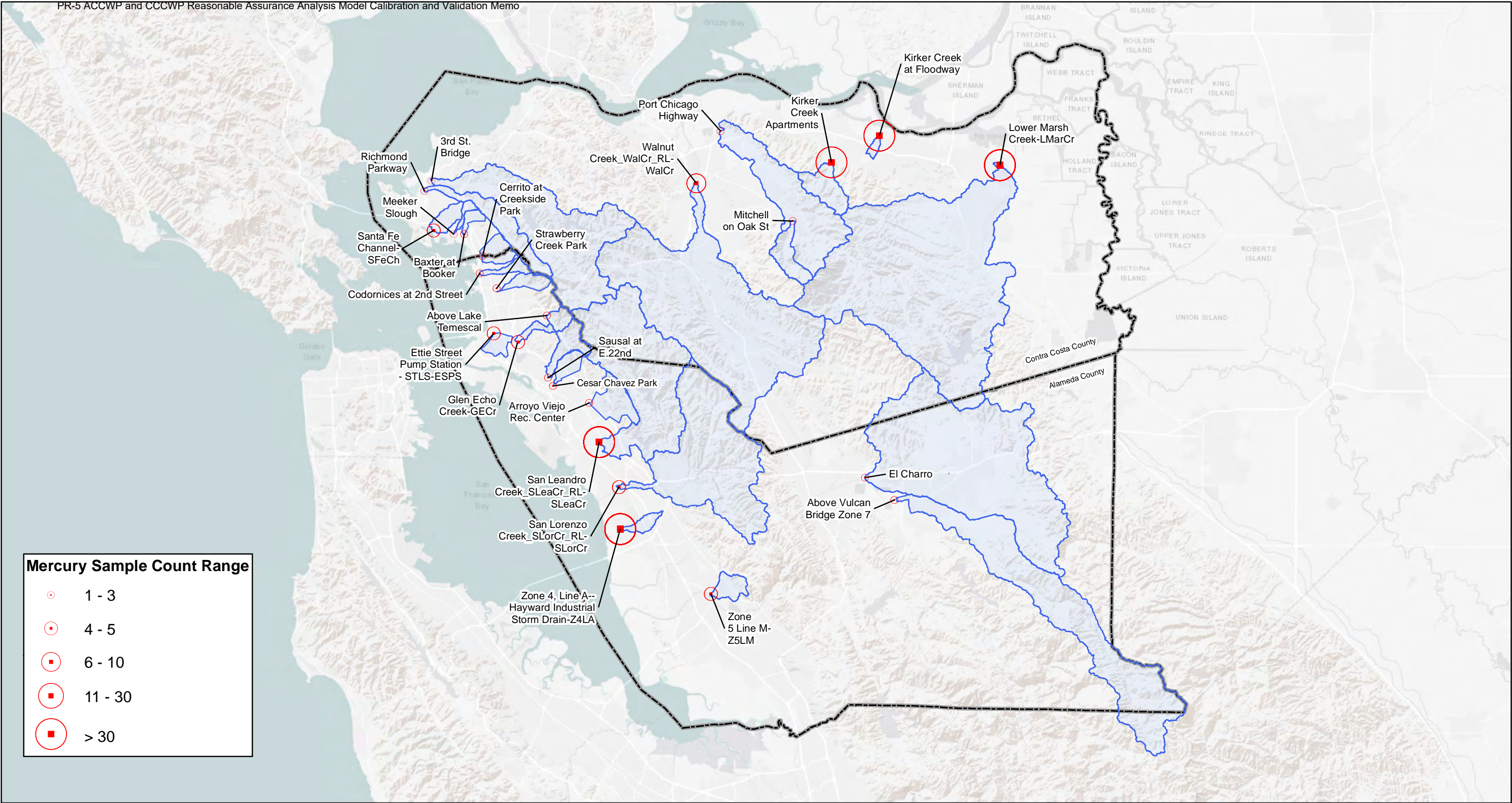
RAA Water Quality Model Validation
Watersheds Tributary to Pollutant Monitoring Locations
used for Comparison of PCBs
Alameda County and Contra Costa County
California

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Figure
PR-5D

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Mercury Sample Count Range

- 1 - 3
- ◻ 4 - 5
- ◻ 6 - 10
- ◻ 11 - 30
- ◼ > 30

Legend

- County Boundary
- Validation Watershed

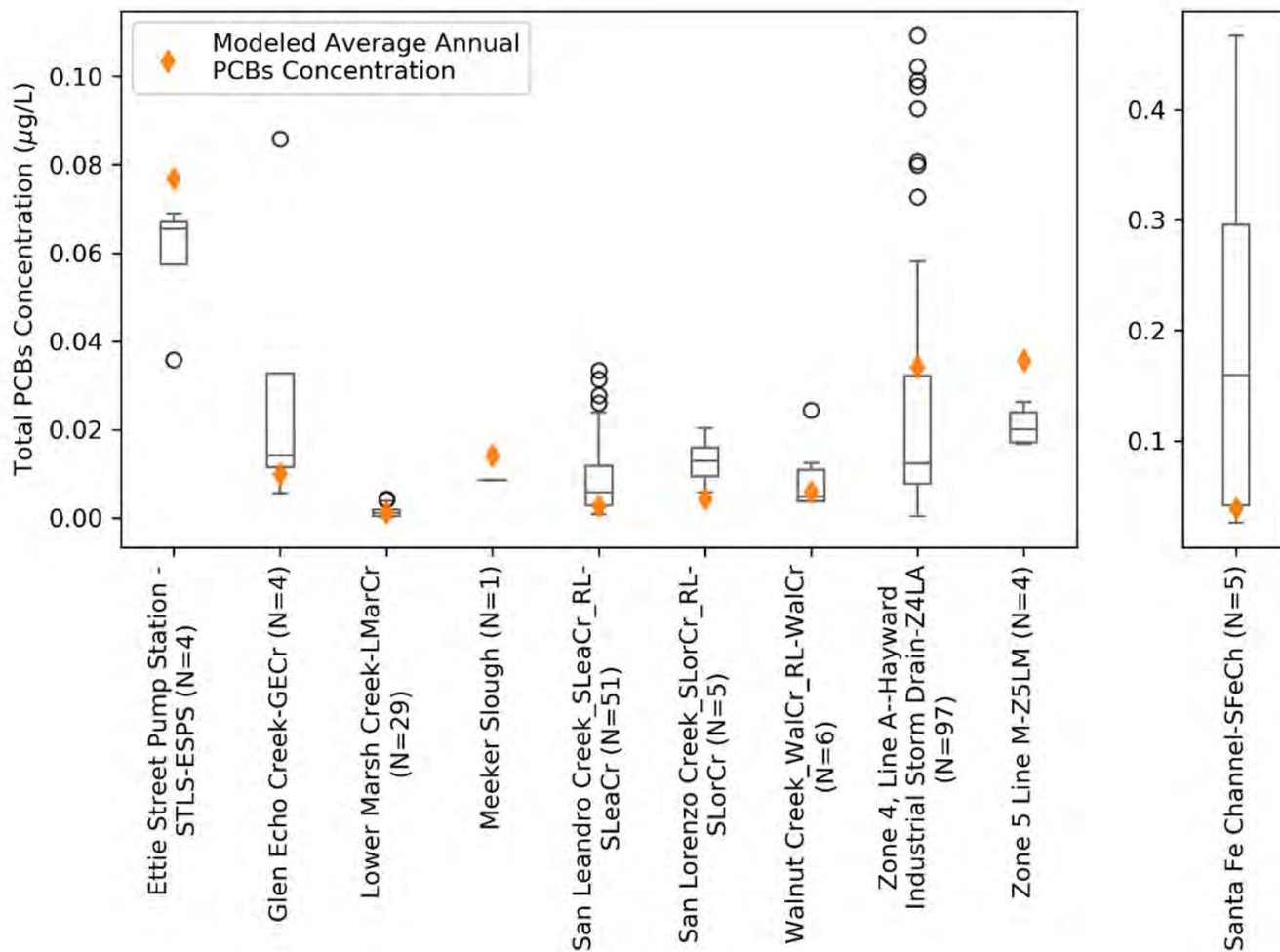
RAA Water Quality Model Validation
Watersheds Tributary to Pollutant Monitoring Locations
used for Comparison of Mercury
Alameda County and Contra Costa County
California

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Figure
PR-5E

Oakland

August 2019



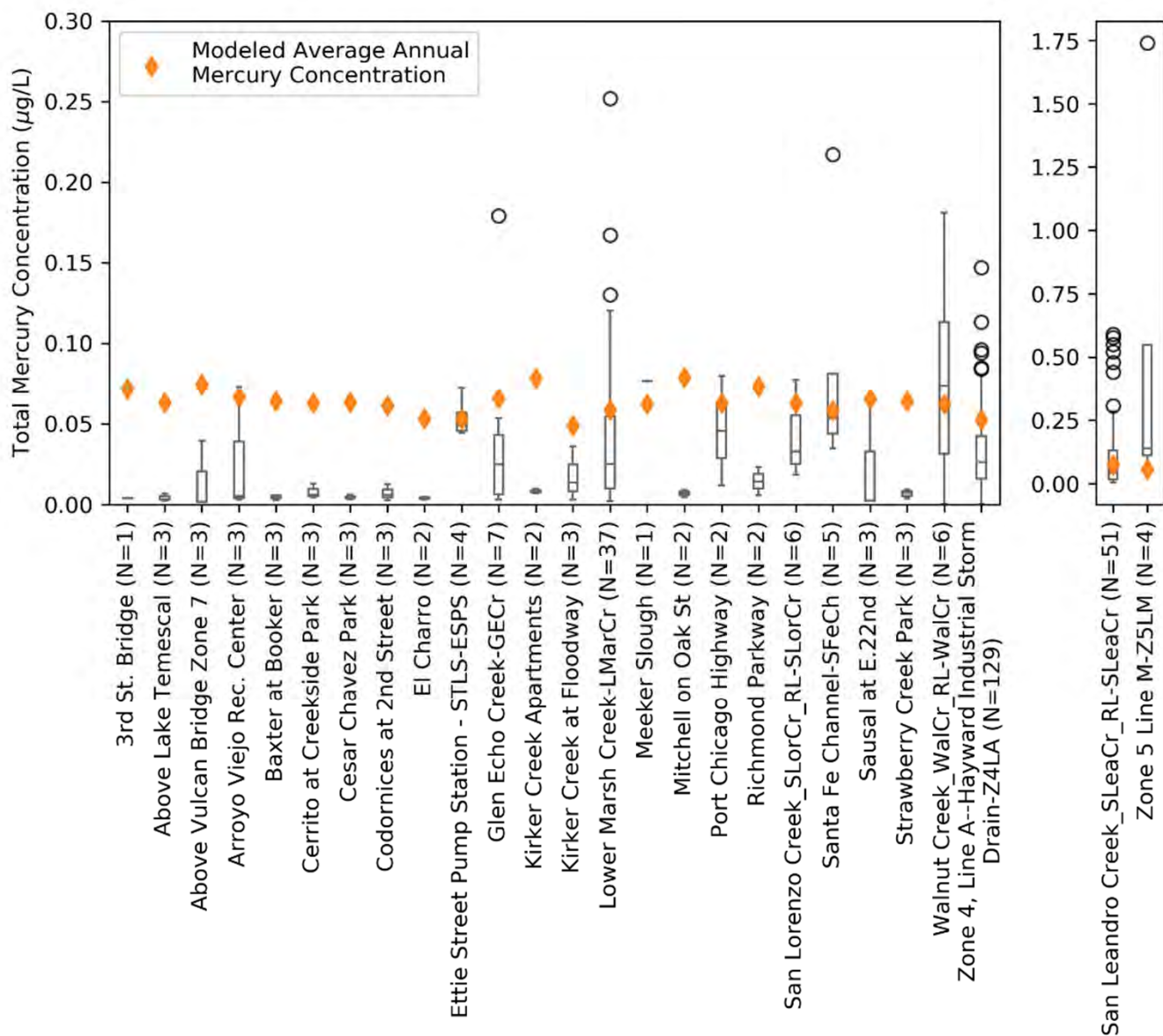
Modeled and Measured PCBs Concentrations for Monitored Watersheds in Alameda County and Contra Costa County

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consultants

Figure
PR-5F

Oakland

August 2019



Modeled and Measured Mercury Concentrations for Monitored Watersheds in Alameda County and Contra Costa County

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Figure
PR-5G

Oakland

August 2019