White Paper on Regional Landscape Characterization for Low Impact Development Site Suitability Analysis

by
Jamie Kass
Jennifer Walker, P. E.
Kristen Cayce
David Senn, Ph. D.
Meredith Williams, Ph.D.

Graphic Design by Linda Wanczyk

SWRCB Agreement #06-345-552-0

CONTRIBUTION NO. 653
DECEMBER 2011

SAN FRANCISCO ESTUARY INSTITUTE
4911 Central Avenue, Richmond, CA 94804
p: 510-746-7334 (SFEI), f: 510-746-7300, www.sfei.org

This report should be cited as:
Kass, J., Walker, J., Cayce, K., Senn, D. and Williams, M. (2011). White Paper on Regional Landscape Characterization for Low Impact Development Site Suitability Analysis. SWRCB Agreement #06-345-552-0. Contribution No. 653. San Francisco Estuary Institute, Richmond, California.

CCA Phase II Task 6.1 – GIS data and methods technical memorandum

Regional Landscape Characterization for Low Impact Development Site Suitability Analysis

White Paper

Author: Jamie Kass

Organization: SFEI

Date: December 27, 2011

Background

California's coast is so rich with species of varied flora and fauna that it was named a biodiversity hotspot (8). Tasked with maintaining this habitat by protecting coastal water quality, the California Coastal Commission (CCC), the State Water Resources Control Board (SWRCB), and their partners in federal, state, regional, and local government created the Critical Coastal Areas Program. It is a non-regulatory program tasked with implementing programs that ensure water quality standards are met and address threats to coastal water quality by diffuse (or "non-point") sources. The critical coastal areas (CCAs) are impaired or sensitive coastal water bodies in need of management measures that maintain or improve beneficial uses. Three such areas (Sonoma, Fitzgerald, and Watsonville) were chosen around the San Francisco Bay Area to be featured in a landscape-scale low impact development site suitability analysis.

Historically, the San Francisco Bay Area was covered by a network of freshwater and tidal wetlands that provided key hydrological and biogeochemical functions, including surface and flood water storage, groundwater recharge, nutrient removal, and sediment transport (7,13). Sweeping land use changes accompanied the wave of new Euro-American settlement to an area that had not previously experienced irrigated agriculture or other intensive management practices by the local indigenous people (7). Much of the region's wetland network underwent large-scale diking and draining starting from the mid-1800's and extending well into the 20th century (4). In addition, a substantial proportion of the region's natural land cover has shifted towards a built environment and its accompanying impervious surface. These changes have resulted in a highly fragmented system of wetlands, increased runoff, and decreased natural attenuation of pollutant and sediment loads, which in turn have led to more frequent and intense flooding, human health hazards, and loss of critical habitat. In order to reduce further impact to existing hydrologic conditions, and to remedy some of the damage already caused, a

national movement, called low impact development (LID), to engineer landscapes that behave like natural, pre-development conditions is gaining momentum.

The effects of urban development, which increases total impervious surface area and dramatically alters natural hydrology (i.e. rerouting waterways through storm drains, removing vegetated riparian areas, etc.), manifest most clearly during storm events. The natural network of wetlands has historically served as an enormous sponge during storms; much of the excess water infiltrates through layers of bioactive soil, is filtered of nutrients, and slowly seeps down to recharge groundwater. Runoff that flows over saturated soil or natural impervious surfaces like rock aggregates into channels and is retained in lakes and ponds, or escapes into the bay or ocean. In contrast, traditional stormwater management practices usually seek to displace runoff from the site as quickly as possible and into storage tanks or ponds, leading to both an increase in peak flow and a decrease in flow duration (5). High peak flow, characterized by punctuated high volume bursts, and low flow duration, meaning that water passes over surfaces quickly without much infiltration, are characteristic of built landscapes with low imperviousness. In these systems, water is routed to drains, where networks of underground pipes lead either to treatment plants or directly empty to a water body. Due to the capacity issues of treatment plants, high volumes of stormwater runoff in urban areas often contain toxins such as heavy metals and pesticides, and nutrients from partially treated or untreated wastewater can overflow during storm events (11,12). Paradoxically, although built systems have an increased need for retention, infiltration, and treatment, the compromised surrounding natural system cannot mitigate the effects of development. Furthermore, constraints in an urbanized setting, such as lack of space and scant pervious ground, make it difficult to integrate unaltered natural systems into the built landscape.

With the goal of approaching conditions similar to the pre-development hydrologic landscape, LID presents a viable stormwater management alternative. LID technically refers to any practice which aims to address a stormwater management need through structural design that stores, infiltrates, evaporates, and detains runoff onsite, and at its best, emulates pre-development hydrology conditions (12). The main goals of LID are to treat runoff as close to the source of origin as possible, recharge groundwater, improve outfall water quality, reduce off-site runoff, and ultimately mitigate the hydrological impacts of development (10). LID also has the potential to reduce operations and maintenance costs through its stormwater services, and to provide cities with harvestable rainwater to augment water supplies (6).

Currently, most LID implementation seems to be planned on an opportunistic basis rather than at the landscape level, and does not incorporate a site suitability component to prioritize areas for treatment. Some work has been done using geographic information systems (GIS) to overlay land features in order to select suitable sites, but mostly on a small scale. Most of these studies

focus on a customized GIS overlay analysis. A weighted overlay is a technique that sums different variables multiplied by weights. A fuzzy overlay fits variables to curves which describe each variable's relationship to the overarching concept, which in this case would be LID treatment types. The values are scaled from 0 to 1, where "0" and "1" mean perfect indirect and direct relationships between the variables and the concept, respectively. Fuzzy overlays generally produce "smoother" results, as many more values are considered in the analysis. Both of these techniques are explained in detail in "Methods". Wang et al. (14) developed a residential development plan on a 3 ha subwatershed using a weighted overlay to prioritize construction sites with the lowest predicted runoff increases using predictor variables slope, soil hydrologic type, and soil drainage type. This analysis did not predict suitability for construction of LID treatments, but suggested sites for development that had the fewest hydrological impacts (conservation of pervious areas and those suited for detention). The San Francisco Public Utilities Commission (11) estimated implementable area for several LID types and potential stormwater benefits in the city of San Francisco. GIS-based extrapolations for the city were made of features like parking lots, roofs with varying slopes, pavement coverage, etc. based on digitized sample areas. The estimated areas were then overlaid with landscape constraints like slope, depth to bedrock, etc. to narrow them down to suitable areas. The results were input into a rainfall/runoff simulation model developed by the EPA (the Stormwater Management Model—SWMM) to estimate differences in runoff volume, peak flows, and combined sewer outflows between the LID and base condition scenarios. This pilot study attempted to examine areas for possible infiltration treatments, but the study was switched to assess lined treatments that empty into the sewer after finding unpromising results for total possible infiltrative area for San Francisco. Eslami et al. (3) performed a fuzzy overlay that fit variables to linear equations describing suitability for bioretention on a 7 ha developed plot using predictor variables slope, distances from buildings, drainage network, and drainage points. Variables were fit to linear equations based on the allowable ranges for 3 qualitative categories "poor", "fair", and "good". Sites were selected with the highest scores and compared with peak flows derived from SWMM.

In this study, we developed a GIS-based LID site suitability tool for the SF Bay Area that combines overlays of topographic, geologic, and built environment features to identify areas where five different LID treatment types can be best implemented. This work builds upon recent site suitability exercises, but does so over a much larger extent (San Francisco Bay Area Region; Fig. 1). It also incorporates several additional components, including comparisons between categorical and fuzzy overlays, inclusion of local cleanup sites and the Bay Area Aquatic Resource Inventory, or BAARI (1), dataset for wetland locations, and an illustrative conceptual model of our proposed regional scale site suitability process centered on the Bay Area.

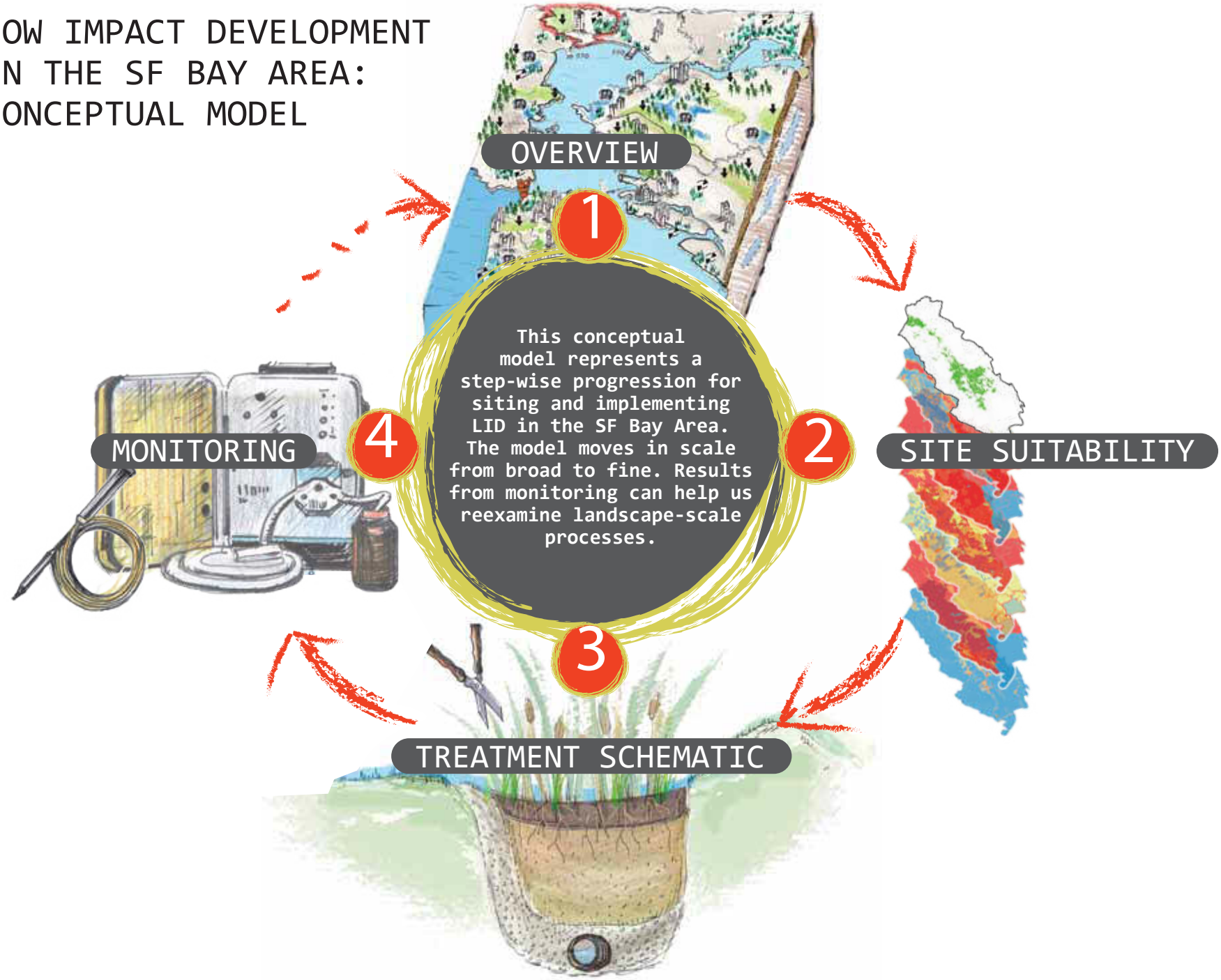
A hydrologic modeling component was also completed to quantify peak flow reductions associated with wide-scale LID implementation for both 2-year and 10-year design storms in a representative subwatershed in Sonoma. Along with statistics from BAARI and the landscape variables, total areas of estimated suitable area for several treatment types were used as input to the model. Brief results can be found in the Conclusions section, and a report on methodology can be found in Appendix 5.

The work was completed in two parts: one fashioned after the SFPUC San Francisco pilot study for infiltrative treatments and was extended to the landscape scale, and a second incorporating more informative variables and fuzzy logic. The goal was to determine if these additions would substantially influence the results. This report describes the approach and key findings, which are featured in maps both throughout the text and in Appendices 3 and 4. Figures use the LID treatment type “bioretention” as an example throughout the report, though all treatment results for the CCA watersheds are shown in the appendix.

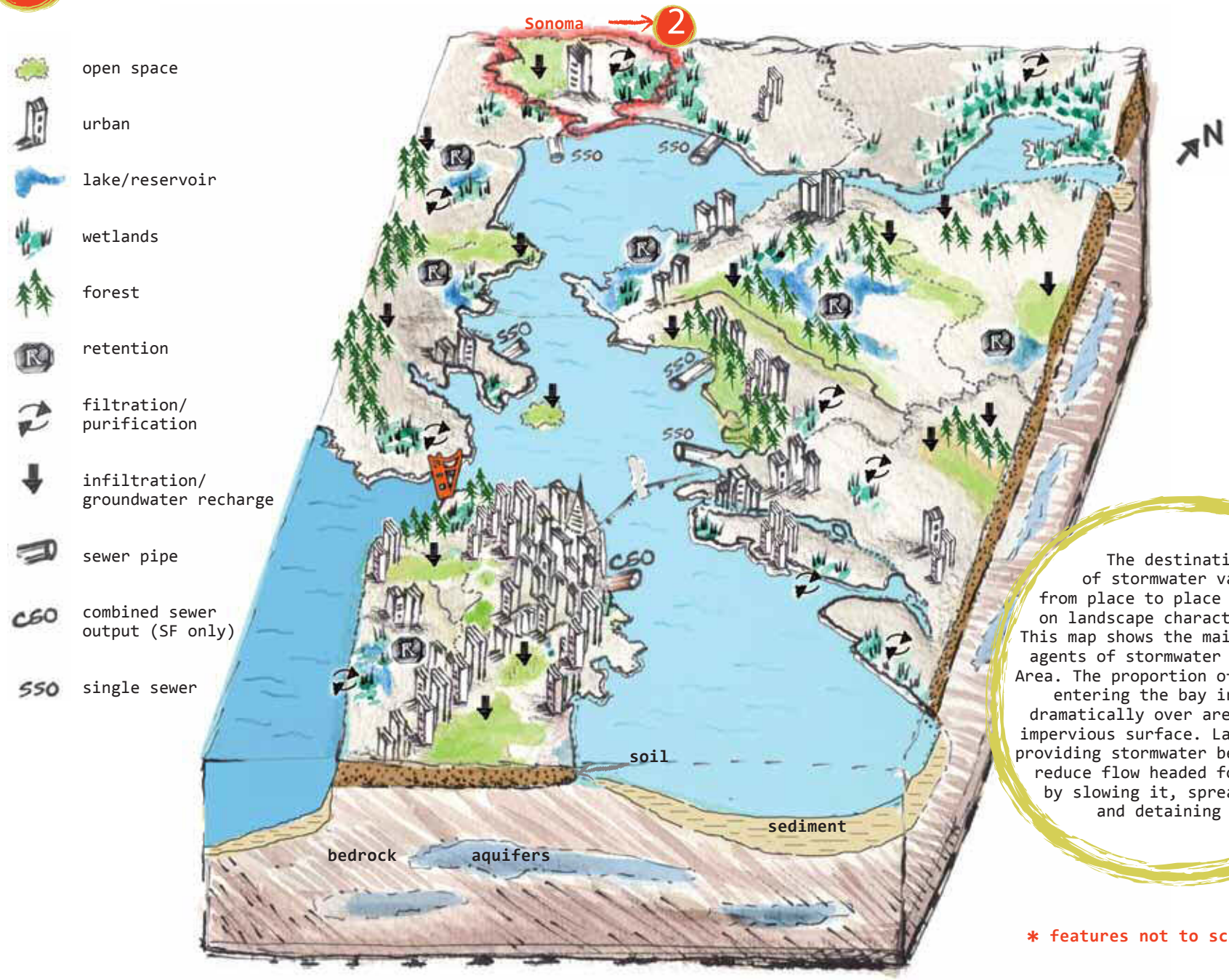
Conceptual Model

With the interests of representing the broad-scale planning process this paper advocates in an illustrative way, we created a conceptual model specific to the SF Bay Area that presents our vision of landscape-scale LID implementation. The model steps through different views of scale from broad to fine, and demonstrates how the process can return to the broad scale after rounds of monitoring are completed. Planners and managers can benefit from this cyclical method of LID implementation to ensure that implemented sites are indeed the most suitable in the landscape, and if monitoring results prompt siting reconsideration, broad-scale selection criteria can be modified for fine-tuned results.

LOW IMPACT DEVELOPMENT IN THE SF BAY AREA: CONCEPTUAL MODEL



1 OVERVIEW - Destination of Stormwater in the SF Bay Area

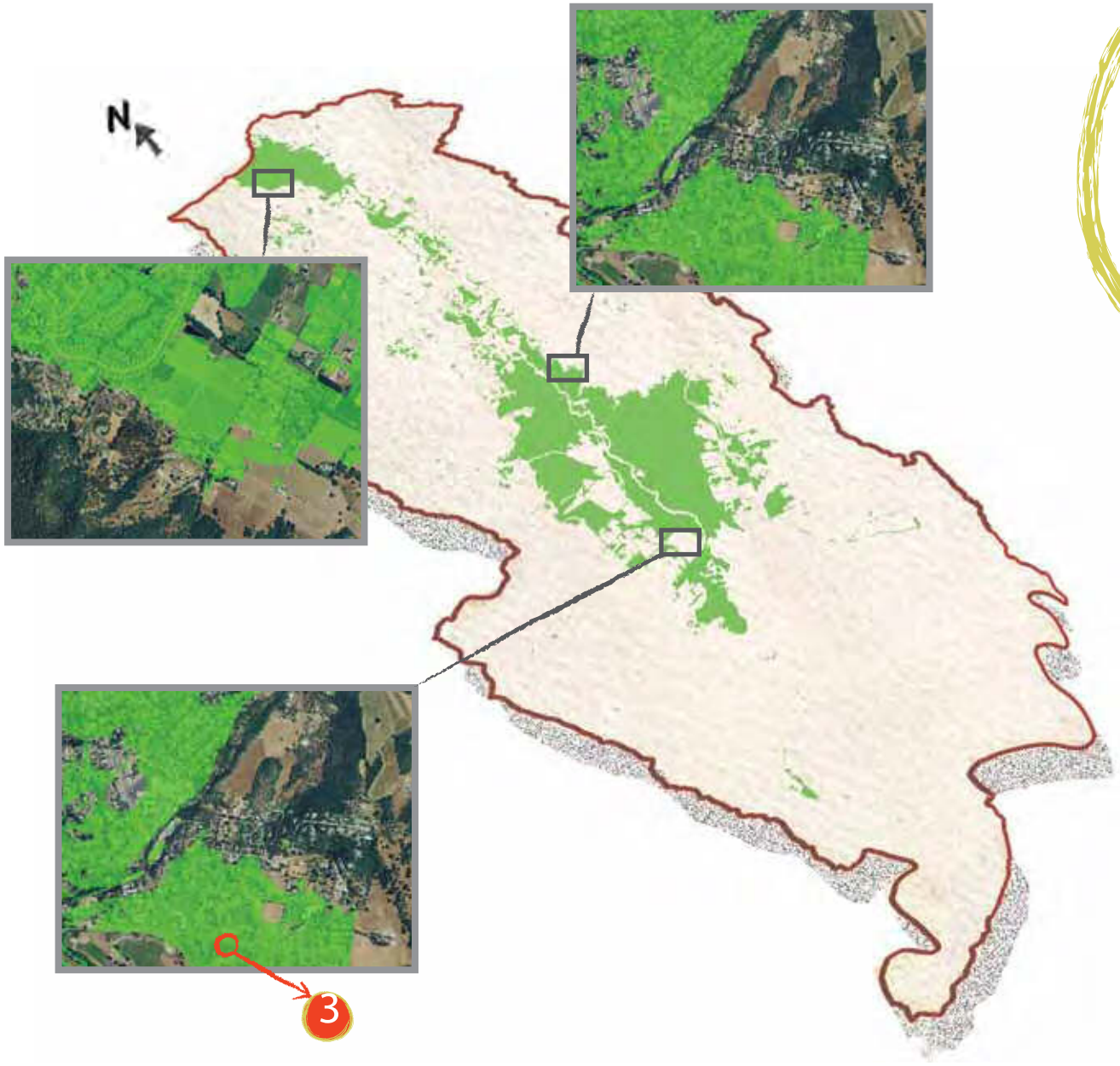


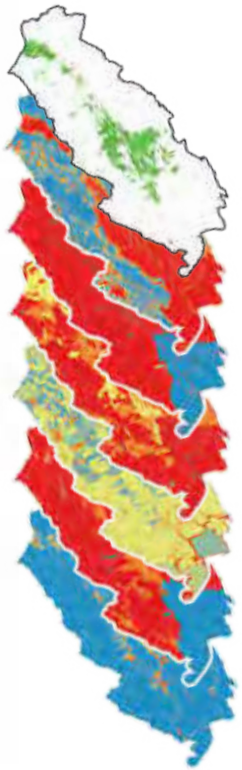
The destination of stormwater varies from place to place depending on landscape characteristics. This map shows the main receiving agents of stormwater in the Bay Area. The proportion of stormwater entering the bay increases dramatically over areas of high impervious surface. Land features providing stormwater benefits help reduce flow headed for the bay by slowing it, spreading it, and detaining it.

* features not to scale

2 SITE SUITABILITY - Sonoma Watershed bioretention

A site suitability analysis greatly aids landscape-level planning by providing a holistic view that compares sites to one another. Typically, GIS is used to combine landscape variables that act as predictors for suitable areas. The green spots on this map represent recommended (suitable) sites for bioretention implementation produced by our LID site suitability tool.





Site Selection

Percent Slope

Depth to Water Table

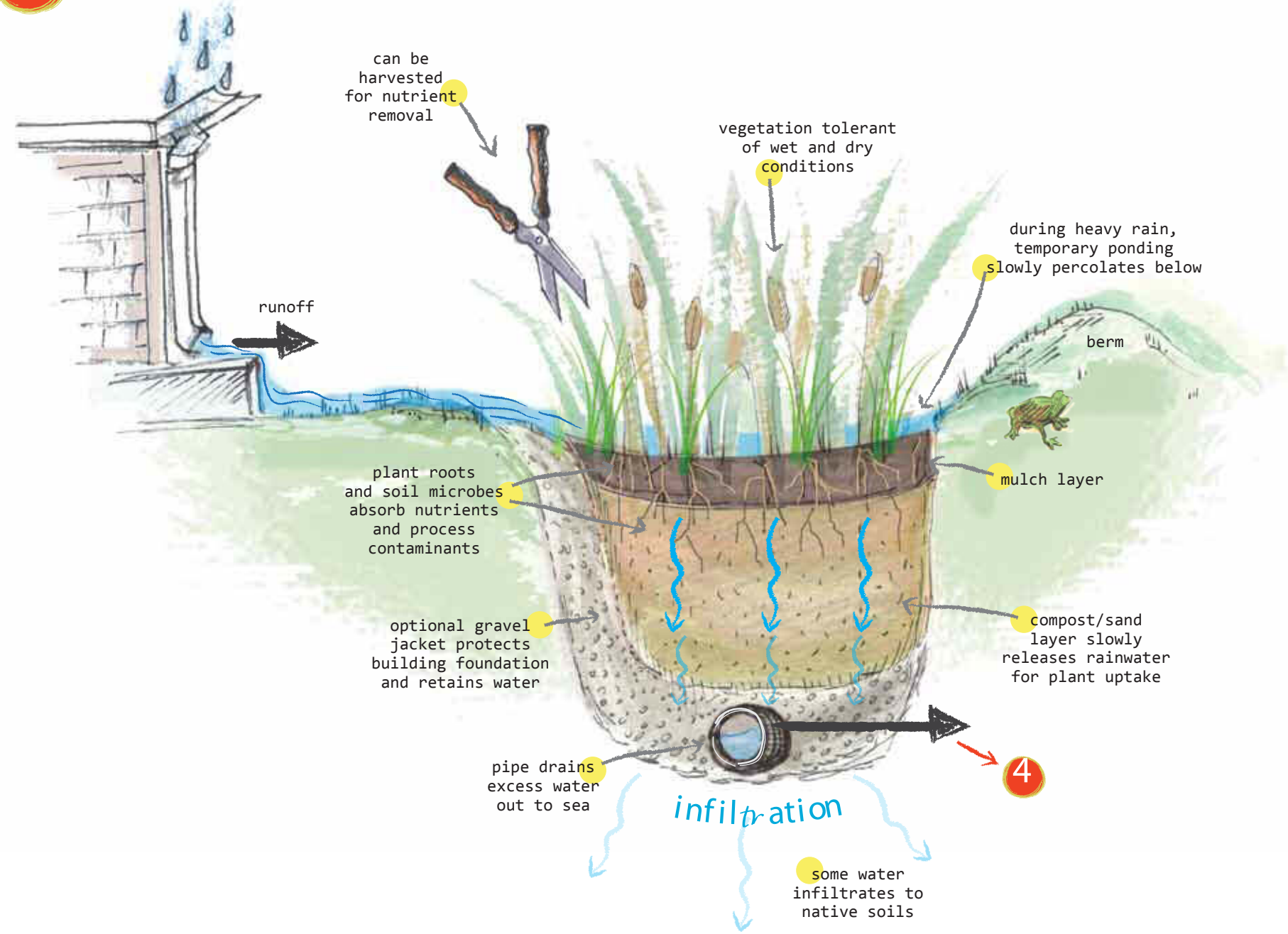
Soil Hydrologic Type

Land Use

Liquefaction Risk

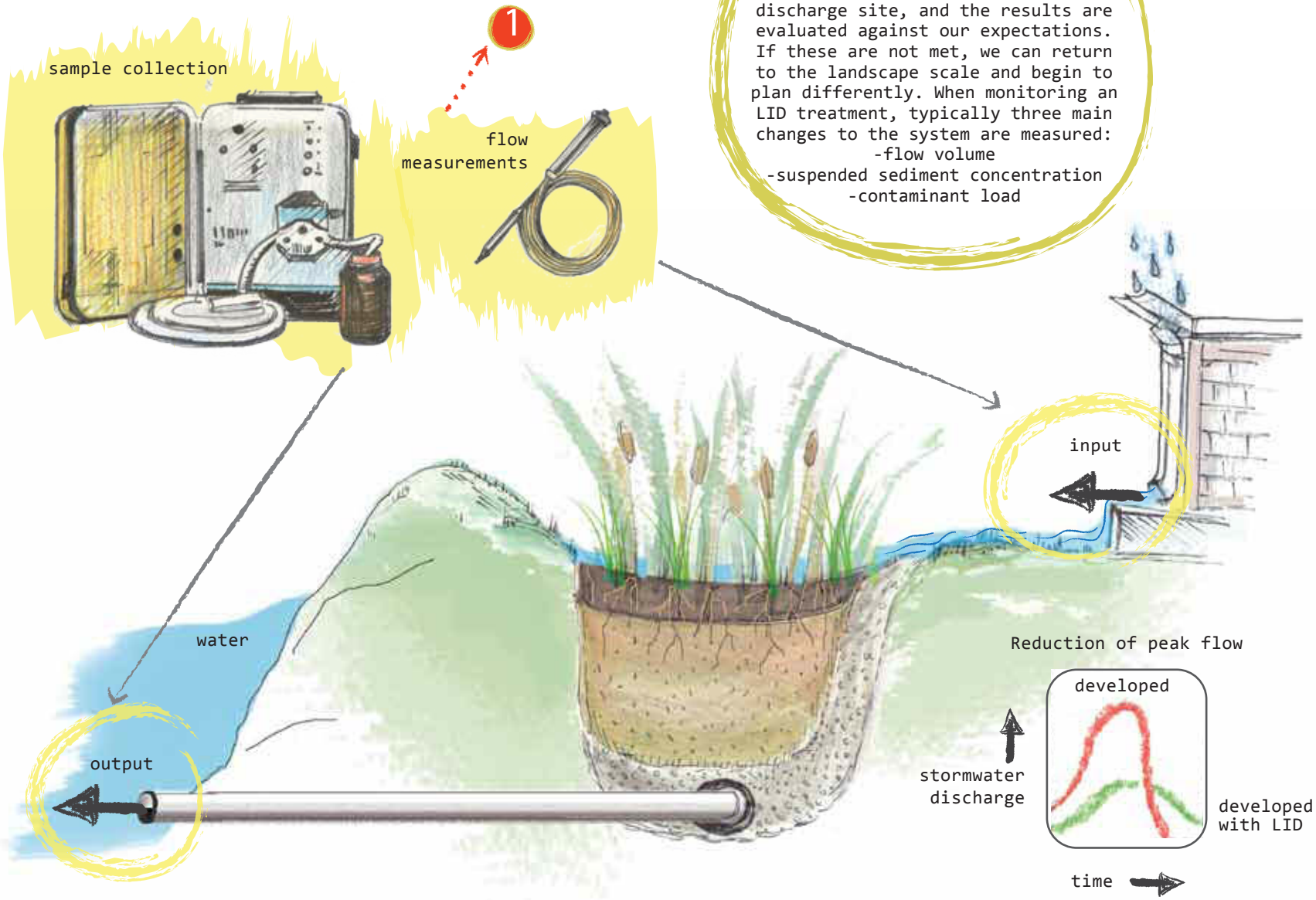
Impervious Surface

3 TREATMENT SCHEMATIC - bioretention



4 MONITORING

The following is a simplified schematic with a single input and output. Measurements are taken at each discharge site, and the results are evaluated against our expectations. If these are not met, we can return to the landscape scale and begin to plan differently. When monitoring an LID treatment, typically three main changes to the system are measured:
-flow volume
-suspended sediment concentration
-contaminant load



Methods

Project Extent

The extent used for the analysis is the SF Bay Regional Water Board boundary plus the addition of Watsonville watershed. The watershed dataset is a modified version of the Calwater 2.2.1 dataset that was edited to correct fine-scale errors in watershed delineation. These edits were made based on ancillary data sources including elevation, slope, contour lines, and aerial imagery. Figure 1 shows the project extent with the CCA watersheds highlighted in red.

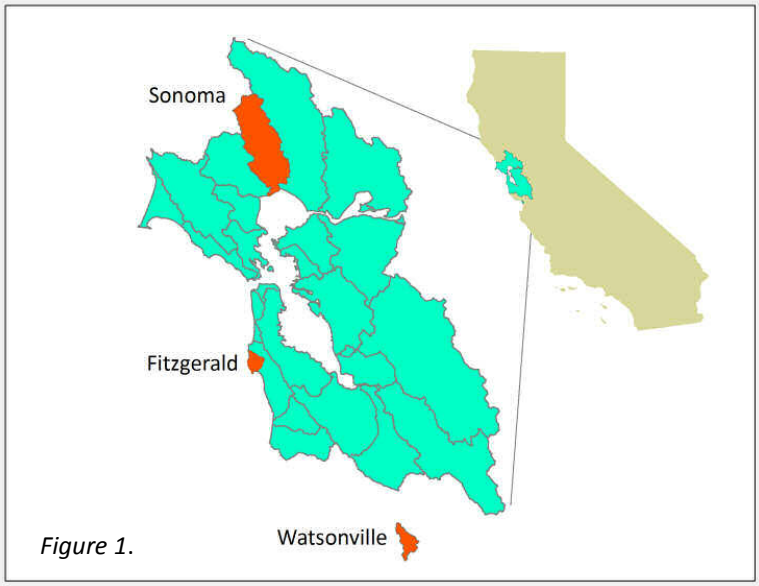


Figure 1.

LID Treatments

Five LID treatment types were chosen for the analysis based on the individual uniqueness of each and their collective ubiquity in the industry: bioretention (bior), permeable pavement (prpv), stormwater wetland (swwt), vegetated swale (vgsw), and wet pond (wtpd). Although these treatment types can have flexible definitions in practice, for the purposes of this project they needed to be defined in order to assign weights and relationships to variables. Bioretention refers to a small-scale treatment composed of vegetation, a soil mixture, and a drainage mechanism that provides storage and infiltration of runoff and treats contaminants. Permeable pavement is a porous load-bearing surface primarily used in parking lots and low-traffic streets that can provide storage and infiltration of runoff. Stormwater wetlands are constructed wetlands that have a fluctuating level of low-depth water and vegetation which provide detention and treatment of runoff. Vegetated swales are shallow vegetated channels that collect and slowly convey runoff to discharge areas. Wet ponds are relatively deep bodies of water that detain runoff, allow settling of contaminants, and slowly drain excess water (2).

Analysis

As stated above, two overlay methods run in ArcGIS 10.0 were used to perform site suitability analyses on the Bay Area for the five LID treatment types. The first was a categorical weighted

overlay (CWO), which assigns weights to categorical variables, reclassifies them to a common qualitative scale, and produces a matrix of cells (raster) with values somewhere on the common scale (influenced by the sum of the input variables multiplied by their weights). The second was a fuzzy weighted overlay (FWO), which follows the same weighting scheme as the former, but converts variables to a decimal scale based on strength of suitability instead of assigning qualitative values. As the variety of available curves in the ArcGIS 10.0 toolbox is limited, best fits for each fuzzy variable were chosen for curve type and parameters. Our hypothesis was that the FWO would paint a more varied and detailed picture of suitability, which can be useful on the multiple scales to prioritize areas for implementation.

Six landscape variables were used as inputs to the site suitability tool: percent slope, depth to water table, liquefaction risk, land use, soil hydrologic type, and percent impervious surface (Table 1). The CWO used the first five variables, and the FWO adds impervious surface and two other proximity variables: BAARI non-tidal wetlands database and local contaminant cleanup sites (discussed later, shown in Appendix 3).

Table 1. Landscape variables used for both overlays, data types, weights assigned, and sources.

Landscape Variable	Data Type	CWO Weight	FWO Weight	Source
Percent Slope	raster continuous	27	25	10 meter National Elevation Dataset (NED)
Depth to Water Table	polygon continuous*	27	25	Natural Resource Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO)
Soil Hydrologic Type	polygon categorical	20	15	Natural Resource Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO)
Land Use	polygon categorical	16	15	Association of Bay Area Govts (ABAG) 2005
Liquefaction Risk	polygon categorical	10	10	US Geological Survey (USGS)
Percent Impervious Surface	raster continuous	x	10	National Land Cover Dataset (NLCD) 2006

* considered continuous (defined as >10 unique values) although data is polygonal and not raster, see General Preprocessing

Categorical overlays are generally more restrictive, as they require an initial binning of continuous variables and enforce common scales, while fuzzy overlays allow fitting continuous variables to membership curves that better describe relationships and allow for the input of more unique values. Rather than generalizing to three bins (Appendix 1) using the CWO method, FWO reclassifies the variable on a continuous scale from 0 (“unsuitable”) to 1 (“recommended”) (Appendix 2). The CWO method used in our study was modeled after the SFPUC’s pilot study “Low Impact Design Modeling” report, which found less than 15% of the urban landscape to be suitable for infiltration techniques. The variables from this attempt (except soil contamination, which was unavailable for the entire Bay Area) were used in the CWO analysis. The FWO method was an attempt at refining the output by incorporating fuzzy

logic and new proximity analyses. The inclusion of proximity variables help influence our suitability decisions by giving preference to particular locations over others, and can help us select areas that improve hydrologic and habitat connectivity and are distant from contaminated areas. This information can be useful for stormwater managers and city planners who wish to maximize the runoff benefits inherent in particular sites or avoid those that could potentially pose human health hazards.

General Preprocessing

Significant preprocessing of the landscape variable datasets was needed to prepare them for analysis. While weighting the variables according to expert opinion on suitable land attributes for different LID treatments, it became clear that: 1) some values were not applicable to this suitability analysis and would therefore need to be excluded (e.g. high slopes, certain land uses, etc.), 2) some variables had extents differing from the project boundaries and would need to be modified, 3) some variables had values that warranted consolidation rather than exclusion. Further, variables with areas of no data that fell within the project boundaries needed to be given a numerical value, as cells with no data in any variable input are excluded from tool operations. This section summarizes the preprocessing that was done to each dataset before it was used in the analyses.

Percent slope, which is a derived product of the 10 meter NED, needed to be restricted to a lower range. LID can be implemented in high slope areas, but as siting constraints usually include requirements for mild slopes to either maximize infiltration capacity or enable ponding, significant engineering is required (10, J. Walker pers. com.). Therefore, only slopes less than 15% were called suitable, and those above 25% were set to null. Slopes in the 15 - 25% range were kept to demonstrate that, with some extra cost and engineering, LID treatments can be implemented in some moderately high-slope areas. Therefore, slopes in this range are given the same value, which is "1" in the CWO and the minimum slope suitability value in the FWO.

ABAG 2005 land use has many unique use types, and needed to be generalized into 6 main classes, which were residential, commercial, industrial, agriculture, transportation, and open space. These general land use classes are better applied to a relatively coarse analysis on a landscape scale than specific classes. Land use classes that would not be proposed for new LID development were generalized to forest, wetland, and water, and were all classified with a cell value of 0. Also, as ABAG land use has several wide data gaps between county lines and features with no data, these areas were also given a value of 0. This results in some error, as these areas may contain suitable sites, but it is likely negligible due to their small total area.

For the USGS Liquefaction Risk shapefile, the classes "high" and "very high" were aggregated, as risks high and above were considered equally unsuitable. The SSURGO soil hydrologic type classes include "bare rock" and "open water", which were both excluded by giving them a value

of 0. Liquefaction Risk also contains an "open water" class which similarly received a value of 0. Present in both datasets, these "open water" areas include many lakes, ponds, etc. that do not align with aerial imagery and the BAARI wetlands, and were kept as 0's to attempt at offsetting error. If time allowed, whole-scale editing of these datasets would have been preferable.

Depth to water table had many more unique values than the other polygonal data (32 compared with 10 or less) and was thus binned in the CWO. Therefore, it was not binned and instead treated as a continuous variable and in the FWO in order to express fully the variation of the input variable. Impervious surface was input unaltered as a continous variable into the FWO.

Results

Categorical Weighted Overlay

The CWO included five landscape variables (impervious surface was excluded). All variables were reclassified, and the continuous variables binned, to an "unsuitable" / "adequate" / "recommended" scheme (see Appendix 1). The variables were then weighted according to expert opinion of the greatest impact to site placement ("CWO Weight" in Table 1). A conscious attempt was made to highlight unique attributes of each LID treatment in order to clearly differentiate between treatments. A weighted overlay was performed, and the top scoring cells ("recommended") were isolated by setting all other values to null. This was done to reduce data complexity for conversion to polygon. Once in polygon form, minimum areas can be enforced on the most suitable output shapes that, according to expert opinion, reflect areas above which each LID treatment can be successfully implemented. This involves deleting all features with areas below the cutoff point. Figure 2 highlights the results for the CCA watersheds.

Fuzzy Weighted Overlay

This overlay was done as an improvement on the CWO in a number of ways. In addition to using a fuzzy overlay procedure, a new dataset was added (impervious surface), and two proximity variables were incorporated (Table 2). Impervious surface provides a good contrast to land use, as some uses have considerable variability in surface makeup. Inclusion of the cleanup sites (CU) penalizes suitable sites for being too close to contaminated areas, and proximity to BAARI wetlands identifies which sites contribute most to hydrologic and/or habitat connectivity. As in the CWO, "recommended" polygons are isolated to facilitate conversion to polygon, and are enforced by the same minimum area requirements. For the FWO, "recommended" is defined as the top 25% scoring cells. The "recommended" sites for the FWO have a diversity of suitability values, while the CWO features just one "recommended" value. Figures 3 (variables) and 4 (site suitability) highlight the FWO results for suitability of bioretention in the CCA watersheds.

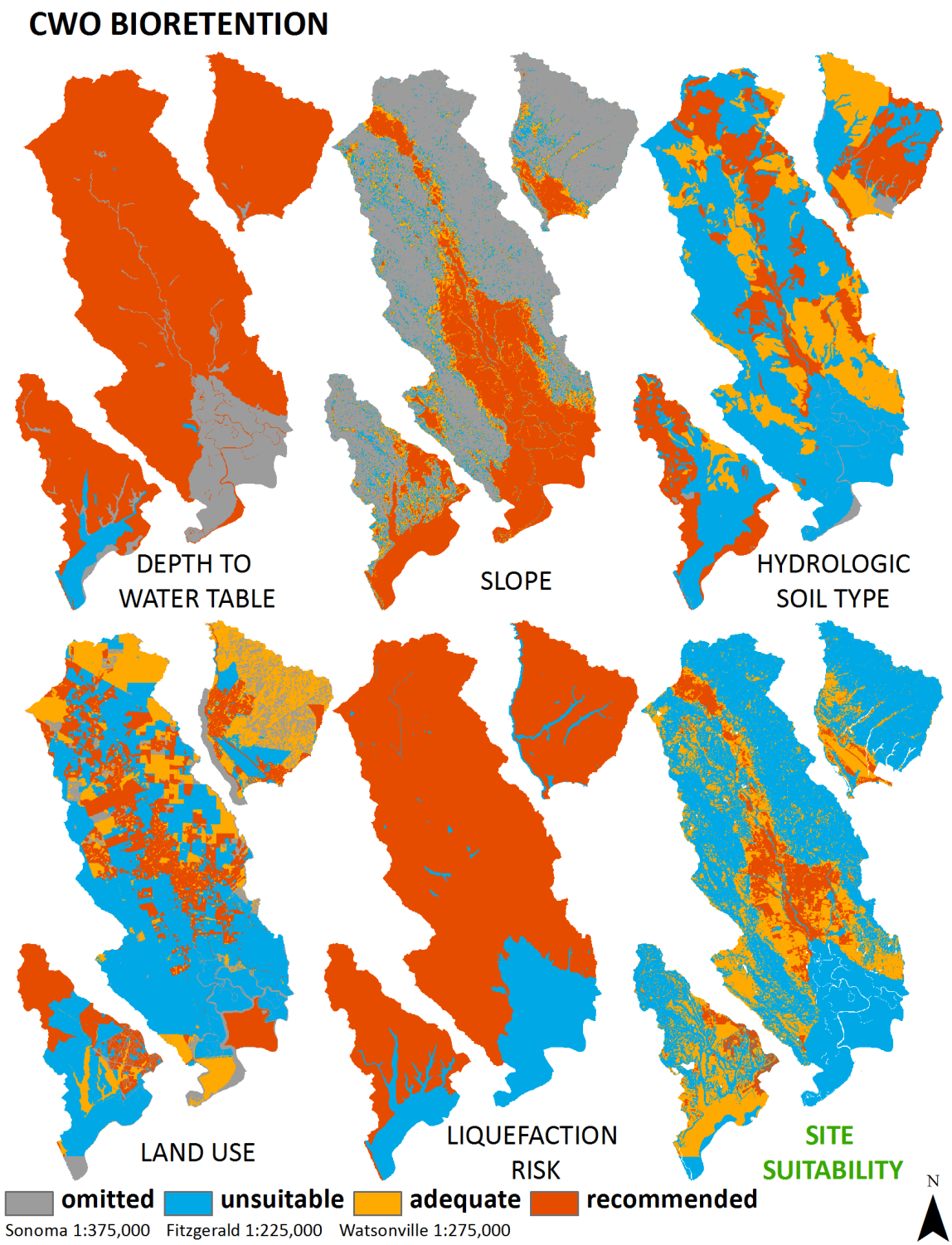


Figure 2. CCA watershed variables for bioretention categorical weighted overlay. Suitability represented in three categories. Watersheds are from left to right: Watsonville, Sonoma, Fitzgerald.

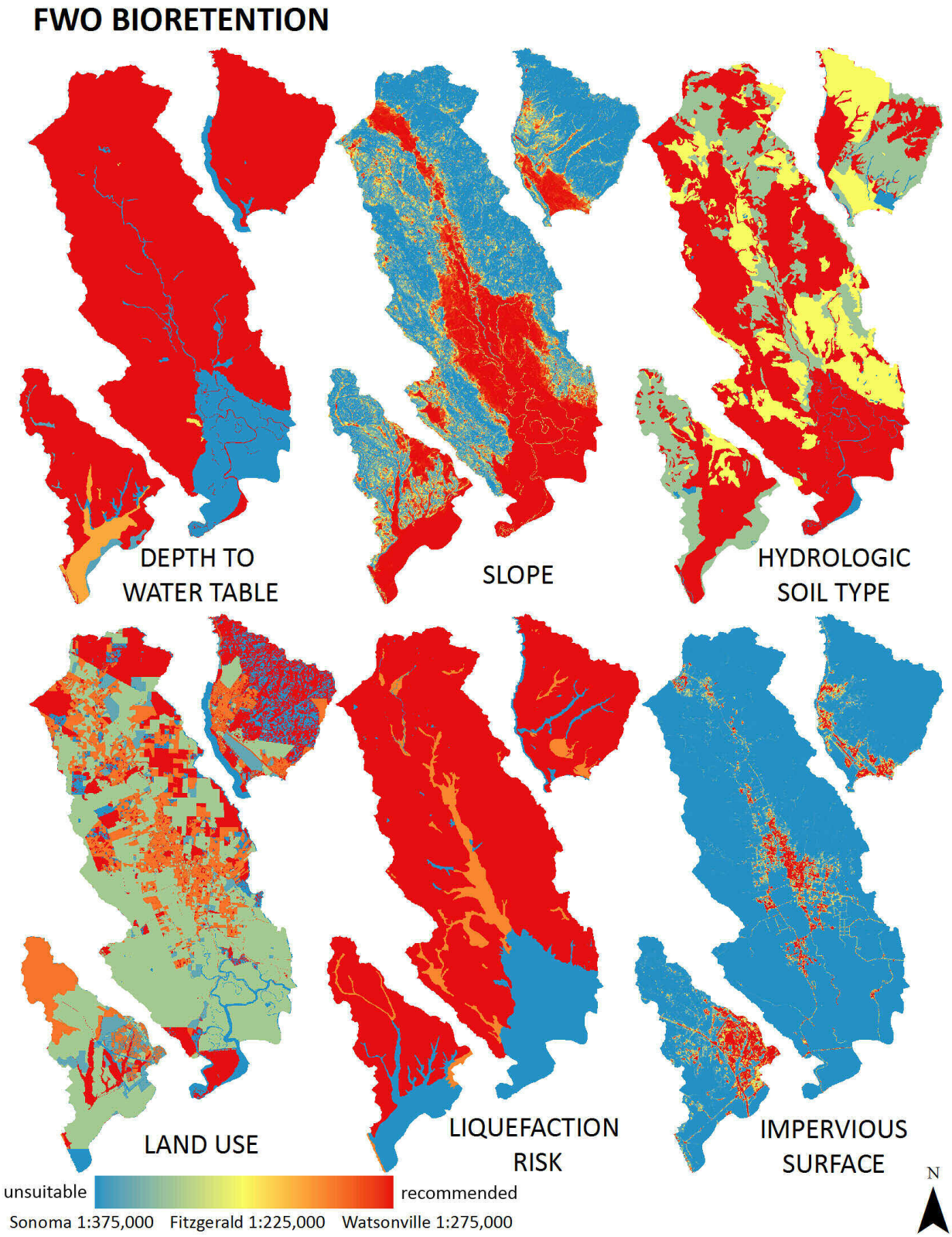


Figure 3. CCA watershed fuzzy variables for bioretention fuzzy weighted overlay. Suitability represented on a continuous scale.

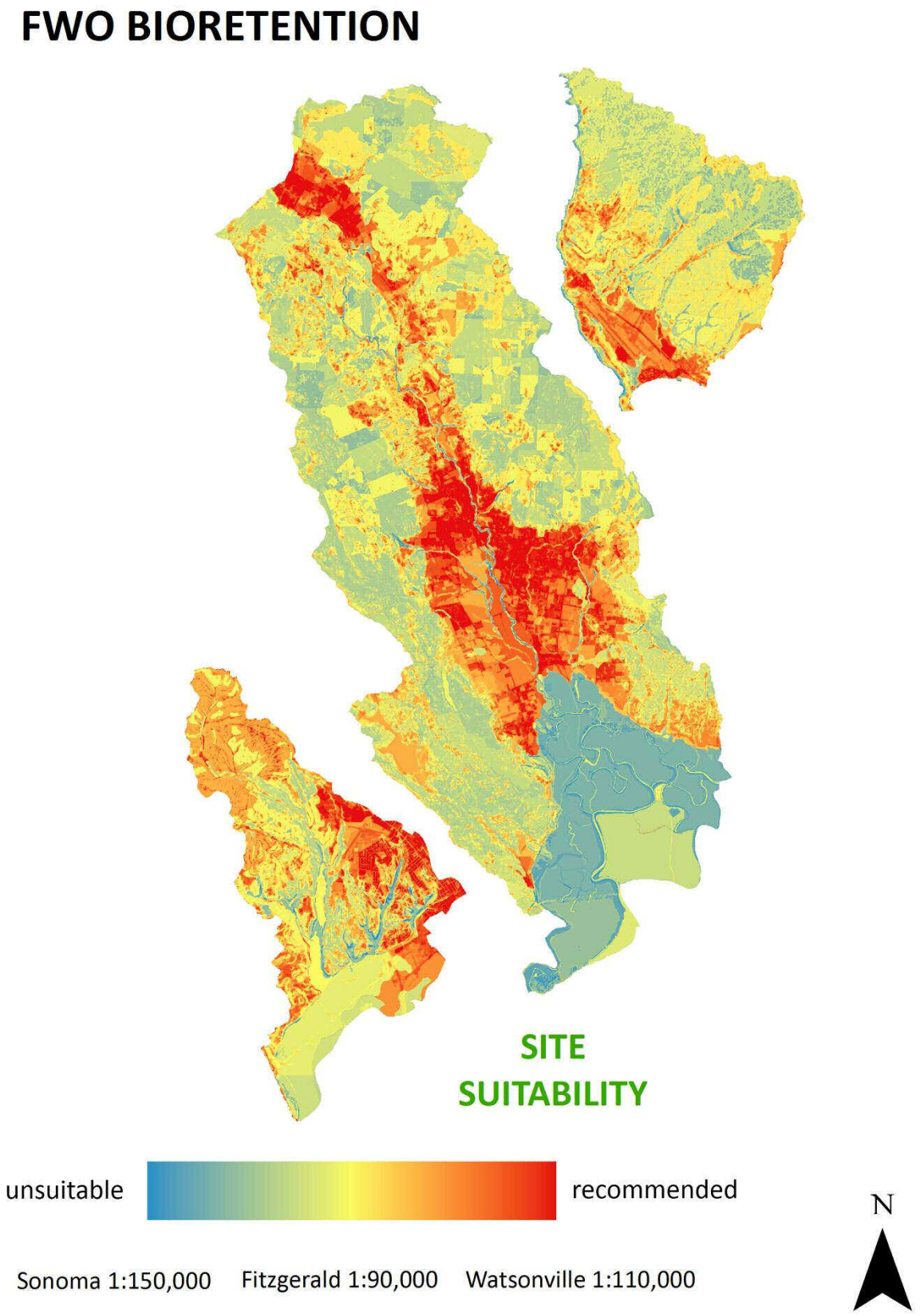


Figure 4. Fuzzy bioretention site suitability for CCA watersheds. Suitability represented on a continuous scale.

The range available for input values broadened greatly from 3 categories to all decimal values between 0 and 1. The categorical inputs with less than 10 values (soil hydrologic types, liquefaction risk, land use) needed to be converted to values within this range to ensure that "1" is the maximum value. As this process allowed for more input values, we took the opportunity to add values that better describe relationships with LID treatments. The continuous variables (slope, impervious surface, depth to water table) were fit to fuzzy membership curves which best matched the unique relationships from the CWO. Although depth to water table, the only polygonal "continuous" variable, was converted to a fuzzy product, it proved to vary little from the original. Figure 3 illustrates the differences between the raw variables and the fuzzy membership product, and Figure 4 shows the zoomed-in FWO product. A comparison between Figures 2, 3, and 4 makes clear the increase in data variation from the CWO to the FWO.

The fuzzy products (both continuous curve-fit and categorical reclassified) were then multiplied by a new set of weights ("FWO Weight" in Table 1) and summed. This was done instead of using the ArcGIS 10 native "fuzzy overlay" tool, which does not give the option of weighting, a critical aspect of our analysis. Instead, it gives a number of non-algebraic Boolean options for returning a single value chosen from one of the variables for each cell. None of these options suited this analysis, so we opted for a weighted summing procedure. The FWO is an improvement on the CWO because it scales continuous data inputs instead of binning them, and therefore allows for a more gradient-rich output that represents a full range of suitability values. Figure 5 shows the differences between CWO and FWO to an urban area in Santa Clara, and Figure 6 shows how the FWO alters the raw impervious surface data (both examples for bioretention). Also, this technique preserves the weights we wanted to ascribe our variables, although they were slightly modified to accommodate one new variable. Information on the variable parameters and shape of the fuzzy curves used for the FWO are found in Appendix 2.

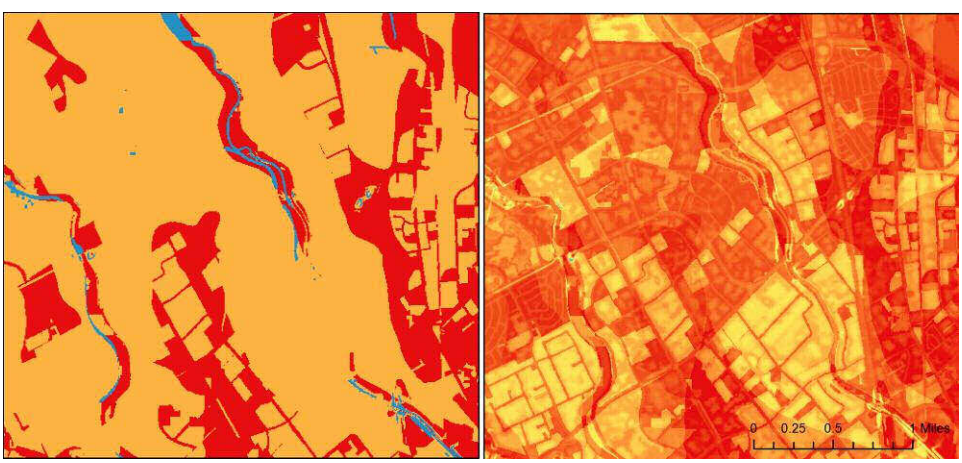


Figure 5. Example of differences in suitability resolution between CWO (left) and FWO (right) in the urban landscape (Santa Clara) for bioretention.

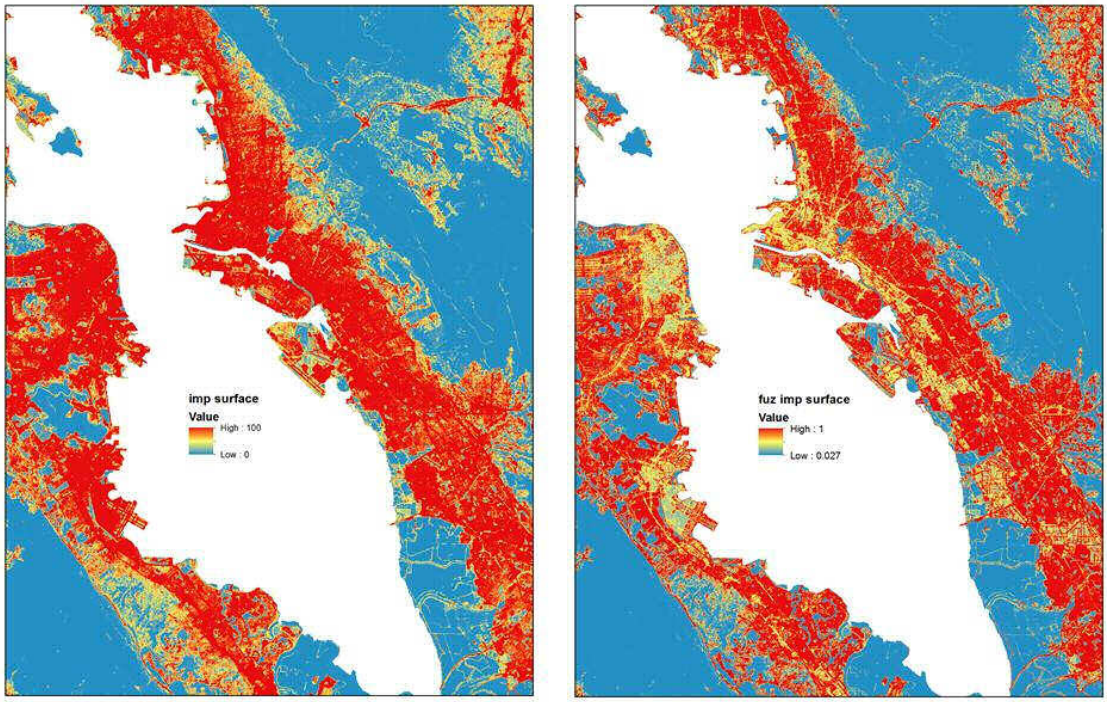


Figure 6. Impervious surface (left) and fuzzy impervious surface fit for bioretention (right). Note the favorable moderately impervious areas that show up in urban areas.

The proximity variables were added to further refine areas that were determined to weigh importantly into site suitability decisions, but because they served as proximities to suitable sites determined by the landscape variables, they received no weights and entered the analysis after the raster overlay was complete (Table 2). Both proximity distances differed among LID treatments.

Table 2. Proximity variables used in the FWO, the effects they have on the output, and sources.

Proximity Variable	Effect	Data Source
Cleanup Sites (CU)	Cells within proximity receive (-10) if completed, (-25) if open	ca.gov GeoTracker (1960-2007)
Wetlands	Polygons within proximity are overlayed via *Union* tool	BAARI (2009)

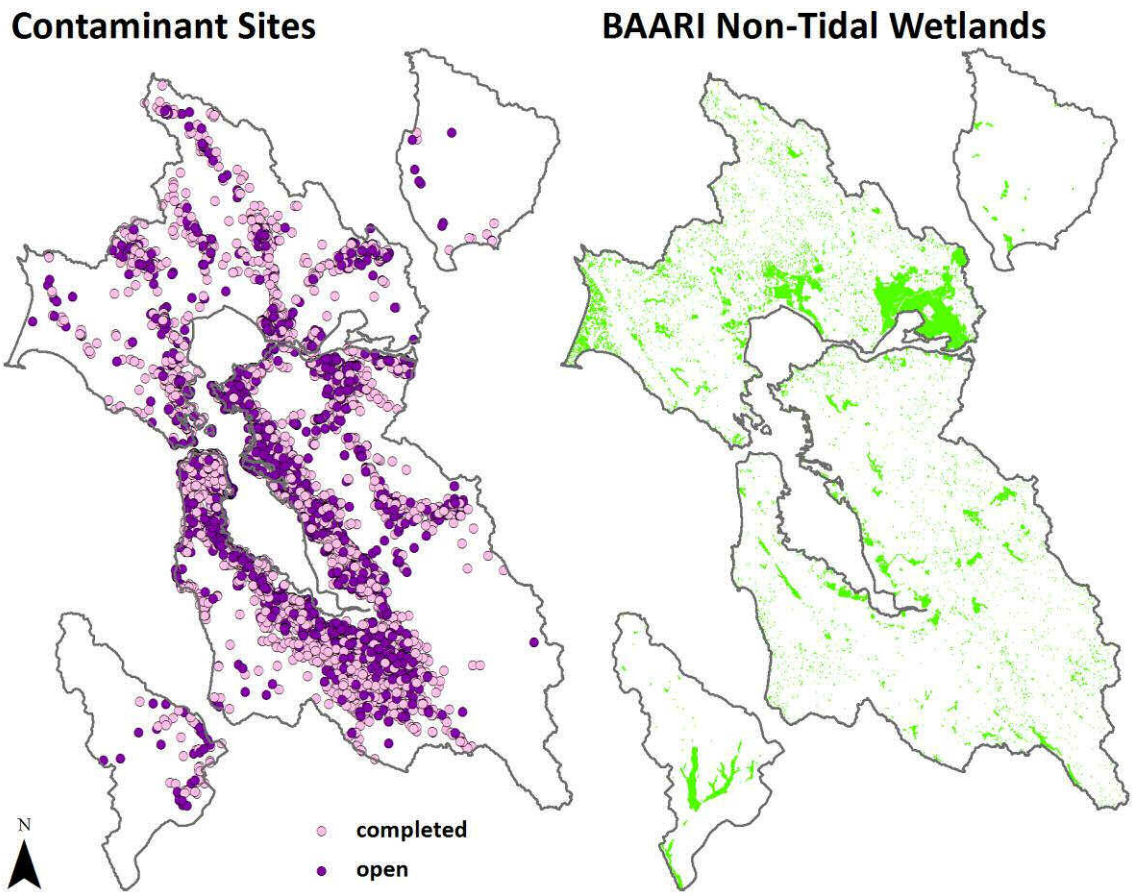


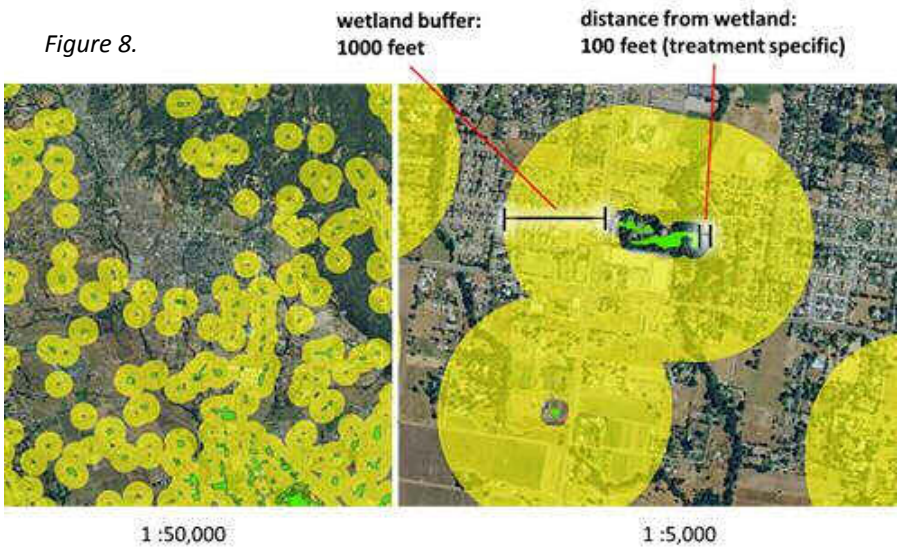
Figure 7.

Proximity to CUs was added as a score penalty to the overlay cells. The dataset consisted of sites in two main stages of development: "open" and "completed" (Fig. 7). After consulting with an expert, it was decided that "completed" status sites still posed a contaminant threat, though probably less so than an "open" status site. The penalty needed to be somewhat severe in order to ensure that no ideally suitable areas were within proximity of CUs. Therefore, "open" sites received a -25 penalty while "completed" sites received -10.

The enforcement of minimum areas, above which by expert opinion each LID treatment can be successfully implementated, presented a challenge in the FWO. As each polygon in the “recommended” category represents a discrete integer score value, unlike the CWO in which “recommended” polygons all had one value, excluding polygons smaller than the minimum area would remove small sites adjacent to larger sites with scores in a similar range. Therefore, all polygons were dissolved (all adjacent features merged) before enforcement of minimum areas, then intersected with the originals to reattribute polygons with their scores.

There is a growing consensus among practitioners that LID treatments can help mitigate the influx of nutrients and contaminants to near-by wetlands (J. Walker, pers. com.). Treatment types that can double as habitat (e.g. bior, swwt, vgsw, wtpd) could potentially create habitat linkages with existing wetlands and support local wildlife. However, as more studies need to be done to quantify these benefits, it was decided that this relationship is too complex to be explained by simple algebra, and that proximity to BAARI wetlands would not modify suitability scores as do CUs. Therefore, proximity to wetlands is incorporated by overlaying buffers taken at treatment-specific distances from wetlands on the "recommended" sites (Fig. 8). These functional separation distances from wetlands (see Appendix 2) were enforced because some treatment types may pose contamination risks to aquatic systems. All distance values were derived from expert opinion and reflect unique relationships with each LID treatment. This final step allows for the differentiation between suitable areas both inside and outside wetland buffers without affecting suitability value.

Figure 8.



Discussion of Results

All LID treatments experienced differences in total suitable area (representing the “recommended” top 25% scoring cells) between the two overlay methods (Fig. 9). To be expected, as the FWO features many more values than the CWO, vast regions that were previously “unsuitable” gained a range of intermediate values that help visualize the suitability landscape much better. This was especially evident in urban areas, where suitability scores varied enough between land use types that distinct features stood out, causing the urban landscape to come into full view (see Fig. 5).

Stormwater wetland (swwt) was the only treatment type to show a large increase in suitable area from CWO to FWO (230% larger). Although it shared some similarities with wet pond (wtpd), swwt was the only treatment to favor low depth to water table, and was slightly more restrictive in slope range. This was likely responsible for swwt having the lowest CWO total area.

Due to the range of values considered in the FWO, more than twice the number of suitable sites were found. Permeable pavement (prpv) and vegetated swale (vgsw) experienced dramatic decreases in suitable area from CWO to FWO (375% and 290% respectively). Permeable pavement had the most restrictive slope range and exclusions for two land uses in the CWO, which resulted in a total area lower than all treatments besides stormwater wetlands. The FWO further restricted the suitability range by preferring a narrow impervious surface range (approx. 80-90%). Vegetated swales had the broadest suitability ranges for slope, soil hydrologic group, and land use in the CWO, pushing its total higher than all other treatment types (~600,000 acres), although its FWO total was in range with the other treatments (~200,000 acres). This may have been due to the tightness of fit of the fuzzy curves, as areas that previously translated to a maximum score in the CWO may have been reduced to mid-range scores in the FWO. Further, as with prpv, a restrictive impervious surface range was preferred (approx. 20-50%).

The application of the CUs penalty moderately decreased the suitable area for bior (5%), swwt (2%), vgsw (6%), and wtpd (12%), yet prpv experienced a greater loss of 23%. This was likely due to the propensity of CUs to fall on ABAG transportation features (~90%), which are preferred by the parameters set for prpv. Overall, the CU penalty systematically reduced total suitable area by a sizeable percent, preventing sites from entering the top score quartile that were close to areas with possible contamination.

The proportion of FWO with CU penalty that fell within wetland buffers varied from 15% (bior) to 33% (swwt). These results show that a considerable share of favorable sites could provide extra benefits by bolstering hydrologic and/or habitat connectivity. Further, all these sites are an advisable distance from these wetlands to prevent direct contamination during heavy storm events. Maps of FWO results can be found in Appendix 4.

The hydrologic modeling component produced a first look at quantifiable stormwater benefits of widespread LID implementation in a CCA watershed. The modeling focused on conceptual peak flow reductions in the Dowdall Creek subwatershed of Sonoma, which was chosen for its combination of relatively small size, moderate imperviousness, and variety among soil hydrologic groups, land use, and slopes. Analysis of smaller subwatersheds was preferred for this study to limit the number of drainage-sheds modeled. Further, Dowdall Creek has the highest imperviousness of all subwatersheds in its size class, and total impervious area is a good indicator of a strong LID response. Lastly, the diversity of land types makes Dowdall Creek a good representative of an average low-density urban area. Area totals and landscape variable statistics outputs from the LID Site Suitability Tool were used as inputs. Although Dowdall Creek has a low urban density and is highly agricultural, a peak flow reduction of 29% was estimated for a 10-year design storm event. This estimate jumped to 52% peak flow reduction if all semi-urban drainage-sheds were assumed to have 60% impervious cover, which approaches higher

urban density levels. Detailed methodology, tables, figures, and more results can be found in Appendix 5.

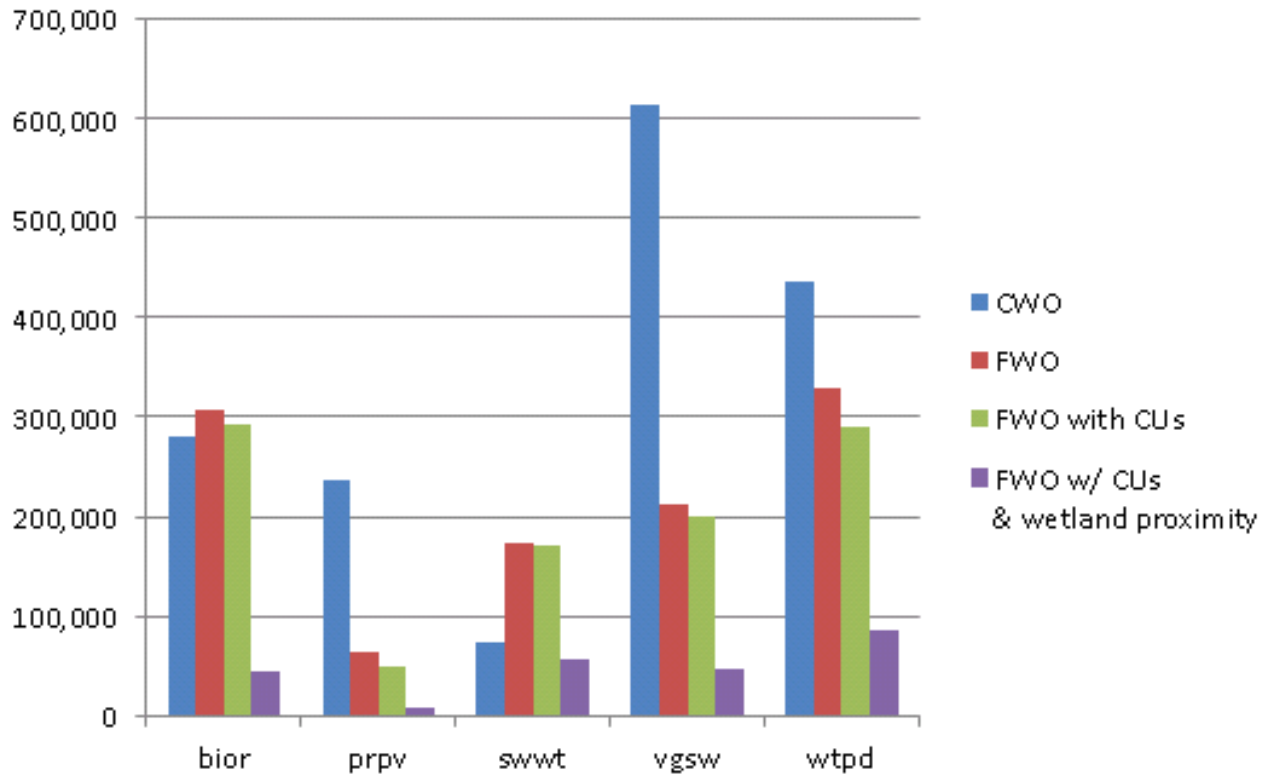


Figure 9. Total "recommended" area for LID treatment types between CWO and all steps of FWO.

Limitations and Recommendations for Future Work

1) The input data used in this study are publicly available, covered our geographic extent, and are consistent with data used in similar studies. However, in some cases these data could be refined to reflect on-the-ground changes or increased detail (e.g. errors in ABAG land use, or refinement of the coarse SSURGO soils dataset). Even with this known limitation, we believe the datasets in this analysis acted well as predictor variables for suitable sites. The ArcGIS model was built with the intent to encourage customization of variable inputs, and to allow users to utilize any available local data.

2) Building upon 1), the tool output can be directly edited to conform large blocks of suitable area to the shapes of features on the ground for a more precise result. This study did not attempt to represent actual features, as this was outside the current scope. The current tool output features a suitable area that only discriminates between input landscape variables, and does not show the outlines of structures unless they are fully represented in the land

use dataset. However, should the output be edited as a next step, suitable area could be represented by parcel blocks, building footprints, parking lots, etc.

3) Although cells with values of 0 did not contribute any benefit in the overlay operation (e.g. while land use = residential for bioretention would receive 0.8 cell value * 10 weight for the land use score, areas with missing land use data would receive 0 score value), they received all benefits from the other input variables and were considered in the final output. Therefore, all cells within the extent receive a score, although cells with values of 0 for a contributing variable are handicapped.

4) The curves for the *Fuzzy Membership* tool were chosen based on expert opinion, and were restricted to the selection offered by ArcGIS 10. The relationships used sufficiently represented the data for the current analysis, but better representation may be achieved if custom curves were developed that best fit averages from the literature.

5) The numerical penalty used for areas intersecting with CU buffers was based on expert opinion, and is meant to inflict a sizeable reduction on site suitability score, as areas in proximity to CUs are likely to be detrimentally affected by contaminants. The wetlands buffer, on the other hand, was incorporated via a geometrical union, as the intent is simply to identify priority sites close to but within a defined distance of wetlands. In future work, it may be more ideal to generate formulas for each that impact the suitability score based on findings from relevant studies.

Conclusions

The LID Site Suitability Tool expands on existing work in this area in both tool complexity and geographic scope. The results show that there are numerous areas potentially suitable for LID implementation throughout the SF Bay. Although urban areas have traditionally received most of the attention in the LID arena, as the scale of this tool is so broad, areas outside the urban landscape are also thoroughly examined for suitability. Along the same lines, areas higher in the watershed that are often overlooked are included in the analysis as well. We hope this tool will prove useful to stormwater managers, watershed planners, and urban developers alike who want to begin planning for LID implementation on the landscape scale. The outputs of this tool can be used as the foundation for a multi-phase process (outlined in the Conceptual Model attached). The next step in the site suitability phase would include carving out feature footprints (as mentioned in the previous section) that represent actual buildable areas. As opposed to a more opportunistic approach to implementation, the LID Site Suitability Tool enables smart site selection that has an overall cost savings and increased benefit.

References

1) BAARI: A Bay Area Aquatic Resources Inventory, 2011. http://www.sfei.org/BAARI

2) California Stormwater Quality Association. 2003. "California Stormwater BMP Handbook."

3) Eslami et al. 2011. "GIS-based model to evaluate low impact development suitability location." Geospatial World Magazine, March.

4) Goals Project, 1999. Baylands Ecosystem Habitat Goals. "*A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project*." First Reprint. U.S. Environmental Protection Agency, San Francisco, Calif./S.F. Bay Regional Water Quality Control Board, Oakland, Calif.

5) Holman-Dodds J. et al. 2003. "Evaluation of Hydrologic Benefits of Infiltration Based Urban Storm Water Management." Journal of the American Water Resources Association. Pp. 205-215.

6) Kennedy, L. et al. 2008. "*Low Impact Development: San Francisco's green approach to stormwater management promises to reduce energy use, increase natural habitat, and enhance the quality of urban life.*" Water Environment & Technology. pp. 35-43.

7) Lightfoot KG, Parrish O. 2009. California Indians and their environment: an introduction. Berkeley, CA: University of California Press.

8) Myers et al. 2000. "Biodiversity hotspots for conservation priorities." Nature 403:24 pp. 853-858.

9) Millennium Ecosystem Assessment, 2005. "*Ecosystems and Human Well-Being: Wetlands and Water Synthesis*." World Resources Institute, Washington, DC.

12) Prince George's County, Maryland Dept. of Environmental Resources. "Low-Impact Development Design Strategies – An Integrated Design Approach." June 1999.

13) SFPUC. 2009. "Task 800: Technical Memorandum No. 809 Low Impact Design Modeling." City and County of San Francisco 2030 Sewer System Master Plan.

14) Stoms, David M., 2010. "*Change in Urban Land Use and Associated Attributes in the Upper San Francisco Estuary, 1990-2006*." San Francisco Estuary and Watershed Science, 8(3).

15) Sutula et al, 2008. "*California's Wetland Demonstration Program Pilot*." Southern California Coastal Water Research Project.

16) Wang et al. 2010. "Low Impact Development Design—Integrating Suitability Analysis and Site Planning for Reduction of Post-Development Stormwater Quantity." Sustainability, 2, pp. 2467-2482.

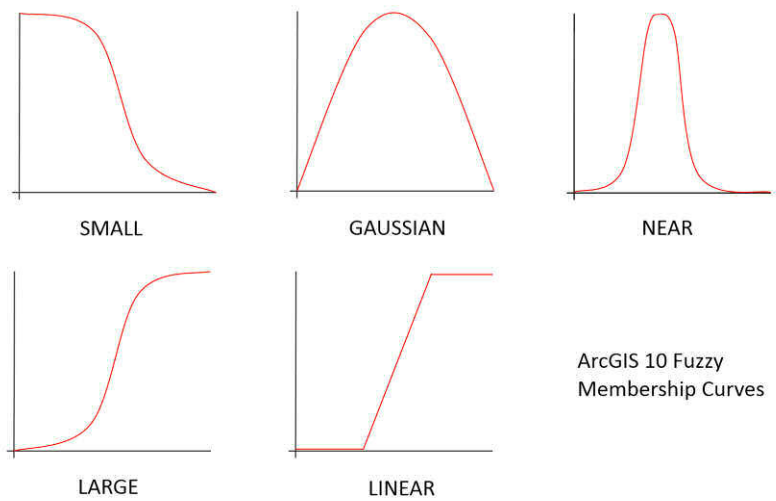
Appendix 1 — Values/weights table for Categorical Weighted Overlay

			OVERLAY VALUES (1-low -> 3-high)				
			BIOR	SWWT	WTPD	VGSW	PRPV
27	depth to water table	0-2 ft	x	3	x	x	x
		2-3 ft	x	2	1	x	x
		3-5 ft	1	2	1	1	2
		> 5 ft	3	1	3	3	3
27	slope	0-2 %	3	3	3	3	3
		2-3 %	3	2	3	3	2
		3-5 %	2	2	2	3	1
		5-7 %	2	1	2	2	x
		7-8 %	1	1	1	2	x
		8-10 %	1	x	1	2	x
		10-12 %	1	x	x	1	x
		12-15 %	x	x	x	1	x
		> 15 %	x	x	x	x	x
20	soil hydrologic type	A	3	1	1	3	3
		B	3	1	1	3	3
		C	2	2	2	3	2
		D	1	3	3	3	2
16	land use	residential	3	2	3	3	2
		commercial	3	2	2	2	3
		open space	2	3	3	3	x
		agriculture	1	3	2	3	x
		transportation	3	2	2	3	3
		industry	1	1	1	1	1
10	risk of lique-faction	very low	3	3	3	3	3
		low	3	3	3	3	3
		medium	3	3	3	3	3
		high/very high	1	1	1	1	1

Appendix 2 — A)Fuzzy curves, B) Values/weights table for Fuzzy Weighted Overlay

*note: parameters chosen to shape curves were based upon the relationships in Appendix 1

2A.

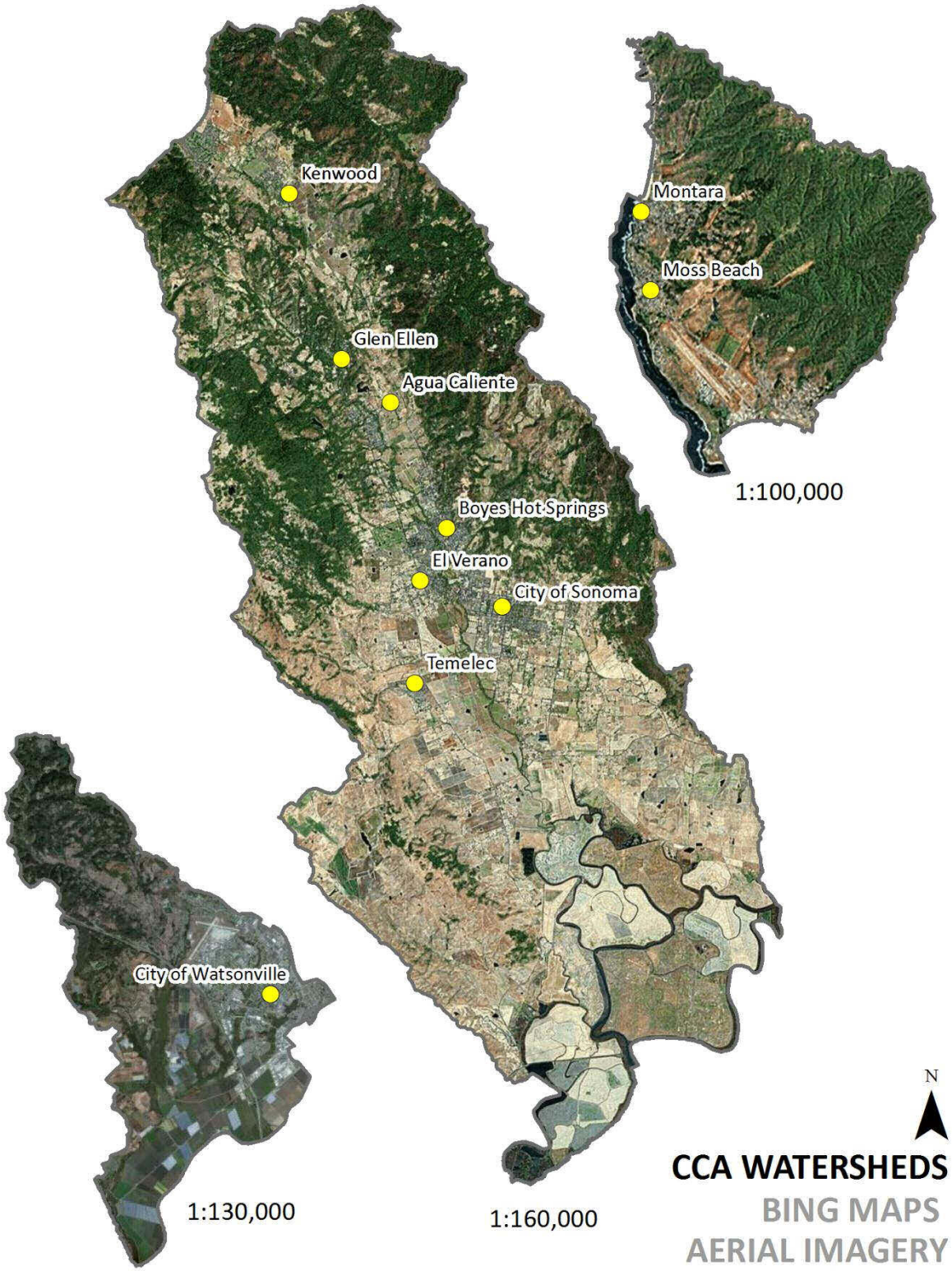


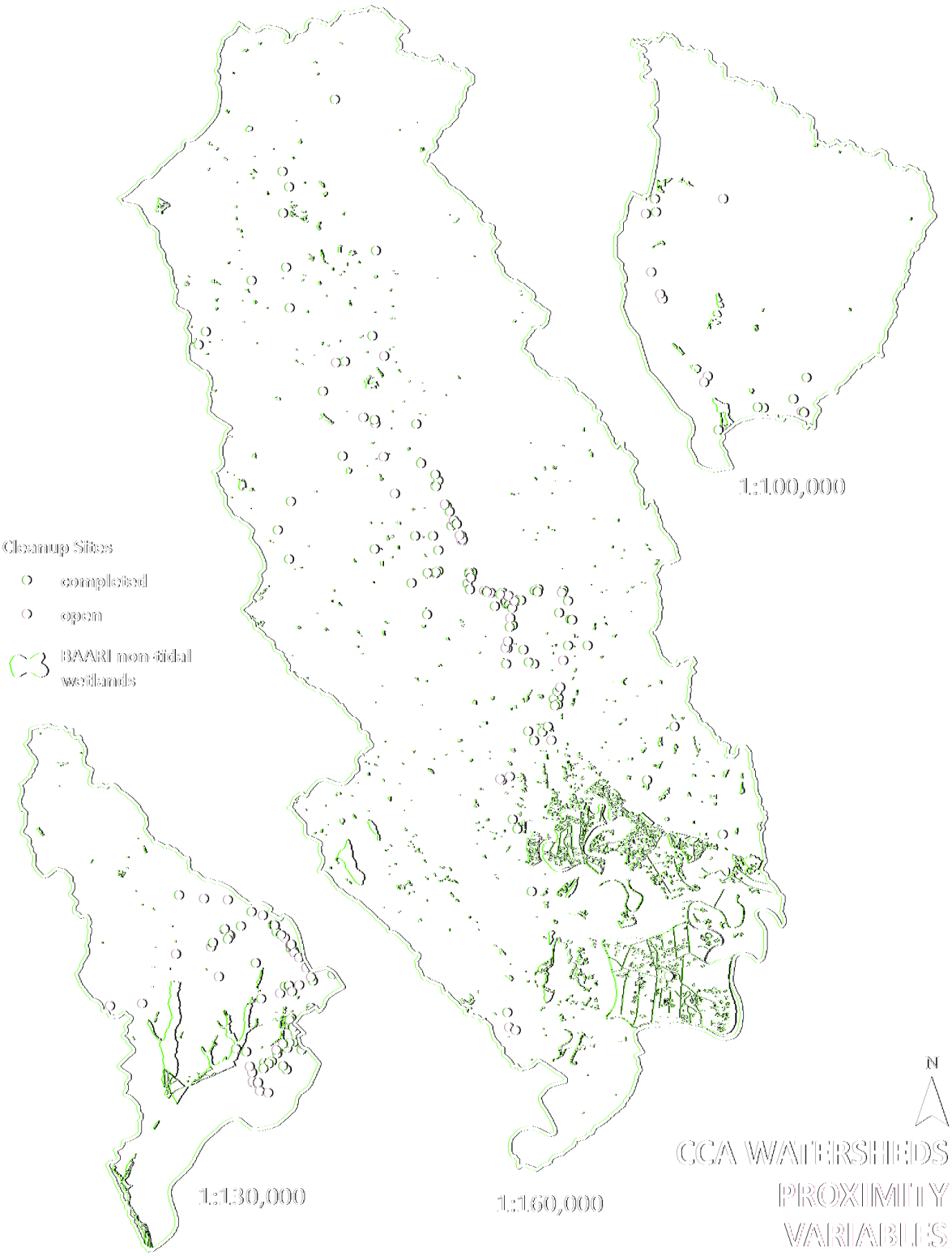
2B.

weight	variable	value	BIOR	SWWT	WTPD	VGSW	PRPV
25	depth to water table	0 - >5ft	LARGE	SMALL	LARGE	LARGE	LARGE
25	slope	0 - >15%	SMALL	SMALL	SMALL	SMALL	SMALL
10	impervious surface	0 - 100 %	GAUSSIAN	LINEAR	LINEAR	GAUSSIAN	NEAR
15	soil hydrologic type	A	1	0.25	0.25	1	1
		B	1	0.25	0.25	1	1
		C	0.5	0.5	0.5	1	0.5
		D	0.25	1	1	1	0.5
15	land use	residential	1	0.75	0.75	0.75	0.25
		commercial	1	0.1	0.25	0.25	1
		open space	0.5	1	1	0.8	0.1
		agriculture	0.25	0.75	0.25	0.5	0
		transportation	0.8	0.25	0.8	1	0.8
		industry	0.1	0.1	0.1	0.1	0.1
10	risk of liquefaction	very low	1	1	1	1	1
		low	1	1	1	1	1
		medium	0.8	0.8	0.8	0.8	0.8
		high/very high	0.1	0.1	0.1	0.1	0.1
score penalty	proximity to cleanup sites	buffer	250 ft	500 ft	500 ft	250 ft	500 ft
buffer union	proximity to BAARI wetlands	buffer	100 ft	0 ft	100 ft	50 ft	1000 ft

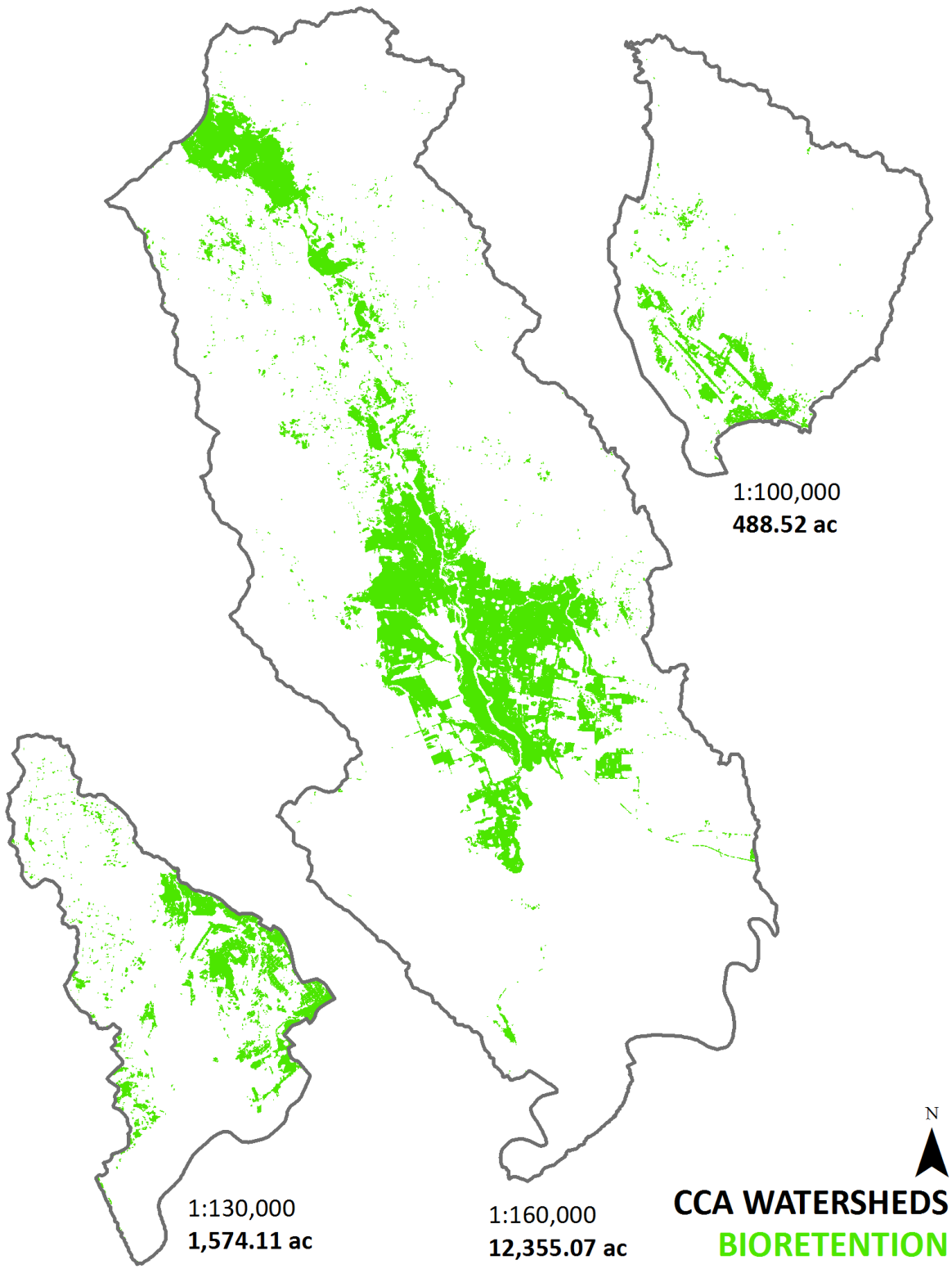
*curves based on the following suitable impervious ranges based on expert opinion: bior 20-90, swwt 0-30, wtpd 0-50, vgsw 20-50, prpv 80-90

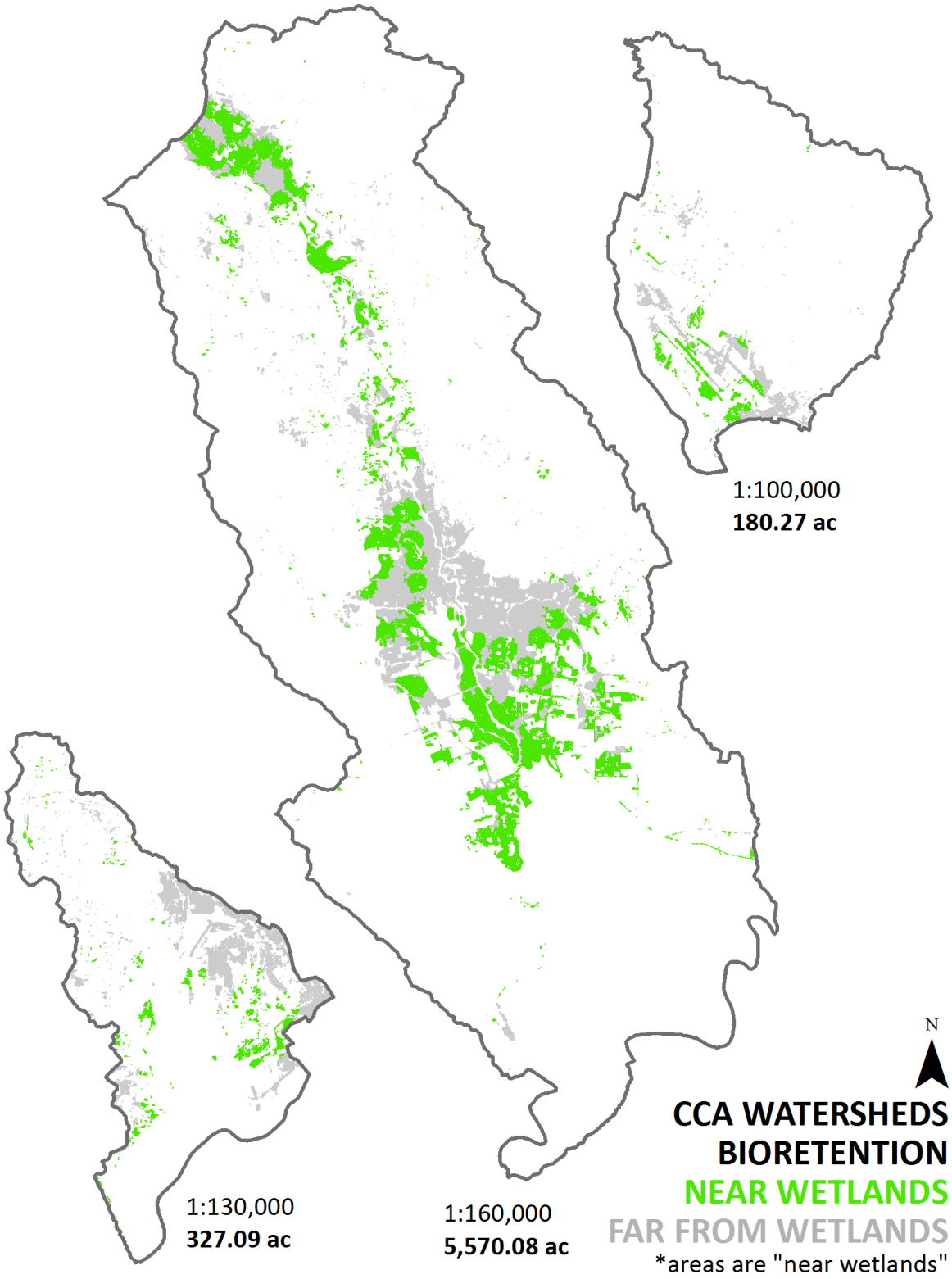
Appendix 3 — CCA watersheds with aerial imagery and proximity variable locations

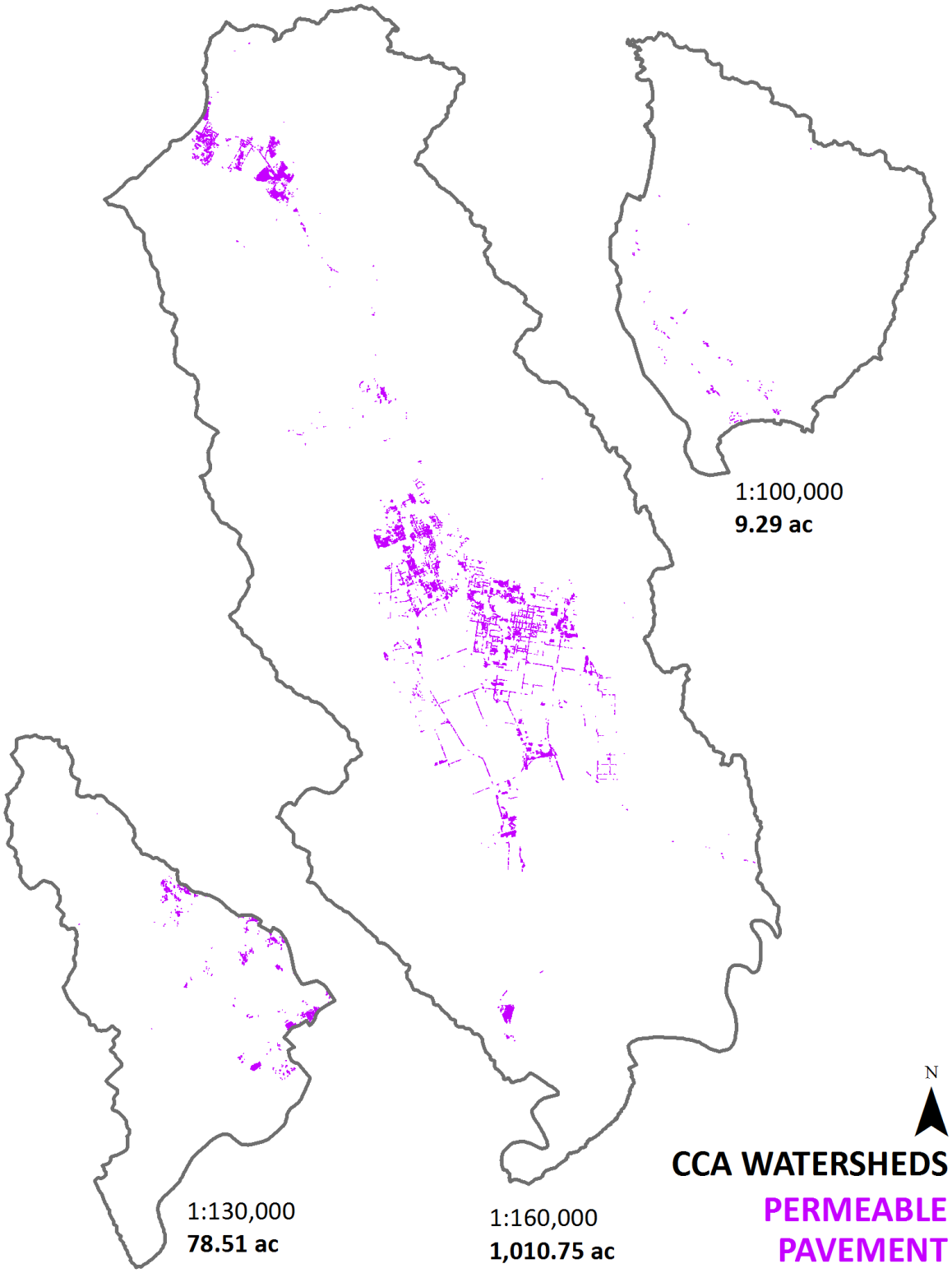


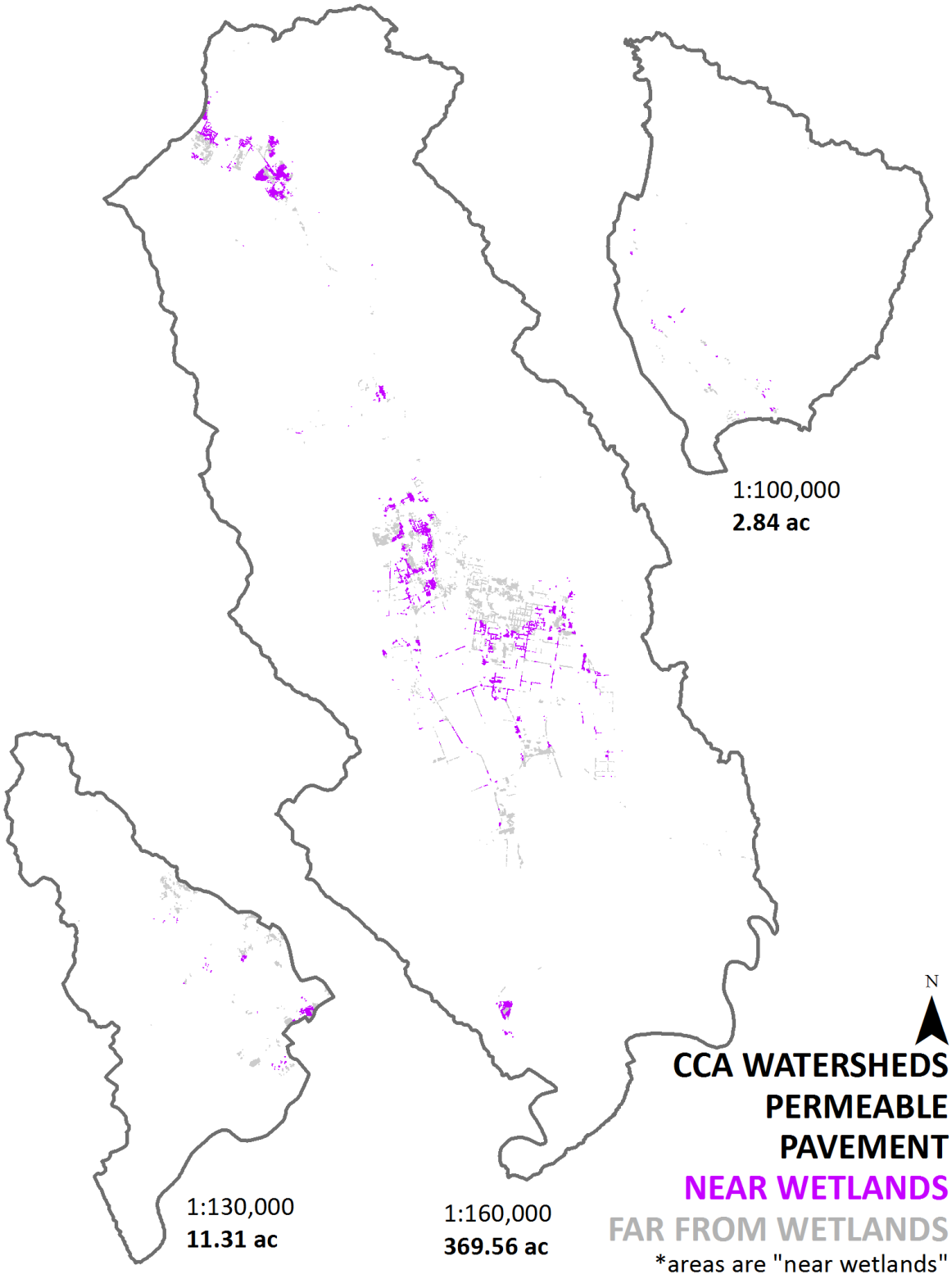

Cleanup Sites
completed
open
BAARI non-tidal wetlands
1:100,000
1:130,000
1:160,000
N
CCA WATERSHEDS
PROXIMITY
VARIABLES

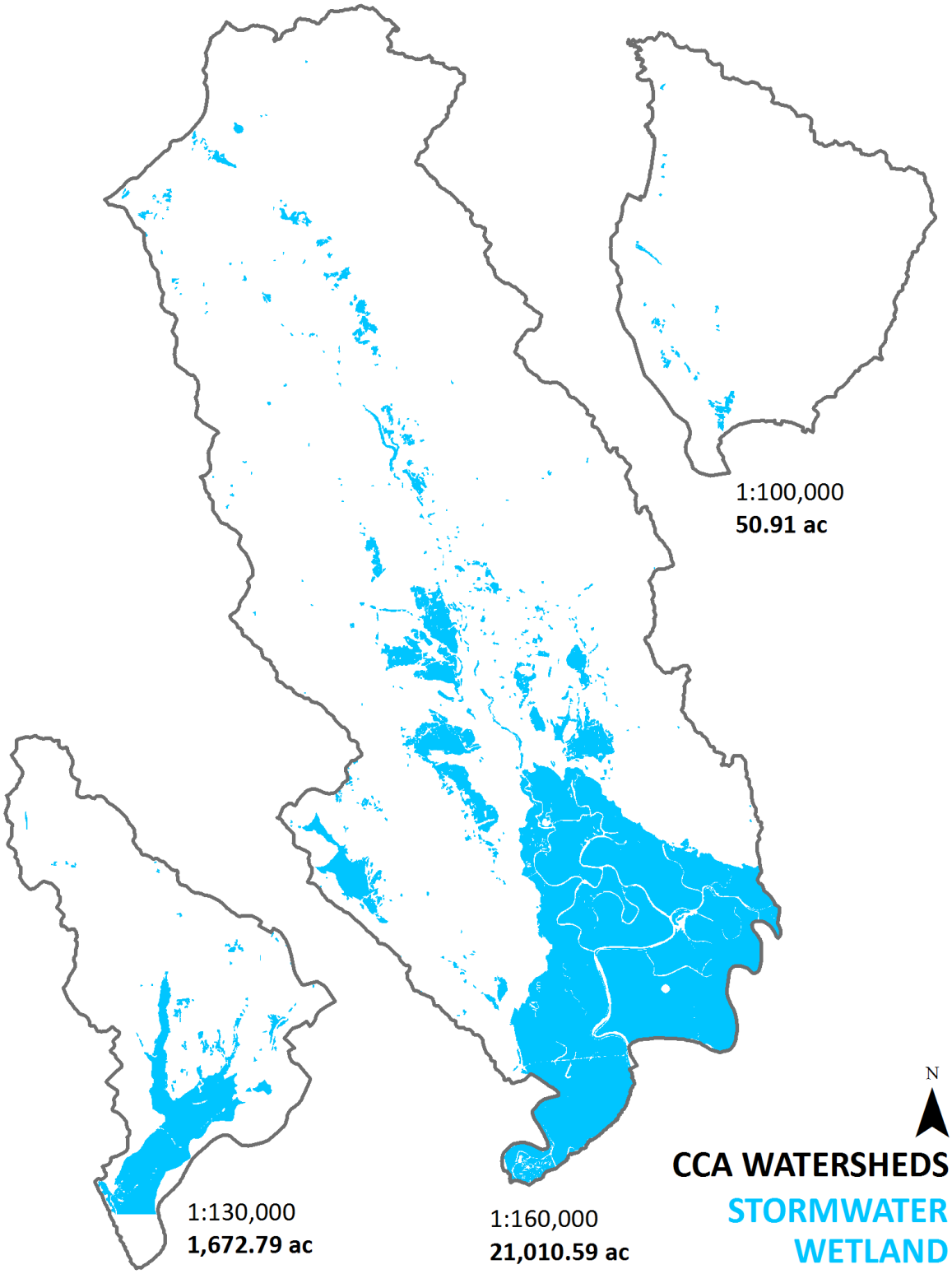
Appendix 4 — CCA watersheds with FWO LID site suitability (cleanup penalty included) and wetland proximity

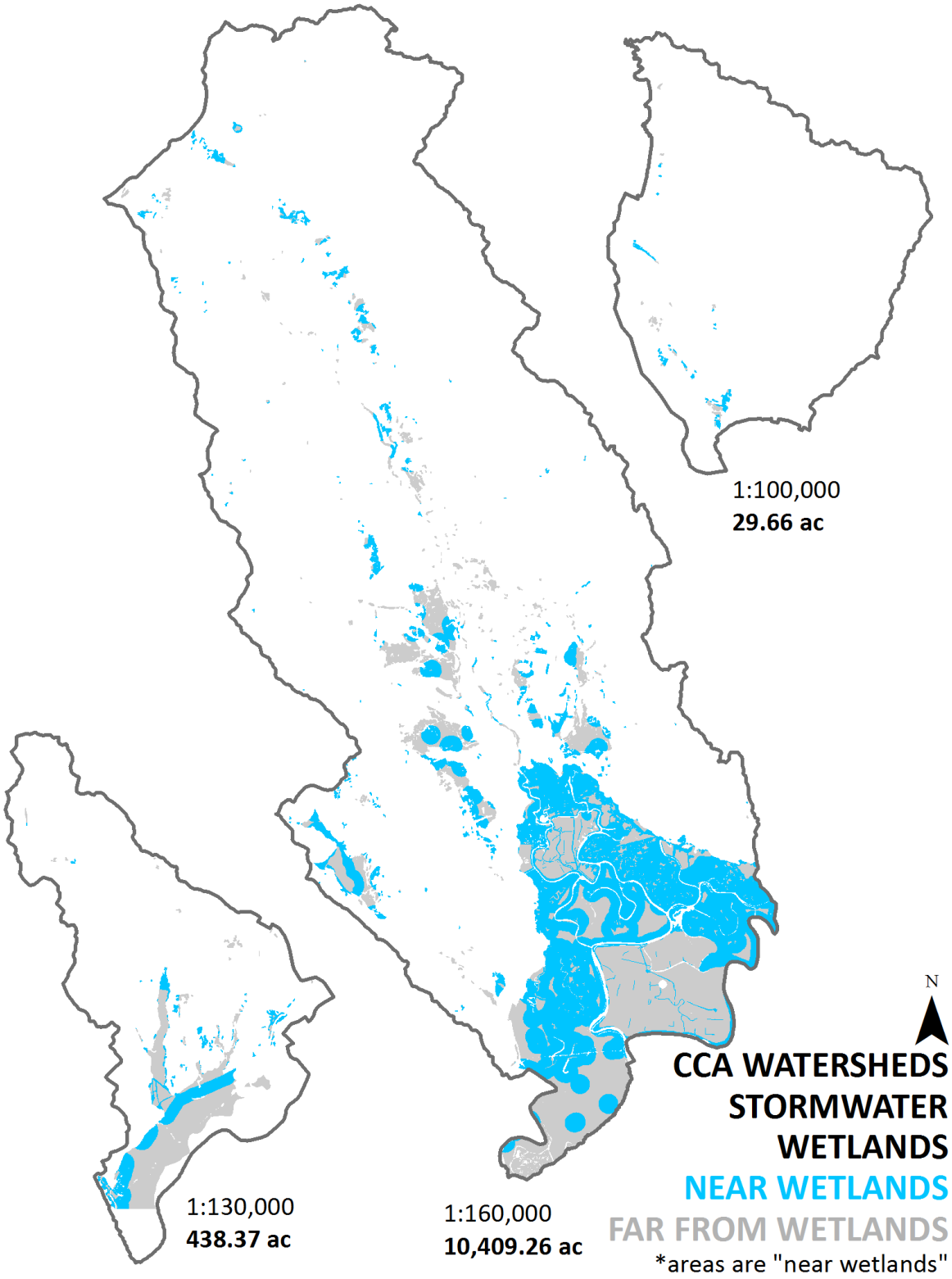


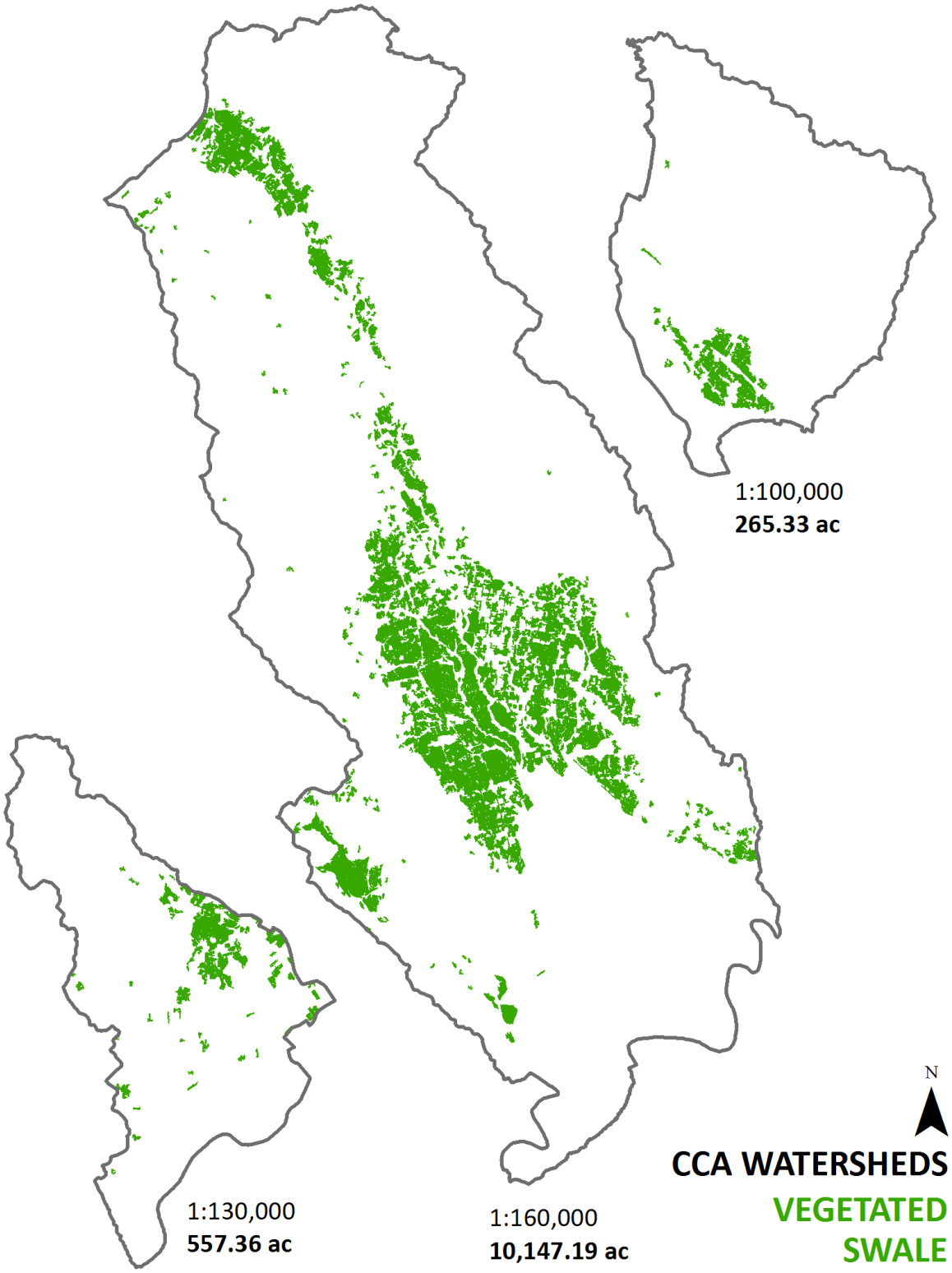

1:100,000
180.27 ac
1:130,000
327.09 ac
1:160,000
5,570.08 ac
N
CCA WATERSHEDS
BIORETENTION
NEAR WETLANDS
FAR FROM WETLANDS
*areas are "near wetlands"

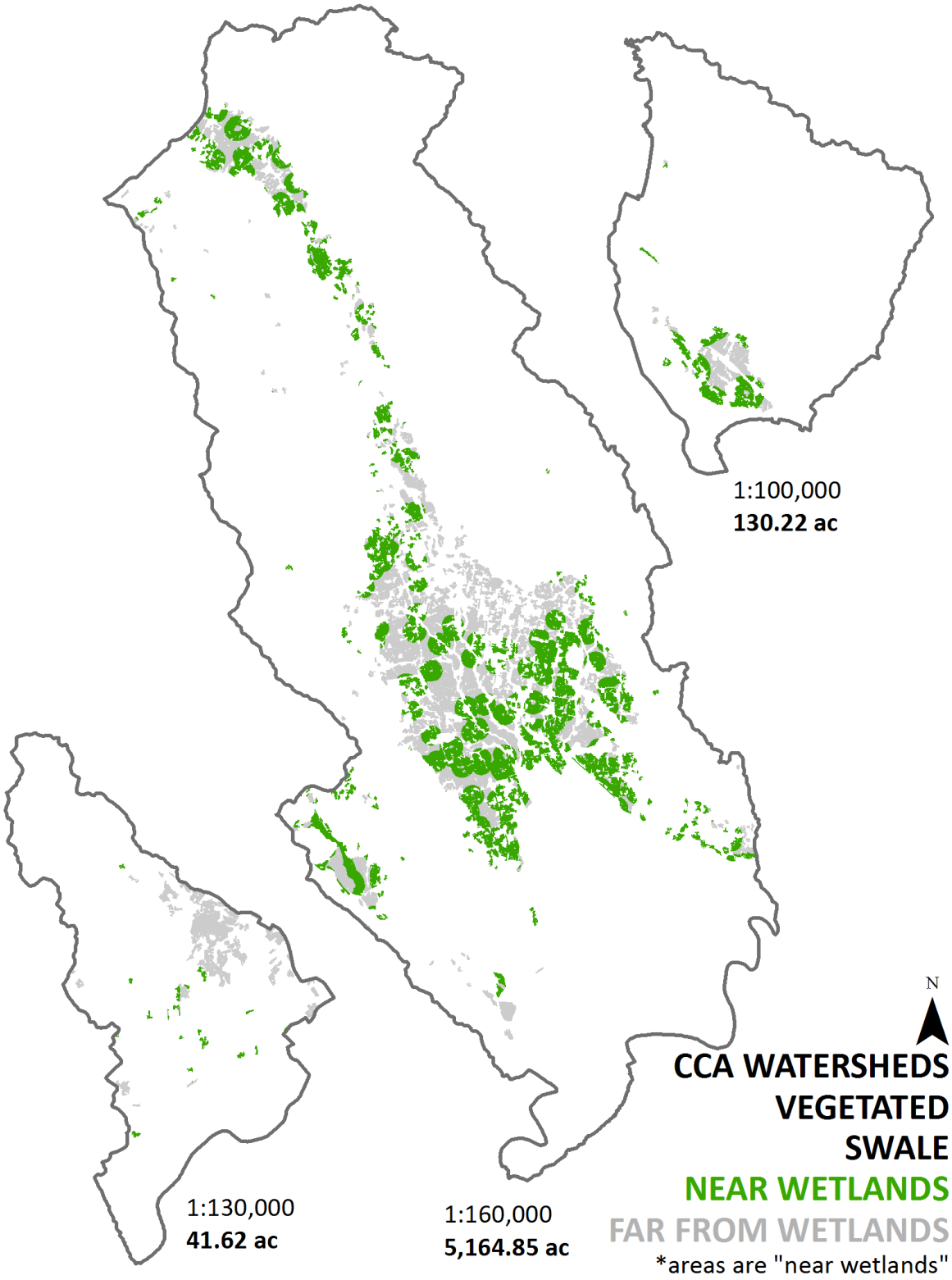

1:100,000
9.29 ac
1:130,000
78.51 ac
1:160,000
1,010.75 ac
N
CCA WATERSHEDS
PERMEABLE
PAVEMENT

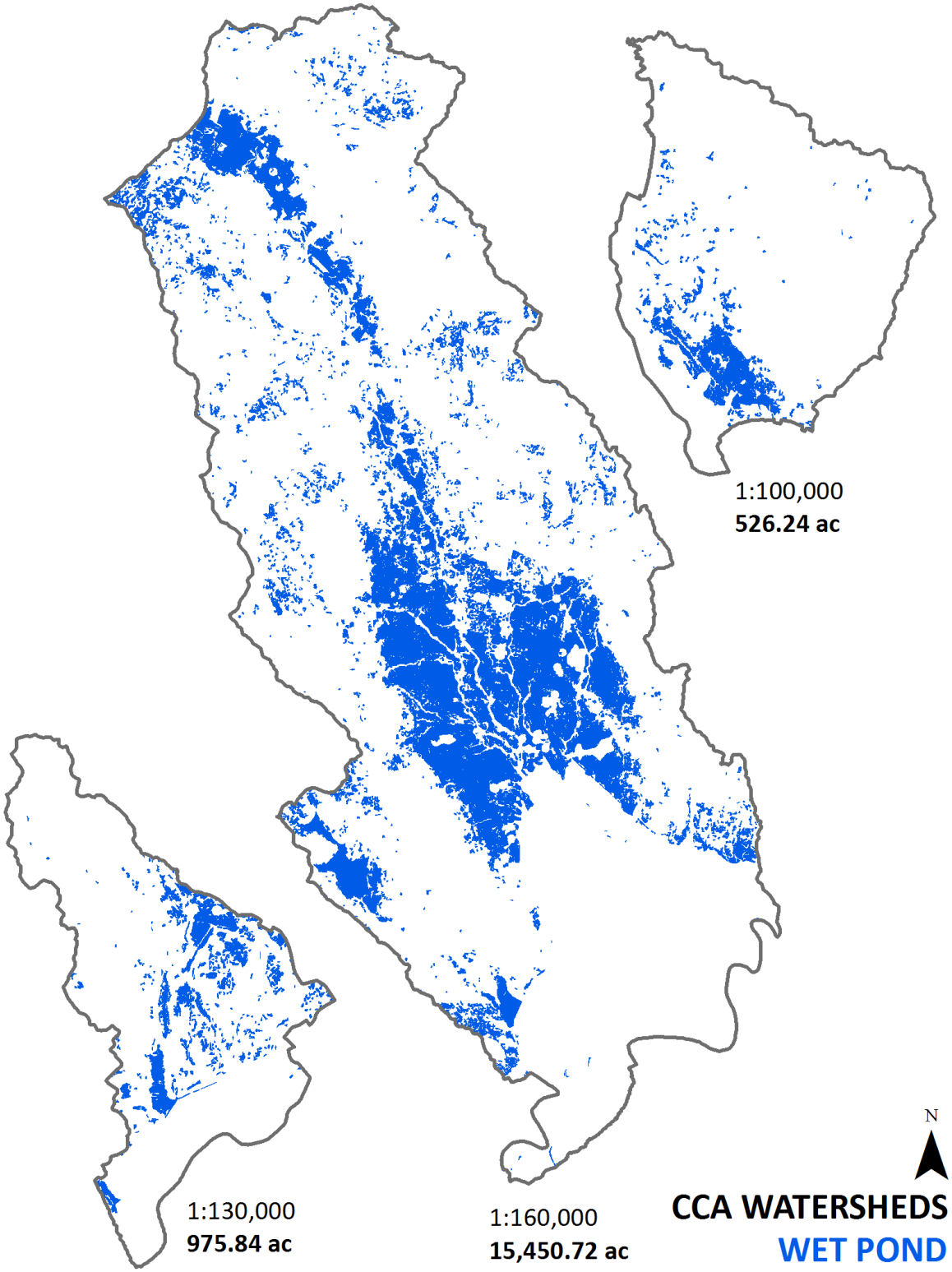

1:100,000
2.84 ac
1:130,000
11.31 ac
1:160,000
369.56 ac
N
CCA WATERSHEDS
PERMEABLE
PAVEMENT
NEAR WETLANDS
FAR FROM WETLANDS
*areas are "near wetlands"

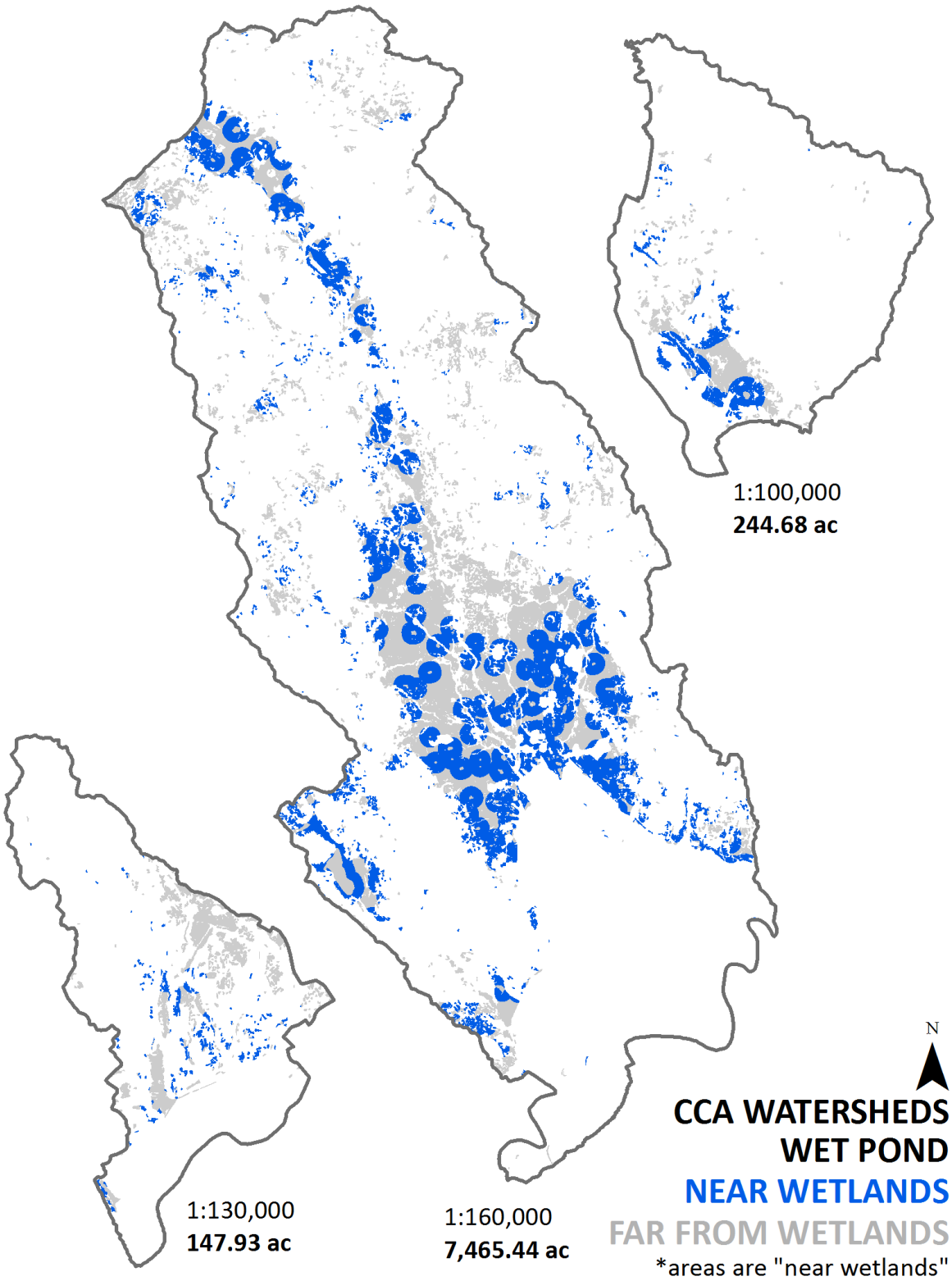

1:100,000
50.91 ac
1:130,000
1,672.79 ac
1:160,000
21,010.59 ac
N
CCA WATERSHEDS
STORMWATER
WETLAND


1:100,000
29.66 ac
1:130,000
438.37 ac
1:160,000
10,409.26 ac
N
CCA WATERSHEDS
STORMWATER
WETLANDS
NEAR WETLANDS
FAR FROM WETLANDS
*areas are "near wetlands"


1:100,000
265.33 ac
1:130,000
557.36 ac
1:160,000
10,147.19 ac
N
CCA WATERSHEDS
VEGETATED
SWALE


1:100,000
130.22 ac
1:130,000
41.62 ac
1:160,000
5,164.85 ac
N
CCA WATERSHEDS
VEGETATED
SWALE
NEAR WETLANDS
FAR FROM WETLANDS
*areas are "near wetlands"


1:100,000
526.24 ac
1:130,000
975.84 ac
1:160,000
15,450.72 ac
N
CCA WATERSHEDS
WET POND


1:100,000
244.68 ac
1:130,000
147.93 ac
1:160,000
7,465.44 ac
N
CCA WATERSHEDS
WET POND
NEAR WETLANDS
FAR FROM WETLANDS
*areas are "near wetlands"

Appendix 5 — Hydrologic Model Results for Dowdall Creek, Sonoma Watershed

The Sonoma Creek watershed was selected for conceptual hydrologic modeling to estimate reductions in peak flows associated with wide-scale implementation of Low Impact Development (LID) facilities. This watershed is one of the three targeted CCA watersheds, and an existing hydrologic (HEC-HMS) model is available and documented in a study entitled *Sonoma Creek and Tributaries Basin Hydrologic Investigation*, which was prepared by Philip Wiliams & Associates (PWA) for the U.S. Army Corps of Engineers San Francisco District in January, 2004. Within the Sonoma Creek watershed, Dowdall Creek was selected because of its relatively small size and distribution of various slopes, land uses, and soils, and then further subdivided into appropriately sized subcatchments for modeling purposes (1986 acres [ac], or 3.11 square miles [sq. mi.]). The modeling described in this section was performed by Watearth, Inc. with support from SFEI in developing hydrologic and hydraulic parameters from the GIS database.

Although five types of LID facilities are evaluated in the LID Site Suitability Tool, only bioretention, permeable pavement, and vegetated swales are included in this conceptual analysis as distributed and decentralized treatment options. Stormwater wetlands and wet ponds are typically centralized facilities and are not included in this evaluation.

The U.S. Environmental Protection Agency's (EPA) publicly-available Storm Water Management Model (SWMM) 5.0.022 was utilized for the LID modeling in this project. The current version of SWMM includes LID controls and detailed analysis options not previously included in SWMM5. The SWMM model accounts for infiltration/percolation through various vertical LID layers (i.e., growing media in Bioretention and drain rock (gravel storage reservoir) in Bioretention and Porous Pavement), evapotranspiration, infiltration into the native soil, and overflows and discharge from the LID facilities (see figure below).

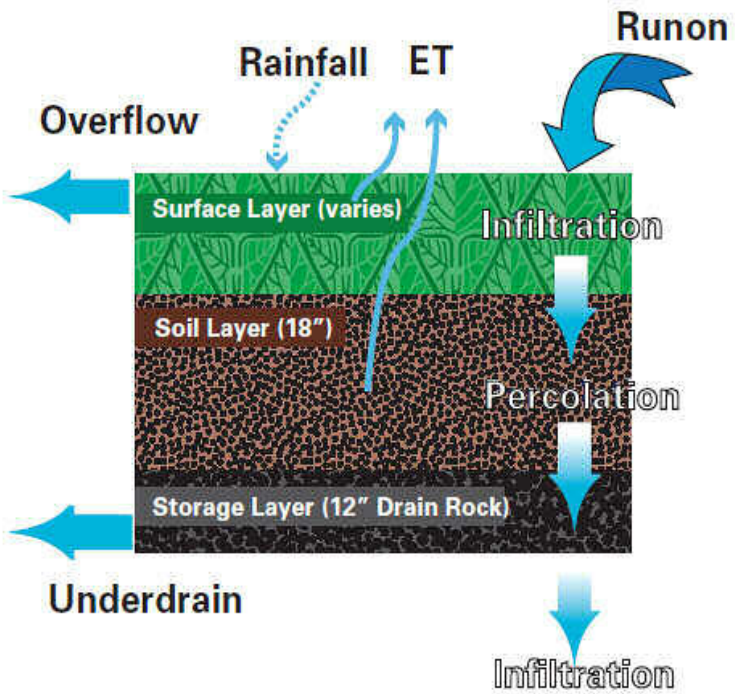


Figure 1. Conceptual schematic of LID infiltration/percolation in SWMM.

Graphic Courtesy of Watearth, Inc. Copyright 2010.

Recent studies by the EPA found similar results when aggregated (lumped) LID controls in drainage sub-areas of 100 ac or more are compared to micro-drainage sub-areas for each lot and LID control (distributed approach; 1). For a 128-acre drainage sub-area, the difference in peak flows between the aggregated and distributed approaches computed in the EPA study is 4%. Similar findings with regard to the aggregated approach were also reported by the City of Portland's Bureau of Environmental Services (3). Since this is a conceptual analysis, the aggregated approach was appropriate for this project, and allowed for efficient model development.

Table 1 lists hydrologic parameters associated with ten subdivided drainage-sheds within Dowdall Creek. The drainage-shed boundaries and hydrologic parameters were estimated based on landscape variables used by the LID Site Suitability Tool. With the exceptions of dc-5 and dc-6, which are currently undeveloped and located in the upstream portion of Dowdall Creek, all of the drainage-sheds were subdivided to be less than 170 ac to facilitate the aggregated BMP approach used for the conceptual LID modeling.

Table 1. Dowdall Creek Hydrologic Parameters

Drainage Shed	Hydrologic Parameters								
	Area (ac)	Imp. Cover (%)	Overland Flow Length (ft)	Width (A/L) (ft)	Slope (%)	Depression Storage (in)		Manning's n-value	
						Impervious	Pervious	Impervious	Pervious
dc-6	415.54	0.66%	500	36,202	9.7	0.06	0.25	0.011	0.29
dc-5	585.30	2.32%	500	50,991	2.4	0.06	0.25	0.011	0.21
dc-4	79.30	7.95%	500	6,909	3.3	0.06	0.25	0.011	0.12
dc-3b	101.96	26.85%	500	8,883	1.1	0.06	0.25	0.011	0.10
dc-3a	69.86	39.07%	500	6,086	0.9	0.06	0.25	0.011	0.10
dc-2b	169.54	10.41%	500	14,770	1.3	0.06	0.25	0.011	0.11
dc-2a	124.62	28.88%	500	10,857	1.3	0.06	0.25	0.011	0.11
dc-2ab	157.47	18.57%	500	13,719	0.3	0.06	0.25	0.011	0.11
dc-2	118.33	17.76%	500	10,309	1.4	0.06	0.25	0.011	0.17
dc-1	166.70	1.69%	500	14,523	0.3	0.06	0.25	0.011	0.15
TOTAL	1,988.62								

Notes:

1. Hydrologic parameters estimated by SFEI with guidance from Watearth.
2. All subareas assumed to route to outlet (i.e., no disconnected impervious cover under existing conditions).
3. Overland flow lengths default down to 500 ft, which is the maximum recommended value.
4. Interception capacity of tree canopy not included due to design storm analysis.
5. Evaporation data based on California Irrigation Management Information System (CIMIS), Region 5.

The Direct Determination Runoff method as described in the EPA SWMM User's Manual (2) is used to estimate runoff and generate hydrographs of each drainage-shed within the SWMM model. The Green & Ampt method, which is based on physically-measurable soil parameters, is used to estimate losses due to infiltration. This method is commonly used for LID modeling and typically produces more accurate results for uncalibrated models than the Curve Number (CN) Method used in the calibrated Sonoma Creek watershed HEC-HMS models. As shown in Table 2, the hydraulic conductivity, suction head, and initial deficit parameters are estimated from standard tables for various Natural Resources Conservation Service (NRCS) soil textures due to the conceptual nature of this evaluation.

Soil types or textures range from sandier Type A soils with relatively high infiltration rates, to Type D soils that are dominated by poorly infiltrating clay. Type A soils tend to have less than 10% clay and can infiltrate at greater than 5.0 in/hr. Type B soils consist of 10 to 20% clay and have associated infiltration rates between 0.3 and 5.0 in/hr. Type C soils are typically 20 to 40% clay and exhibit infiltration rates ranging from 0.1 to 3.0 in/hr. Type D soils are more than 40-percent clay with corresponding infiltration rates from 0.01 to 1.0 in/hr.

Table 2. Dowdall Creek Soils Classification

Drainage Shed	Area of Each Soil Type (ac)					Composite Green & Ampt Parameters		
	A	B	C	D	Total	Suction Head (in)	Conductivity (in/hr)	Initial Deficit
dc-6	0.00	0.00	4.38	411.15	415.53	11.391	0.020	0.229
dc-5	0.00	160.44	36.80	388.06	585.30	9.038	0.238	0.264
dc-4	0.00	19.78	50.98	8.35	79.11	7.627	0.242	0.273
dc-3a	0.00	27.78	30.26	11.82	69.86	7.021	0.349	0.287
dc-3b	0.00	96.92	4.56	0.46	101.94	3.638	0.768	0.347
dc-2b	0.00	152.73	0.00	6.51	159.24	3.694	0.773	0.347
dc-2a	0.00	89.55	0.00	45.36	134.91	6.073	0.541	0.311
dc-2ab	0.00	79.62	0.00	77.85	157.47	7.347	0.417	0.291
dc-2	0.00	75.23	0.00	43.10	118.33	6.299	0.519	0.307
dc-1	0.00	40.45	0.00	126.36	166.81	9.467	0.210	0.259

Notes:

1. Areas estimated by SFEI.
2. Initial moisture deficit for Western U.S. assumed from www.water-research.net
3. Conductivity and suction head values assumed for various soil types from EPA *SUSTAIN User's Manual*.

For this planning-level analysis, only steady flow hydraulic routing was performed, as detailed stream cross-section data is not readily available for Dowdall Creek and is beyond the scope of this project. With this approach, runoff hydrographs are simply combined with those generated for the next subcatchment (drainage-shed) downstream throughout the Creek. Data on hydraulic parameters used for steady flow routing are listed in Table 3.

Table 3. Dowdall Creek Hydraulic Parameters

Stream Reach	Hydraulic Parameters				
	Length (ft)	Slope (ft/ft)	U/S FL (ft)	D/S FL (ft)	Mannings n-value
L6-5	2,923	0.0062	59	41	0.04
L5-4	823	0.0024	41	39	0.04
L4-3	4,149	0.0029	39	27	0.04
L3-2	4,102	0.0015	27	21	0.04
L2-1	3,204	0.0012	21	17	0.04
L2ab-2a	4,060	0.0032	41	28	0.04
L2a-2	2,677	0.0026	28	21	0.04

Notes:

1. Hydraulic parameters estimated by SFEI with guidance from Watearth.
2. Flowlines approximated from course DEM data as survey data is not available.
3. Manning's n-value assumed at 0.04 for all stream segments in model.

Table 4 lists potential LID acreages by soil type as determined from the output of the LID Site Suitability Tool for each of the three LID types analyzed. Even though LID facilities are not

modeled in the undeveloped drainage-sheds dc-5 and dc-6, Possible Areas for LID Facilities are included for illustrative purposes.

Table 4. Dowdall Creek Possible Area for LID Facilities from LID Site Suitability Tool

Drainage[4] Shed	Shed Area (ac)	Possible Area for LID Facilities (ac)						
		Bioretention Type B Soils	Bioretention Type C-D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales	Total LID Area	LID % of Shed
dc-6	415.54	0.00	29.96	0.00	0.00	32.56	62.53	15%
dc-5	585.30	142.51	11.05	3.56	0.00	129.95	287.08	49%
dc-4	79.30	18.76	14.38	2.60	0.07	40.33	76.13	96%
dc-3b	101.96	94.48	4.90	13.36	1.88	25.56	140.19	137%
dc-3a	69.86	26.96	38.00	5.89	9.49	12.19	92.52	132%
dc-2ab	157.47	77.46	64.49	3.27	5.53	63.47	214.21	136%
dc-2b	169.54	144.24	0.00	4.12	0.00	75.64	224.00	132%
dc-2a	124.62	89.25	41.63	23.57	2.53	46.04	203.01	163%
dc-2	118.33	68.64	17.66	8.85	1.45	36.87	133.47	113%
dc-1	166.81	29.50	0.56	0.00	0.20	82.94	113.20	68%

Drainage Shed	Modeled Area for LID Facilities (ac)						
	Bioretention Type B Soils	Bioretention Type C-D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales	Total LID Area	LID % of Shed
dc-6	---	---	---	---	---	---	---
dc-5	---	---	---	---	---	---	---
dc-4	4.69	3.59	1.30	0.03	10.08	19.70	25%
dc-3b	14.76	0.77	4.18	0.59	3.99	24.29	24%
dc-3a	4.55	6.42	1.99	3.21	2.06	18.23	26%
dc-2ab	12.39	10.31	1.04	1.77	10.15	35.66	23%
dc-2b	24.48	0.00	1.40	0.00	12.84	38.71	23%
dc-2a	8.28	3.86	4.37	0.47	4.27	21.25	17%
dc-2	14.96	3.85	3.86	0.63	8.04	31.34	26%
dc-1	7.38	0.14	0.00	0.10	20.73	28.35	17%

Notes:

1. Possible LID areas estimated by SFEI from LID Site Suitability Tool.
2. Facilities not further divided by slopes due to conceptual nature of study.
3. Possible Area for LID Facilities includes areas in multiple LID types, which in some instances results in total possible LID areas greater than the area of each individual drainage-shed.
4. Possible Area for LID Facilities shown for illustrative purposes only for dc-6 and dc-5 as LID facilities were not modeled in these undeveloped drainage-sheds.
5. Modeled Area for LID Facilities estimated by scaling back LID facilities for a maximum of 100% of each drainage-shed. Factors of 25% used for Bioretention and Vegetated Swales and 50% for Permeable Pavement.

Because the Possible Area for LID Facilities includes areas that may be suitable for more than one type of facility, in some instances the Total LID Area is greater than the area of each individual drainage-shed. In these instances, the Possible Areas are scaled-back to a maximum

of 100% of the drainage-shed. Recognizing that it is neither feasible nor desirable to construct LID facilities where buildings or other features exist, an upper limit of 25% of the area is estimated as available for Bioretention and Vegetated Swale treatment.

Since Permeable Pavement can be constructed within a larger site, a factor of 50% is used to estimate the maximum area. With this approach, the maximum percent of each drainage-shed occupied by LID facilities is 26%. While individual sites could dedicate a higher land percentage to LID, this approach represents the theoretical upper limits for wide-scale LID implementation within a watershed.

Table 5 lists the conceptual sizes and number of BMP units assigned to each drainage-shed. 100% of the impervious cover within each drainage-shed is assumed to be disconnected and to drain through various LID facilities. The discharge from the LID facilities is assumed to drain into a conveyance system (storm drain, stream, etc.).

Table 5. Dowdall Creek LID Facilities Area Details

Drainage[2] Shed	Shed Area (ac)	Modeled Area for LID Facilities (sq ft)				
		Bioretention Type B Soils	Bioretention Type C-D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales
dc-4	79.30	204,321	156,570	56,528	1,490	439,142
dc-3b	101.96	643,138	33,365	181,914	25,646	173,980
dc-3a	69.86	198,330	279,573	86,624	139,666	89,690
dc-2ab	157.47	539,578	449,242	45,507	77,032	442,119
dc-2b	169.54	1,066,196	-	60,882	-	559,117
dc-2a	124.62	360,588	168,175	190,425	20,420	185,999
dc-2	118.33	651,824	167,717	168,047	27,570	350,156
dc-1	166.81	321,297	6,121	-	4,398	903,182

Drainage Shed	Size of Each LID Facility (sq. ft.)				
	Bioretention Type B Soils	Bioretention Type C-D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales
dc-4	5,000	5,000	56,528	1,490	5,000
dc-3b	5,000	5,000	181,914	25,646	5,000
dc-3a	5,000	5,000	86,624	139,666	5,000
dc-2ab	5,000	5,000	45,507	77,032	5,000
dc-2b	5,000	5,000	60,882	-	5,000
dc-2a	5,000	5,000	190,425	20,420	5,000
dc-2	5,000	5,000	168,047	27,570	5,000
dc-1	5,000	5,000	-	4,398	5,000

Drainage Shed	# of Units Each Type of LID Facility				
	Bioretention Type B Soils	Bioretention Type C-D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales
dc-4	41	31	1	1	88
dc-3b	129	7	1	1	35
dc-3a	40	56	1	1	18
dc-2ab	108	90	1	1	88
dc-2b	213	-	1	-	112
dc-2a	72	34	1	1	37
dc-2	130	34	1	1	70
dc-1	64	1	-	1	181

Drainage Shed	% of Impervious Area in Drainage Shed Treated by Each LID Type					
	Bioretention Type B Soils	Bioretention TypeC- D Soils	Perm Pvmt Type B Soils	Perm Pvmt Type C-D Soils	Vegetated Swales	Total
dc-4	23.8%	18.2%	6.6%	0.2%	51.2%	100.0%
dc-3b	60.8%	3.2%	17.2%	2.4%	16.4%	100.0%
dc-3a	25.0%	35.2%	10.9%	17.6%	11.3%	100.0%
dc-2ab	34.7%	28.9%	2.9%	5.0%	28.5%	100.0%
dc-2b	63.2%	0.0%	3.6%	0.0%	33.2%	100.0%
dc-2a	39.0%	18.2%	20.6%	2.2%	20.1%	100.0%
dc-2	47.7%	12.3%	12.3%	2.0%	25.6%	100.0%
dc-1	26.0%	0.5%	0.0%	0.4%	73.1%	100.0%

Notes:

1. All LID facilities assumed not to discharge into storm drain or conveyance systems rather than into pervious or landscaped areas.
2. Possible Area for LID Facilities shown for illustrative purposes only for dc-6 and dc-5 as LID facilities were not modeled in these undeveloped drainage-sheds.
3. Modeled Area for LID Facilities estimated by scaling back LID facilities for a maximum of 100% of each drainage-shed. Factors of 25% used for Bioretention and Vegetated Swales and 50% for Permeable Pavement.

Due to the various design configurations required for Permeable Pavement and Bioretention based on soil type, Permeable Pavement and two types of Bioretention facilities are modeled. Both of these LID facilities are divided into soil Type B and soil Types C and D to provide flexibility in adding underdrains to the LID facilities located on Types C and D soils. Since the Vegetated Swales are modeled with a sloped bottom, underdrains are not needed and only one category is used. Table 6 lists the typical configuration for each of these LID facilities.

Table 6. Dowdall Creek LID Conceptual Configurations

LID Facilities	Bioretention (B Soils)	Bioretention (C-D Soils)	Permeable Pavement (B Soils)	Permeable Pavement (C-D Soils)	Vegetated Swales
Perm. Pvmt. Thickness (in)	---	---	3	3	---
Perm. Pvmt. Infilt. (in/hr)	---	---	100	100	---
Perm. Pvmt. Void Ratio	---	---	0.15	0.15	---
Avg. Surface Depth (in)	12	12	---	---	24
Top Width (ft)	---	---	---	---	10
Side Slope (H:V)	---	---	---	---	4:1
Veg. Cover (%)	75	75	---	---	75
Manning's n-value	---	---	0.013	0.013	0.24
Surface Slope (%)	---	---	1%	1%	1%
Depth Soil Media (in)	18	18	---	---	---
Initial Media Saturation (%)	30	30	---	---	---
Drain Rock (in)	9	9	12	12	---
Void Ratio	0.75	0.75	0.75	0.75	0.75
Underdrain?		●		● elevated 6"	
Conductivity Underlying Soil	0.805	0.040	0.805	0.040	---

Notes:

1. Green & Ampt hydraulic parameters for growing media (amended soil) based on loamy sand with a hydraulic conductivity of 1.18 in/hr.
2. No clogging assumed on permeable pavement (i.e., maintenance at appropriate intervals assumed).
3. LID Conceptual Configurations based on typical LID configurations for various soil types.

The design storm rainfall data for the son4 watershed contained in the HEC-HMS model (4) is used for this simulation. Table 7 provides existing conditions and LID conditions peak flow comparisons for each of the drainage-sheds and the entire Dowdall Creek watershed system for the 2-year, 48-hour and 10-year, 48-hour design storm events. As noted in the table, drainage sheds with lower impervious cover values show less benefit from the extensive implementation of LID improvements.

Table 7. Dowdall Creek Peak Flows for 2-Year and 10-Year Design Storm Events

Drainage Shed	Exist. Conditions Peak Flows (cfs)		Prop. (LID) Conditions Peak Flows (cfs)		Difference in Peak Flows (cfs)	
	2-Yr	10-Yr	2-Yr	10-Yr	2-Yr	10-Yr
dc-6	107.7	502.6	107.7	502.6	0%	0%
dc-5	16.4	170.7	16.4	170.7	0%	0%
dc-4	7.6	31.5	2.9	26.5	-62%	-16%
dc-3a	27.8	57.4	5.3	12.5	-81%	-78%
dc-3b	30.0	59.4	1.5	6.0	-95%	-90%
dc-2b	21.0	40.3	0.7	7.0	-97%	-83%
dc-2a	39.5	78.2	3.2	12.7	-92%	-84%
dc-2ab	30.7	62.0	8.4	13.9	-73%	-78%
dc-2	24.3	47.3	3.2	6.7	-87%	-86%
dc-1	3.4	35.2	4.6	41.7	35%	18%
Dowdall Creek System	303.1	1056.5	137.9	755.1	-54%	-29%

Although drainage-shed dc-1 has minimal impervious cover (i.e., 1.69%), LID implementation is modeled in this shed to illustrate the relatively small benefit in undeveloped watersheds. For dc-1, increases in peak flows of 18% and 35% are noted in the two-year and ten-year events, respectively, and attributed to discharge from the system due to the 30% growing media saturation used at the start of the design storm event. For dc-4, with a low impervious cover of 7.95%, peak flow reduction is approximately 16% in the ten-year event as compared to an average reduction in peak flow of 83% in the remaining six drainage-sheds with impervious cover greater than 10%. In the 2-year event, the peak flow reduction is approximately 62% in dc-4 as compared to an average reduction of 87% in the remaining six drainage sheds with impervious cover greater than 10%.

Figure 2 illustrates existing and LID condition hydrographs from the outlet (mouth) of Dowdall Creek for the 10-year, 48-hour design storm event with a peak flow reduction of 29% for the current level of development (approximately 9% impervious cover). The model shows a 52% reduction in peak flow if the existing impervious cover in all drainage-sheds within Dowdall Creek except dc-5 and dc-6 is 60%, or 31% over the entire watershed (Figure 3). Figures 4 and 5 depict existing and LID conditions hydrographs from the outlet (mouth) of Dowdall Creek for the 2-year, 48-hour design storm event. For the current impervious cover of approximately 9%, the peak flow reduction is 54%, whereas a reduction of 74% is shown for an impervious cover of 60% in all drainage sheds except dc-4 and dc-6 (31% of the entire watershed).

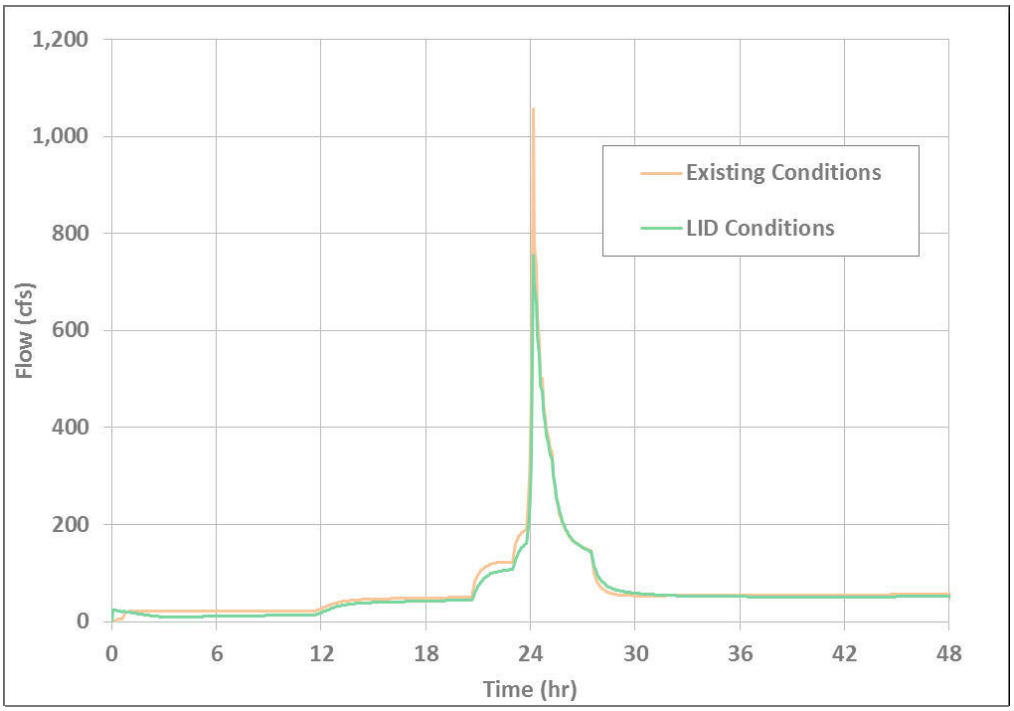


Figure 2. Ten-Year, 48-Hour Hydrographs from Dowdall Creek Watershed with Existing Development

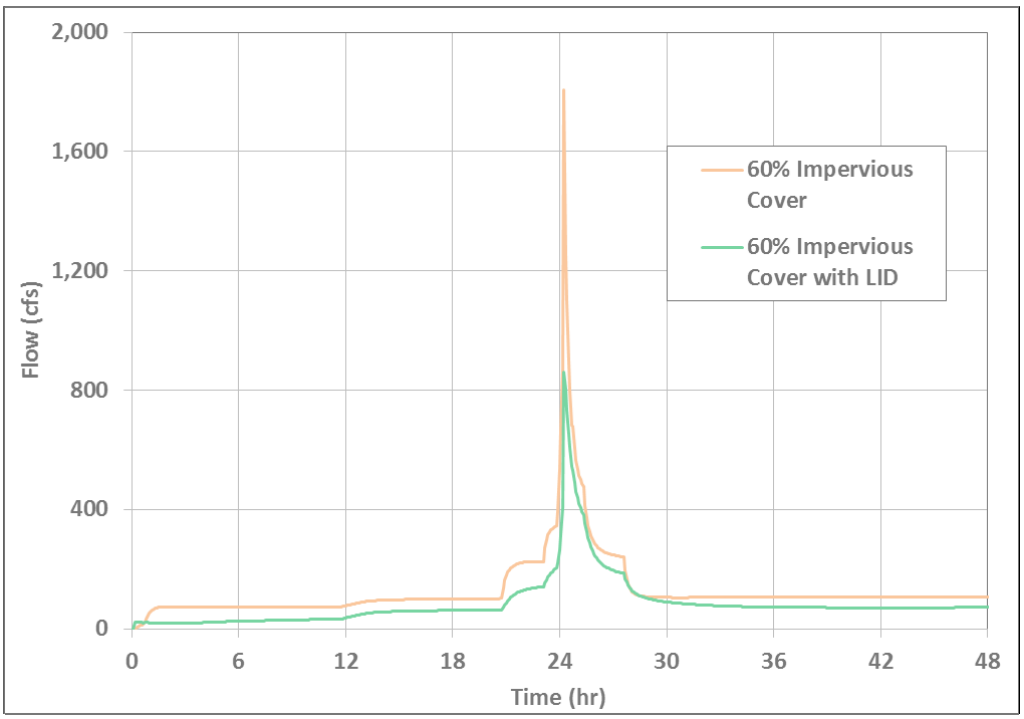


Figure 3. Ten-Year, 48-Hour Hydrographs from Dowdall Creek Watershed with 60% Impervious Cover

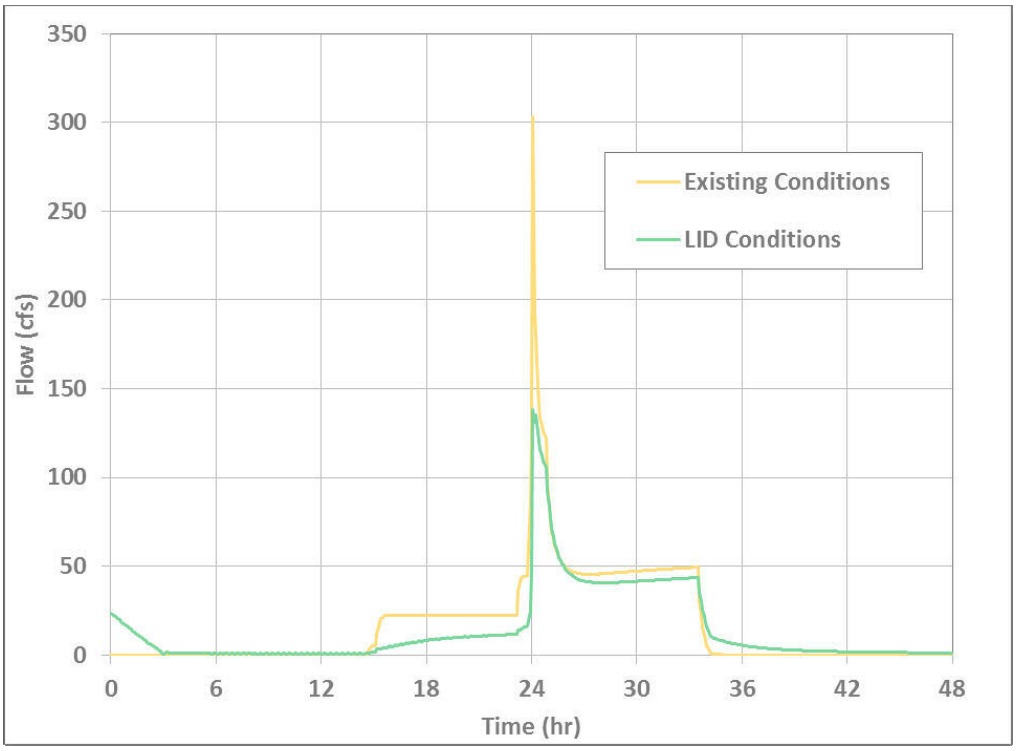


Figure 4. Two-Year, 48-Hour Hydrographs from Dowdall Creek Watershed with Existing Development

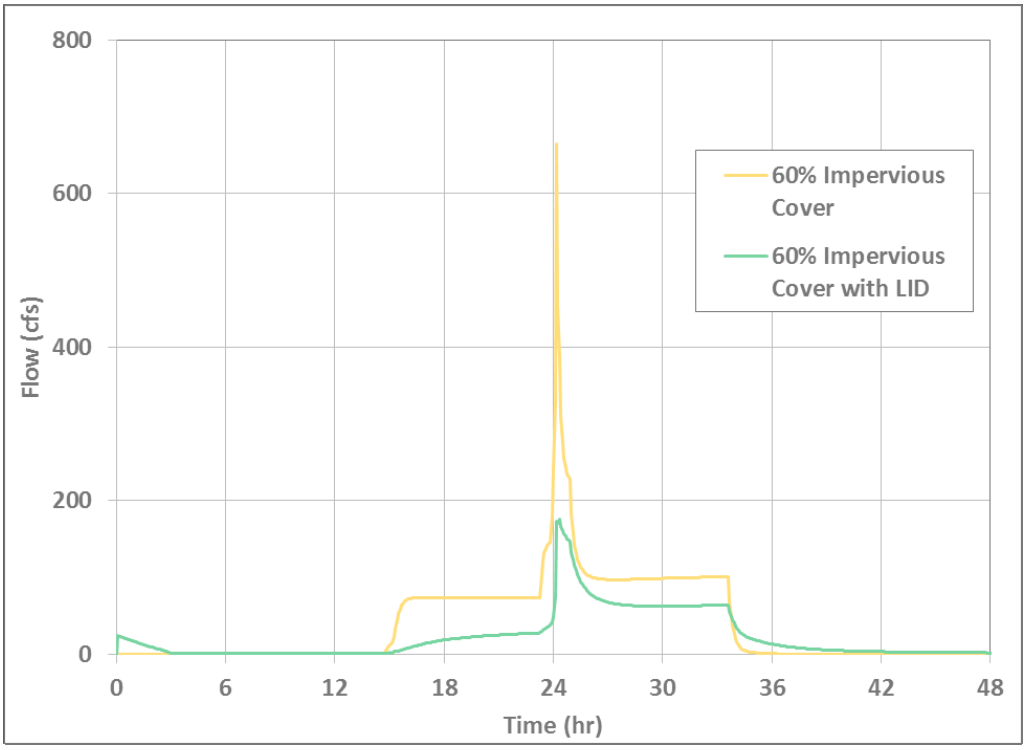


Figure 5. Two-Year, 48-Hour Hydrographs from Dowdall Creek Watershed with 60% Impervious Cover

Figures 6, 7, and 8 illustrate storage depths within the following layers of the LID facilities simulated within drainage-shed dc-3b, which has the highest impervious cover value (39.07%) within the Dowdall Creek watershed:

- 12-inch surface storage layer of Bioretention
- 24-inch surface storage layer of Vegetated Swales
- 9-inch drain rock layer of Bioretention
- 12-inch drain rock layer of Permeable Pavement

Both Permeable Pavement and Bioretention are further divided into Type B and Types C-D soils. As indicated in these figures, the simulated LID facilities are not fully utilized (i.e., storage does not fill) due to the relatively low impervious cover within each drainage-shed. For watersheds with higher levels of urbanization and development, LID facilities are anticipated to be more fully utilized and may also be optimized at lower percentages of the watershed with detailed modeling. Additionally, drain rock (i.e., gravel storage reservoir) may not be needed as extensively as modeled in the Type B soils.

Initial storage depth in the Bioretention drain rock layer is due to the simulated 30% growing media saturation at the beginning of the design storm event. For consistency, all figures stop at the 48-hour mark, although additional time shows the Vegetated Swales and drain rock layer in the Type C-D Permeable Pavement drain out completely.

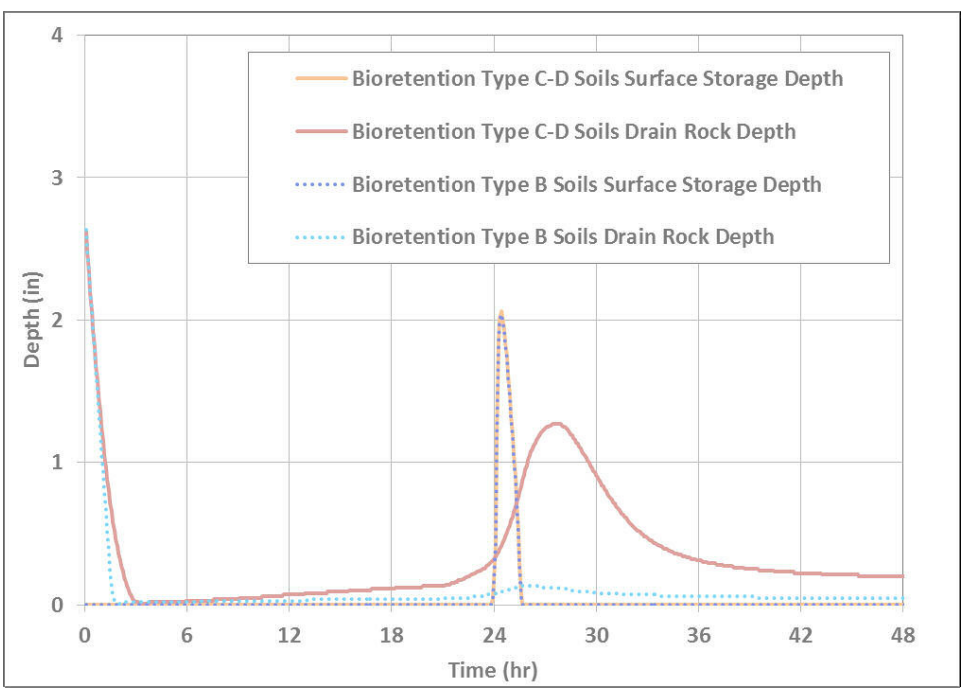


Figure 6. 10-Year, 48-Hour Hydrographs for Bioretention in Drainage-shed dc-3b.

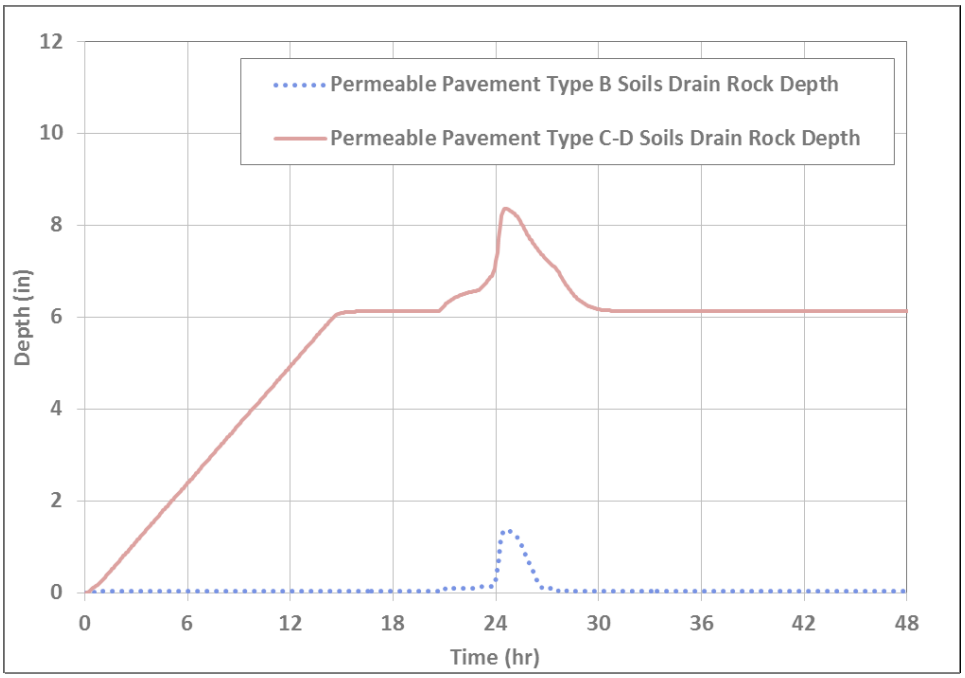


Figure 7. 10-Year, 48-Hour Hydrographs for Permeable Pavement in Drainage-shed dc-3b.

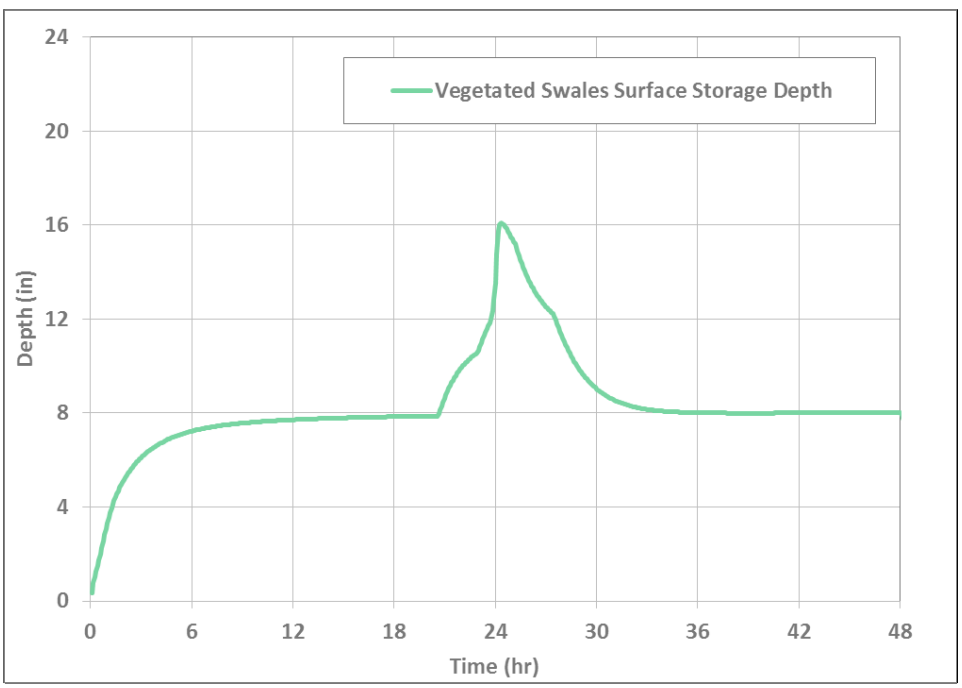


Figure 8. 10-Year, 48-Hour Hydrograph for Vegetated Swales in Drainage-shed dc-3b.

While the initial intent of the project was to assess reductions in peak flows downstream in Dowdall Creek, final HEC-HMS models from the *Sonoma Creek & Tributaries Basin Hydrologic Investigation* (4) could not be obtained within the project time-frame. Since the design storm

peak discharge rates in the HEC-HMS models collected for this project did not match those reported in the *Investigation*, a comparison is made at the location in the Sonoma Creek model where Dowdall Creek discharges into Sonoma Creek. This location is labeled as Jct104 in the HEC-HMS model and referenced study and the 10-year, 48-hour peak flow rate in Sonoma Creek is 11,820 cfs. The 2-year, 48-hour peak flow rate in Sonoma Creek is 3,081 cfs.

The 10-year, 48-hour peak flow reduction achieved with wide-scale implementation in the Dowdall Creek watershed is 301 cfs. This represents an approximately 3% reduction in peak flows in Sonoma Creek assuming other sub-watersheds are not treated with LID, and neglecting timing changes due to hydrograph routing. For the scenario analyzed with 60% impervious cover in Dowdall Creek, the 949 cfs reduction represents an approximately 8% reduction in peak flows in Sonoma Creek (also while neglecting timing). This result begins to approximate performance of some regional (centralized) stormwater management facilities or detention basins.

For the 2-year, 48-hour design storm events, wide-scale implementation of LID in Dowdall Creek reduces the peak flow in Sonoma Creek at the confluence with Dowdall Creek by 5%, again assuming no LID in the other Sonoma Creek sub-watersheds. For the scenario with 60% impervious cover in Dowdall Creek, the 2-year reduction of 490 cfs results in an approximately 16% reduction in Sonoma Creek. Results from the two-year event support the strategy that watershed-scale implementation of LID in highly developed watersheds improves water quality and helps reduce peak flows associated with stream-forming rainfall events.

While the conceptual models developed for this study are not calibrated, these results support the assumption that wide-scale implementation of LID has the most significant impact on peak flows in the tributary in which it is implemented. Furthermore, a more significant peak flow reduction is expected in watersheds with higher levels of impervious cover, or in mitigating future development within a watershed back to pre-development conditions. To achieve a significant reduction in peak flows on the main stem of the watershed, watershed-wide implementation of LID may be required within strategic tributaries. This is consistent with the regional detention (flood control) implementation often used throughout watersheds.

Further modeling of smaller and larger design storm events as well as continuous simulation modeling of historical periods with rainfall records of 20 to 40 years is recommended. The continuous simulation modeling addresses peak flow exceedance and flow duration for a range of events and evaluates water budget performance (i.e., infiltration, evaporation, runoff, etc.) for the long-term. Typically, events ranging from a percent of the 2-year up to the 10-year are of greatest interest in continuous simulation modeling, as these events typically cause the most

significant stream hydromodification and water quality issues. Future work may also address the cost-benefits of watershed-scale implementation of LID, the differences in performance in implementing LID in residential vs. commercial areas, and the cost optimization of watershed-scale implementation.

References

1) Shoemaker, et al. 2009. "SUSTAIN – A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality". pp. 3-63 – 3-65.

2) Gironas, et al. 2009. "Storm Water Management Model Applications Manual." U.S. EPA.

3) Huber & Cannon. 2003. "Modeling Non-Directly Connected Impervious Areas in Dense Neighborhoods". 9th International Conference on Urban Drainage, Portland, OR 9/8-13/02.

4) Philip Williams & Associates (PWA). 2004. "Sonoma Creek & Tributaries Hydrologic Investigation". Prepared for US Army Corps of Engineers, San Francisco District Office, Southern Sonoma County Resource Conservation District.