Urban Stormwater Management at UC Berkeley: A Low Impact Development Solution

Manon von Kaenel

ABSTRACT

Nonpoint source pollution and hydromodification in urban landscapes cause urban stream syndrome, symptoms of which include poor water quality, reduced biodiversity, and increased storm discharges. Conventional stormwater infrastructure often fails to address the impacts of urbanization on creek health. I model the behavior of urban runoff in ArcGIS on the Upper North Fork subcatchment of the UC Berkeley campus by estimating flow accumulation and the relative impact on runoff infiltration caused by changes in surface permeability. I supplement this model by estimating key hydrological parameters for predevelopment and current conditions and testing the water quality of runoff. I then propose a Low Impact Development installation to mitigate the most pertinent negative impacts of urban runoff on Strawberry Creek and evaluate its impacts. I found that runoff on the site is currently 40% faster-flowing and 6,000% more voluminous than under predevelopment conditions. In addition, this runoff exceeds acidity, zinc, and copper standards for aquatic life protection. To return at or below the effective imperviousness threshold for a healthy watershed, the campus needs to remove 14 acres of impervious surfaces from the site. Because the heaviest flow accumulates over University Drive along the northwestern edges of Memorial Glade and the creek suffers from a history of heavy metal pollution, I strongly recommend an installation of permeable pavement. An installation of 0.2 acres of permeable pavement on University Drive would decrease runoff volume by 1-1.4% and provide infiltration and filtration benefits. This approach is most appropriate when assessing a site with limited groundwater flow, few structures, and surfaces with varying permeability levels.

KEYWORDS

urban runoff, permeable pavement, Strawberry Creek, GIS, LID best management practices

INTRODUCTION

Since 1986, the US EPA has identified urban runoff and nonpoint source pollution as a leading cause of water quality problems in urban water systems (EPA 1986). Specifically, nonpoint source pollution causes "urban stream syndrome," symptoms of which include: increased discharges during flood events, reduction in groundwater recharge, higher concentrations of pollutants and nutrients, erosion and channel enlargement, increased temperature, and reduced biodiversity in local creeks (Paul and Meyer 2001, Walsh et al. 2005b). The primary causes of urban stream syndrome are runoff from large interconnected impervious surfaces and an overuse of traditional end-of-pipe stormwater management strategies (Walsh et al. 2005b, Komínková 2012). Urban runoff often contains sediment, oil and grease, nutrients, metals, trash, and other anthropogenic contaminants that can harm stream habitat and endanger aquatic life (Walsh et al. 2005b, Vassilios and Hamid 1997, CASQA 2003). Conventional stormwater infrastructure often fails to address the impact of developed impervious areas and resulting surface runoff on urban stream health and vitality (Booth and Jackson 1997, Walsh et al. 2005b, Komínková 2012).

Low-Impact Development (LID) has become a popular nontraditional stormwater management tool over the past decade (Walsh et al 2005b, EPA 2000, Holman-Dobbs et al 2003, BPWE 2011). LID best management practices use simple design features such as vegetation, natural slope gradients, and various forms of pervious surfaces to mimic pre-development hydrological regimes and mitigate harmful effects of urbanization on the local waterways by managing runoff at its source (Curry and Wynkoop 1999, EPA 2007; Holman-Dobbs et al. 2003). LID is now a recommended strategy by both the city of Berkeley and the state of California, according to the Berkeley Watershed Management Plan of 2011. The strategies and features used in an LID installation depend on its intended functions, which include conservation, infiltration, runoff storage, runoff conveyance, and filtration (LIDDC 2010). The specific size and design of an LID installation is determined by site-specific criteria such as typical storm size, slope, soil infiltration rate, and water table depth (EPA 2000, EPA 2007). In addition to reducing runoff, LID installations such as bioretention or swales also offer important land value, ecosystem health, and quality of life benefits (EPA 2007). LID is also an effective strategy for stream restoration because it improves water quality by filtering sediment and contaminants, increases vegetation cover and builds habitat, and reduces bank instability (Curry and Wynkoop 1999, Walsh et al. 2005a).

Strawberry Creek is an urban stream on the University of California, Berkeley campus that serves as an important educational, ecological, and recreational resource for the community, but suffers many symptoms of urban stream syndrome (Hans and Mananza 2007; T. Pine, personal communication). Historical flooding patterns, inconsistent water quality, and increasingly severe bank erosion (Hans and Mananza 2007; T. Pine, personal communication) in Strawberry Creek require a change in the campus stormwater system to improve habitat health. UC Berkeley is in the second year of the small, non-traditional MS4 phase 2 permit, which includes a requirement to treat and/or infiltrate the 1-2 year storm runoff from new construction projects (SWRCB 2013). LID practices such as bioretention areas and permeable pavement (Dietz 2007) can fulfill this requirement and not only maintain net runoff but also reduce it for the campus (EPA 2000). However, it is necessary to first understand site-specific impacts of urban runoff to Strawberry Creek water quality and habitat to install the appropriate LID features. The purpose of this study is to model how the urbanization of the University of California, Berkeley campus has affected its hydrology, identify the most pressing stormwater-related problems facing Strawberry Creek, and ultimately propose an LID practice to ameliorate these problems and best protect the stream habitat. I first model and estimate various hydrological parameters of the site under both predevelopment and current conditions using ArcGIS and test runoff for key water quality criteria. I then propose the most appropriate LID installation and evaluate its impacts on my baseline model. This study will use the Upper North Fork subcatchment as a case study to assess the applicability of this approach to other subcatchments on the UC Berkeley campus and in other similar landscapes.

STUDY SITE DESCRIPTION

My study site will be confined to what I will call the Upper North Fork subcatchment, a small portion of the Strawberry Creek watershed on the University of California, Berkeley campus (Figure 1).

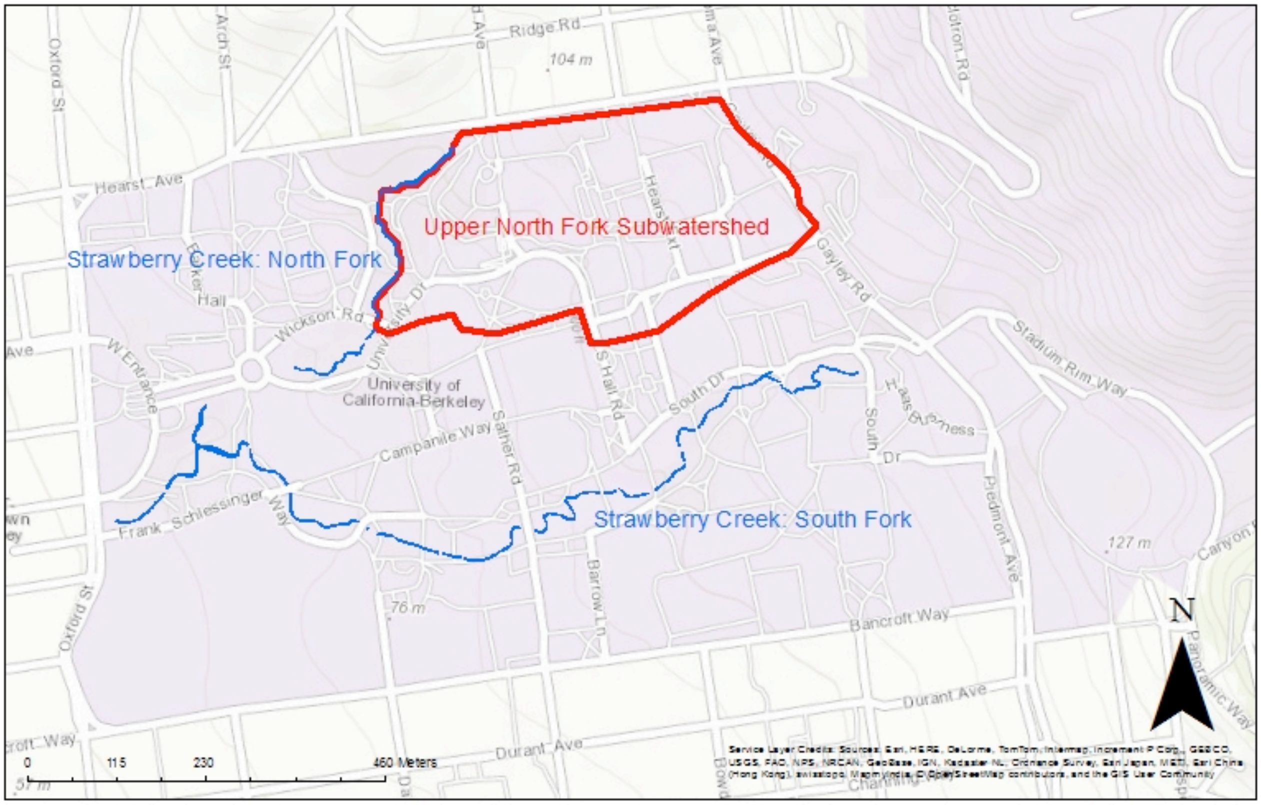

Figure 1. Upper North Fork Subcatchment. Study site is outlined in red. The two forks of Strawberry creek on campus are outlined in blue.

This subcatchment, measuring 30.7 acres, contains the area of the main UC Berkeley campus from which surface runoff flows into the portion of the North Fork of Strawberry Creek bounded by its entrance into the campus at North Gate to the first major stormwater discharge point just below Memorial Glade. I chose to focus on this particular subcatchment because it is an ideal example of the type of urbanized landscape characteristic to the UC Berkeley campus, including a combination of lawn, roads, and buildings. Due to the topography and road network of the campus, this area is also one of the largest basins or subcatchments on campus, with runoff accumulating here from the North Gate area, Evans Hall area, and even further upslope towards the Campanile Tower. In fact, the UC Berkeley Office of Environment, Health and Safety has identified the area around Memorial Glade as a region of high priority for its poor runoff quality, especially regarding a history of heavy metal pollution in the North Fork (Hans and Maranzana 2007). My study site also contains a major infrastructural stormwater system, with most storm drains connecting to a major pipe and discharge point at the very southwestern tip of my study site (Vera 2010).

The North Fork of Strawberry Creek starts in the Berkeley hills, flows through north Berkeley residential neighborhoods, and enters the UC Berkeley campus just west of the Euclid Rd-Hearst Ave intersection. It travels approximately 2,150 feet on the central campus, after which it joins with the South Fork of Strawberry Creek at the Eucalyptus Grove, enters the Oxford Street culvert, and flows mostly underground through the city of Berkeley to ultimately discharge into the San Francisco Bay at the Berkeley Marina (Figure 2). The study site is located on the 18% of the Strawberry Creek watershed area that is considered unsuited to hydrologic soil classification because it is covered by urban structures, but most of the natural watershed is covered by soils with slow to very slow infiltration rates (Charbonneau 1987). The study site is located on the UC Berkeley campus, which extends 178 acres (Hans and Maranzana 2007) and serves over 37,000 students, staff and professors.

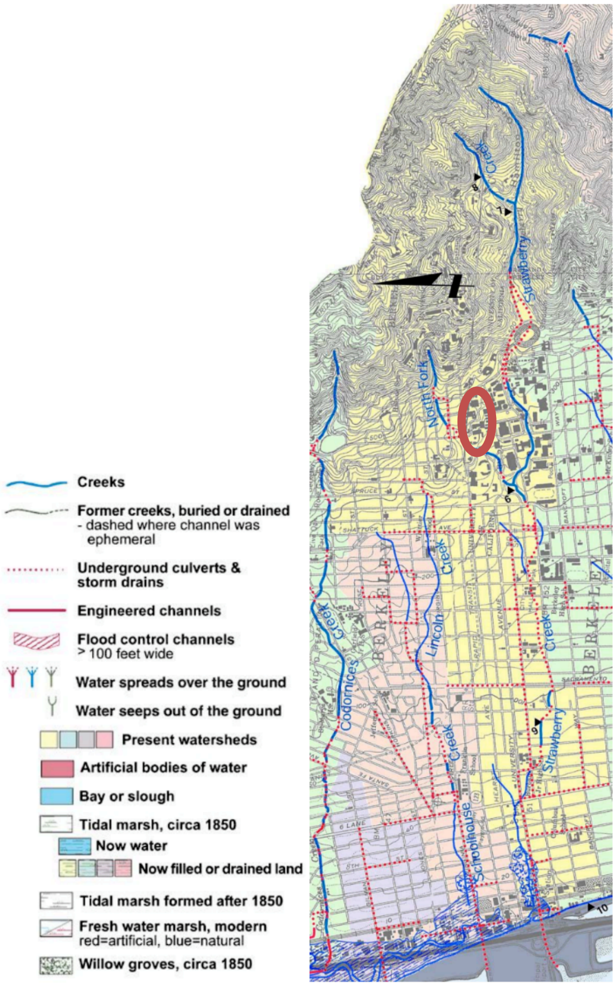

Figure 2: Strawberry Creek Watershed. Strawberry Creek Watershed is delineated in yellow. Approximate study site circled in red. (Map found in Hans and Maranzana 2007, originally from Oakland Museum).

Strawberry Creek has faced a long history of water quality problems, flooding, and erosion ever since the early settlements in the 1770s (Charbonneau 1987). The creek became a sewage conveyance system, leading to chronic pollution problems only partially solved by the construction of a sewage treatment plant in 1952 (Charbonneau 1987). Channelization and culverting has also seriously disturbed the stream's natural habitat and hydrologic regime (Charbonneau 1987). In 1987, the UC Berkeley Office of Environment, Health and Safety issued a Strawberry Creek Management Plan, which has led to significant stream health improvement and a variety of restoration programs (Charbonneau and Resh 1992). However, both forks of Strawberry Creek still suffer from typical urban stream syndrome symptoms, including high heavy metal pollution during runoff events, occasional flooding damage and bank erosion – all of which can hamper native species reintroduction efforts and reduce the recreational and aesthetic value of the stream (Hans and Maranzana 2007, T. Pine personal communication).

ASSESSMENT OF RUNOFF CONDITIONS

Approach: ArcGIS Urban Hydrology Model

I used a combination of ArcGIS (ArcGIS 10.2) hydrology tools, common rainfall-runoff equations, and water quality lab tests to assess relative flow accumulation, runoff volume, pollution loads, and surface permeability of the study site to identify the potential negative impacts to the stream from urban runoff.

Hydrological Parameters

Because the purpose of LID is to manage stormwater by mimicking historic or pre-development hydrologic conditions, I first estimated both current and historic effective imperviousness, composite soil curve number, runoff depth, peak discharge, runoff volume, and overland flow time (Table 1). I used a map of surface cover type with corresponding soil curve numbers produced by Karl Hans for the UC Berkeley Office of Environment, Health and Safety in 2011 to model current conditions (Hans 2011) (Figure 3). I assumed the predevelopment site was dominated by oak-aspen forests, correlating to a soil curve number of 48 (USDA 1986)

(Figure 3). Soil curve numbers are an empirical parameter developed by the USDA Natural Resources Conservation Service to predict direct runoff from rainfall on different surfaces (SCS 1985). These values range from a highly permeable 30 to an extremely impermeable 98. I calculated precipitation intensity and depth based on a 24-hour, 2-year recurrence interval design storm, the most commonly used when planning LID (LIDDC 2010). The approximate precipitation depth for this design storm for Berkeley, as measured by the National Oceanic and Atmospheric Administration at Station 05-0693, is 2.66 inches. Unless otherwise specified, I used the same two predevelopment and current surface cover maps and design storm size throughout this study.

Table 1. Hydrological Parameters. I selected these hydrological parameters because these are the ones typically calculated for LID planning in the literature.

Parameter	Equation	Variables
Effective Imperviousness (Walsh et al. 2005a)	$EI = A_i/A_t$	A_i = total impervious area (m^2)* A_t = total area (m^2)*
Composite Soil Curve Number (SCS Runoff Curve Number Method, SCS 1985)	$CN_C = (A_1 * CN_1 + A_2CN_2 + A_3CN_3 + \ldots A_nCN_n) / A_t$	CN_n = Soil Curve Number A_n = the corresponding area of each surface type
Runoff depth (SCS Runoff Curve Number Method, SCS 1985)	$Q_r = (P - I_A)^2 / ((P - I_A) + S)$	Qr = runoff depth (in) P = precipitation (in) I_A = initial abstraction (in), S = 0.2S S = potential maximum retention after runoff begins (in), = 1000/CN_C - 10
Runoff Volume (SCS Runoff Curve Number Method, SCS 1985)	$Q = Q_r * A$	Q = runoff volume (ft^3) Qr = runoff depth (in) A = area (ft^2)
Peak Discharge (Rational Method, SCS 1985)	$Q_p = CiA$	Q_p = peak discharge, (m^3/s) C = rational method runoff coefficient, C = P/Q_r I = rainfall intensity, (m/s) A = total area (m^2)*
Overland Flow Time (Seelye Method)	*Seelye Chart (See Appendix A)*	T_c = time of concentration (for overland flow) L = length in feet** C = coefficient of imperviousness Percentage slope***

*Areas calculated from the surface cover map (Figure 3) in ArcGIS
** Length in feet corresponds to the length of the watershed, measured on ArcGIS
***Percentage slope estimated from slope surface calculated with ArcGIS Slope tool (Spatial Analyst tool)

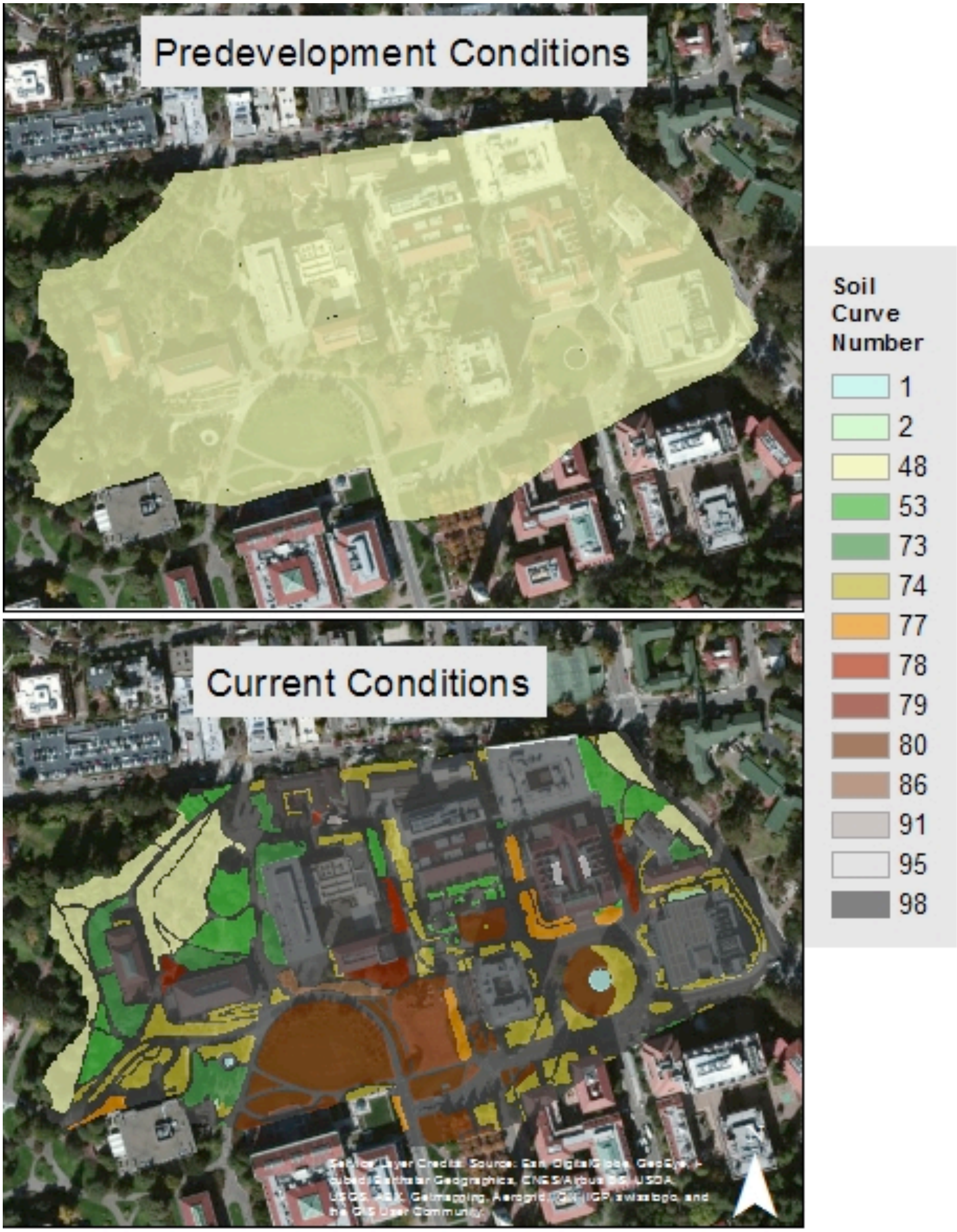

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Figure 3. Soil Curve Numbers for Predevelopment and Current Conditions. The higher the curve number, the greater the runoff. The surface cover map for current conditions from Hans 2011.

Flow Accumulation Model

I first delineated the study site on a 2-meter resolution topographic Digital Elevation Model (DEM) constructed from the 2006 U.S. Geological Survey Topographic LiDAR data for Alameda County. This particular DEM has mapped the buildings as flat surfaces. I chose my pour point as the stormwater discharge outlet just below Memorial Glade, because this is the largest discharge point on the UC Berkeley extent of the North Fork of Strawberry Creek. I estimated the boundary of this subcatchment using a combination of the ArcGIS watershed tool, the 3D slope tool, and my own observations of runoff behavior. I chose to base the subcatchment boundary purely on topography, and thus did not consider the individual drainage areas of each stormwater drain within the site. I then used the ArcGIS hydrology toolset to model the relative weights of runoff flows on the site by first filling in topographic sinks to produce a depressionless DEM, modeling flow direction, and ultimately calculating flow accumulation. The resulting raster grid displayed flow accumulation weights for each pixel as a sum of all the cells that would flow into it. This flow accumulation model assumes that runoff behaves as purely overland flow, and does not model the impact of stormwater drains or buildings. I then categorized flow accumulation on the site into 15 classes based on geometric interval, to more easily analyze the range and distribution of runoff flows. I calculated the contributing drainage area for each of these flow classes by multiplying their flow accumulation value by the area of each pixel (45 ft^2). I then estimated the runoff volume that would accumulate at each flow class for a 2.66-inch rainfall event using the average runoff depth value I calculated in the previous section.

Surface Permeability Model

I then used map overlay in ArcGIS to calculate what I am calling the flow-impermeability score across my study site for both predevelopment and current condition, by adding a weighted flow accumulation raster with a permeability raster weighted by soil curve number. Both layers were divided into 15 classes based on geometric intervals, with scores 1-15 corresponding to low-high flow accumulation and low-high soil curve numbers. This purpose of this process is to more accurately estimate the relative flow accumulation on the site by incorporating the effect of varying surface permeability into the model. Additionally, I wanted to display the spatial differences in predevelopment and current surface permeability and quantify their relative impacts on flow accumulation.

Water Quality Testing

I conducted water quality tests on samples of stream water, outfall water, and runoff at 6 locations in the study site (Figure 4). I collected at least 200 ml samples of runoff and creek water at each site to bring back to the lab in sanitized plastic sampling containers. I conducted the pH, chloramine, and temperature tests on site. I tested creek water at Site A during dry weather to establish baseline conditions. I then tested 3 samples of stormwater runoff produced from roads in my study site (Sites B, C, and D). I also tested one sample of runoff produced from the Memorial Glade Lawn (Site E), and one sample of an outfall stormwater discharge (Site F). Finally, I tested one sample of creek water during the storm (Site A). I tested these samples for 9 water quality parameters (Table 4).

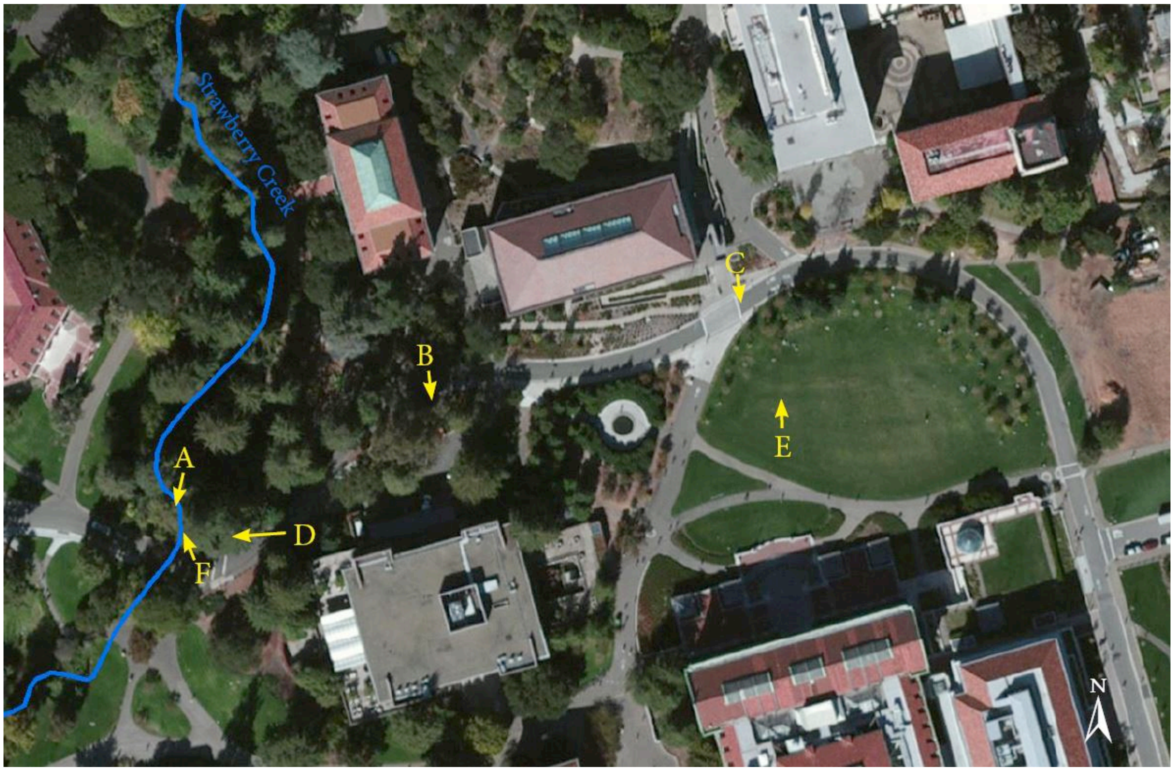

Figure 4. Sampling Sites for Water Quality Tests. Locations approximate. Dry weather samples taken on Feb. 3, 2015. Wet weather samples taken on Feb. 6, 2015.

Table 4. Water Quality Parameters. Selection of methods was determined by an availability of test kits and recommendations by the Office of Environment, Health and Safety (A. Massell, personal communication).

Parameter	**Method**
Conductivity (microS/cm)	Con 6 Conductivity Method
pH	ColorpHast pH Indicator Strips
Color (APHA Platinum Cobalt Units)	LaMotte Octet Comparator with Axial reader
Chloramines (ppm)	Hach Water Quality Test Strips for Total Chlorine, Free Chlorine
Copper	LaMotte Copper Low Range Kit
Zinc	LaMotte Zinc Octa-Slide 2, 0.0-1.4 ppm Kit
Nitrate-N (ppm)	LaMotte Nitrate-N Phosphate Kit
Orthophosphates (ppm)	LaMotte Nitrate-N Phosphate Kit
Trash	Field Observations

Results

Hydrological Parameters

The runoff depth for a 24-hour 2-year storm rainfall of 2.66 inches under predevelopment conditions (assumed to be oak-aspen forest, with a soil curve number of 48) is 0.02 inches (Table 5). In comparison, the runoff depth under current conditions ranges from 0 to 2 inches (Figure 4). The highest runoff depth occurred on pavement surfaces with a soil curve number of 98, which cover 61% of the study site. The lowest current runoff depth of 0 inches occurred over the decorative fountain, on the assumption that the fountain captures all rainfall. The next lowest current runoff depth, 0.002 inches, occurs in the natural areas with a soil curve number of 48. On average, the runoff depth, runoff volume, and peak discharge increased nearly 65 times from predevelopment conditions. The overland flow time decreased by 18 minutes from predevelopment conditions. The effective imperviousness of the site is currently 61%, over 4 times greater than the threshold for healthy urban watersheds of 14% (Burns et al. 2014).

Table 5. Hydrological Parameters. Hydrological parameters calculated for a design storm of 2.66 inches (equivalent to a 2-year recurrence interval, 24-hour storm event for Berkeley).

Parameter	**Predevelopment Conditions**	**Current Conditions**	**Change**
Effective Imperviousness (EI)	0%	61%	--
Composite Soil Curve Number	48	86.4	+80%
Overland Flow Time (min)	45	27	-40%
Runoff Depth (in)	0.02	1.4	+6,445%
Runoff volume (ft^3)	2,396	156,797	+6,445%
Peak Discharge (ft^3/s)	0.08	0.53	+6,445%

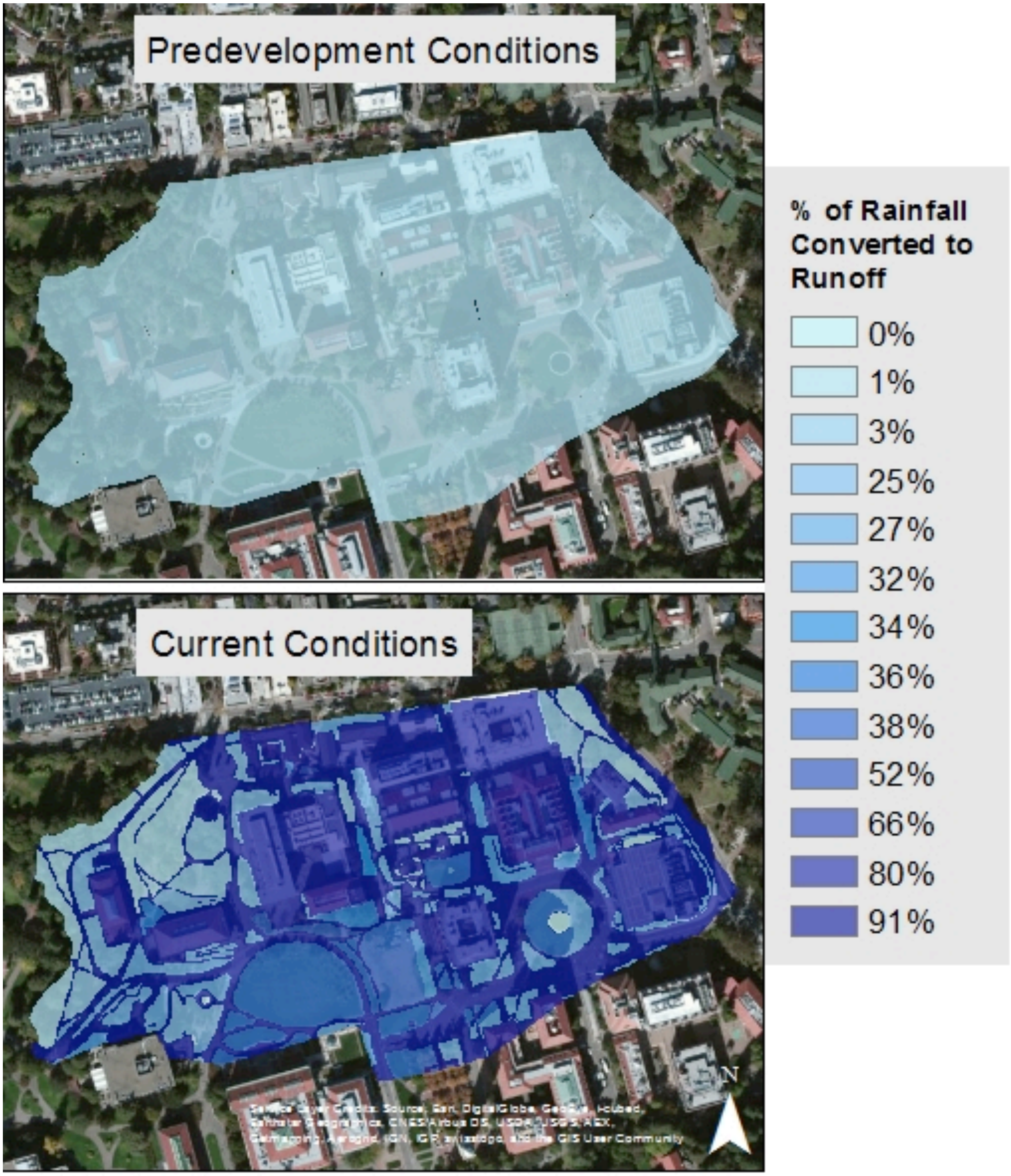

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Figure 4. Runoff Depth for Predevelopment and Current Conditions. Areas in dark blue indicate the highest runoff depth, of 2.0720 in for a 2.66 rainfall event. The areas in white indicate the lowest runoff depth, of 0 in for a 2.66 in rainfall event. Rainfall depth is displayed on the map as a percentage of rainfall converted to runoff for a 2.66 in rainfall event.

Flow Accumulation Model

The area of highest flow accumulation (class 1) on the study site occurs along University Drive along the northwestern edge of Memorial Glade (Figure 6). This class of flow accumulation corresponds to a contributing area of 368,802 to 542,613 ft^2, or a runoff volume under current conditions and with a design storm of 2.66 inches of about 43,214 to 63,581 ft^3 (Table 2). This class of flow accumulation only covers 0.2% of the total study site but produces an average of about one third of the total runoff volume from the site. In comparison, the lowest class of flow accumulation, in yellow on Figure 6, covers 90% of the study site but produces less than 1% of the total runoff volume.

Table 2. Flow Accumulation Classes. Summary of the contributing area, accumulated runoff volume, and percent of total study site are for each class of flow accumulation. The heaviest flow class is bolded.

Class (low to high)	Contributing Area (ft^2)	Approximate Accumulated Runoff Volume (ft^3)*	Area (% of total)
1	0-1,702	0-200	90.10
2	1,702-2,861	200-335	2.50
3	2,861-4,564	335-535	1.88
4	4,564-7,067	535-828	1.07
5	7,067-10,748	828-1,259	0.72
6	10,748-16,160	1,259-1,894	0.66
7	16,160-24,118	1,894-2,826	0.51
8	24,118-35,819	2,826-4,197	0.70
9	35,819-53,022	4,197-6,213	0.31
10	53,022-78,316	6,213-9,178	0.47
11	78,316-115,507	9,178-13,535	0.45
12	115,507-170,189	13,535-19,942	0.20
13	170,189-250,589	19,942-29,363	0.10
14	250,589-368,803	29,363-43,214	0.09
15	**368,803-542,614**	**43,214-63,581**	**0.20**

*For sample calculations, see Appendix C.

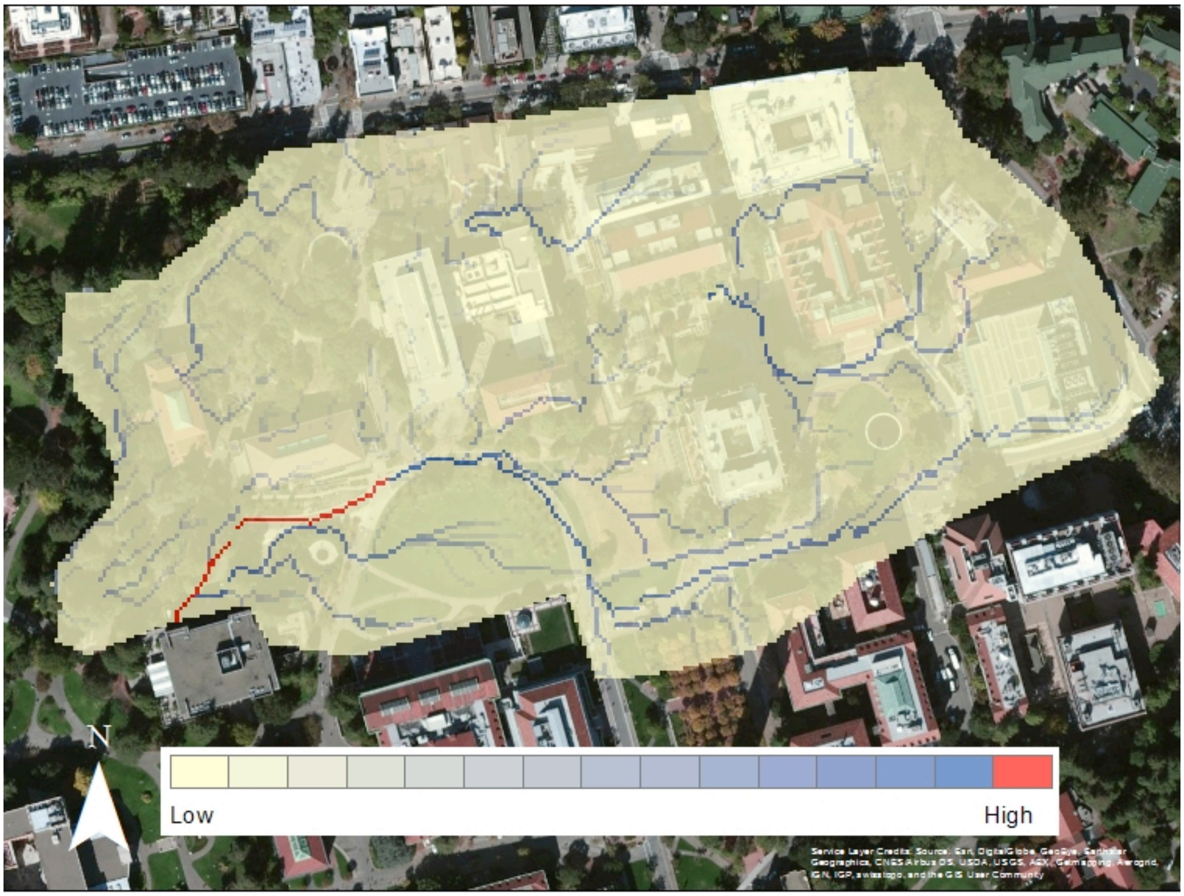

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Figure 6. Flow Accumulation. Areas in red indicate the highest flow accumulation. The areas in yellow indicate the lowest flow accumulation. Flow accumulation is broken up into 15 classes based on geometric interval.

Surface Permeability Model

The area with the highest flow-impermeability score, under both predevelopment and current conditions, is the section of University Drive to the north and northwest of Memorial Glade (Figure 7). This score, of 30 for current conditions and 19 for predevelopment conditions, corresponds to an area with both the highest flow accumulation and highest. Across the site, the flow-impermeability scores ranged from 5 to 19 under predevelopment conditions, and from 2 to 30 for current conditions. The areas with the largest increase in flow-impermeability score (+11) after development are those areas that are currently covered with surfaces of soil curve number 98, or the most impermeable surfaces (Figure 3). The only areas with a lower flow-permeability score under current conditions are: the decorative fountain with a score of 2, and air intakes with a score of 3. These surfaces have a soil curve number of 1 or 2 (Figure 3).

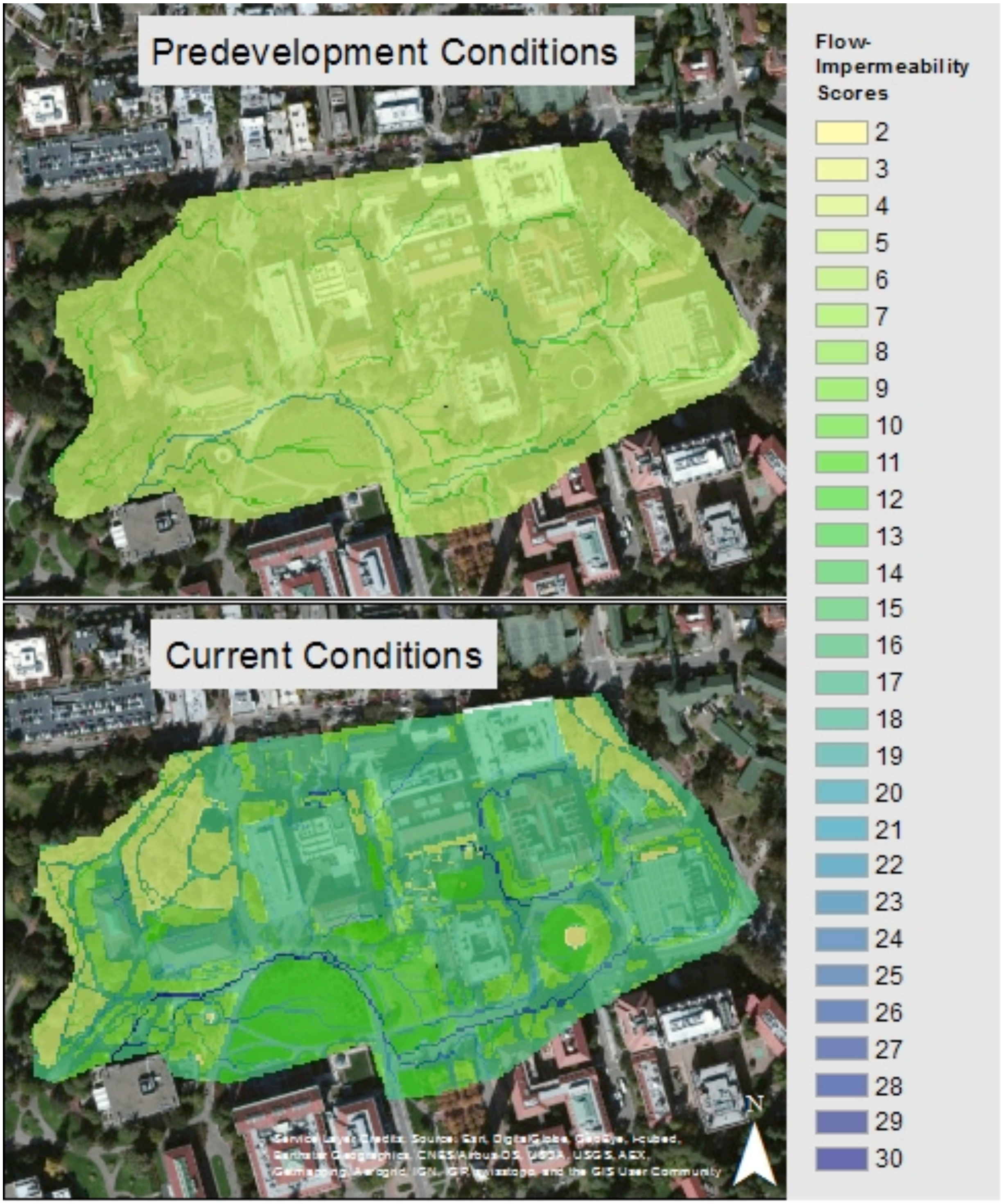

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Figure 7. Flow-Impermeability Scores for Predevelopment and Current Conditions. Areas in blue illustrate the areas with the highest flow-impermeability score – that is, areas with high flow accumulation and low permeability. Areas in yellow indicate the lowest flow-impermeability score, or those areas with both high permeability and low flow accumulation.

Water Quality Testing

Overall, I found that the acidity level of runoff at sites all the sites I tested (A-F) exceeded the EPA water quality goals for the protection of freshwater aquatic life (EPA 1986) (Figure 8). Additionally, runoff at sites A, B, D, and F exceeded standards for zinc concentration (EPA 1986). Runoff at sites A, D, E, and F exceeded the standards for copper concentrations (EPA 1986). The dry weather creek did not exceed any standards.

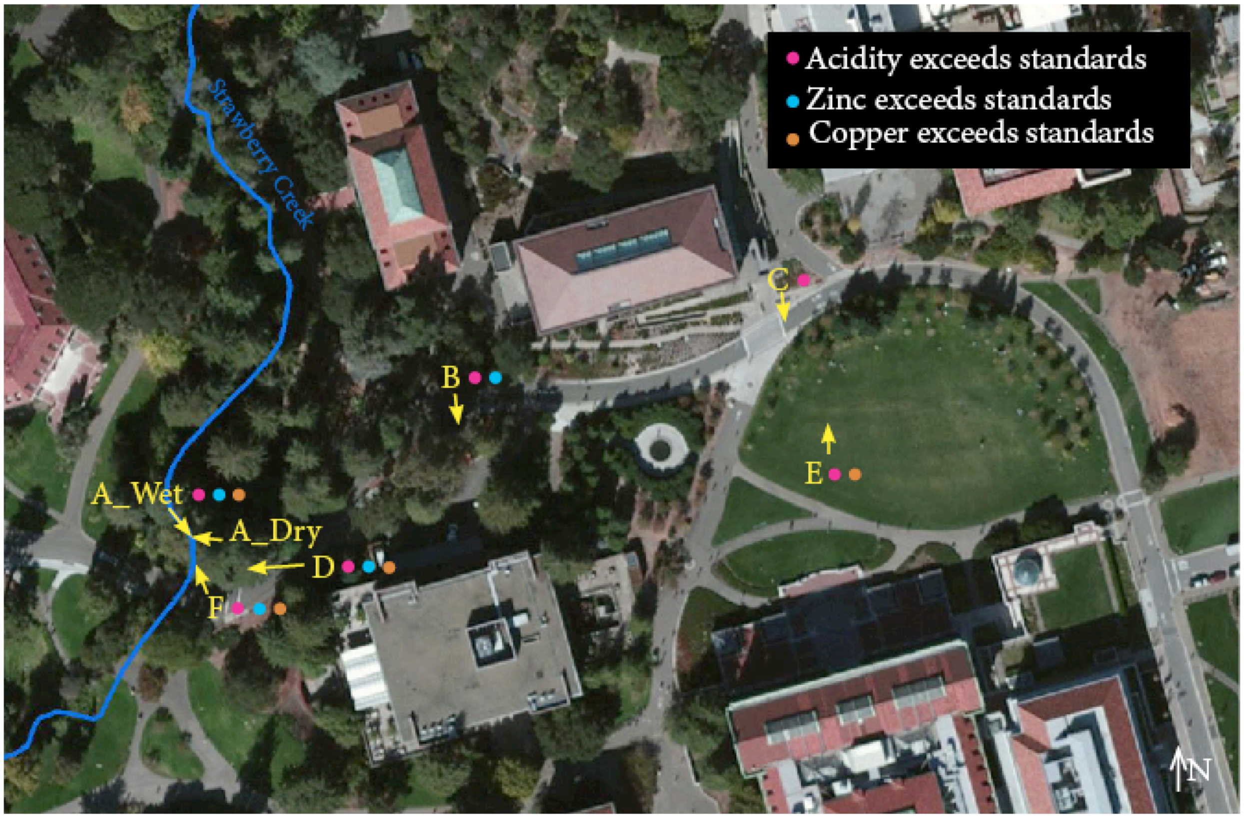

Figure 8. Violations of Water Quality Goals. This map shows the presence of the violations of EPA's water quality goals for the protection of freshwater aquatic life for three parameters: acidity, copper, and zinc, at each sample site. The color-coded dots indicate a violation.

About 2 hours into a storm event around 1:00pm on Feb. 6th 2015, I found that the creek experienced: a 28% increase in acidity, an increase in copper load by 50ppm, a 400% increase in color, a 75% drop in nitrate concentration, a 33% drop in orthophosphate concentration, a 92% drop in conductivity, and a 100% drop in zinc load (Appendix C). The hardness of the water went from "hard" to "very soft". The wet weather creek water exceeded the EPA water quality goals for the protection of freshwater aquatic life (used for the rest of this study) (EPA 1986) for copper loads by about 4 times, and for acidity by about 77%.

Stormwater runoff flowing into the North Fork of Strawberry Creek was on average 27% more acidic than the creek during dry weather. The pH values for all runoff samples and the wet weather creek were at least 20% below the EPA water quality goal of 6.5-9. The conductivity decreased by an average of 88%, making all runoff either “soft” or “very soft”. On average, the runoff contained a one-fold increase in zinc load when compared to the baseline dry weather creek water. The runoff sample with the highest zinc load was the outlet discharge (site F), with 4 times more zinc than the baseline and over 3 times more zinc than the EPA water quality goal. Runoff from sites D and B also exceeded the EPA water quality goal for zinc, by an average of 2 times. All runoff samples exceeded the EPA water quality goal for zinc by at least 3 times. The runoff samples from Memorial Glade (site E) and from the outlet discharge (site F) contained an increase of copper of 50ppm, which is almost 4 times higher than the EPA water quality goal for acute exposure to copper for aquatic life health. One road runoff sample (site D) contained an increase of 100ppm of copper, which exceeds the stated EPA standard nearly 8 times.

Most runoff samples experienced a 6-fold increase in color (measured in CAPHA Platinum Cobalt Units) from the baseline creek water, while the runoff generated by the Memorial Glade lawn (site E) had a color value 8 times higher than the baseline. The only runoff sample to contain more Nitrate-N than the baseline was the outlet discharge (site F), with a 3-fold increase in Nitrate-N. All other runoff samples contained around 4 times less Nitrate-N. None of the runoff samples contained a detectable amount of orthophosphates. Ammonia and chloramine levels were undetectable in all the water samples. Water quality goals for conductivity/TDS, nitrate-N, color, and orthophosphates were nonexistent, irrelevant, and/or dependent on other uncalculated variables. For a table of complete water quality results, see Appendix C.

Implications

The model identifies how urbanization has changed the hydrological landscape of the study site: primarily, that increasing impermeable surfaces has led to less infiltration of incoming precipitation – leading to more voluminous, faster-flowing, and more polluted runoff flows. It quantifies the magnitude and range of flow accumulation and impermeability across the study site, and identifies particular locations, such as University Drive to the north and west of Memorial Glade, where those problems are especially pronounced. In summary, my results imply that the stormwater-related problems on the site most harmful to the Strawberry Creek habitat are:

- High runoff depth, volume, and peak discharge caused by high effective imperviousness
- High flow accumulation along University Drive on the northwestern edge of Memorial Glade
- Low infiltration rates at areas of highest flow accumulation (University Drive, and around Evans Hall)
- Acid runoff with the capacity for high non-point source pollution
- Heavy metal pollution from roadways

Hydrological parameters

The increase in runoff volume, peak discharge, and runoff depth from predevelopment conditions can be attributed to a change in the composite soil curve number and runoff coefficient of the site – that is, changes in the permeability caused by the widespread addition of impervious or pavement surfaces through development projects. Because all three of those parameters rely directly on a measure of the infiltration rates of the drainage site, they all increased by the same amount. The overland flow time also depends on a measure of surface permeability, so a decrease in permeability has logically led to a decrease in flow time. Because of this, I would suggest an LID that reduces the total area of impervious surfaces on the site.

To put the results in some context, the runoff coefficient of the site under current conditions, 0.49, most closely matches the runoff coefficient identified by the City of Berkeley for detached, multi-units residential drainage areas (Hans and Maranzana 2007). This implies that any city-wide policies regarding stormwater management and LID for residential areas are also applicable to the study site and most likely, the entire UC Berkeley campus. Also, during a storm in 1987 that produced 1.09 inches of rain in 24 hours (with a rainfall intensity of 0.045in/hr), the North Fork discharge at North Gate was measured at 25.4cfs (Charbonneau 1987). My estimates imply that my study site has the capacity to produce a peak of 0.718cfs of discharge for a similar sized storm (see Appendix for calculations). Because the Upper North Fork subcatchment only covers about 8% of the total 388 acres of the entire North Fork drainage subcatchment (Hans and Maranzana 2007), most of which occurs before the stream enters campus, this comparison is reasonable.

Flow accumulation, permeability, and existing stormwater infrastructure

The most common flow-impermeability score (5, Figure 7) and soil curve number (48, Figure 3) of the site under predevelopment conditions matches the score and curve number for the natural areas by Strawberry Creek under current conditions. This implies that one method to return the site to predevelopment conditions would be to completely cover the site with surfaces similar to these natural areas (characterized by bare soil, underbrush, and redwoods). Specifically, the campus would need to remove 14 acres of impervious surface from the site to return the watershed to an effective imperviousness level considered "healthy" (Burns et al. 2014, Walsh et al. 2005a). However, this is extremely unreasonable, expensive and unnecessary, because many stormwater-related problems can be mitigated using less radical methods, such as strategically placed LID installations.

Regardless, the fact that the regions of highest flow accumulation also correspond to the regions of lowest permeability (such as along University Drive) is especially troubling because this means that the runoff here is not only very high, but also has little to no capacity or time to infiltrate down into the surface. However, the model overestimates the intensity of flow accumulation on the site because it does not directly model the potentially mitigating effects of the current stormwater infrastructure. First, the flow accumulation model treats rooftops, which are known to drain to underground infrastructure, as flat surfaces from which runoff flows downslope. Additionally, it overlooks the effect of stormwater drains, including includes a series of storm drains and man holes along University Drive around Memorial Glade, to remove runoff from the surface by routing it through an underground system of pipes that ultimately discharge at the outlet pipe at the southwestern corner of the study site. Ideally, this reduces the risk of flooding along the road and reduces overland flow volume. However, these drains often get clogged and fail to capture all the runoff as the flow rate and volume increases (personal observations). Also, these drains do nothing to treat runoff for pollution. Regardless of the placement and relative functionality of these drains, all runoff is eventually transported into Strawberry Creek, via overland flow or underground stormwater pipes. Consequently, an LID installation should intercept the runoff flow before it reaches a storm drain so it can treat it for pollution and either reroute back into the existing stormwater system or allow it to completely infiltrate into the soil and act as groundwater flow.

Sources and impacts of non-point source pollution

Although this study only tests runoff directly for the presence of zinc, copper, chloramines, nitrates, and phosphates and indirectly (via the conductivity test) for sediment load, all of the common contaminants found in urban runoff (Table 3) have the potential to affect Strawberry Creek because the study site contains most of the surface types from which these contaminants originate. Although I was only able to conclusively compare the study's water quality results to national standards for zinc, copper, and acidity, the runoff from the study site may still exceed other standards, such as for total suspended sediment or nitrates, but more site-specific information, such as the ionic content of the water and its natural nutrient load, is necessary to make further conclusions. Also, I did not detect any chloramines in runoff or the stream, despite this contaminant being flagged by UC Berkeley's Office of Environmental Health and Safety at UC Berkeley as a probable runoff contaminant on the campus (A. Massell, personal communication). This non-detection most likely exists because the source of chloramines is treated drinking water used for irrigation, and the lawns and vegetated areas of the site had not been recently irrigated.

Table 3. Contaminants typically found in urban runoff. Summary of contaminant type, potential sources, and impacts on stream habitat. All of these contaminants can occur on the UC Berkeley campus.

Pollutant	Source	Impact
Sediment (Total Suspended Sediment)	Construction sites, disturbed soil	Sediment can impede photosynthesis, respiration, growth, and other important biological functions of aquatic life. (CASQA 2003).
Oil and grease	Roadways	Oil, grease, and other hydrocarbon compounds produced from the use of vehicles can be toxic to aquatic life (CASQA 2003).
Nutrients	Lawns or vegetated areas	Excessive nutrients like nitrogen and phosphorus can lead to vegetative growth, poor dissolved oxygen levels, and eutrophication (CASQA 2003). The major anthropogenic source of nutrients is fertilizer use.
Bacteria and viruses	Sanitary sewer overflow, animal excrement	Bacteria and viruses originate from animal excrement and sanitary sewer overflow. These can be toxic to both human and aquatic life. Fecal coliform is often employed as an indicator bacterium.
Metals	Roadways	Heavy metals like lead, zinc, cadmium, copper, chromium, and nickel accumulate on artificial urban surfaces. These can bioaccumulate to very toxic levels and contaminate drinking water supplies (CASQA 2003).
Pesticides	Lawns or vegetated areas	Pesticides and other chemical agents contain toxins that undergo bioaccumulation in aquatic life (CASQA 2003).
Gross pollutants	Dumpsters and construction sites	Trash and debris from construction sites or dumpsters can harbor other harmful pollutants and can clog drains and pipes (CASQA 2003).
Chloramines	Irrigated lawns	The Office of Environmental Health and Safety at UC Berkeley has identified chloramines as a unique pollutant present on campus. Used to treat drinking water – which is used for irrigation at UC Berkeley, chloramines can be toxic to aquatic life (EPA 1986).

Regardless, water quality tests emphasized three important points. First, the results indicate that runoff and storm stream water have a consistently lower pH than the both the recommended range and the baseline. A common problem in urban environments, acid runoff is primarily caused by acid precipitation (EPA 1986). Variations in pH can change the water chemistry of the stream, which can affect the biological processes of aquatic organisms (EPA 1986). For example, many heavy metals are more harmful when dissolved in acidic water (EPA 1986). Infiltration of runoff before it reaches the creek and a buffering filter can reduce the effect of storm-related episodic acidification of the creek (EPA 2010). Second, runoff from the road contains above-standard concentrations of both zinc and copper. The primary sources of heavy metals, like zinc and copper, in an urban environment are associated with vehicles and roads, and include: tires, automobile exhaust, road asphalt, fuel combustion, parking dust, roof shingles, and gutters (EPA 1986). Heavy metals can bioaccumulate to toxic levels in aquatic organisms. (CASQA 2003). Because high heavy metal concentrations has also been a consistent historical problem in the North Fork of Strawberry Creek (Hans and Maranzana 2007), I would recommend a LID practice aimed at removing heavy metals to protect the Strawberry Creek habitat. Thirdly, runoff produced from Memorial Glade had a very high color value and high conductivity value, indicating a high suspended solids load. Suspended solids can interfere with basic biological processes of aquatic organisms, and can easily transport other pollutants such as nutrients, trace metals, and hydrocarbons (CASQA 2003). The Memorial Glade runoff also, somewhat unusually for lawn runoff, exceeded copper standards. This copper can come from fertilizers or pesticides applied to the turf, or from the soil itself. I would thus recommend a LID practice that filters contaminants from Memorial Glade, perhaps located at one of the gutters in the lawn.

Objectives of LID Installation:

The objectives of the ideal LID practice to mitigate the major stormwater-related problems of the site would thus include:

- Reduction of impermeable surfaces
- Removal of heavy metals from road runoff
- Buffering of acidic runoff
- Reduction of runoff flow and volume along the road at the north edge of Memorial Glade
- Reduction of runoff flow and volume from Memorial Glade lawn
- Reduction of suspended sediments, copper, and chloramines from Memorial Glade runoff

LOW IMPACT DEVELOPMENT (LID): SELECTION AND IMPACTS

The next section of this study will propose a Low Impact Development (LID) solution to the stormwater-related problems identified by the model and the site assessment. I will select, locate, and size the most appropriate LID installation for the study site and evaluate its impacts.

Approach: LID design philosophy and process

The LID site design process can be broken up into five steps: site assessment, definition of goals, implementation of LID principles, use of LID Best Management Practices (BMPs), and evaluation of design (LIDDC 2010). Using this five-step framework, I describe my approach to selecting the most appropriate LID Best Management Practice (BMP), selecting its location and size, and conducting an assessment of its impacts to the study site.

Selection of LID Practice

The very first step to a comprehensive site assessment should be to gather information regarding the site's hydrology, topography, soils, geology, vegetation, existing development, contamination, and other infrastructural considerations or regulatory context (LIDDC 2010). The purpose of a site assessment is to understand the constraints and opportunities for an LID practice at the site. I have conducted a site assessment (see: "Site Assessment") to evaluate current site conditions, and the model assesses the hydrologic conditions and pollutants of concern (see: "Implications"). Second, we must define the specific goals for the LID installation, which will define the level of LID implementation required for the project. The broader goal of all LID is to return the site to its predevelopment hydrological conditions, but there exists a variety of both regulatory and environmental stewardship sub-objectives that can be applied to an LID design. For example, an LID can harvest rainwater for reuse, achieve LEED certification, protect habitat, and/or help meet water quality or hydromodification requirements set by local, state, or federal regulations (LIDDC 2010). I have already identified objectives of an ideal LID installation within my study site (see "Objectives of LID Installation"). Thirdly, specific LID principles are implemented to minimize the driving causes that lead to stormwater-related problems. This step begins to bridge the planning process from identifying stormwater-related concerns to identifying potential solutions. The planning principles most relevant to the Memorial Glade study site are: minimizing directly connected impervious areas (and, conversely, maximizing permeability), and using drainage as a design element (BASMAA 1999). Other principles include minimizing construction footprint, re-vegetating disturbed areas, or implementing source control measures (LIDDC 2010). These principles should be incorporated as much as possible in any new construction project. Because this study proposes a LID installation on an already developed landscape, this third step is less important. The fourth step focuses on selecting specific LID practices to further mitigate the otherwise unavoidable impacts of stormwater runoff. There exists a number of handbooks and manuals to assist site planners to make this decision, but I have based my reasoning on the California Stormwater

Quality Association's Stormwater Best Management Practice Handbook for New Development and Redevelopment (CASQA 2003), the Bay Area Stormwater Management Agencies Association's Start at the Source manual (BASMAA 1999), and the Low Impact Development Center's Low Impact Development Manual for Southern California (LIDDC 2010). There exist six categories of LID practices (Table 4), all of which incorporate elements of three basic LID functions: capture and reuse, infiltration, and filtration (see Appendix D), and fulfill the goals of LID principles. Installation and maintenance costs should also be taken into consideration when selecting an LID practice (see Appendix E).

Table 4. Categories of LID Practices. Summary of the 6 categories of LID practices, gathered from EPA 2007.

Category of LID Practice	Description	Examples
Conservation designs	Preserve open space and natural areas to minimize the generation of runoff. These open spaces reduce runoff volume, minimize impervious surfaces, and preserve important landscape features.	Cluster development, open space preservation, reduced pavement widths, shared driveways, reduced setbacks, site fingerprinting during construction
Infiltration practices	Engineered structures or landscape features that capture and infiltrate runoff. These can reduce both the volume of runoff and the infrastructure needed to convey it, as well as recharge groundwater.	Infiltration basins and trenches, porous pavement, disconnected downspouts, rain gardens and other vegetated treatment systems
Runoff storage practices	Captures and stores runoff from impervious surfaces to be later infiltrated, evaporated, or reused. These practices can lower peak flow hydrograph, reduce flow volume, and irrigate landscapes.	Parking lot, street, and sidewalk storage; rain barrels and cisterns; green roofs; depressional storage in landscape islands
Runoff conveyance practices	Routes excess runoff from large storm events away from the site. These practices slow flow velocity, lengthen the time of concentration, and promote infiltration and filtration.	Eliminating curbs and gutters; creating grassed swales and grass-lined channels; roughening surfaces; creating long flow paths over landscaped areas; installing smaller culverts, pipes, and inlets; creating terraces and check dams
Filtration practices	Treat runoff by filtering it through media designed to remove pollutants. These practices can also provide infiltration benefits (such as reducing flow volume).	Bioretention/rain gardens; vegetated swales; vegetated filter strips/buffers
Low impact landscaping	Selection and distribution of plants to reduce impervious surfaces, improve infiltration potential, and improve the aesthetic quality of the site.	Planting native, drought-resistant plants; converting turf areas to shrubs and trees; reforestation; encouraging longer grass length; amending soil to improve infiltration

Location and Sizing

When selecting a suitable location for the chosen LID practice, it is important consider the site configuration and several design-specific constraints. These constraints include: soil group and absorption capacity, depth to groundwater, depth to bedrock, and slope (see Appendix F) (LIDDC 2010). I also considered the types of locations in which the chosen LID practice is typically installed, based on a variety of case studies.

Sizing of the LID practice is determined by the chosen practice and, if infiltration-based, the corresponding water quality volume, or the amount of water that can be managed to protect water quality (BASMAA 1999). There are a variety of methods for defining water quality volume, based on the regulatory standard and style of BMP. I used the standards outlined in the Phase II Small MS4 General Permit from the National Pollutant Discharge Elimination System that UC Berkeley is currently undergoing (SWRCB 2013). BMPs are either volume-based, in which pollutant removal depends on the volumetric capacity, or flow-based, in which pollutant removal depends on the rate of flow, and must be able to effectively treat the design runoff quantity. Volume-based BMP practices include detention, retention, and infiltration basins, and should be sized to filter the volume of annual runoff required to achieve 80% or more capture (SWRCB 2013), which in the San Francisco Bay Area correlates to the first 0.50-1.25 inches of rain, or a 2-year recurrence interval storm (BASMAA 1999). I used the highest estimate, 1.25 inches, in my calculations. Flow-based BMP practices include swales, sand filters, and screening devices, and should be designed to accommodate the peak flow produced from a rain event equal to at least 0.2 inches per hour intensity (SWRCB 2013).

Evaluation of LID Design

The fifth and final step in the LID design process is an evaluation of the LID installation. A successful LID design must meet the goals defined at the beginning of the planning process (LIDDC 2010). I estimated the changes to the study site caused by the LID installation by calculating the runoff volume produced by that surface, using the appropriate runoff coefficient as defined by the literature. I then calculated the result of this change on the total runoff volume, peak discharge, and effective imperviousness of the study site. I also compared the estimated impacts and benefits – both qualitative and quantitative – of my LID installation to the impacts of similar LID installations from case studies in the literature (BASMAA 1999, EPA 2007, CASQA 2003).

University Drive Permeable Pavement: Summary of Proposal

To mitigate the negative impacts of urban runoff from study site to Strawberry Creek, I am proposing 9,871 square feet of permeable pavement spread across three sections: the walkway on University Drive in front of the C.V. Starr East Asian Library, the edges of the University Drive road downslope from this walkway, and a portion of the Moffitt loading dock and parking. Although this installation will reduce the total runoff volume produced by the entire study site by only about 1%, it specifically caters to the primary runoff-related problems I've identified by infiltrating and filtering the one of the most severely pollutant-laden and heaviest runoff flows of the Upper North Fork subcatchment.

Design: Selection and Reasoning

To select the LID best management practice to install on the site, I first identified the primary function (infiltration, filtration, and/or storage) (see Appendix D), and appropriate design criteria (volume-based and/or flow-based) and philosophies (zero-discharge, self-treating, and/or runoff reduction) (see Appendix G) of the LID installation. Because my primary objective is to reduce runoff volume and flow accumulation over University Drive, this LID installation would need to be volume-based and runoff reducing, by providing infiltration services. In addition, to mitigate the impact of pollution to the creek, the LID would need to include self-treating philosophies such as filtration. I also want the LID installation to reduce impervious areas, because most of the stormwater-related problems I've identified originate from or correlate with impervious road surfaces. The only type of LID installation to reasonably fulfill all of these criteria in an already-developed urban landscape is permeable pavement.

Permeable pavement, as opposed to regular pavement, contains enough void space to allow flowing water to infiltrate down into the subsurface (BASMAA 1999). The pavement's infiltration rate is determined by the type, size, and depth of surface material, which can include:

brick, turf blocks, unit pavers, cobbles, pervious concrete, crushed aggregate, or others (BASMAA 1999). This surface material is sometimes underlain by a sand setting bed and/or various filter fabrics (BASMAA 1999). Most permeable pavements then contain a reservoir base course made of open-graded crushed stone. This base temporarily stores water and allows the pavement to retain its load-bearing utility. Infiltrated water can then be absorbed by the soil, or partially or completely drained by underground pipe systems.

I have selected unit pavers on sand (Figure 1) as the most appropriate type of permeable pavement for the study site, because it is: one of the cheapest types of pavement; considered ADA accessible; typically used for low volume streets, travel lanes and bikeways; easy to repair and maintain; and has a relatively low runoff coefficient, of 0.1-0.35 depending on the size and type of unit paver (BASMAA 1999). The underlying filter fabric can help remove heavy metals and other pollutants from the infiltrating water (BASMAA 1999).

Although I have selected permeable pavement as the LID practice particularly suited to mitigate the most harmful stormwater problems on the study site, other LID practices can also help alleviate Strawberry Creek's urban stream syndrome. These alternative LID installations include but are not limited to: low impact landscaping around the Memorial Glade drain to filter out lawn-related contaminants such as sediment and chloramines; permeable parking lots by Haviland Hall and McCone Hall to filter and infiltrate runoff; and screening filters at storm drains to remove various pollutants.

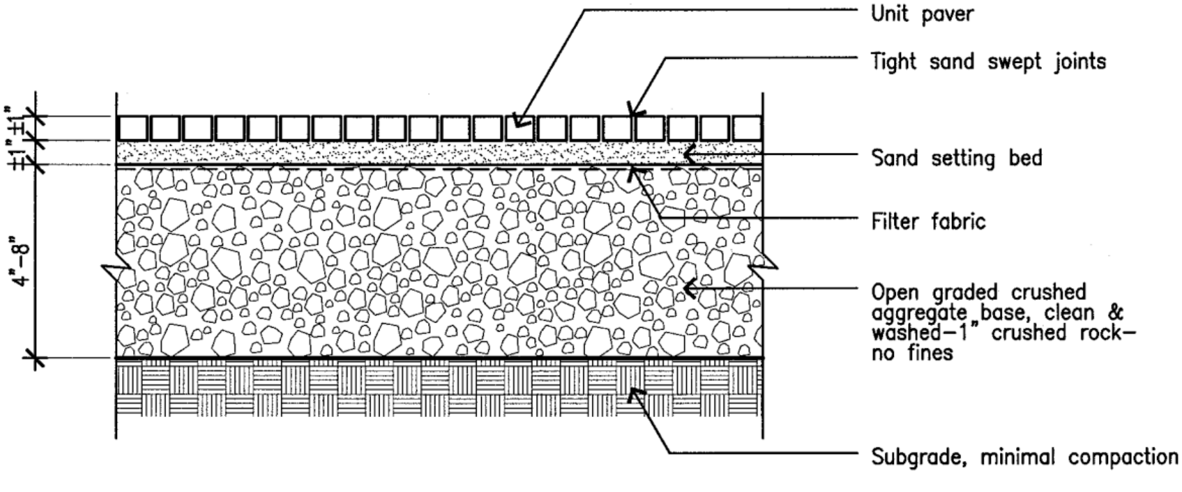

Figure 9: Unit Pavers on Sand. A sample design of an installation of unit pavers on sand. Image acquired from BASMAA 1999.

Size and Location: Selection and Reasoning

I used overlay techniques in ArcGIS to identify the areas on the study site most suitable for a permeable pavement installation. Permeable pavement installation is constrained by slope and various soil conditions such as depth to impermeable layers and hydrologic soil group type (LIDDC 2010). I was limited by data availability about soil conditions on the site, so I chose to focus uniquely on slope constraints. I used ArcGIS to produce a slope map of the site, and isolated those areas with slopes under 5°, the maximum appropriate slope for permeable pavements (LIDDC 2010). I then overlaid this layer with my flow accumulation model and selected the areas with both suitable slope and the highest flow accumulation class (Figure 10). These areas included three surfaces typically used for permeable pavement: a walkway, a parking lot, and a section of road. I decided it was unreasonable and financially irresponsible to dig up and replace only a small section of road with permeable pavement; instead, I chose to propose permeable pavement along just the edges of the road by the curbs, where runoff tends to accumulate. This LID technique already exists on Campanile Way on the UC Berkeley campus.

Because permeable pavement is an infiltration-based design, sizing is volume-based rather than flow-based. So, the water quality volume of the University Drive permeable pavement installation is 668-925 cubic feet (see calculation 1 in Appendix H). Given this value, I recommend further research to be conducted to evaluate the suitability of the site's subsurface for infiltration. The ideal soil properties for infiltration and pollutant removal include a depth to groundwater of at least 10 feet; 1.5-10% organic content; sand, loamy sand, sandy loam, or loam; a hydrologic soil group of A or B; an infiltration rate of 0.5 in/hr, and a pH of 5.5-7.5 (LIDDC 2010). If the subsurface is not suitable for infiltration or unable to infiltrate the water quality volume, the LID installation runs the risk of flooding and poor performance.

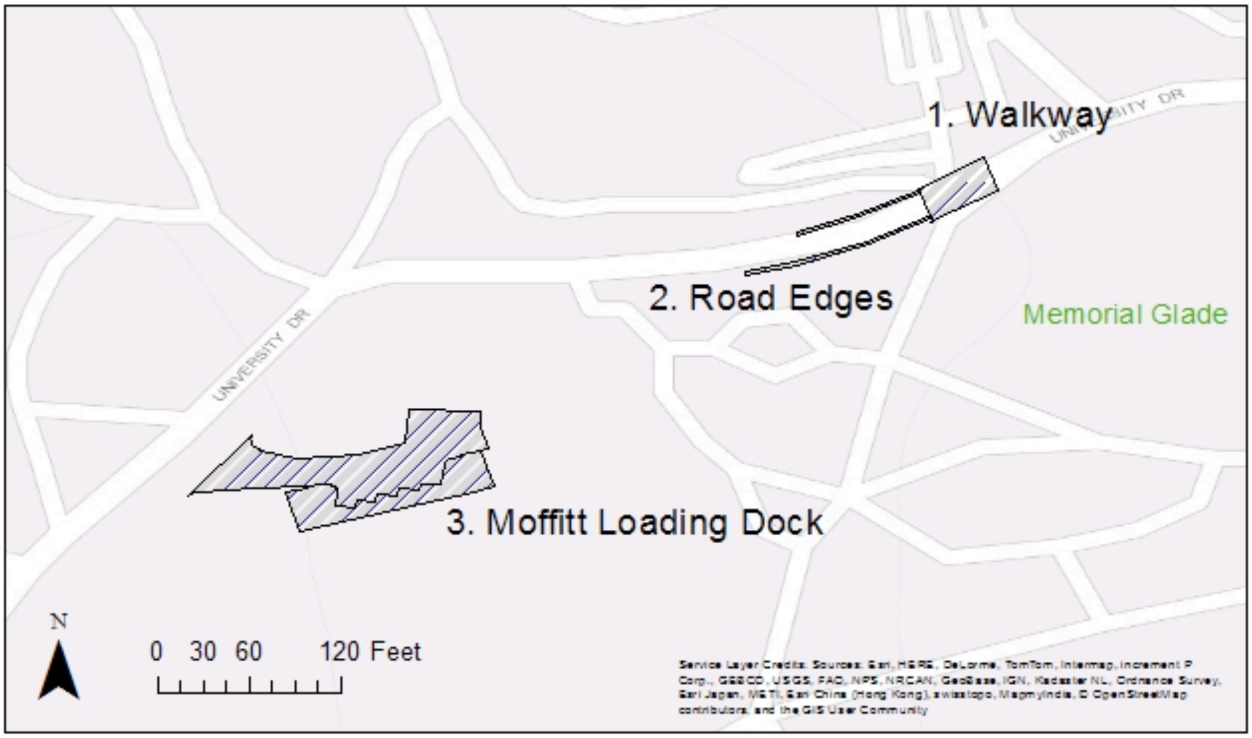

Figure 10. University Drive Permeable Pavement Proposal. This map displays a proposal for permeable pavement to be installed in three locations on and near University Drive on the UC Berkeley campus.

Impacts and Benefits: Evaluation

I have found that this LID installation only slightly decreases the total runoff volume of the site, but has a significant capacity to infiltrate and filter the site's most polluted and heaviest flow and provide important environmental benefits.

A common concern with permeable pavement is the installation cost, which is typically higher than regular pavement (EPA 2013). However, many LID installations have been found to be fiscally beneficial, especially when considering the environmental improvements and construction-related savings (EPA 2013). For the purpose of this study, unit pavers cost $9-15 per square foot, making the installation cost of the University Drive permeable pavement $88,800-148,000 (BASMAA 1999). Although little research has been conducted to quantify the environmental benefits of LID, it is generally believed that this initial investment can be offset by both qualitative and quantitative benefits to the study site (EPA 2013).

First, permeable pavement can significantly reduce runoff generation. In some studies, virtually no surface runoff was produced from permeable pavement (Brattebo and Booth 2003). The Low Impact Development Center has also labeled infiltration-based permeable pavement as "highly effective" in terms of runoff volume reduction, groundwater recharge, and peak flow reduction (LIDDC 2010). The University Drive permeable pavement will reduce the total runoff volume, peak discharge, and average runoff depth of the Upper North fork subcatchment by 1-1.4% (see calculation 3 in Appendix H). It will reduce the effective imperviousness by 1% (see calculation 2 in Appendix H). I cannot directly model the impact of this installation on flow accumulation using the ArcGIS flow accumulation model because it does not alter the site's topography. However, because unit pavers have a runoff coefficient of 0.1-0.35 and thus the capacity to infiltrate and filter 65-90% of overland flow, I expect flow accumulation over University Drive to significantly decrease. This implies that the proposed installation will effectively fulfill its runoff-reducing objectives.

Permeable pavement can also help remove pollutants from runoff (LIDDC 2010, BASMAA 1999). For example, UNI Eco-stone, a common type of unit pavers, has been found to reduce elevated zinc and copper concentrations to well below the national standards and remove all motor oil from infiltrated water, even after 6 years of use (Brattebo and Booth 2003). This indicates excellent durability and capacity for water quality improvement. So, the University Drive permeable pavement will be able to alleviate the water quality problems, particularly high heavy metal concentrations, I have identified on the site.

Furthermore, the University Drive permeable pavement installation can save money for the university by reducing the need for restoration and cleanup programs and/or stormwater infrastructure repair. Because this LID installation is located in a high-visibility, frequently visited portion of campus, it can also help the university promote an eco-friendly, pro-sustainability image and educate students, staff, faculty, and the public about sustainable landscaping. Ultimately, this LID installation can improve the health of Strawberry Creek by mitigating the symptoms of urban stream syndrome via infiltration and filtration techniques.

CONCLUSIONS

Limitations and comparison to other stormwater models

The approach to LID planning employed in this study, which I have referred to as the ArcGIS Urban Hydrology Model approach, is best suited to model the runoff flows of a small subcatchment area in urban areas with varying surface cover. Because LID planning is so dependent on each site's characteristics like surface cover and development type, I recommend the complete ArcGIS Urban Hydrology Model approach only be used on sites of similar characteristics to the Upper North Fork subcatchment, such as the Faculty Glade area on the UC Berkeley campus. Regardless, a runoff generation and/or flow accumulation model should be employed at all scales and development situations when planning an LID. Many other stormwater models exist, such as: MOUSE, MUSIC, P8, PURRS, RUNQUAl, SLAMM, StormTac, SWMM, UVQ, WBM (Elliott and Trowsdale 2007). These models have varying spatial and temporal resolutions, potential uses, runoff generation and routing methods, and contaminants and LID measure models (Elliott and Trowsdale 2007). Unique beneficial features of the ArcGIS Urban Hydrology Model include: the ability to model relative impacts of surface permeability on runoff generation using the SCS Curve Number, the ability to model both predevelopment and current conditions based on SCS Curve Number, the capacity to model the relative load and pathway of type of contaminant based on source surface, and the inclusion of actual water quality tests and calculations of hydrological parameters. No other model requires actual water quality tests to estimate pollution load (Elliott and Trowsdale 2007). On the other hand, the ArcGIS Urban Hydrology Model does not provide as many runoff generation and routing methods as do other models; these include: runoff coefficient, conceptual rainfall-runoff, SCS Curve Number, groundwater/baseflow, routing to drainage network, routing through devices, hydrologic routing in drainage network, and hydraulic routing (Elliott and Trowsdale 2007). From this list, the ArcGIS Urban Hydrology Model employs only the SCS Curve Number and conceptual rainfall-runoff (flow accumulation) methods. Other limitations of the ArcGIS Urban Hydrology Model include: a dependency of accuracy on the resolution of topographical data, a lack of flow rate calculations, a lack of ability to estimate actual pollutant load of runoff flows, and a lack of the existing drainage network. The flow accumulation model produced in the ArcGIS Urban Hydrology Model Approach is particularly misleading because it does not consider any flow diversion caused by buildings or existing stormwater drains.

Next Steps: Installation

There are a few more steps to complete before installing the LID, which should then be followed by a rigorous monitoring schedule to assess its performance. First, as previously mentioned, the subsurface should be analyzed for infiltration suitability. Then, a more accurate estimation of flow accumulation at the installation location, perhaps using one of the other rainfall-runoff models, should help a professional landscape architect or engineer design the LID practice. After installation, careful monitoring of the pollutant load in the runoff before and after the LID installation, the behavior and depth of runoff flows in and around the LID installation, and the pollutant load of the creek during wet weather will evaluate the performance of the LID. Finally, the installation of educative signage nearby the installation will allow the public – both students, staff, and campus guests – to learn about creek-friendly stormwater infrastructure and promote the campus's eco-friendly values and image.

Future Research Directions

I would highly recommend future stormwater-related research on the campus to analyze the capacity of the subsurface to infiltrate stormwater, in order to more thoroughly assess the suitability of infiltration-based LID installations and model the potential impacts on groundwater flow. More frequent water quality monitoring of both forks of Strawberry Creek and contributing runoff throughout the year would also help establish a more complete baseline assessment of the impacts and sources of pollution on stream habitat. More research on the impact of particular pollutants of concern – such as chloramines, zinc, and copper – on native species along Strawberry Creek will help the Office of Environment, Health, and Safety prioritize restoration and water quality improvement programs.

Additionally, there exist many avenues for further development and application of the ArcGIS Urban Hydrology Model approach. Particularly, a more accurate estimation of flow accumulation, especially one that incorporates the divertive impacts of existing stormwater infrastructure and buildings, is necessary to properly size and design this and other LID installations. The approach developed in this study can then be applied to plan LID installations on other subcatchments on the UC Berkeley campus (such as Faculty Glade) and elsewhere.

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REFERENCES

Booth, D.B, and C.R. Jackson. 1997. Urbanization of aquatic systems: degradation threshholds, stormwater detection, and the limits of mitigation. Journal of the American Water Resources Association 33:1077-1099.

Brattebo, B.O., Booth. D.B. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Research 37:4369-3476.

Burns, M.J., C.J. Walsh, T.D. Fletcher, A.R. Ladson, and B.E. Hatt. 2014. A landscape measure of urban stormwater runoff effects is a better predictor of stream condition than a suite of hydrologic factors. Ecohydrology: [doi: 10.1002/eco.1497]

Bay Area Stormwater Management Agencies Association [BASMAA]. 1999. Start at the Source: Design Guidance Manual for Stormwater Quality Protection. Forbes Publishing, New York, USA.

California Stormwater Quality Association [CASQA]. 2003. Stormwater Best Management Practice Handbook: New Development and Redevelopment. CASQA, Menlo Park, California, USA.

Charbonneau, R. 1987. Strawberry Creek Management Plan. Prepared for the Office of Environment, Health and Safety, University of California at Berkeley.

Charbonneau, R., Resh, V. 1992. Strawberry Creek on the University of California, Berkeley Campus: A case history of urban stream restoration. Aquatic Conservation: Marine and Freshwater Ecosystems 2 293-307.

City of Berkeley Public Works Engineering [BPWE]. 2011. Watershed Management Plan. City of Berkeley (1.0). City of Berkeley, Berkeley, CA, USA.

Curry, W.K., Wynkoop, S.E. 1999. Low-Impact Development Design Strategies: An Integrated Design Approach. Department of Environmental Resources. Prince's George County, Largo, Maryland, USA.

Elliott, A., S. Trowsdale, S. 2007. A review of models for low impact urban stormwater drainage. Environmental Modelling Software 22:394-405.

Environmental Protection Agency [EPA]. 1986. Quality Criteria for Water. Office of Water Regulations and Standards. EPA 440-5-86-001. Environmental Protection Agency, Washington DC, Maryland, USA.

Environmental Protection Agency [EPA]. 2000. Low Impact Development: A Literature Review. Office of Water Regulations and Standards. EPA-841-B-00-005. Environmental Protection Agency, Washington DC, Maryland, USA.

Environmental Protection Agency [EPA]. 2007. Reducing Stormwater Costs through Low Impact Development (LID). Strategies and Practices. Nonpoint Source Control Branch. EPA 841-F-07-006. Environmental Protection Agency, Washington DC, Maryland, USA.

Environmental Protection Agency [EPA]. 2013. Green Infrastructure Case Studies: Municipial Policies for Managing Stormwater with Green Infrastructure. Office of Wetlands, Oceans and Watersheds. EPA-841-F-10-004. Environmental Protection Agency, Washington DC, Maryland, USA.

Hans, K. 2011. UC Berkeley Campus Surface Permeability Map. Prepared for the Office of Environment, Health and Safety, University of California at Berkeley.

Hans, K., Maranzana, S. 2007. University of California, Berkeley Strawberry Creek Hydrology – 2006 Status Report. Office of Environmental Health and Safety. 2006 Status Report. University of California at Berkeley, Berkeley, CA, USA.

Holman-Dodds, J.K., Bradley, A.A., Potter, K.W. 2003. Evaluation of hydrologic benefits of infiltration based urban storm water management. Journal of the American Water Resources Association 39:205-215.

Komínková, D. 2012. The Urban Stream Sydrome – a Mini-Review. The Open Environmental & Biological Monitoring Journal 5:24-29.

Low Impact Development Center, Inc [LIDDC]. 2010. Low Impact Development Manual for Southern California: Technical Guidance and Site Planning Strategies. Southern California Stormwater Monitoring Coalition and State Water Resources Control Board. Low Impact Development Center, Beltsville, Maryland, USA.

Massell, Aysha. Personal communication. Sept. – March 2014.

Paul, M.J., Meyer, J.L. 2001. Streams in the Urban Landscape. Annual Review of Ecology and Systematics 32:333-365.

Pine, Tim. Personal communication. Feb. 2014.

Soil Conservation Service [SCS]. 1985. National Engineering Handbook. Section 4-Hydrology. United States Department of Agriculture, Washington DC, Maryland, USA.

State Water Resources Control Board [SWRCB]. 2013. Phase II Small MS4 General Permit. 2013-0001-DWQ. California Environmental Protection Agency,

United States Department of Agriculture [USDA]. 1986. Urban Hydrology for Small Watersheds. 210-VI-TR-55. Natural Resources Conservation Service, United States Department of Agriculture, Washington DC, Maryland, USA.

Vassilios, A.T., Hamid, R. 1997. Modeling and Management of Urban Stormwater Runoff Quality: A Review. Water Resources Management 11:137-164.

Vera, A. 2010. Storm Sewer System Map. Produced for the University of California, Berkeley Physical Plant Campus Services.

Walsh, C.J., T.D Fletcher, and A.R. Ladson. 2005a. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. Journal of the North American Benthological Society 24(3):690-705.

Walsh, C. J., A.H. Roy, J.W. Feminella, P.D Cottingham, P.M Groffman, and R.P Morgan. 2005b. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24(3):706-723.

APPENDIX A: Seelye Chart

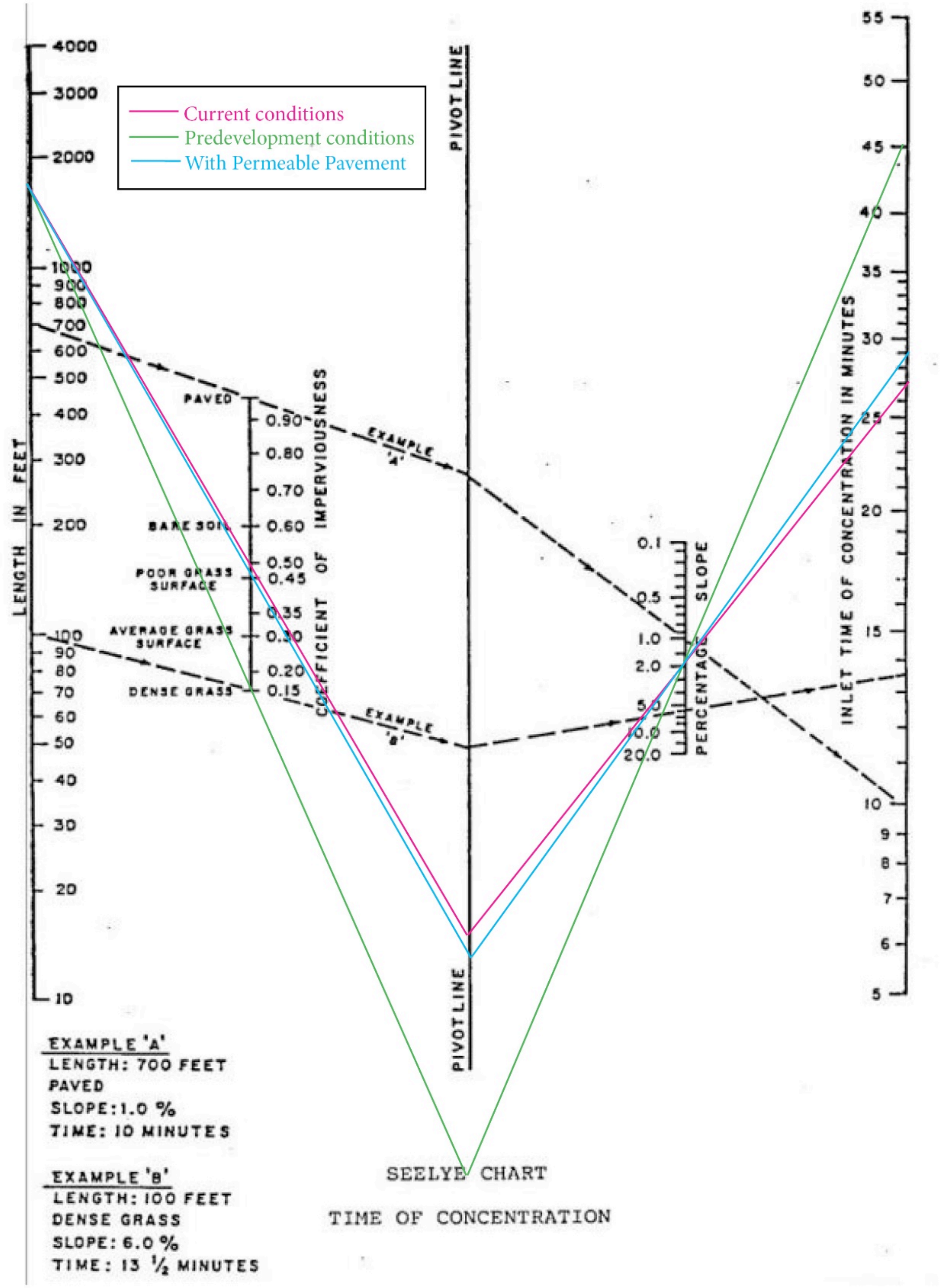


Figure A1. Overland Flow Time. Overland flow time for current, predevelopment, and new (with permeable pavement) conditions was roughly estimated using the Seelye Chart method. Image from: http://water.me.vccs.edu/courses/CIV246/lesson8_3.htm

APPENDIX B: Flow Accumulation Sample Calculation

1). Contributing drainage area for each flow class

Contributing Drainage Area (A_d) = Flow Accumulation Value (F) * Cell Area (A_c)

$A_c = 45.5\ ft^2$

Sample calculation for flow class 15:
Minimum: $A_d = 8{,}114.6765 * 45.5\ ft^2 = 368{,}803\ ft^2$
Maximum: $A_d = 11{,}939 * 45.5\ ft^2 = 542{,}614\ ft^2$

2). Average accumulated runoff for each flow class

Accumulated Runoff (R) = Runoff Depth for Current Conditions (Q_r) * Contributing Drainage Area (A_d)

Q_r = 1.4 inches (average runoff depth for 2.66 in rainfall event under current conditions)

Sample calculation for flow class 15:
Minimum: $R = 1.4$ inches * (1 ft / 12 inches) * $368{,}803\ ft^2 = 43{,}214\ ft^3$
Maximum: $R = 1.4$ inches * (1 ft / 12 inches) * $542{,}614\ ft^2 = 63{,}581\ ft^3$

3). Percent of total site area covered by each flow class

% Area of Total Site Area (A_f) = [Cell Count (C) * Cell Area (A_c)] / Total Area (A_t) * 100

Sample calculation for flow class 15:
$A_c = (60 * 45.5\ ft^2) / 1{,}338{,}141\ ft^2 * 100 = 0.20\ \%$

APPENDIX C: Water Quality Test Results

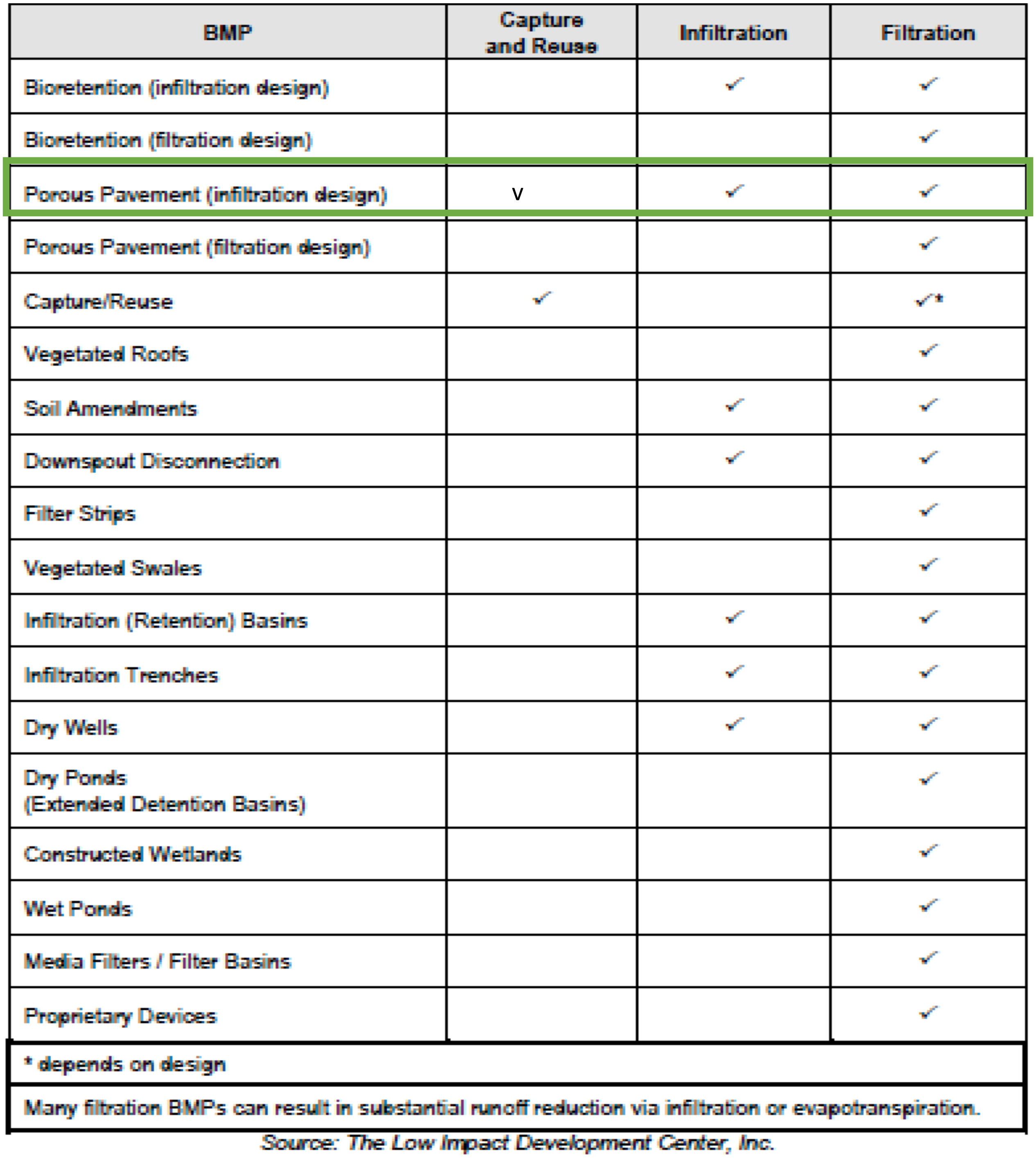
Table A1. Water Quality Results. Measured water quality parameters for samples of creek and runoff from the study site. Wet weather samples were taken within 3 hours of the start of the storm event on Feb. 6, 2015. Dry weather samples were taken on Feb. 3, 2015. All samples tested within 10 days of sampling date.

Type	Creek (dry)	Creek (dry)	Creek (wet)	Creek (wet)	Road runoff	Road runoff	Road runoff	Lawn Runoff	Outlet Discharge	Water Quality Goals**
Site	Eucalyptus Grove	A	A	Eucalyptus Grove	B	C	D	E	F	--
Date	2001*	2015	2015	2000*	2015	2015	2015	2015	2015	--
Temp (°F)	-	55.6	57.2	-	56.5	59.7	57.9	58.2	58.6	--
pH	7.5	7	5	-	5	5	5	5.5	5	6.5-9
Chloramine	-	ND	ND	-	ND	ND	ND	ND	ND	--
Nitrate-N (ppm)	-	0.8	0.2	-	0.3	0.2	0.2	<0.2	1	
Phosphorus (ppm orthophosphates)	-	0.3	0.2	-	<0.2	<0.2	<0.2	<0.2	<0.2	--
Conductivity (µS/cm)	-	687	56.5	-	45.2	33.7	31	106	166.1	Depends on ion concentrations
Hardness****		Hard	Very Soft		Very Soft	Very Soft	Very Soft	Very Soft	Soft	--
Zinc (µg/L)	22	100	0	620	300	100	200	0	400	120 / 120***
Copper (µg/L)	ND	0	50	130	0	0	100	50	50	13 / 9.0***
Color (CAPHA Platinum Cobalt Units)	-	20	100	-	100	150	150	400	40	NA
Trash	-	6	2	-	3	0	0	10	2	--

*Results found in Hans and Maranzana 2006.
** National Recommended Water Quality Criteria for Freshwater Aquatic Life (EPA 1986).
*** Criterion presented as maximum concentrations and continuous concentrations.
****Hardness estimated based on conductivity range (EPA 1986)

APPENDIX D: Low Impact Development Functions

Table A2. LID Functions. LID best management practices can provide up to three functions. Relevant practice is boxed in green. Table acquired from LIDDC 2010.

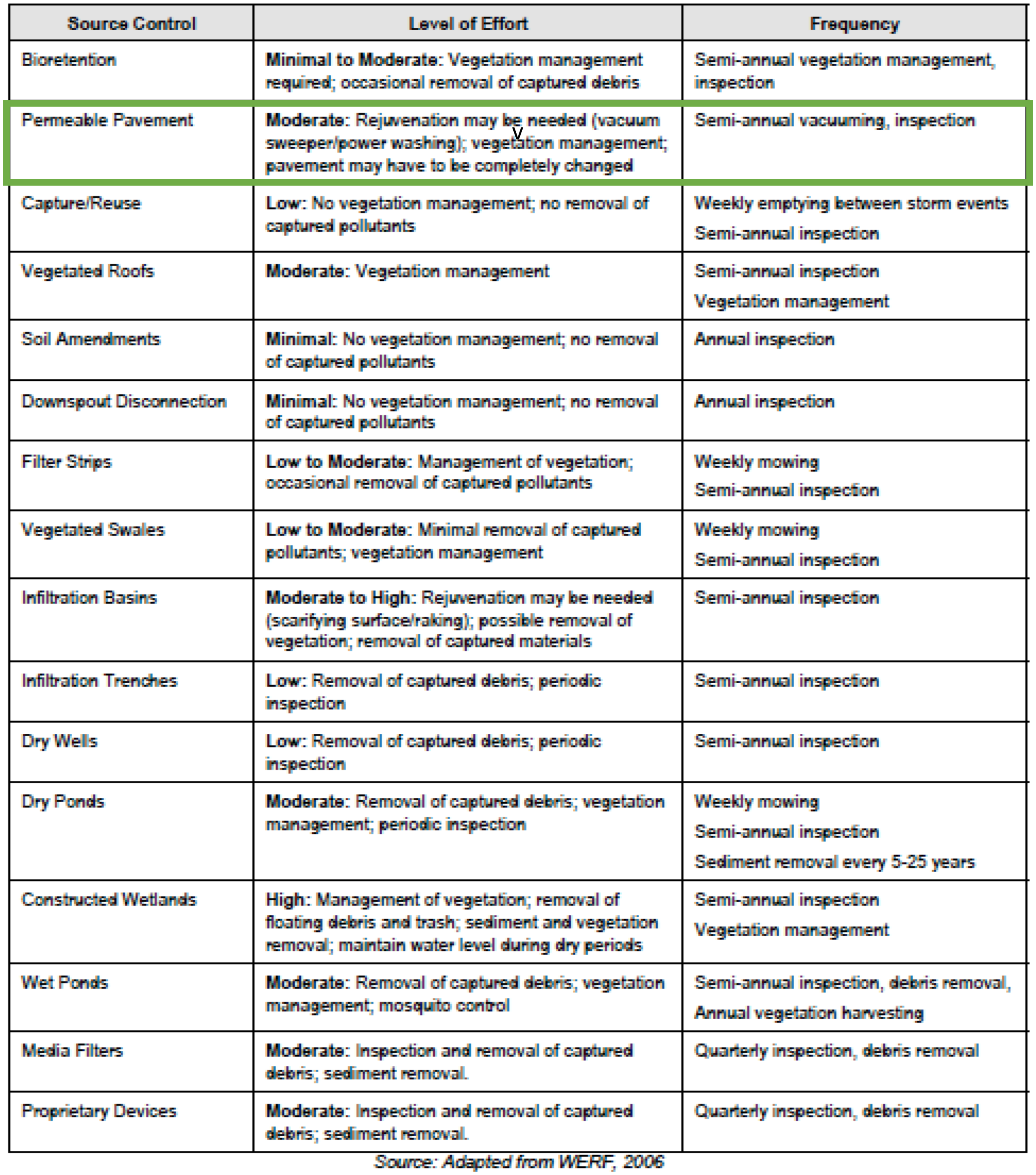


BMP	Capture and Reuse	Infiltration	Filtration
Bioretention (infiltration design)		✓	✓
Bioretention (filtration design)			✓
Porous Pavement (infiltration design)	v	✓	✓
Porous Pavement (filtration design)			✓
Capture/Reuse	✓		✓*
Vegetated Roofs			✓
Soil Amendments		✓	✓
Downspout Disconnection		✓	✓
Filter Strips			✓
Vegetated Swales			✓
Infiltration (Retention) Basins		✓	✓
Infiltration Trenches		✓	✓
Dry Wells		✓	✓
Dry Ponds (Extended Detention Basins)			✓
Constructed Wetlands			✓
Wet Ponds			✓
Media Filters / Filter Basins			✓
Proprietary Devices			✓
* depends on design			
Many filtration BMPs can result in substantial runoff reduction via infiltration or evapotranspiration.			

Source: The Low Impact Development Center, Inc.

APPENDIX E: Low Impact Development Maintenance Costs

Table A3. LID Maintenance Costs. Summary of level of effort and frequency of maintenance for a selection of LID best management practices. Relevant practice is boxed in green. Table acquired from LIDDC 2010.

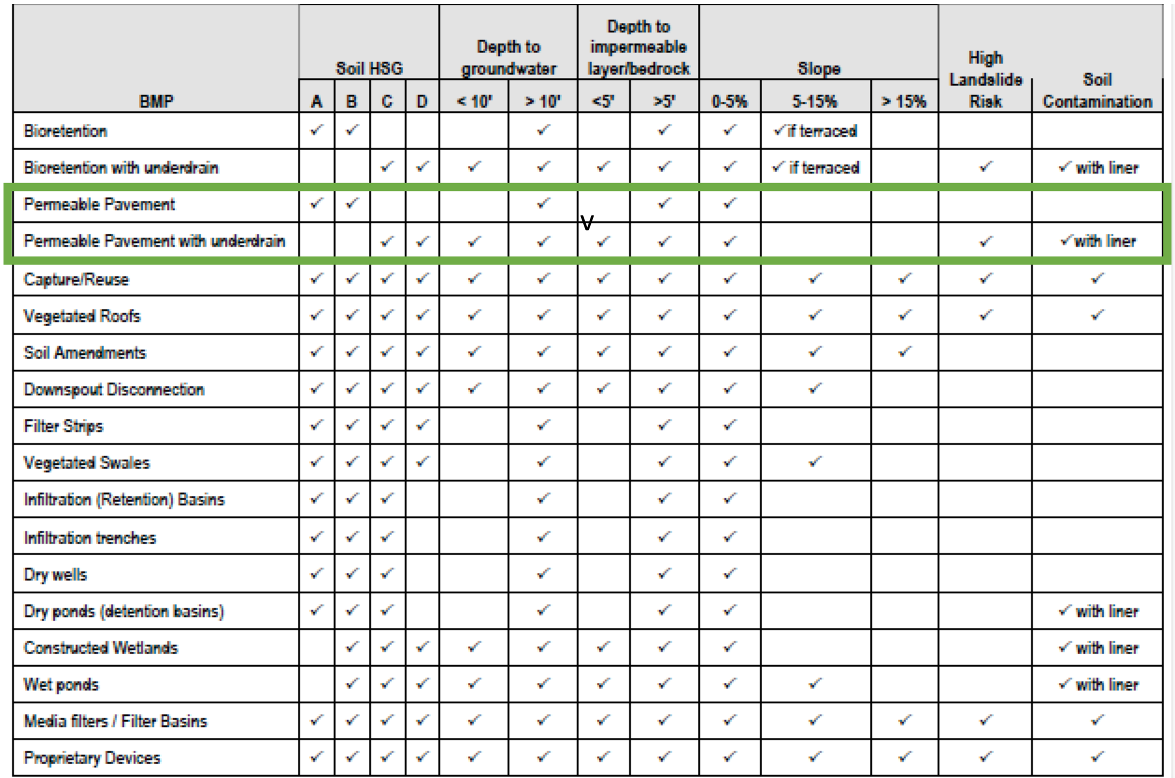


Source Control	Level of Effort	Frequency
Bioretention	**Minimal to Moderate:** Vegetation management required; occasional removal of captured debris	Semi-annual vegetation management, inspection
Permeable Pavement	**Moderate:** Rejuvenation may be needed (vacuum sweeper/power washing); vegetation management; pavement may have to be completely changed	Semi-annual vacuuming, inspection
Capture/Reuse	**Low:** No vegetation management; no removal of captured pollutants	Weekly emptying between storm events Semi-annual inspection
Vegetated Roofs	**Moderate:** Vegetation management	Semi-annual inspection Vegetation management
Soil Amendments	**Minimal:** No vegetation management; no removal of captured pollutants	Annual inspection
Downspout Disconnection	**Minimal:** No vegetation management; no removal of captured pollutants	Annual inspection
Filter Strips	**Low to Moderate:** Management of vegetation; occasional removal of captured pollutants	Weekly mowing Semi-annual inspection
Vegetated Swales	**Low to Moderate:** Minimal removal of captured pollutants; vegetation management	Weekly mowing Semi-annual inspection
Infiltration Basins	**Moderate to High:** Rejuvenation may be needed (scarifying surface/raking); possible removal of vegetation; removal of captured materials	Semi-annual inspection
Infiltration Trenches	**Low:** Removal of captured debris; periodic inspection	Semi-annual inspection
Dry Wells	**Low:** Removal of captured debris; periodic inspection	Semi-annual inspection
Dry Ponds	**Moderate:** Removal of captured debris; vegetation management; periodic inspection	Weekly mowing Semi-annual inspection Sediment removal every 5-25 years
Constructed Wetlands	**High:** Management of vegetation; removal of floating debris and trash; sediment and vegetation removal; maintain water level during dry periods	Semi-annual inspection Vegetation management
Wet Ponds	**Moderate:** Removal of captured debris; vegetation management; mosquito control	Semi-annual inspection, debris removal, Annual vegetation harvesting
Media Filters	**Moderate:** Inspection and removal of captured debris; sediment removal.	Quarterly inspection, debris removal
Proprietary Devices	**Moderate:** Inspection and removal of captured debris; sediment removal.	Quarterly inspection, debris removal

Source: Adapted from WERF, 2006

APPENDIX F: Low Impact Development Constraints

Table A4. LID Constraints. A summary of development constraints for a selection of LID best management practices. Relevant practices are boxed in green. Table acquired from LIDDC 2010.

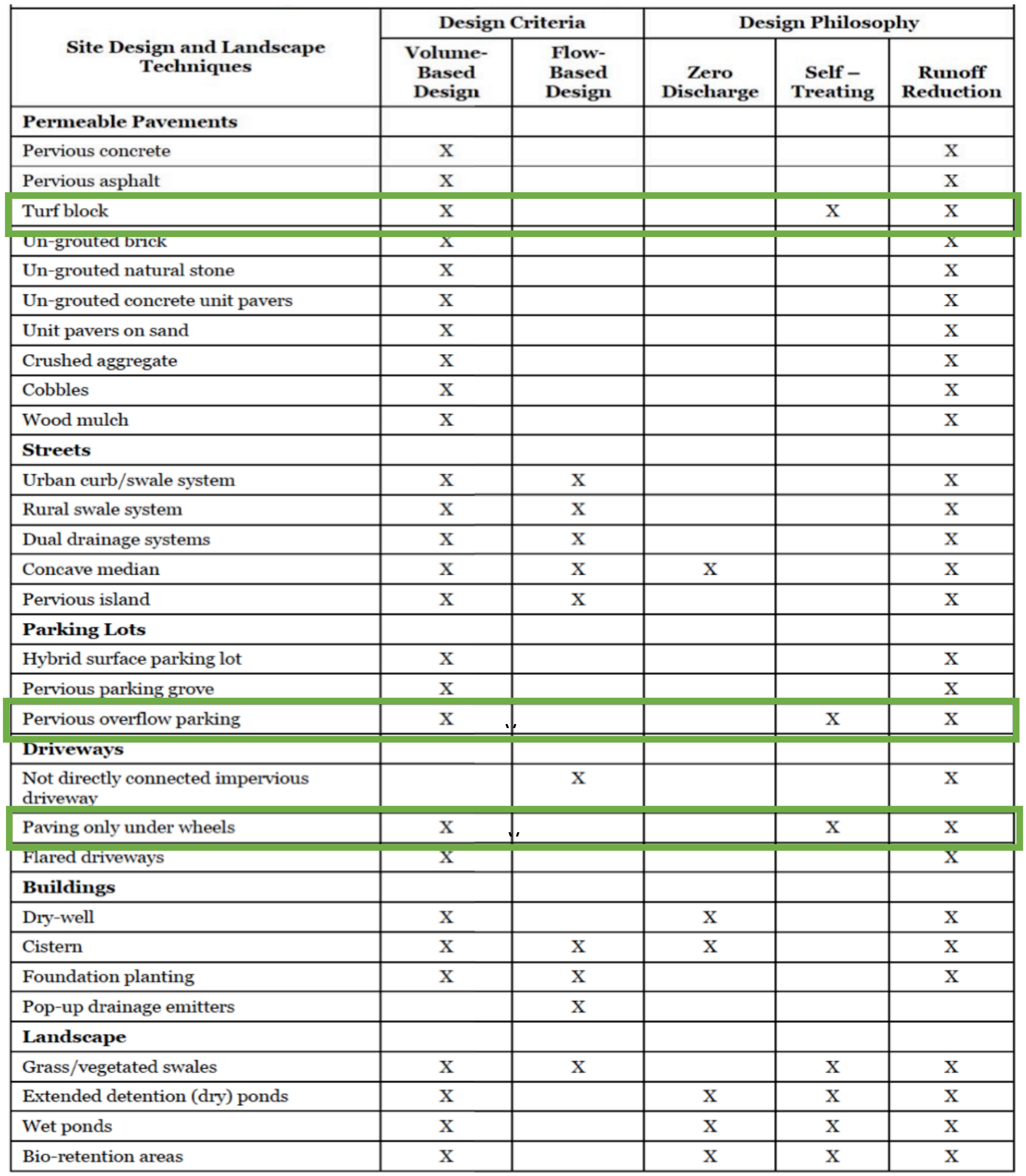


BMP	Soil HSG				Depth to groundwater		Depth to impermeable layer/bedrock		Slope			High Landslide Risk	Soil Contamination
	A	B	C	D	< 10'	> 10'	<5'	>5'	0-5%	5-15%	> 15%		
Bioretention	✓	✓				✓		✓	✓	✓if terraced			
Bioretention with underdrain			✓	✓	✓	✓	✓	✓	✓	✓ if terraced		✓	✓ with liner
Permeable Pavement	✓	✓				✓	V	✓	✓				
Permeable Pavement with underdrain			✓	✓	✓	✓	✓	✓	✓			✓	✓with liner
Capture/Reuse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vegetated Roofs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Soil Amendments	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Downspout Disconnection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Filter Strips	✓	✓	✓	✓		✓		✓	✓				
Vegetated Swales	✓	✓	✓	✓		✓		✓	✓	✓			
Infiltration (Retention) Basins	✓	✓	✓			✓		✓	✓				
Infiltration trenches	✓	✓	✓			✓		✓	✓				
Dry wells	✓	✓	✓			✓		✓	✓				
Dry ponds (detention basins)	✓	✓	✓			✓		✓	✓				✓ with liner
Constructed Wetlands		✓	✓	✓	✓	✓	✓	✓	✓				✓ with liner
Wet ponds		✓	✓	✓	✓	✓	✓	✓	✓	✓			✓ with liner
Media filters / Filter Basins	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Proprietary Devices	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Source: The Low Impact Development Center, Inc.

APPENDIX G: Low Impact Development Design Criteria and Philosophy

Table A5. LID Design Criteria and Philosophies. Summary table of design criteria and philosophies for selection of LID best management practices. Relevant practices are boxed in green. Table acquired from LIDDC 2010.



Site Design and Landscape Techniques	Design Criteria		Design Philosophy		
	Volume-Based Design	Flow-Based Design	Zero Discharge	Self – Treating	Runoff Reduction
Permeable Pavements					
Pervious concrete	X				X
Pervious asphalt	X				X
Turf block	X			X	X
Un-grouted brick	X				X
Un-grouted natural stone	X				X
Un-grouted concrete unit pavers	X				X
Unit pavers on sand	X				X
Crushed aggregate	X				X
Cobbles	X				X
Wood mulch	X				X
Streets					
Urban curb/swale system	X	X			X
Rural swale system	X	X			X
Dual drainage systems	X	X			X
Concave median	X	X	X		X
Pervious island	X	X			X
Parking Lots					
Hybrid surface parking lot	X				X
Pervious parking grove	X				X
Pervious overflow parking	X			X	X
Driveways					
Not directly connected impervious driveway		X			X
Paving only under wheels	X			X	X
Flared driveways	X				X
Buildings					
Dry-well	X		X		X
Cistern	X	X	X		X
Foundation planting	X	X			X
Pop-up drainage emitters		X			
Landscape					
Grass/vegetated swales	X	X		X	X
Extended detention (dry) ponds	X		X	X	X
Wet ponds	X		X	X	X
Bio-retention areas	X		X	X	X

APPENDIX H: Low Impact Development Calculations

1). Water quality volume (WQV)

WQV = Total Precipitation Volume (V_{p_s}) – LID Runoff Volume (Q_{r_pp})

V_{p_s} = Standard for Rainfall Depth (P_s) * Area of Installment (A)

P_s = 1.25 in (high estimate of the 80% capture rate for San Francisco Bay Area (BASMAA 1999))

V_{p_s} = 1.25 in * (1ft / 12in) * 9,871 ft^2 = 1,028 ft^3

Q_{r_pp} = Runoff Coefficient (C) * V_{p_s}

Minimum: Q_{r_pp} = 0.1 * 1,028 ft^3 = 103 ft^3

Maximum: Q_{r_pp} = 0.35 * 1,028 ft^3 = 360 ft^3

Minimum: WQV = 1,028 ft^3 - 103 ft^3 = 925 ft^3

Maximum: WQV = 1,028 ft^3 - 360 ft^3 = 668 ft^3

2). Effective Imperviousness of site with LID surface (EI_{new})

EI_{new} = New Impervious Area (A_{i_new}) / Total Area (A_t) * 100

A_{i_new} = Current Impervious Area (A_i) – LID Area (A_{pp}) = 817,308 ft^2 – 9,871 ft^2 = 907,437 ft^2

EI_{new} = 907,437 ft^2 / 1,338,141 ft^2 * 100 = 60.3%

3). Runoff volume of site with LID surface (Q_{new})

Q_{new} = Current Runoff Volume (Q) – Precipitation Infiltrated by LID (P_i)

P_i = Total precipitation accumulated on LID surface (V_p) – LID Runoff Volume (Q_{pp})

Q_{pp} = Runoff Coefficient (C) * Precipitation for design storm (P) * Area of Installment (A)

Minimum: Q_{pp} = 0.1 * 2.66 in * (1 ft / 12 in) * 9,871 ft^2 = 219 ft^3

Maximum: Q_{pp} = 0.35 * 2.66 in * (1 ft / 12 in) * 9,871 ft^2 = 766 ft^3

V_p = Precipitation for design storm (P) * Area of Installment (A)

V_p = 2.66 in * (1 ft / 12 in) * 9,871 ft^2 = 2,188 ft^3

Minimum: P_i = 2,188 ft^3 – 219 ft^3 = 1,969 ft^3

Maximum: P_i = 2,188 ft^3 – 766 ft^3 = 1,422 ft^3

Minimum: Q_{new} = 156,797 ft^3 – 1,969 ft^3 = 154,828 ft^3

Maximum: Q_{new} = 156,797 ft^3 – 2,188 ft^3 = 154,609 ft^3