Appendix 03.1 - Hydrologic Modeling the "Levels of Green"

01 – INTRODUCTION

Regulations in the City and County of Denver's (CCD) Municipal Separate Storm Sewer System Permit do not require roadway projects to include stormwater control measures (SCM) to mitigate water quality impacts unless the project disturbs >1.0 ac. CCD has an opportunity to provide runoff and water quality control from all right-of-way construction projects by including green infrastructure even if the project does not trigger this regulatory requirement.

Green infrastructure can include SCMs as described in CCD's *Ultra Urban Green Infrastructure Guidelines*[1] that store the Water Quality Capture Volume (WQCV): a volume storage standard based on the SCM's tributary area and percent impervious cover[2]. However, green infrastructure projects can also use simpler measures that do not store the WQCV but add pervious, vegetated areas to the landscape that filter and infiltrate stormwater runoff. These SCMs can include trees that mitigate the urban heat island and improve urban streetscapes for bikers and pedestrians.

A core concept of the *Denver Green Continuum: Streets* is that the design of green infrastructure in the public right-of-way separated into five Levels of Green. At higher Levels of Green there is greater stormwater volume control than at lower Levels, but the amount of engineering and construction impacts is higher (Figure A.03.1.1). However, the SCMs that comprise each Level of Green have not been defined yet.

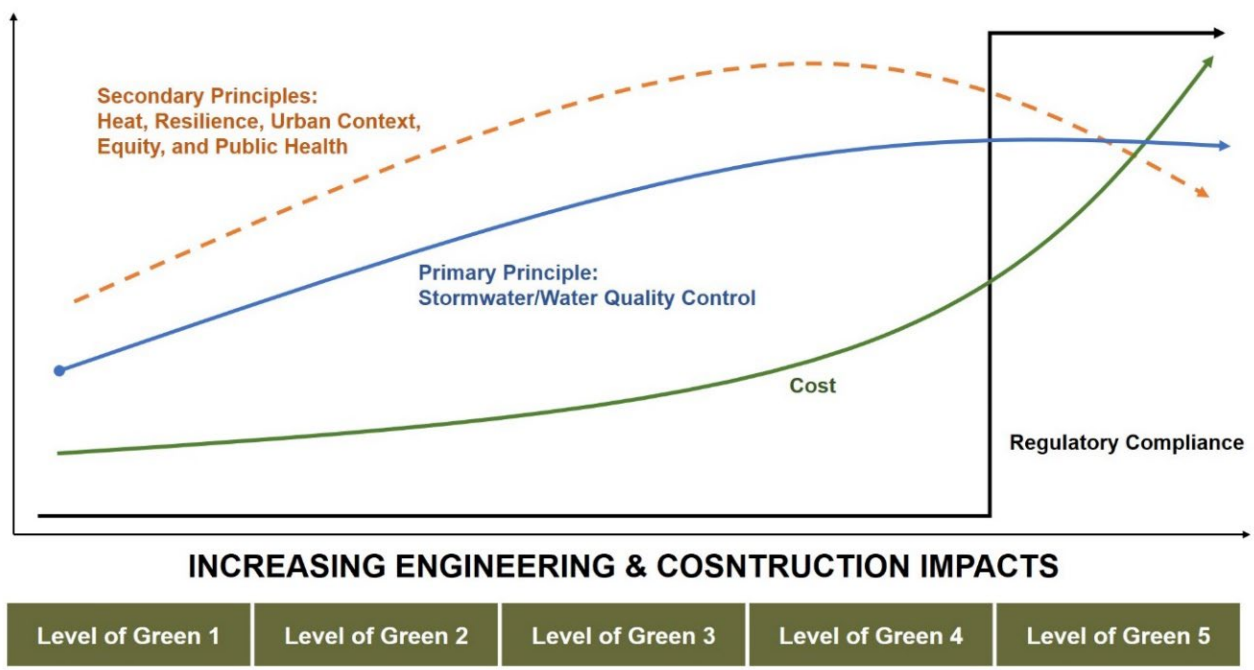

Figure A.03.1.1: The Green Continuum Concept

01.02 – PURPOSE OF STUDY

The purpose of this analysis is to identify potential green infrastructure SCMs, to model their hydrologic performance, and to use the model results to define the SCMs that fall into each Level of Green. This analytical procedure is strongly driven by simulated hydrologic performance, including runoff reduction and peak flow reduction of the water quality storm, because stormwater management is the primary principle of the *Denver Green Continuum: Streets*.

02 – METHODS

02.01 – SUMMARY

1. Identify a generic street cross sections suitable for the SCMs
2. Conceptualize a suite of SCMs and generate basic design parameters such as length, width, depth, and spacing based on city standards and best professional judgement
3. Use the Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM) to build a series of models for each SCM
    a. These include 2 control layouts for comparison and 24 invention layouts representing the SCM configurations
    b. The layouts will have varied soil type, longitudinal slope, cross slope, and detention storage to account for site and model parameter variability
4. For each SWMM model simulate:
    a. The water quality design storm: a 2-hr design storm with a 0.6" point rainfall depth
    b. 10 years of continuous rainfall-runoff simulations
5. Compare the results for each layout to the results of the control layouts to determine the SCM's performance in terms of percent reductions of peak flow and runoff
    a. Runoff reduction is used as a proxy for water quality improvement assuming wet weather pollutant loads will decrease linearly with runoff volume reduction
6. Use the results to separate the SCMs into different Levels of Green and quantify a range of hydrologic performance of each Level

02.02 – MODEL DOMAIN AND DISCRETIZATION

This analysis is focused on managing runoff from the public right-of-way within the public right-of-way. Therefore, the model domain was half of a single, idealized city block. Future analyses can easily scale up results from this study to sub-basin and basin scales based on the number of city blocks.

The right-of-way cross section was first divided into seven zones (Figure A.03.1.2). Then, this cross section was converted to a generic street plan (Figure A.03.1.3).

Draft versions of CCD's *Complete Street Design Guidelines*[3] were reviewed to understand current and planned street typologies and cross sections to help prescribe dimensions to each of the seven zones. Example typologies from the *Complete Street Design Guidelines* are "Downtown Arterial", "Commercial Collector", and "Residential Local". The original intent was to model each SCM considered in each street typology. Ultimately, it was determined that one general street typology would be enough for this analysis because the SCMs under consideration would contribute more to hydrologic variability than the differences in street typologies described in the *Complete Street Design Guidelines*.

The idealized half city block was set at 400 ft long in the direction of traffic and 40 ft wide in the perpendicular direction (Figure A.03.1.3). The average and median street segment length in the City and County of Denver is 346 ft and 473 ft, respectively. A 40 ft width was chosen as it is half of 80 ft, which is the most commonly occurring right-of-way width in CCD, excluding residential areas. The plan assumed that the block was drained by one storm sewer inlet on the downstream end of the block, and that one quarter of an intersection drains along the block's curb (Figure A.03.1.3).

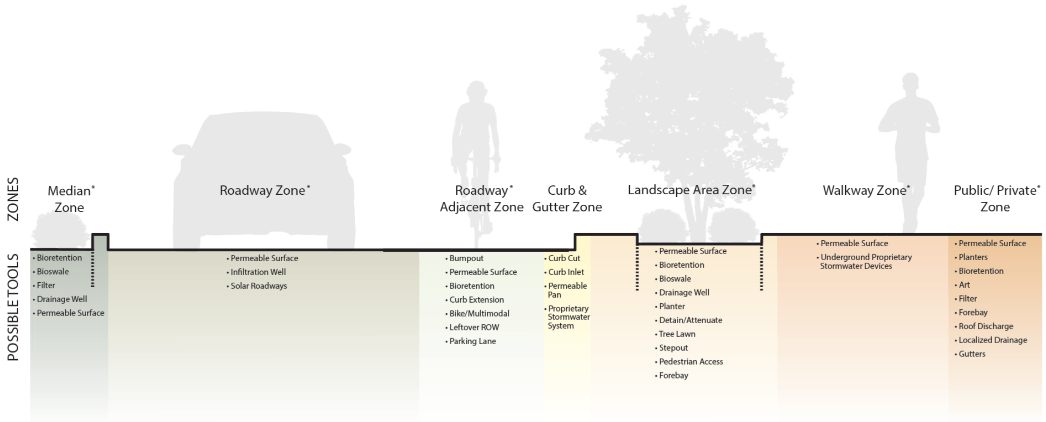

Figure A.03.1.2: Seven zones in the right-of-way perpendicular to traffic flow

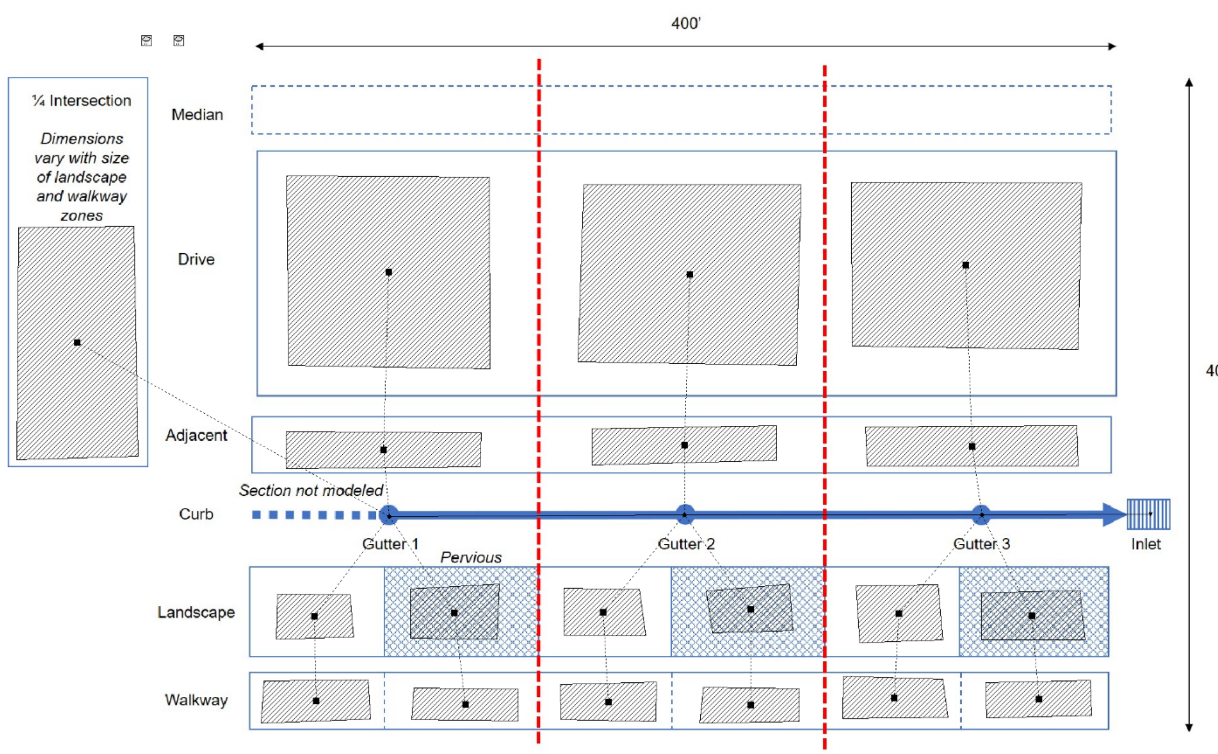

Figure A.03.1.3: Generic half city block in plan view showing a single layout of SWMM subcatchments in hatched polygons and their hydrologic connectivity

The model domain was then further discretized into three sections in the direction of flow, indicated by the dashed red lines in Figure A.03.1.3. Each zone and third block plus the quarter intersection was modeled as a subcatchment in SWMM, shown as hatched polygons in Figure A.03.1.3. This discretization allows for more hydrologic variability along the block. If the SCM layout required, the Walkway and Landscape zones were also subdivided to account for the existence of a pervious area within the landscape zone and to route flow from the Walkway into the pervious Landscape area.

The length, width, and hydraulic connectivity of each of the subcatchments shown in Figure A.03.1.3 were altered for each simulation, described below. However, the block always fit within a 40' wide and 400' long block. Other site and model parameters such as longitudinal slope, road cross slope, and soil type were also systematically varied as described below.

Runoff from each of the zones was conveyed to the inlet by a 6" curb-and-gutter open channel between the Landscape and Adjacent zones, however the transect of the curb-and-gutter channel varied as road cross slopes were changed.

02.03 – CONTROL SIMULATIONS

First, two control layouts were established to compare the results of SCMs simulations against:

1. **Historic Control**: fully impervious, with the sidewalk attached to the curb and a paved landscape zone. This is meant to represent the highest runoff conditions found in the city.
   - A 100% impervious Drive zone, 26 feet wide
     - For modeling simplicity, the Adjacent zone was modeled as part of the drive Zone
   - A 100% impervious, 8' wide Landscape zone
   - A 100% impervious, 6' wide Walkway zone
   - A 100% impervious intersection, 26' by 26' long

2. **Tree Grate Control**: Like the historic control, with the addition of 11 trees to the Landscape zone each set in a 5' x 5' tree grate. The number of trees is the most that can fit in the block, per Denver Office of the City Forester's current standards.
   - A 100% impervious Drive zone, 26 feet wide
     - For modeling simplicity, the Adjacent zone was modeled as part of the Drive zone
   - 8' wide Landscape zone, with 11 5' x 5' openings for tree grates where infiltration can occur
   - A 100% impervious Walkway zone, 6' wide
     - Only the walkway area directly adjacent to the tree grates is routed to the pervious landscape area for infiltration
   - A 100% impervious intersection, 26' by 26'

02.04 – SCM SIMULATIONS

The 24 different SCM layouts were organized into 4 groups and are listed below. Refer to Table A.03.1.1 for a numerical description of the layouts that includes variables such as percent impervious cover, the percent of directly connected impervious area (DCIA) routed to the storm inlet without first passing a pervious area, and the percent of the required WQCV stored by the SCMs, where applicable.

Table A.03.1.1: Numerical Summary of the SWMM layouts

Simulation Number	Description	Impervious Cover [%]	DCIA [% of Total Area]	Pervious Area [ft^2]	Pervious Area Storage Depth [in]	Tributary Area to Pervious Area [ft^2]	%WQCV Stored
Control 1	100% impervious right-of-way, no trees	100	100	0	0	0	NA
Control 2	11 trees in 5' x 5' tree grates taking flow from only the adjacent walkway	98.4	95.7	275	4	440	NA
SCM 1	11 trees in 15' x 5' landscape planters, raised / hydrologically disconnected	95.1	95.1	825	4	0	NA
SCM 2	11 trees in 15' x 5' landscape planters, at walk grade	95.1	87.1	825	0	1320	NA
SCM 3	11 trees in 15' x 5' landscape planters, 2" below walk grade	95.1	87.1	825	2	1320	NA
SCM 4	11 trees in 15' x 5' landscape planters, 4" below walk grade	95.1	87.1	825	4	1320	NA
SCM 5	11 trees in 15' x 5' landscape planters, at gutter grade	95.1	0.0	825	0	15851	NA
SCM 6	11 trees in 15' x 5' landscape planters, 2" below gutter grade	95.1	0.0	825	2	15851	NA
SCM 7	11 trees in 15' x 5' landscape planters, 4" below gutter grade	95.1	0.0	825	4	15851	NA
SCM 8	3 landscape areas 40' x 5' (equal to SSP area), raised / hydrologically disconnected	96.4	96.4	600	4	0	NA
SCM 9	3 landscape areas 40' x 5' (equal to SSP area), at walk grade	96.4	90.6	600	0	960	NA
SCM 10	3 landscape areas 40' x 5' (equal to SSP area), 2" below walk grade	96.4	90.6	600	2	960	NA
SCM 11	3 landscape areas 40' x 5' (equal to SSP area), 4" below walk grade	96.4	90.6	600	4	960	NA
SCM 12	3 landscape areas 40' x 5' (equal to SSP area), at gutter grade	96.4	0.0	600	0	16076	NA
SCM 13	3 landscape areas 40' x 5' (equal to SSP area), 2" below gutter grade	96.4	0.0	600	2	16076	NA
SCM 14	3 landscape areas 40' x 5' (equal to SSP area), 4" below gutter grade	96.4	0.0	600	4	16076	NA
SCM 15	1 continuous tree lawn (350' x 5'), raised / hydrologically disconnected	89.5	89.5	1750	4	0	NA
SCM 16	1 continuous tree lawn (350' x 5'), at walk grade	89.5	72.7	1750	0	2800	NA
SCM 17	1 continuous tree lawn (350' x 5'), 2" below walk grade	89.5	72.7	1750	2	2800	NA
SCM 18	1 continuous tree lawn (350' x 5'), 4" below walk grade	89.5	72.7	1750	4	2800	NA.1
SCM 10	1 SSP (40'x5') with underdrain, and 2 landscape planters (40'x5') at walk grade	96.4	0.0	600	11.61	16076	113.2
SCM 20	1 SSP (40'x5') with no underdrain, and 2 landscape planters (40'x5') at walk grade	96.4	0.0	600	11.61	16076	113.2
SCM 21	2 SSPs (40'x5') with underdrain, and 1 landscape planter (40'x5') at walk grade	96.4	0.0	600	7.74	16076	75.5
SCM 22	2 SSPs (40'x5') with no underdrain, and 1 landscape planter (40'x5') at walk grade	96.4	0.0	600	7.74	16076	75.5
SCM 23	3 SSPs (40'x5') with underdrain, and 0 landscape planters	96.4	0.0	600	3.87	16076	33.7
SCM 24	3 SSPs (40'x5') with no underdrain, and 0 landscape planters	96.4	0.0	600	3.87	16076	33.7

02.04.01 – Group 1: 15’ x 5’ Tree Box Simulations:

1. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone with a 6” curb hydrologically separating them from the adjacent walkway preventing inflow
2. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone at the same grade as the adjacent walkway allowing flow to enter but with no depth for storage
3. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone depressed 2” from the adjacent walkway allowing flow to enter with some storage
4. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone depressed 4” from the adjacent walkway allowing flow to enter with more storage
5. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone at the same grade as the adjacent gutter line allowing flow from the road to enter and exit but with no storage
6. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone depressed 2” from the adjacent gutter line allowing flow from the road to enter with some storage
7. 11 fully open, pervious 15’x5’ tree boxes located in the Landscape zone depressed 4” from the adjacent gutter line allowing flow from the road to enter with more storage

02.04.02 – Group 2: 40’ x 5’ Landscape Planter Simulations:

8. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone with a 6” curb hydrologically separating them from the adjacent walkway preventing inflow
9. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone at the same grade as the adjacent walkway allowing flow to enter but no storage
10. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone depressed 2” from the adjacent walkway allowing flow to enter with some storage
11. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone depressed 4” from the adjacent walkway allowing flow to enter with more storage
12. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone at the same grade as the adjacent gutter line allowing flow from the road to enter and exit but with no storage
13. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone depressed 2” from the adjacent gutter line allowing flow from the road to enter with some storage
14. 3 fully open, pervious 40’x5’ landscape areas in the Landscape zone depressed 4” from the adjacent gutter line allowing flow from the road to enter with more storage

02.04.03 – Group 3: 350’ x 5’ Continuous Tree Lawn Simulations:

15. 1 continuous 350’x5’ fully open landscape area in the Landscape zone with a 6” curb hydrologically separating it from the adjacent walkway preventing inflow.
16. 1 continuous 350’x5’ fully open landscape area in the Landscape zone at the same grade as the adjacent walkway allowing flow to enter but with no storage
17. 1 continuous 350’x5’ fully open landscape area in the Landscape zone depressed 2” from the adjacent walkway allowing flow to enter with some storage
18. 1 continuous 350’x5’ fully open landscape area in the Landscape zone depressed 4” from the adjacent walkway allowing flow to enter with some storage

02.04.04 – Group 4: 40’ x 5’ Streetside Stormwater Planter (SSP) Simulations:

A streetside stormwater planter (SSP) is a fully engineered, rectangular bioretention area as detailed in the *Ultra Urban Green Infrastructure Guidelines*[1].

19. 3 40’x5’ SSPs with an underdrain in the Landscape zone collecting water from the Drive zone
20. 3 40’x5’ SSPs without an underdrain in the Landscape zone collecting water from the Drive zone
21. 2 40’x5’ SSPs with an underdrain in the Landscape zone collecting water from the Drive zone, plus 1 40’ x 5’ landscape area at walk grade collecting runoff from the adjacent sidewalk only
22. 2 40’x5’ SSPs without an underdrain in the Landscape zone collecting water from the Drive zone, plus 1 40’ x 5’ landscape area at walk grade collecting runoff from the adjacent sidewalk only
23. 1 40’x5’ SSPs with an underdrain in the Landscape zone collecting water from the Drive zone, plus 2 40’ x 5’ landscape areas at walk grade collecting runoff from the adjacent sidewalk only
24. 1 40’x5’ SSPs without an underdrain in the Landscape zone collecting water from the Drive zone, plus 2 40’ x 5’ landscape areas at walk grade collecting runoff from the adjacent sidewalk only

02.04.05 – Other Notes and Justification for SCM Simulations

Trees and Interception

- 11 trees were chosen as this is the maximum amount that can fit in a 400’ block keeping Denver Officer of the City Forester’s standard of 25-35’ spacing between trees and 25’ from intersections
- The 15’ x 5’ tree box was chosen because that is the Denver Department of Transportation and Infrastructure standard for street trees
- The 350’ x 5’ landscape area was assumed to have 11 trees in it
- Each 40’ x 5’ landscape area or SSP was assumed to have 1 tree in it
- All trees were assumed to be Honeylucst (the most common tree species in Denver) with a 20’ tree canopy diameter and an interception storage depth of 0.67 mm[4]
- Interception was modeled by increasing the detention store of the Landscape, Walkway, and/or Adjacent zone subcatchments that contain the tree canopy
- Interception was only simulated during leaf out months of May 1 to October 31 with a step function

Landscape Areas

- The simulations using 3 landscape areas 40’ x 5’ were chosen because the pervious area was equal to the pervious area in the SSP scenarios, allowing for more equivalent comparisons of the SCMs themselves rather than the extent of their implementation
- Infiltration into the landscape areas was modeled with the Horton Infiltration model modified to account for soil drying, as this is the method recommended by the Mile High Flood District (MHFD)[5]. This is of note because infiltration in the SSPs was modeled using the Green-Ampt method.
- The 350’ x 5’ landscape area was not simulated as receiving flow from the street because this was deemed infeasible to implement in the field without flow short circuiting

SSPs

- 3 SSPs 40’ x 5’ were chosen as this would provide 113% storage of the WQCV for the block, just above the regulatory threshold
- 40’ length is the max length, per the *Ultra Urban Green Infrastructure Guidelines*

- The other SSP simulations quantified performance of fully-engineered stormwater systems that received runoff from the entire block but did not provide full WQCV storage. In this case, one SSP provides 37% of WQCV storage for the block, while two SSPs provide 77% of WQCV
- The remaining SSP parameters used and their sources are summarized in Table 2 below.

Table A.03.1.2: SWMM LID Control Editor parameters for the SSP

Parameter	Value	Assumption / Source
LID Type	Bioretention	NA
Area [ft^2]	200	Uses 40' length, max per UUGIG
Width [ft]	5	Typical
Berm Height [in]	8.25	UUGIG; Typical
Vegetation Volume Fraction	0.05	SWMM User Manual
Surface Roughness / Manning's n	0.32	SWMM User Manual
Surface Slope [%]	3	Typical
Soil Thickness [in]	24	UUGIG, Typical
Soil Porosity [volume fraction]	0.149	UUGIG, Calibrated**
Soil Field Capacity [volume fraction]	0.021	Calibrated
Soil Wilting Point [volume fraction]	0.016	Calibrated
Soil Conductivity [in/hr]	17.8	Calibrated
Soil Conductivity slope	30.4	Calibrated
Soil Suction Head [in]	7.63	Calibrated
Storage Thickness [in]	4	UUGIG
Storage Void Ratio [voids/solids]	0.54	UUGIG
Storage Seepage Rate [in/hr]	0.81	Calibrated
Drain Flow Coefficient*	0.234	SWMM Drain Advisor
Drain Flow Exponent*	0.5	SWMM Drain Advisor
Drain Flow Offset [in]*	1.0	UUGIG, Typical

*For the SSP configuration with an underdrain only
**Calibration was performed using observed data from two synthetic runoff tests performed on 9/16/2020 and 9/17/2020 at an SSP on Brighton Blvd. in Denver, CO.

02.05 – OTHER SITE PARAMETERS

Other model parameters were also systematically varied to account for variability in sites and model uncertainty. Table A.03.1.3 lists these parameters as well as the upper and lower values. Here, just the upper and lower bounds of parameter ranges listed were tested to limit the number simulations, but still capture the full range in variability. All parameter combinations are tested (32 total) for each layout. This resulted in a total of 832 [32 * (2 + 24)] SWMM models. Parameter ranges in Table 3 are taken from MHFD Guidence[5] unless noted. The Soils Group parameter effects the surface infiltration rate of pervious subcatchments and the background seepage rate below SSPs in the native subgrade.

Table A.03.1.3: Other SWMM Parameter Ranges

Parameter	Low Value	High Value
Longitudinal slope	1%	4%
Cross slope[6–8]	1.5%	4%
Soils Group	C/D	C/D
Pervious detention storage	0.1 in	0.3 in
Impervious detention storage	0.05 in	0.15 in
Pervious Manning's n	0.1	0.32
Impervious Manning's n	0.01	0.01

02.06 – MODEL CONTROLS AND TIME SERIES DATA

The SWMM model was used for all simulations. A runoff timestep of 45 seconds and a routing time step of 10 seconds were used as testing demonstrated this preserved continuity (<1%). Each of the 832 SWMM models was run with forcing from two meteorological time series:

- **WQCV Design Storm**: To evaluate the effectiveness of the SCMs at managing the peak flows occurring during a WQCV design storm
  - Rainfall: A rainfall time series generated with CUHP v 2.0 for a 2-yr, 2-hr design storm of a 0.6" instantaneous rainfall depth (which totals 0.6942" of rain).
  - Temperature/Evapotranspiration: Evapotranspiration was not simulated during the WQCV design storm, as it is assumed that this process is negligible during periods of precipitation. This is a conservative assumption in terms of computing runoff reductions of SCMs.

- **Average Annual Runoff**: Continuous simulation to evaluate the effectiveness of the SCMs at managing runoff over the longer periods of time
  - Rainfall: 10 years of continuous rainfall data, recorded at 5-minute intervals, taken from the MHFD Rain Gage "Harvard Gulch @ Jackson" from Jan 1, 2009 to Jan, 1 2019
  - Temperature/Evapotranspiration: 10 years of daily maximum and minimum temperature data taken from Denver-Stapleton NCDC meteorological station from Jan 1, 2009 to Jan 1, 2019 which is used to simulate evapotranspiration with the Hargreaves method.

02.07 – POST PROCESSING

Total rainfall, evaporation, infiltration, subcatchment runoff, LID drainage, final storage and peak discharge into the inlet were extracted from SWMM simulation output for post-processing. Two key variables were then analyzed:

1. Peak flow reduction as a percent relative to Tree Grate Control from the WQCV Design Storm
2. Runoff reduction as a percent relative to the Tree Grate Control from the Average Annual Runoff simulation
   a. Runoff was calculated as the sum of direct runoff entering the inlet and LID drainage through an underdrain when applicable

The percent reductions were calculated only using SCM and control simulations with the same Other Site Parameters. This was done to focus results on the effects of the SCMs, rather than variations in the site. For example, a SCM scenario with 1% longitudinal slope, 1.5% cross slopes, C/D soils, 0.1 in of pervious detention storage, 0.05 in of impervious detention storage, and a 0.1 pervious Manning's n was compared to the Tree Grate Control with the same Other Site Parameter values.

03 – RESULTS AND TAKE-AWAYS FOR LEVELS OF GREEN

Figure A.03.1.4 shows the results for peak flow reduction and runoff reduction for all 26 layouts. Since the percent reductions are measured relative to the Tree Grate Control, the results for that simulation always plot at 0%. The bars represent the average percent reduction across the combinations of Other Site Parameters and the whiskers represent one standard deviation in the variability due to the Other Site Parameters. Key take-aways for defining and quantifying the Levels of Green based on the modeling are outlined in the sub-sections that follow, grouped by design practices. The important practices are:

1. Minimizing impervious area
2. Hydrologically disconnecting walkways by routing runoff to pervious areas in the Landscape zone
3. Depressing the Landscape zone receiving runoff from the walkway
4. Hydrologically disconnecting roads and walkways by routing their runoff to a pervious area in the Landscape zone
5. Depressing the Landscape zone receiving runoff from the road and walkway
6. Collecting runoff from the road and walkways into an engineered SSP
    a. SSPs are designed to meet different fractions of the WQCV standard
    b. SSPs are designed with and without underdrains

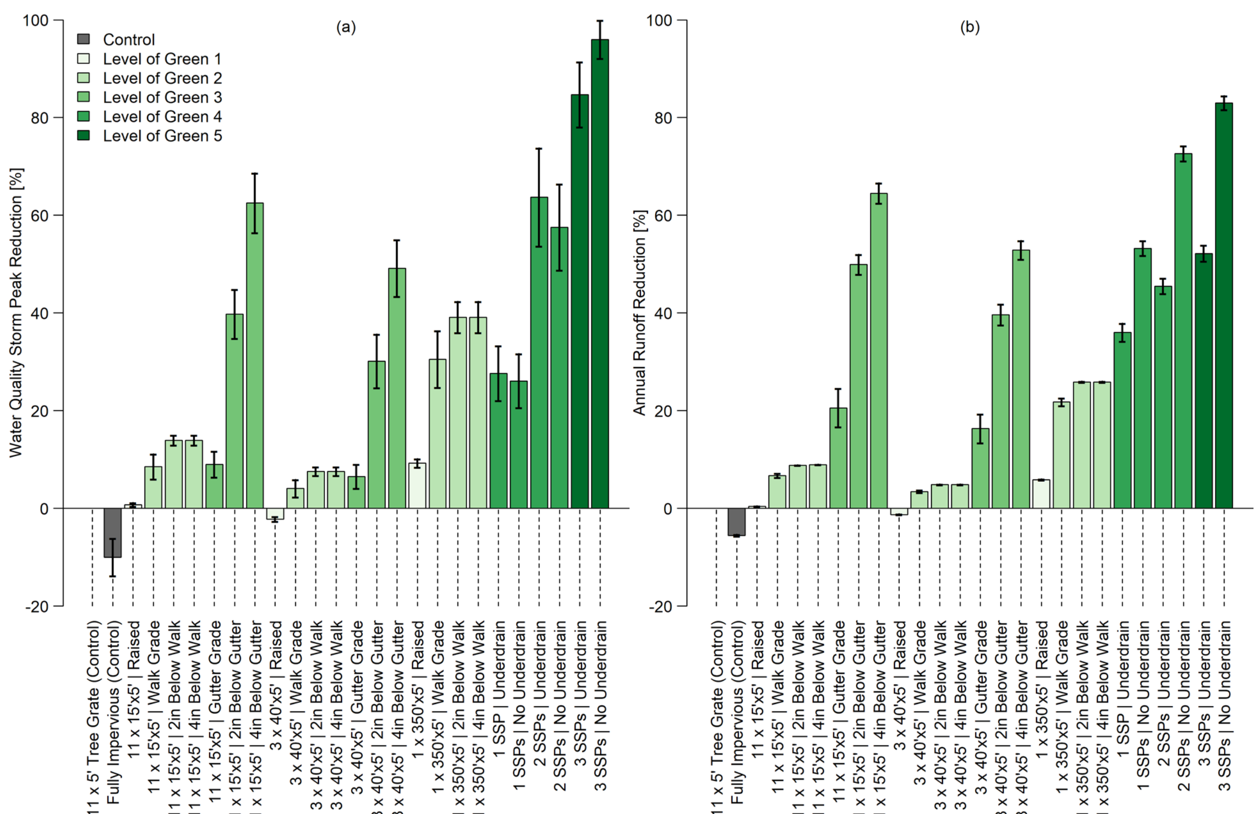

Figure A.03.1.4: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control. The bars represent one standard deviation in variability due to the Other Site Parameters

03.01 – MINIMIZING IMPERVIOUS AREAS:

In Figure A.03.1.5, the amount of pervious area in the right-of-way increases from left to right. Reductions in peak flow and runoff increase linearly relative to the pervious added in the right-of-way if that pervious area has no additional tributary area.

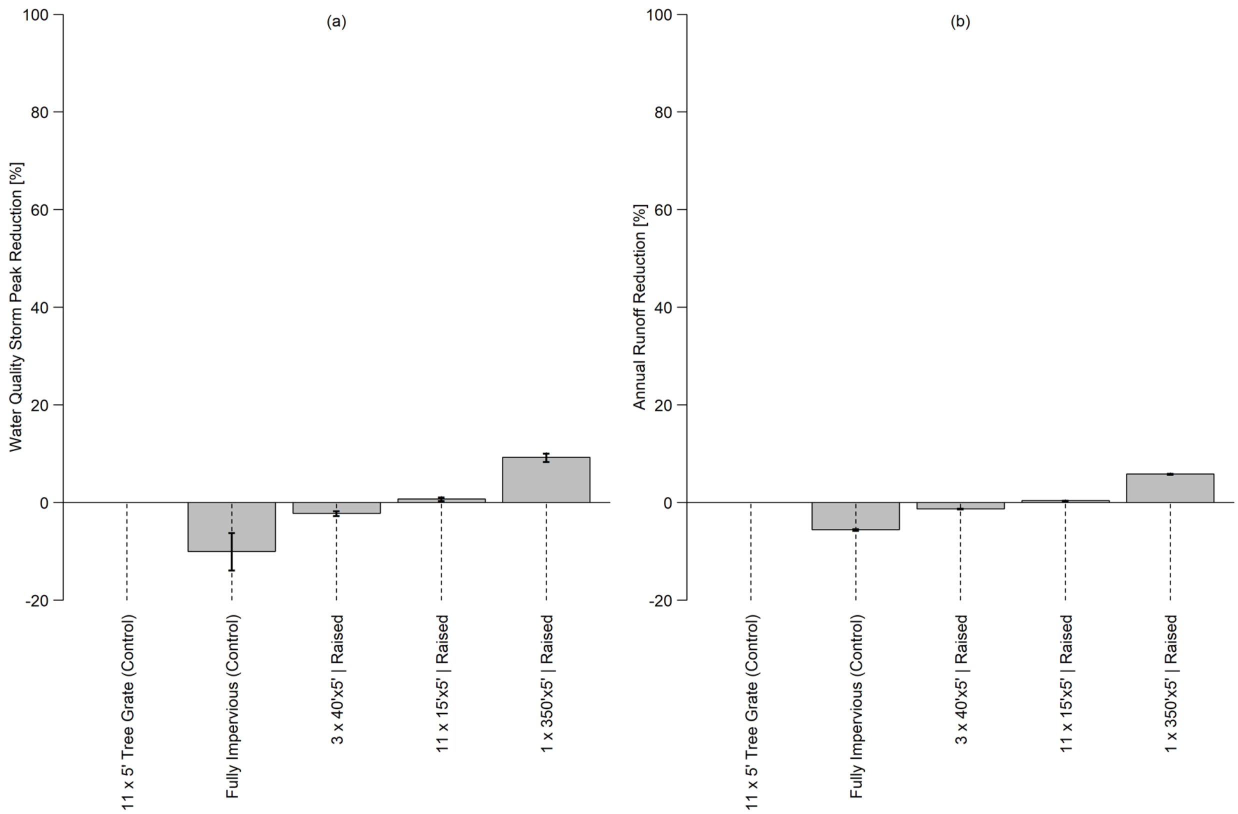

Figure A.03.1.5: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of impervious cover alone. The bars represent one standard deviation in variability due to the Other Site Parameters

03.02 – DISCONNECTING WALKWAYS:

Routing runoff from the walkway to adjacent pervious landscapes, even if there is no surface storage on the landscape, increases runoff and peak flow reduction by ~3x, which can be seen by comparing the Raised vs. Walk grade pairs in Figure A.03.1.6. This large jump in performance makes this practice a good candidate for distinction between Levels of Green.

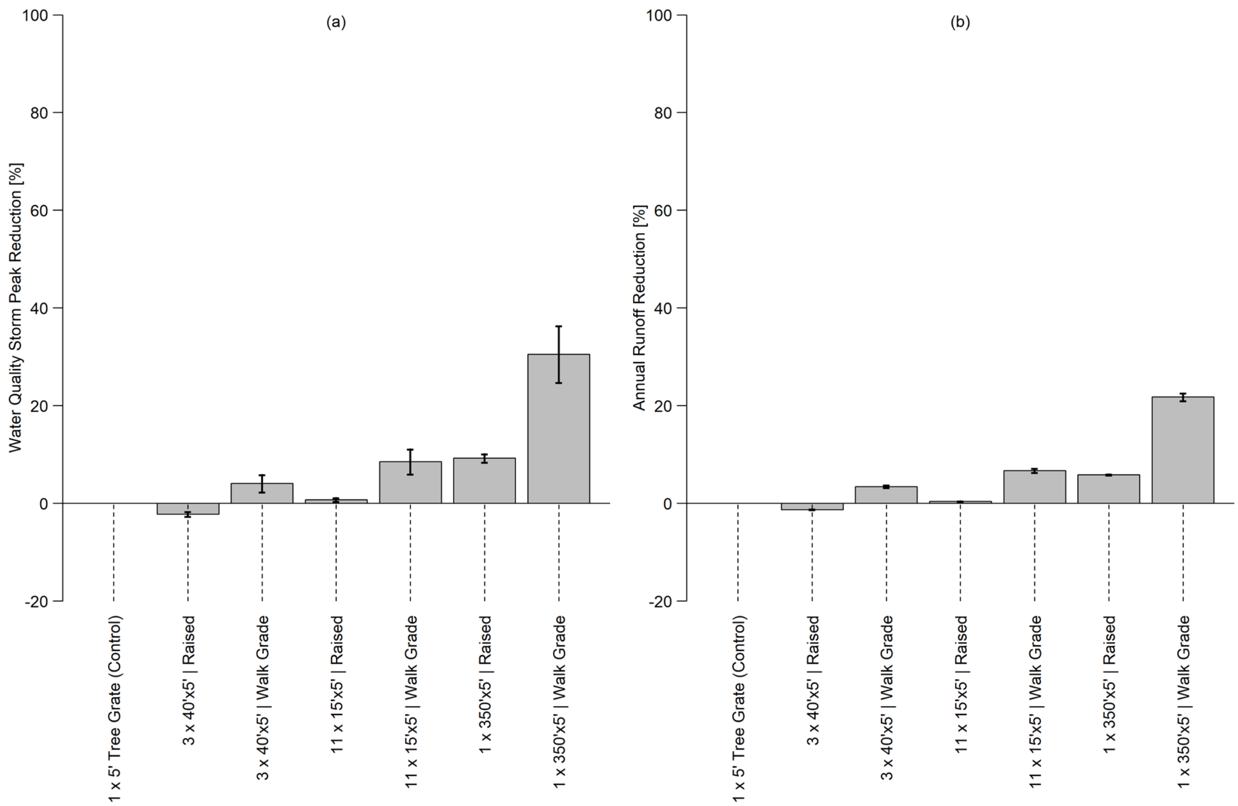

Figure A.03.1.6: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of disconnecting the walkway. The bars represent one standard deviation in variability due to the Other Site Parameters

03.03 – DEPRESSING LANDSCAPES DRAINING WALKWAYS:

Runoff and peak flow reductions do not change much as the storage depth above a pervious landscape area that only receives runoff from the walkway increases. This can be seen by comparing height of the bars between the Walk Grade, 2in Below Walk Grade, and 4in Below Walk Grade triads in Figure A.03.1.7. The natural depression storage on pervious areas (0.1”-0.32”) and infiltration rates of C/D soils are enough to manage runoff from the relatively small, directly adjacent tributary areas. There is almost no difference in performance between a 2” and 4” depression. Therefore, this is not a good distinction between Levels of Green.

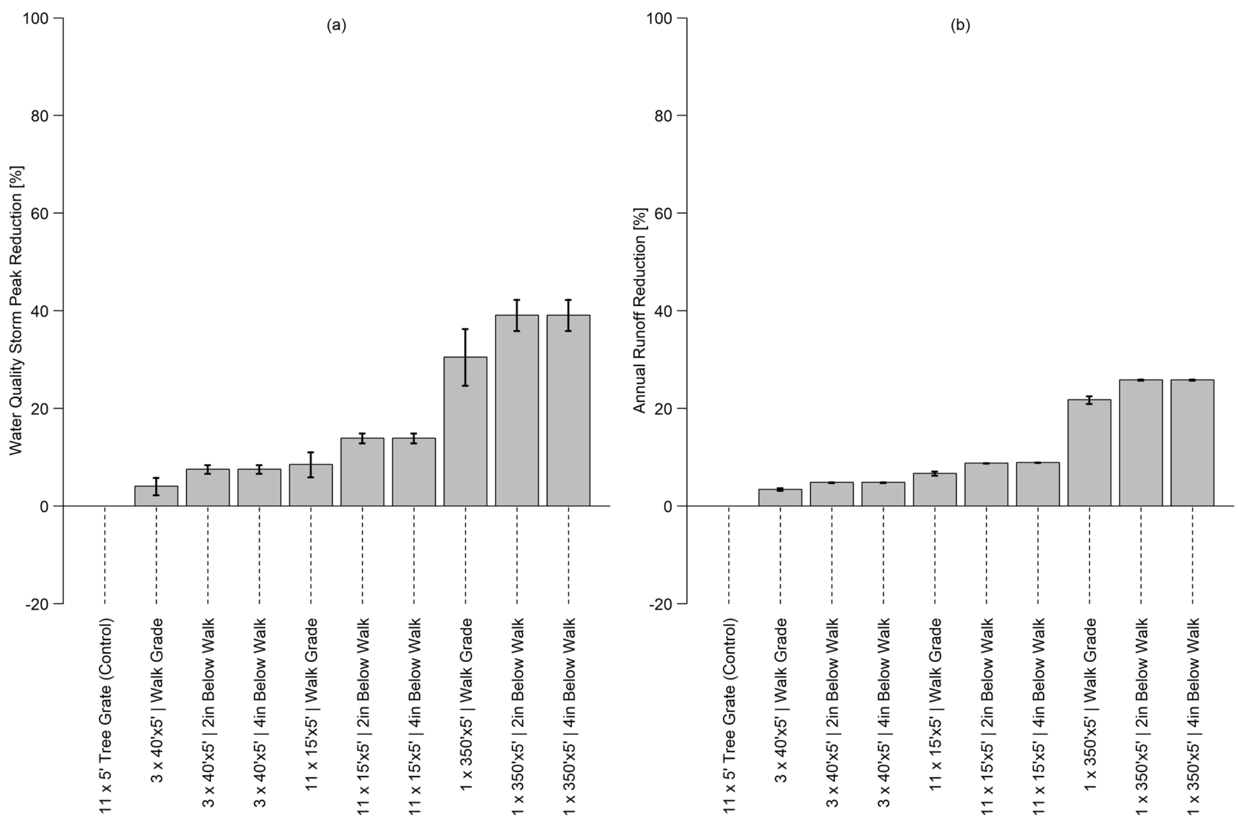

Figure A.03.1.7: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of disconnecting the walkway and depressing the landscape to provide minimal storage. The bars represent one standard deviation in variability due to the Other Site Parameters.

03.04 – DISCONNECTING ROADS:

Runoff reductions increase by a factor of 3-4x when routing runoff from the road to pervious areas compared to routing only the walkway to the same pervious area. This can be shown by comparing the two Walk Grade vs. Gutter Grade pairs in Figure A.03.1.8. There are smaller reductions in peak flow under the same conditions. This indicates that large jumps in performance come when the street is routed to a landscape area and is a good distinction between Levels of Green.

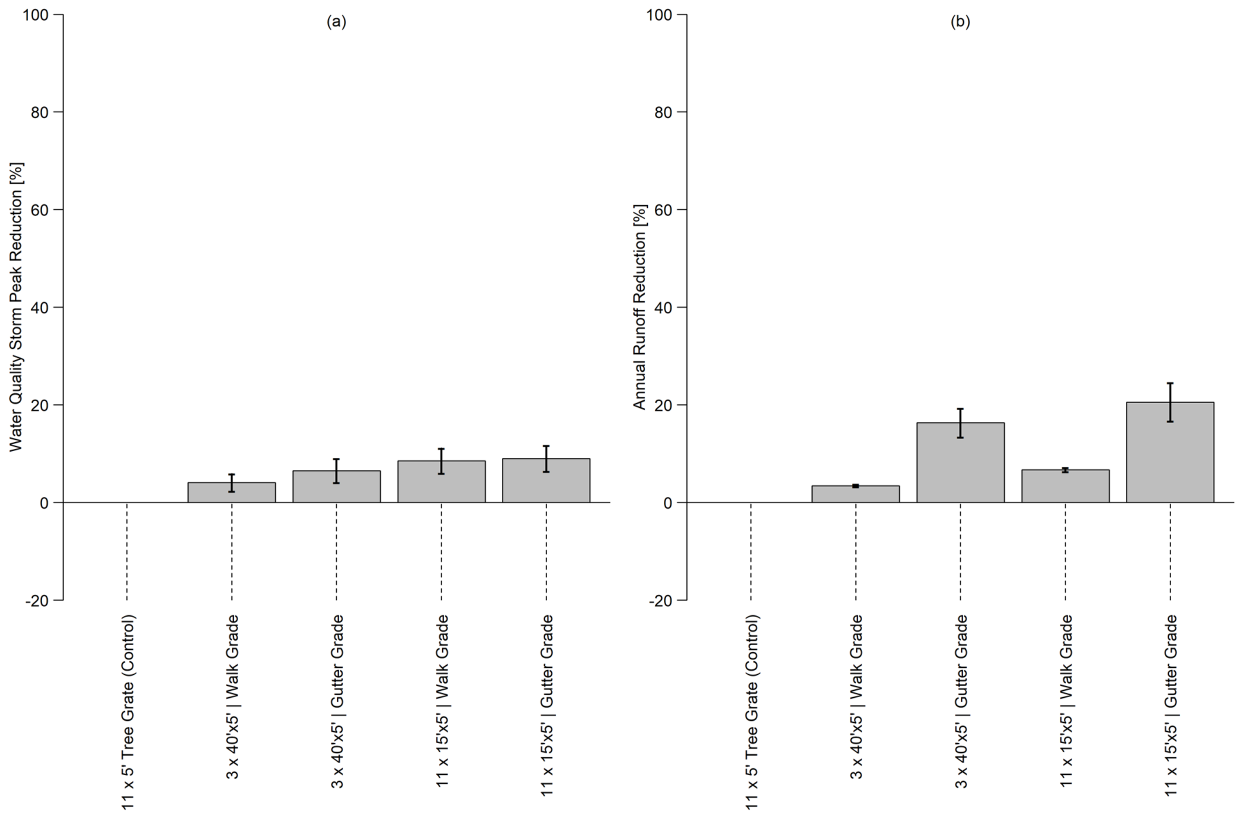

Figure A.03.1.8: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of disconnecting the road and walkways. The bars represent one standard deviation in variability due to the Other Site Parameters.

03.05 – DEPRESSING LANDSCAPES DRAINING ROADS:

Unlike the pervious areas draining just the adjacent walkways, depressing pervious areas draining runoff from the road increases performance considerably. This is shown when comparing the two triads of bar plots with similar landscape area footprints, but different depths at Gutter Grade, 2in Below Gutter, and 4in Below Gutter in Figure A.03.1.9. Peak flow and runoff reductions approach 65% with 4” of storage. This is also a good candidate design practice for separating Levels of Green.

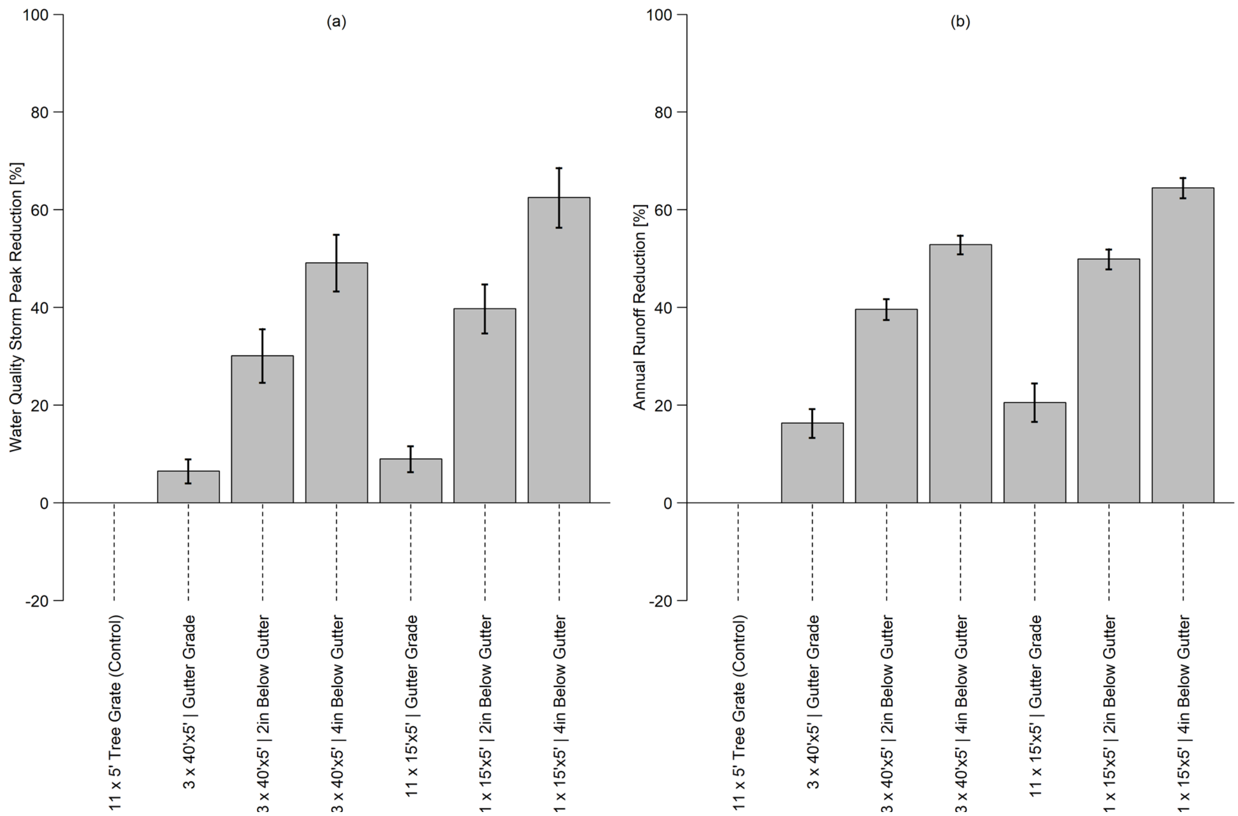

Figure A.03.1.9: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of disconnecting the roadway and depressing the pervious area to provide some storage. The bars represent one standard deviation in variability due to the Other Site Parameters

03.06 – SSP, UNDERDRAINS, AND %WQCV:

SSPs without underdrains outperform those with underdrains, especially for runoff reduction. In fact, 1 SSP capable of storing 38% of the WQCV without an underdrain has greater runoff reductions than 3 SSPs that store 113% of the WQCV but have underdrains (Figure A.03.1.10).

Two options for design practices to separate Level of Green are (1) whether the facility has an underdrain or (2) whether or not the facility treats a certain fraction of the WQCV.

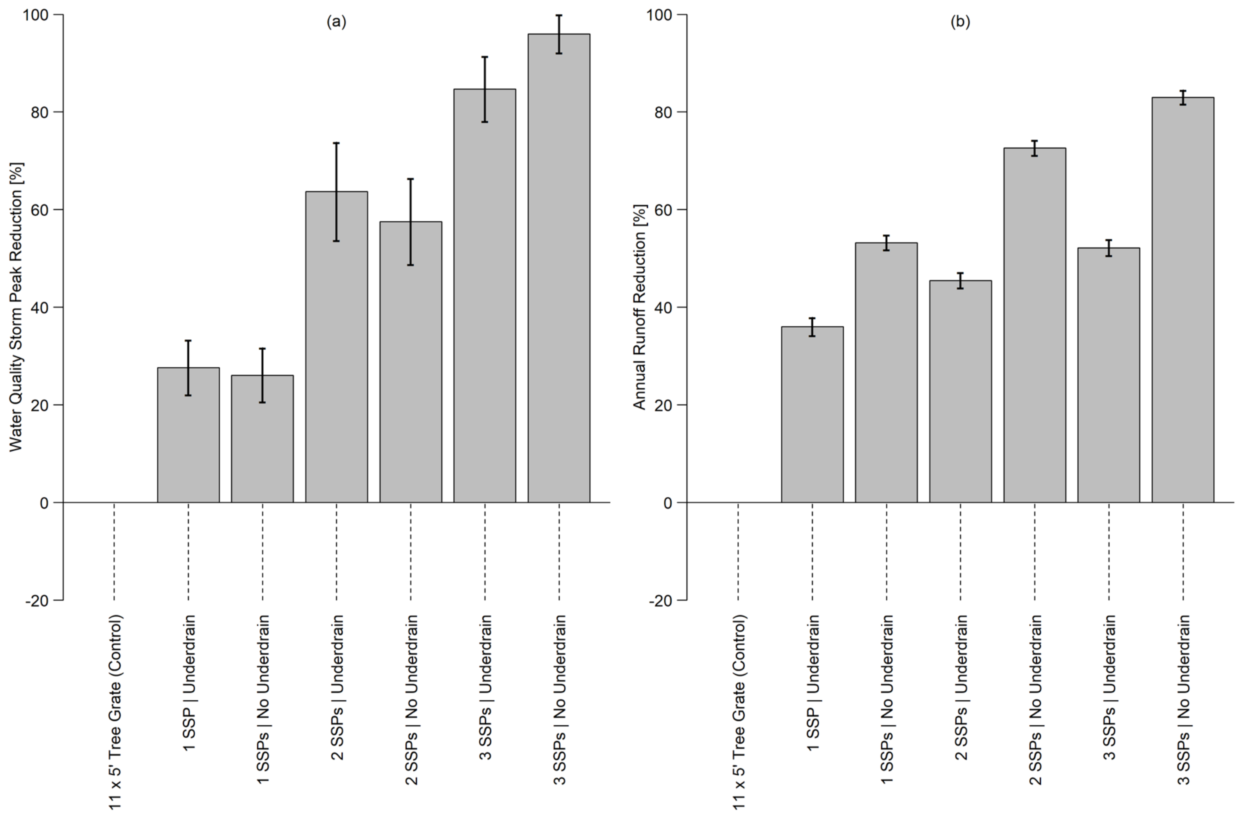

Figure A.03.1.10: Percent reductions in (a) WQCV Peak Flow and (b) Annual Runoff Reduction measured relative to the Tree Grate Control for select layouts highlighting the importance of using SSPs designed with and without underdrains and storing between 38-113% of the site's WQCV. The bars represent one standard deviation in variability due to the Other Site Parameters

04 – LEVELS OF GREEN:

Based on these right-of-way scale simulations five key findings with implications for defining levels of green are:

Finding 1: Reductions in peak flow and runoff increase linearly relative to the pervious added in the right-of-way if that pervious area has no tributary area besides itself.

Finding 2: Routing runoff from the walkway to adjacent pervious landscapes (even if there is no surface storage on the landscape) increases runoff and peak flow reduction by ~3x compared to when the landscapes are raised and hydrologically disconnected.

Finding 3: Runoff reductions increase by 3-4x when routing runoff from the road and walkway to pervious areas compared to routing only the walkway to the same pervious area.

Finding 4: Depressing pervious areas draining runoff from the road and walkway increases performance considerably.

Finding 5: SSPs without underdrains outperform those with underdrains for runoff reduction.

These findings were then used to identify SCM design practices that separate the Levels of Green (Table A.03.1.4). These initial definitions are subject to change with more targeted modeling in the future to define design parameters for each Level of Green (See Appendix 03.2). The Levels of Green are also applied to each of the 26 simulations, shown with color coding in Figure A.03.1.4.

Table A.03.1.4: Preliminary Levels of Green Description and Performance Range

Level of Green	Practice	Findings Supporting Practice	Water Quality Storm peak flow reduction [%]	Annual Runoff Reduction [%]
1	Maximize pervious landscape area in the right-of-way. Landscapes can be raised and do not receive flow from walkway.	Finding 1	2 to 10	1 to 6
2	Route walkways to pervious landscape area. Landscape area does not need to be depressed, and if it is depressed then 2" is sufficient.	Finding 2	15 to 40	5 to 25
3	Route walkways and roads to pervious landscape areas. Landscape area should be depressed to improve performance over Level of Green 2.	Finding 3 and 4	15 to 25 (30 to 65 if depressed > 2")	5 to 10 (40 to 65 if depressed > 2")
4	Provide partial volume storage (35-75% of WQCV) in facility. Avoid underdrains if possible.	Finding 5	35 to 65 (25 to 55 w/o underdrains)	50 to 75 (35 to 55 w/o underdrains)
5	Provide full volume storage, per local regulatory requirements. SCMs have underdrains.	NA	~85	~50

05 – REFERENCES

(1) The City and County of Denver Public Works. *Ultra Urban Green Infrastructure Guidelines*; 2016.

(2) Mile High Flood District. Urban Storm Drainage Criteria Manual Volume 3: Chapter 3 Calculating the WQCV and Volume Reduction. **2019**, *3* (October).

(3) City and County of Denver Department of Transportation and Infrastructure. *Complete Streets Guide DRAFT*; 2020.

(4) Xiao, Q.; McPherson, E. G. Surface Water Storage Capacity of Twenty Tree Species in Davis, California. *J. Environ. Qual.* **2016**, *45* (1), 188–198. https://doi.org/10.2134/jeq2015.02.0092.

(5) Urban Drainage and Flood Control District. Urban Storm Drainage Criteria Manual Volume 1: Chapter 6 Runoff. 2018. https://doi.org/10.1016/j.jaac.2017.06.012.

(6) Colorado Department of Transportation. CDOT Roadway Design Guidelines: Chapter 6 Collector Roads. **2005**, 3–6.

(7) Colorado Department of Transportation. CDOT Roadway Design Guidelines: Chapter 5 Local Roads and Streets. 2018, pp 0–8.

(8) City and County of Denver Public Works. Transportation Standards and Detals for the Engineering Division. 2017.