Appendix 03.2 – Establishing Stormwater Control Measure Design Criteria

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 Streets can be separated into five Levels of Green. At higher Levels of Green there is greater stormwater volume control than at lower Levels of Green, but the cost, amount of engineering, and construction impacts is higher (Figure A.03.2.1).

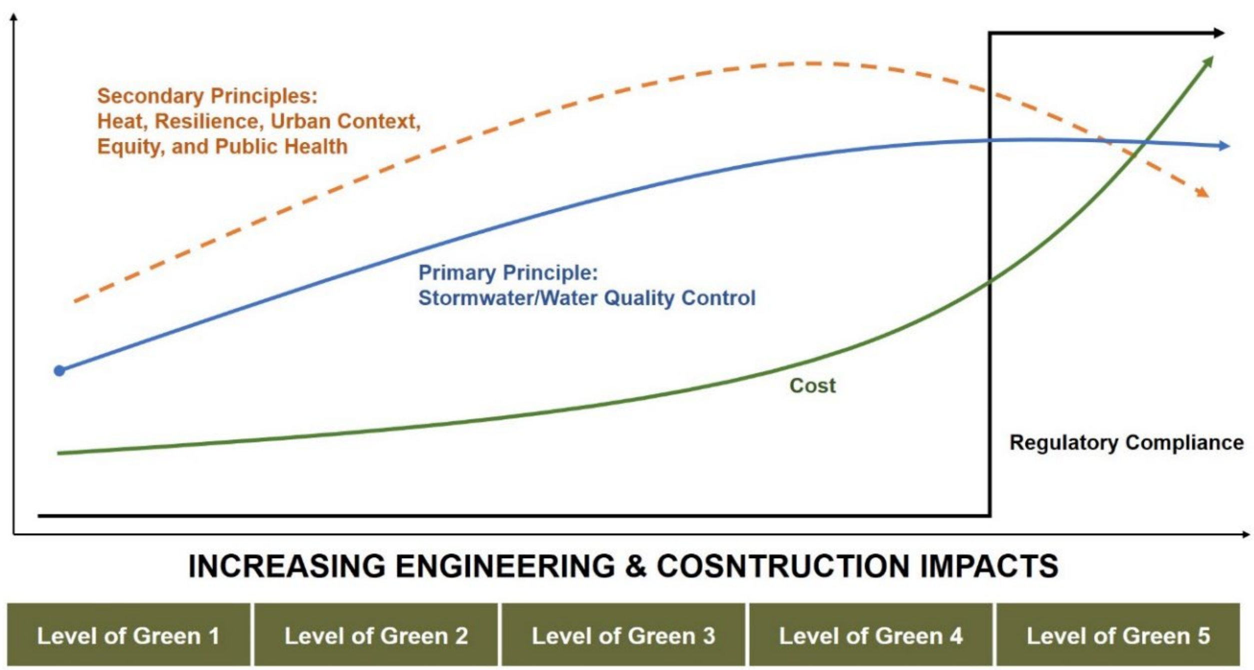

Figure A.03.2.1: The Green Continuum Concept

01.01 – LEVELS OF GREEN

Five design principles separating the Levels of Green were determined from discussions with stakeholders and a previous modeling study to determine hydrologic performance of various SCMs in a typical right-of-way (Appendix 03.1). Brief descriptions of the Levels of Green prior to performing this analysis are:

- **Level of Green 1:** Maximize pervious landscape area. Landscape area may or may not have a tributary area besides itself.
- **Level of Green 2:** Maximize the amount of walkway impervious area that flows to pervious landscape area. Depressing the landscape is not required.
- **Level of Green 3:** Route walkway and roadway impervious area to pervious landscape area. Depressing the landscape area to allow some surface storage is preferred.
- **Level of Green 4:** Route impervious walkway and roadway area to a SCM sized to manage part (60%) of the WQCV, per Mile High Flood District (MHFD) standards[2]. SCMs may or may not have underdrains.
  - 60% WQCV was chosen from the range (35-75%) identified in Appendix 03.1, as it aligns with the MS4 permit's Runoff Reduction standard
- **Level of Green 5:** Route impervious walkway and roadway area to a SCM sized to manage 100% of the required WQCV per MHFD standards[2]. SCMs have underdrains.

01.02 – PURPOSE OF STUDY

The purpose of this study is to use the Environmental Protection Agency's Storm Water Management Model (SWMM) to simulate how design variables impact the effectiveness of SCMs at reducing runoff in the right-of-way. Model results are converted into effectiveness curves, which are then interpreted to recommend ranges of the design variables for each SCM that provide suitable runoff reduction. These results will be used to inform design criteria for Level of Green 1, 2 and 3 SCMs as there are currently no design guidelines in the region. The design variables considered are:

- NRCS Hydrologic Soils Group and associated infiltration rates recommended by the MHFD[3]
- Run-on ratios
- Surface storage depth
- Longitudinal slope
- Media storage depth

Design variables for Level of Green 4 and 5 SCMs are not evaluated in the same way in this study because they have a volume-based design standard. They are modeled here to quantify performance at various run-on ratios, given variation in the other design variables listed above, and whether the SCM has an underdrain.

02 – METHODS

02.01 – SPATIAL SCOPE

The spatial extent of the analysis includes just an SCM and its tributary area. This allows the analysis to inform changes in runoff reduction due to the design of the SCM only (Figure A.03.2.2).

02.02 – SWMM MODELING

02.02.01 – Model Subcatchment Set Up

SWMM models were set up to simulate impervious area (representing the walkway, roadway, or both) running on to a pervious area (representing the SCM). This is modeled in SWMM with two subcatchments: where runoff from one fully impervious subcatchment is routed to one fully pervious subcatchment (Figure A.03.2.2). For Levels of Green 4 and 5, the pervious area was simulated using SWMM's LID Control Editor. Model parameters of the subcatchments are summarized in Table A.03.2.1. The parameters chosen for surface detention are conservative and will likely underestimate reductions in runoff. Note that 0.00459 ac of the pervious subcatchment area represents a 40' x 5' footprint, the size of a typical SCM.

Table A.03.2.1: SWMM Parameters for Impervious and Pervious Subcatchments

Parameter	Impervious	Pervious
Area [ac]	Varies with run-on ratio	0.00459
Length-to-width Ratio	0.3	8
% Impervious	100	0
Manning's n	0.01	0.1
Surface Detention Store [in]	0.05	0.1

02.02.02 – Model Controls and Time Series Data

Ten years of continuous run-off were simulated from 1/1/2009 to 1/1/2019. A runoff and routing timestep of 45 sec was used as testing demonstrated this preserved continuity (<1%). The relatively large routing time step was used because the model set up does not have hydraulic features and the analysis only considers volume, not peak flows. The data forcing the model was:

- **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**: 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

02.03 – DESIGN VARIABLES

The design variables tested in the analysis are:

- National Resource Conservation Service Hydrologic Soils Group
- Run-on ratio
- Longitudinal slope
- Surface storage depth
- Media storage depth

Ranges of the design variables are summarized in Table A.03.2.2. Figure A.03.2.2 shows a graphical guide of how the two subcatchments were configured and how each design variable was varied for each Level of Green.

Table A.03.2.2: Ranges of design variables by Level of Green

Level of Green	Soil Infiltration Rate		Run-on Ratio			Surface Storage [in]			Slope [%]			Media Storage [in]		
	Fast	Slow	Low	High	Step	Low	High	Step	Low	High	Step	Low	High	Step
1	C/D*	C/D	2**	4	1	0	1	1	1	8	1	NA	NA	NA
2	C/D*	C/D	2	9	1	0	4	1	1	8	1	NA	NA	NA
3	C/D*	C/D	10	50	5	0	4	1	1	8	1	NA	NA	NA
4	1.0 in/hr	0.5 in/hr	10	45	5	3	6	1	1	8	1	6	36	6
5	1.0 in/hr	0.5 in/hr	10	35	5	6	9	1	1	8	1	6	36	6

*To be conservative when calculating run-on ratios, only C/D soils were used.
**A minimum of 2 for the run-on ratio was used for Level of Green 1 because in a situation with a run-on ratio of 1, there is no fully impervious tributary area to compare the results to. See Section 02.03.03 below for more details.

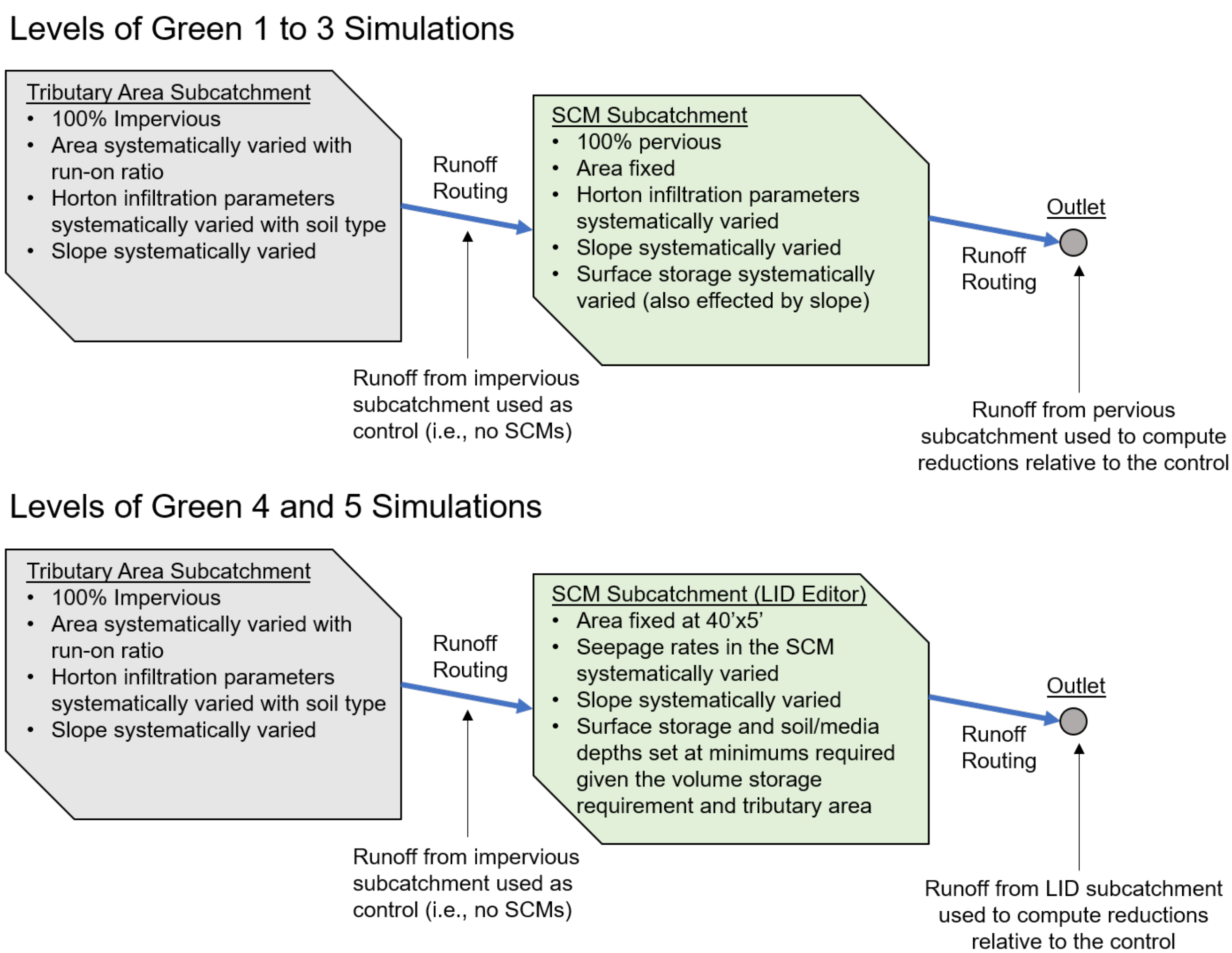

Figure A.03.2.2: Graphical guide showing the subcatchment layouts and design variables

<u>02.03.01 – Levels of Green 1, 2 and 3 Modeling</u>

The SCMs for Levels of Green 1, 2 and 3 were modeled as pervious subcatchment area receiving run-on from an impervious subcatchment. The design variables are varied from the Low value to the High value by the Step listed in Table A.03.2.2. Each of these values was systematically combined with all values of the other design variables to form all possible combinations. The purpose is to evaluate the effectiveness of these SCMs across a range of likely conditions and to help inform design criteria.

02.03.02 – Levels of Green 4 and 5 Modeling:

Because Levels of Green 4 and 5 already have a standard to store of 60% and 100% of the WQCV, respectively, the simulation trials do not systematically vary parameters in the same way as outlined for Levels of Green 2 and 3. Therefore, new standards for design variables are not required. The modeling here instead focuses on quantifying performance.

Run-on ratio was varied, and the SCM was designed to meet the volume storage requirement at the given run-on ratio using the minimum storage and media depth. For Levels of Green 4 and 5, the SCMs were modeled using the LID Control module in SWMM. The Level of Green 4 interventions were modeled as a surface storage layer with a maximum depth of 6” on top of a media layer, both with and without a storage layer and underdrain. The Level of Green 5 interventions were modeled as a surface storage layer with a maximum depth of 9” on top of a media layer and a storage layer with and without an underdrain. Underdrain outflow is controlled by a 3/8” diameter orifice, raised 1” above the bottom of the facility when included. Refer to Tables A.03.2.3 and A.03.2.4 for the design specifications a of each SCM at each run-on ratio considered.

Table A.03.2.3: Design parameters for SCMs meeting the Level of Green 4 (60% WQCV) requirement at different run-on ratios (assumes tributary area is 100% impervious)

Run-On Ratio	60% WQCV [in]	Storage Depth Required [in]	Design Surface Storage [in]	Design Media Storage Depth [in]	Total Effective Storage Depth [in]
10	0.24	2.16	3	6	3.84
15	0.24	3.36	4	6	4.84
20	0.24	4.56	5	6	5.84
25	0.24	5.76	6	6	6.84
30	0.24	6.96	6	12	7.68
35	0.24	8.16	6	18	8.52
40	0.24	9.36	6	24	9.36
45	0.24	10.56	6	36	11.504

Table A.03.2.4: Design parameters for interventions meeting the Level of Green 5 (100% WQCV) requirement at different run-on ratios (assumes tributary area is 100% impervious)

Run-On Ratio	100% WQCV [in]	Storage Depth Required [in]	Design Surface Storage [in]	Design Media Storage Depth [in]	Total Effective Storage Depth [in]
10	0.4	3.6	4	6	4.84
15	0.4	5.6	6	6	6.84
20	0.4	7.6	8	6	8.84
25	0.4	9.6	9	6	9.84
30	0.4	11.6	9	18	11.52
35	0.4	13.6	9	36	14.04

02.03.03 – Run-on Ratio Assumptions:

1. Run-on ratios include the footprint of the SCM. A run-on ratio of 1 would be just the SCM, and a run-on ratio of 2 would include the SCM and an impervious tributary area equal to the footprint of the intervention.
2. Because SWMM simulates infiltration one-dimensionally, the model results for Levels of Green 2 and 3 are mostly scale independent. For example, the runoff reductions computed when 10 ft^2 of impervious area runs on to 1 ft^2 of pervious area is equivalent to 100 ft^2 of impervious area running on to 10 ft^2 of pervious area, because they both have a run-on ratio of 11:1.
   - The only reason why this scale-independence does not hold perfectly is the surface storage parameter was modified to better represent the effects of a longitudinal slope on actual surface storage. For example, a flow through planter with a 4" depression will hold less water when the longitudinal slope is 8% compared to when the longitudinal slope is 1%.
3. Level of Green 1: A run-on ratio of 1:1, which represents a pervious SCM area managing only itself, was not modeled because it does not have the proper control for this analysis. Therefore, the run-on ratio range started at 2:1 and went up to 4:1.
4. Level of Green 2: Assumed that highest run-on ratio is when the minimum landscape width found in the Denver Complete Streets Guides (1.5') manages the widest walkway width in the Complete Streets Guide (12.5')[4]
5. Level of Green 3: The maximum run-on ratio of 50:1 was taken from MHFD criteria that no less than 2% of the tributary area should be occupied by a bioretention facility[5]
6. Level of Green 4 and 5: The maximum run-on ratio was back-calculated based on the volume that maximum surface storage of 6" for Level of Green 4 or 9" for Level of Green 5 and media storage of 36" could treat, per specifications in the *Ultra Urban Green Infrastructure Guidelines*[1].

02.04 – MODEL OUTPUT POST PROCESSING

From each simulation in SWMM, the reduction in runoff was calculated relative to runoff from a fully impervious control catchment without the SCM. This was done by comparing the runoff from both the impervious and pervious subcatchments, in inches, to the runoff from just the impervious subcatchment, also in inches. The modeled runoff reductions for each Level of Green were plotted as effectiveness curves. The effectiveness curves use one design variable on the x-axis and plot the variability in performance due to the other design variables as boxplots. This shows the control each design variable has on SCM performance and allows for comparison across levels.

02.05 – DESIGN VARIABLE SELECTION

The results from the effectiveness curves were post-processed to establish ranges for the design criteria that are likely to result in desirable levels of performance. Criteria were defined by first choosing a threshold for runoff reduction for each Level of Green based on the model results and best professional judgement then identifying a criterion that would result in >75% of the simulations meeting the threshold.

03 – MODEL RESULTS AND DESIGN VARIABLE SELECTION

03.01 – LEVEL OF GREEN 1

Figure A.03.2.3 shows the effectiveness curve for the Level of Green 1 simulations. Specifically, it shows runoff reductions vs. each of the three design variables tested: run-on ratio, surface storage, and slope.

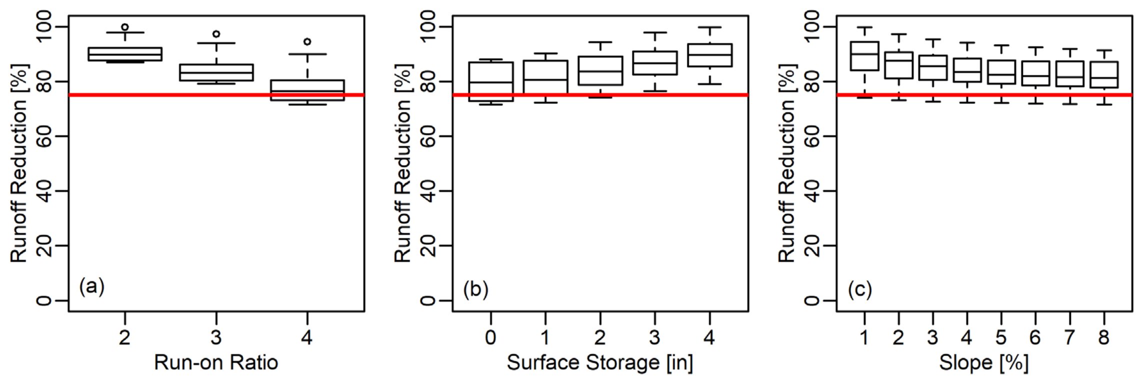

Figure A.03.2.3: Effectiveness curves generated from outputs of SWMM analysis for Level of Green 1

<u>03.01.01 – Runoff reduction threshold: 75%</u>

- Modeling results and best professional judgement indicate that a Level of Green 1 SCM can be required to manage 75% of the runoff from itself and the adjacent walkway that drains to it.
- Therefore, a horizontal red line is draw at 75% runoff reduction on the Level of Green 1 boxplots in Figure A.03.2.3

<u>03.01.02 – Design criterion: Run-on ratios ≤3:1</u>

- Figure A.03.2.4 shows that for run-on ratios ≤3, >75% of situations will reduce runoff by the threshold of 75%. In fact, all simulations meet this >75% runoff reduction criterion.

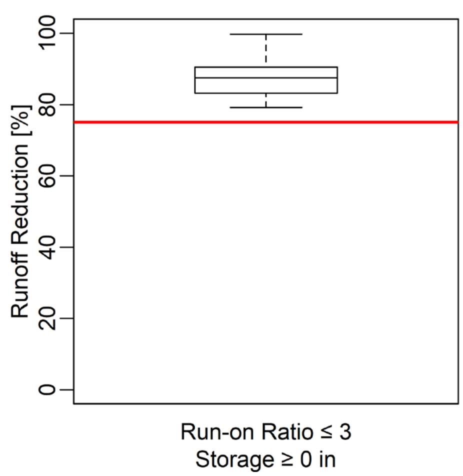

Figure A.03.2.4: Boxplot showing that >75% of the simulations are above the runoff reduction threshold of 75% if the design criterion is met for Level of Green 1

03.02 – LEVEL OF GREEN 2

03.02.01 – Runoff reduction threshold: 75%

- Modeling results and best professional judgement indicate that a Level of Green 2 SCM can be required to manage 75% of the runoff from itself and the adjacent walkway.
- A dashed, horizontal red line is draw at 75% runoff reduction on the Level of Green 2 boxplots in Figure A.03.2.5

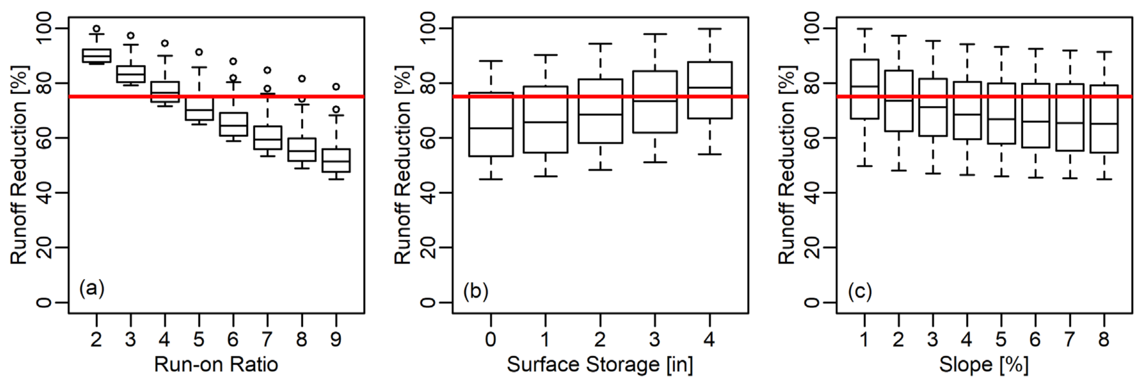

Figure A.03.2.5: Effectiveness curves generated from outputs of SWMM analysis for Level of Green 2

03.02.01 – Two provision design criteria: Run-on ratios ≤6:1 and storage 2-4”

- Figure A.03.2.6 shows that for run-on ratios ≤6 with 2-4” of storage, >75% of situations will reduce runoff by >75%

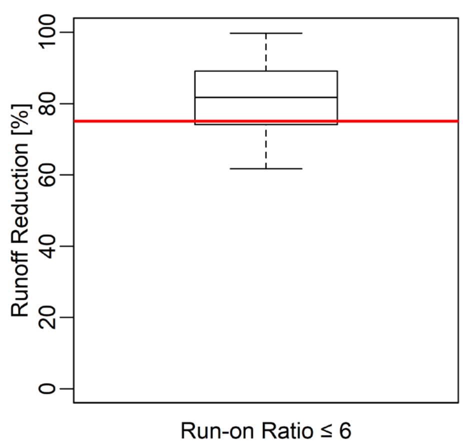

Figure A.03.2.6: Boxplot showing that 75% of the simulations are above the runoff reduction threshold of 75% if the design criteria are met for Level of Green 2

03.03 – LEVEL OF GREEN 3:

03.03.01 – Runoff Reduction Threshold: 25%

- Modeling results and best professional judgement indicate that a Level of Green 3 SCM can be required to manage 25% of the runoff from itself, the walkway, and the roadway. This percentage is lower than for Level of Green 2, but it will manage runoff from more area. It is in line with flow-through type SCMs, designed to filter stormwater rather than infiltrate stormwater.
- A dashed, horizontal red line is draw at 25% runoff reduction on the Level 3 boxplots in Figure A.03.2.7

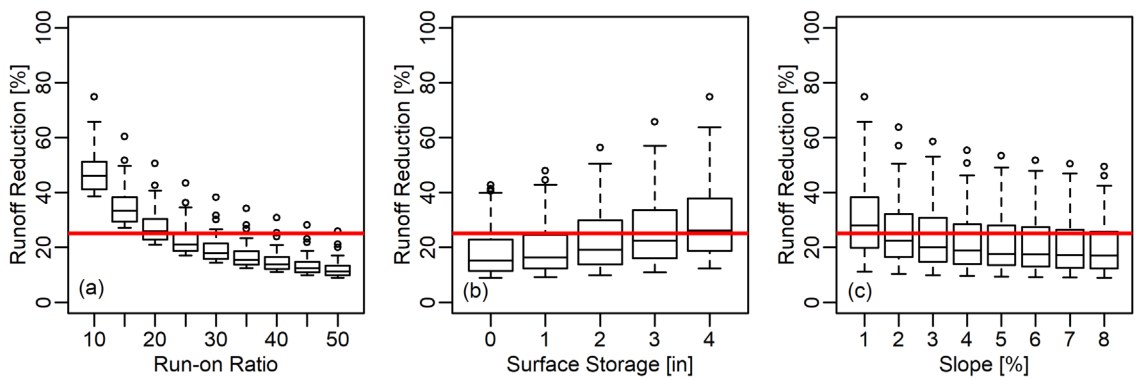

Figure A.03.2.7: Effectiveness curves generated from outputs of SWMM analysis for Level 3

03.03.02 – Design criterion: Run-on ratios ≤20:1

- The boxplot in Figure A.03.2.8 shows that for run-on ratios ≤20 with ≥0" of storage, >75% of situations will reduce runoff by 25%

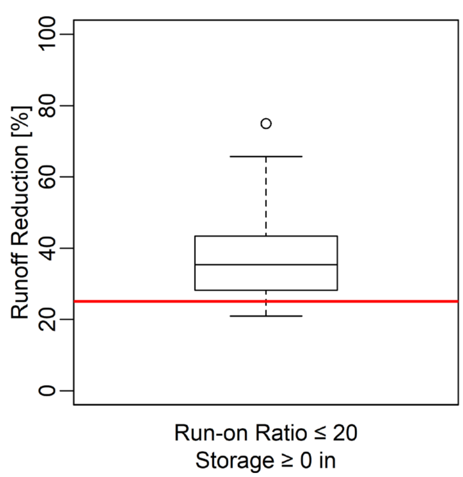

Figure A.03.2.8: Boxplot showing that 75% of the simulations are above the runoff reduction threshold of 25% if the design criterion is met for Level of Green 3

03.04 – LEVELS OF GREEN 4 AND 5

The effectiveness curves for Levels of Green 4 and 5 are shown in Figure A.03.2.9. Because of the existing volume standard, the runoff ratio directly controls the surface storage and media depth. Therefore, the variability shown in each boxplot is due to slope and soil type only. There is no need to establish additional design criteria, only to identify the maximum allowable run-on ratios given the existing standards and the runoff reduction threshold at those run-on ratios. For SCMs with underdrians, the runoff reduction threshold is >30% for Level of Green 4 and >40% for Level of Green 5, and is plotted with the solid red lines Figure A.03.2.9 For SCMs without underdrians, the thresholds are >60% for Level of Green 4 and >75% for Level of Green 5 shown with the dashed red line in Figure A.03.2.9.

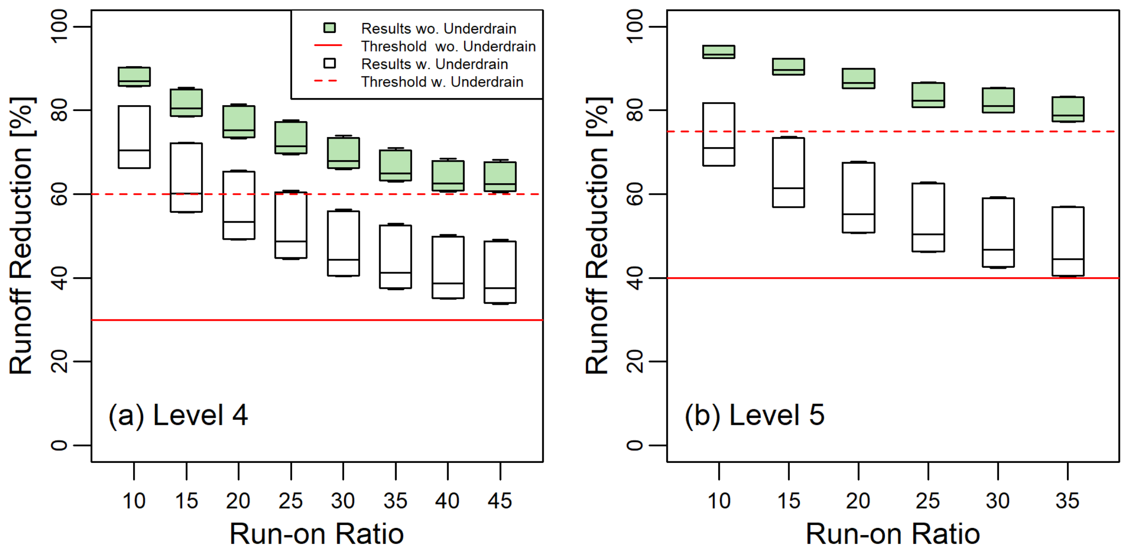

Figure A.03.2.9: Effectiveness Curves for Levels of Green 4 and 5. Variability in the boxplot is due to soil and slope.

04 – CONCLUSIONS AND DESIGN CRITERIA

The design criteria and performance thresholds for all Levels of Green are shown in Table A.03.2.5.

Table A.03.2.5: Design criteria and minimum SCM runoff reduction for each Level of Green

Level of Green	SCM-level runoff reduction threshold	Design Criteria			
	Annual runoff reduction of direct tributary area [%]	Run-on Ratio [tributary area : SCM area]	Volume Storage Requirement [% WQCV]	Surface storage Depth [in]	Media or soil Depth [in]
1	>75	1 to 3	NA	0	Supports tree growth
2	>75	2 to 6	NA	2 to 4	Supports tree growth
3	>25	6 to 20	NA	0 to 4	6 to 18
4	>30 (>60 w/o underdrain)	≤ 45	60	3 to 6	6 to 36

5	>40 (>75 w/o underdrain)	≤ 35	100	6 to 9	18 to 36

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) 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.

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

(5) Urban Drainage and Flood Control District. *Urban Storm Drainage Criteria Manual Volume 3: Chapter 4 Treatment BMPs*; 2018.