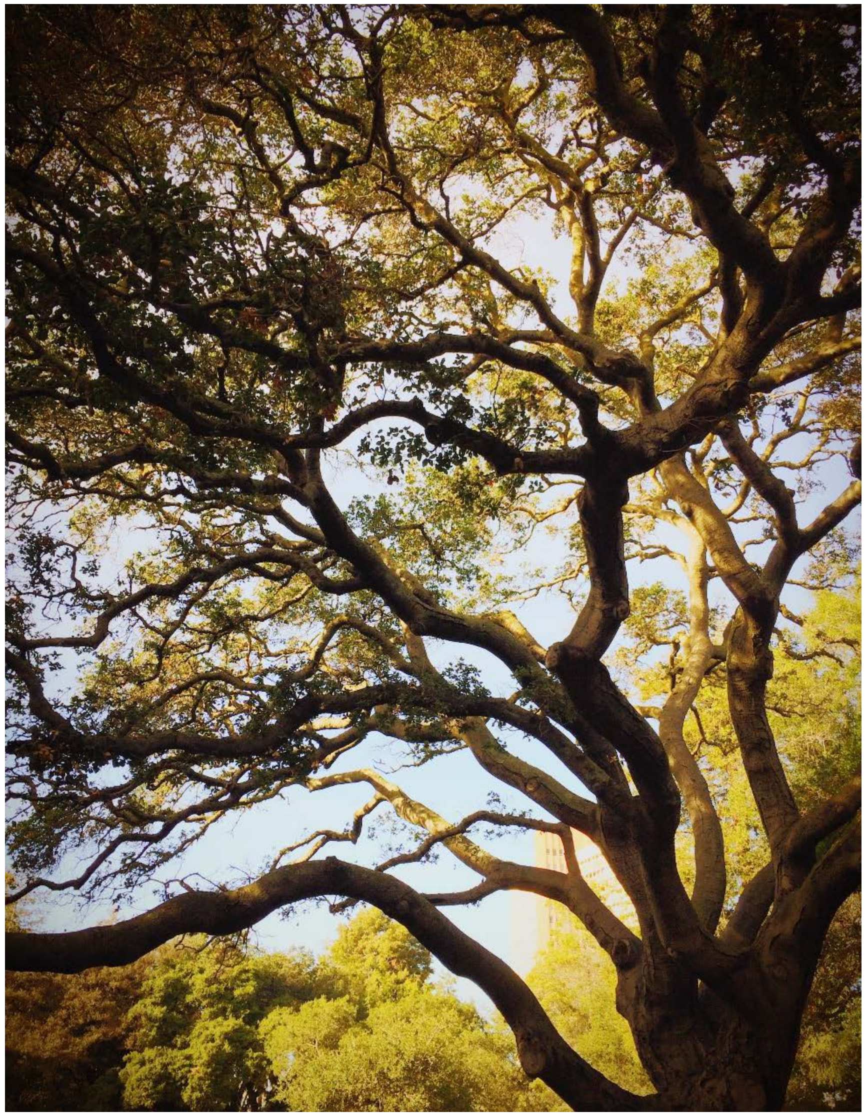
Making Urban Trees Count: A Project to Demonstrate the Role of Urban Trees in Achieving Regulatory Compliance for Clean Water

Center for Watershed Protection

December 2017



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CREDITING FRAMEWORK PRODUCT #7:

Documentation for Stormwater Performance-Based Credit

This project was made possible through a National Urban and Community Forestry Advisory Council grant from the USDA Forest Service

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Suggested citation:

Center for Watershed Protection. 2017. *Documentation for Stormwater Performance-Based Credit*. Crediting Framework Product #7 for the project Making Urban Trees Count: A Project to Demonstrate the Role of Urban Trees in Achieving Regulatory Compliance for Clean Water. Center for Watershed Protection, Ellicott City, MD.

Acknowledgements
The Center extends its gratitude to the following technical reviewers of the Stormwater Performance-Based Credit:

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Stormwater Performance-Based Credit for Urban Tree Planting

Urban trees and forests improve stream quality and watershed health primarily by decreasing the amount of stormwater runoff and pollutants that reach our local waters. The processes of rainfall interception, evapotranspiration, infiltration, and nutrient uptake are important for providing these benefits and are well-accepted in the scientific community. However, it is difficult to quantify the services provided by individual trees because they vary with tree species and age, storm characteristics, climatic conditions, soils, and other factors. It is this uncertainty on how to "credit" trees for runoff and pollutant load reduction that has limited its use as a stormwater BMP for meeting water quality requirements.

The Center for Watershed Protection developed a national Stormwater Performance-Based Credit for tree planting. This method can be adopted by regulatory entities who wish to offer a scientifically defensible credit that encourages greater use of trees for meeting state (or local) stormwater management requirements. The credit quantifies an event-based reduction in runoff volume and nutrient and sediment loads associated with tree planting. It applies to trees planted in the urban environment, but does not apply to planted riparian buffers, large-scale reforestation projects or trees planted in engineered soils, such as bioretention or structural soils.

This paper provides the documentation behind the Stormwater Performance-Based Credit.

The Stormwater Performance-Based Credit provides a relationship between the performance data derived from the modeling results described *Relative and Absolute Reductions in Annual Water Yield and Non-Point Source Pollutant Loads of Urban Trees* (Hynicka and Caraco, 2017). This documentation relates the model output to typical state or local stormwater performance criteria. The method provides a way to utilize the results from the water balance modelling approach such that an annual TMDL-based credit and performance (event) based crediting method are consistent. Although some state stormwater criteria are based on an annual load reduction (e.g., Virginia), it is far more common for these criteria to be event-based. For example, a typical criterion may require treatment of a 1" storm event. Therefore, a method was needed to scale the annual modeling results to a representative storm that authorities may apply to evaluate the effects urban tree planting to locally-define performance standards. While there are many variations of how stormwater criteria are crafted, for simplicity the method divided these event-based criteria into two basic categories, including: 1) runoff reduction-based criteria and 2) pollutant-based criteria. A brief description of each of these is included in Table 1.

Table 1. Stormwater Criteria Summary

Criterion	Runoff Reduction	Pollutant Treatment
Typical formulations	• Reduce the runoff volume from the design storm by a pre-defined percent • Achieve a "pre-developed" runoff volume for the design storm. • Some peak discharge methods can be met with runoff reduction.	• Capture and treat the storm event with a practice that achieves defined pollutant removal efficiency (typical values included 80% TSS or 40% TP). • Reduce the site pollutant loads by a defined percent load reduction.

Although these runoff reduction and pollutant treatment criteria have different stated goals, the water quality benefits of tree planting are directly tied to the volume of runoff reduction. Thus, the runoff reduction credit serves as a "building block" to calculate event-based pollutant reductions on a site. Consequently, a description of the volume reduction credit is first provided, followed by a description of the pollutant removal credit.

Runoff Reduction Calculation

The following method is used to calculate the amount of runoff reduction achieved by tree planting for a certain design storm. This section presents each step of the approach, and includes screen shots from a spreadsheet tool implementing the approach, with an example in Syracuse, NY.

Step 1: Enter Tree Type and Site data

The user selects the Precipitation Station (nearest city), which is then used to determine the climate region based on the classifications used in the modeling (Figure 1). The user also selects the surface over which the tree is planted (from grass over four Hydrologic Soil Groups, and impervious cover), and the tree type.

Step 1: Enter Tree Type and Site Data	1.Precipitation Station (pull-down menu)	2.Region (from Cell 1)	3. Surface (pull-down menu)	4. Tree Type (pull-Down Menu)
	Syracuse, NY	Northeast	Grass - HSG C	BDL

Step 2: Calculate unit runoff reduction

The unit runoff reduction value is a calculated value. It is the volume of runoff reduction per inch of a tree's diameter at breast height (DBH) per inch of annual rainfall (ft^3/inch-DBH/inch-rainfall). This provides a scaled value calculated from the annual water balance modeling results (Hynicka and Caraco 2017). The DBH is provided by i-Tree Forecast output for each given tree at maturity. The unit values are then scaled per inch of *annual* rainfall at that location. Unit runoff reduction values, as well as the data used to calculate these values, are included in Appendix A of this document. This unit assumes that, on an annual basis, the total runoff reduction is proportional to the tree's size, expressed in the DBH, as well as the annual runoff volume.

Step 2: Calculate Unit Runoff Reduction	5.Unit Reduction (cf/inch rainfall/inch DBH) (based on cells 2-4)
	0.0992

Step 3: Identify the representative storm for this location

A representative storm is provided to the user in this step as a means to relate the annual water balance output to an event-based metric. The representative storm is used to relate the unit runoff reduction volume to an event-based standard. The representative storm is based on a location specific rainfall frequency distribution. The representative storm is used to derive a curve number (CN) using TR-55 to replicate the runoff reduction achieved from the annual water balance model (i.e., using similar methods). The CN value derived from the representative storm is then used to calculate the runoff reduction from all rainfall from that location using TR-55. The runoff reduction using this CN was then summed for an annual total runoff and plotted against the water balance model annual values. The representative storm (e.g., 90th percentile) is selected based on the 'best fit' between the TR-55 predicted annual results and the water balance model results (See Appendix B for technical documentation).

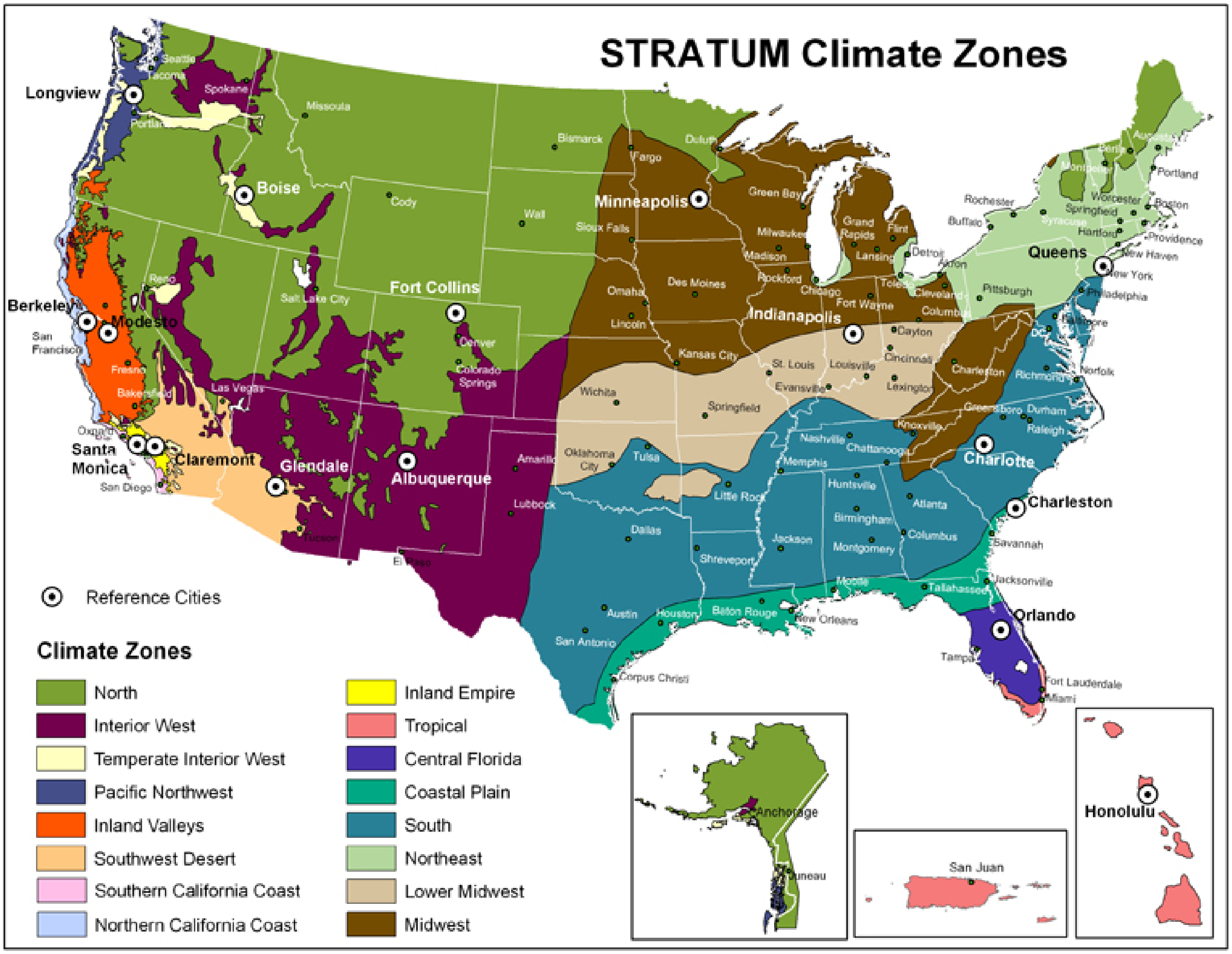

Figure 1. City locations within the 11 climate zones used to develop the water-balance model (see Hynicka and Caraco, 2017).

An analysis of the rainfall records and model results for every city, tree type and surface was used to identify representative storms for each surface type that would align with the annual-based credit. This analysis is described in Appendix B. The results of this analysis determined that a different storm event is appropriate for scaling the effects on each surface, with the following results:

- The 70th Percentile Storm Event for Grass on D Soils.
- The 80th Percentile Storm Event for Grass on B or C Soils, or Impervious Cover.
- The 90th Percentile Storm Event for Grass on A Soils.

Representative storm data for each city are included in Table 2. The spreadsheet tool selects the appropriate storm using a lookup Table. This storm event is used to develop runoff coefficients (i.e., CN) that can be used to find the runoff reduction for any design storm (Step 5). For this example, the 80th percentile storm is defined as the representative storm of 0.6260 (0.63 in Table 2) for Syracuse, NY for HSG C soils.

Step 3: Identify the Representative Storm for this location	6. Representative Storm (inches)
	0.6260

Table 2. Precipitation Event for locations within in 11 Climate Zones.

City	Region	Annual Precipitation	70%	80%	90%
Albuquerque, NM	Southwest interior	8.74	0.35	0.50	0.67
Baton Rouge, LA	Coastal Plain	61.48	0.85	1.19	1.80
Bismark, ND	North	19.39	0.46	0.62	0.90
Boise, ID	Interior West	11.29	0.29	0.36	0.47
Charleston, SC	Coastal Plain	52.07	0.80	1.05	1.55
Chattanooga, TN	South	51.10	0.73	0.97	1.40
Cheyenne, WY	North	15.57	0.34	0.47	0.77
Cincinnati, OH	Lower Midwest	39.97	0.57	0.73	1.06
Corpus Christi, TX	Coastal Plain	29.46	0.73	1.03	1.59
Dallas, TX	South	36.33	0.79	1.08	1.56
Des Moines, IA	Midwest	38.13	0.61	0.81	1.22
Eugene, OR	Pacific Northwest	37.08	0.45	0.58	0.82
Flagstaff, AZ	Southwest interior	20.65	0.49	0.65	0.94
Honolulu, HI	Tropical	16.35	0.52	0.76	1.13
Lansing, MI	Midwest	34.82	0.51	0.65	0.95
Los Angeles, CA	California Coast and Interior	9.67	0.54	0.67	1.00
Lubbock, TX	Southwest interior	18.08	0.50	0.77	1.12
Miami, FL	Tropical	65.40	0.78	1.10	1.63
Minneapolis, MN	Midwest	31.34	0.55	0.73	1.05
Missoula, MT	North	13.46	0.28	0.34	0.47
Pittsburgh, PA	Northeast	38.20	0.48	0.63	0.85
Portland, ME	Northeast	52.00	0.69	0.92	1.36
Reno, NV	Interior West	6.76	0.32	0.45	0.60
Salt Lake City, UT	Interior West	15.12	0.34	0.44	0.57
San Francisco, CA	California Coast and Interior	17.18	0.51	0.65	0.92
Seattle, WA	Pacific Northwest	41.03	0.43	0.57	0.82
St. Louis, MO	Lower Midwest	42.49	0.63	0.87	1.31
Syracuse, NY	Northeast	40.65	0.49	0.63	0.90
Tampa, FL	Coastal Plain	50.20	0.80	1.15	1.68
Washington, DC	South	40.55	0.62	0.81	1.17
Wichita, KS	Lower Midwest	35.96	0.74	1.03	1.47

Step 4: Enter the number of trees, DBH and canopy area

The user enters data characterizing the tree plantings. This is limited to the number of trees planted with default values for tree DBH and tree canopy area provided. These data are used in later calculations to estimate the benefits of these plantings. Default values for tree DBH and canopy area are based on the trees used in Hynicka and Caraco (2017). The user may enter other values. In the example provided below, the user changed the default values provided for both DBH and tree canopy area.

Step 4: Enter the tree DBH, number of trees, canopy area and DBH	7. Number of Trees Planted	Typical DBH (inches) for Guidance)	8. DBH (inches)	Tree Canopy Area (sf) (Suggested)	9. Tree Canopy Area (sf) (Entered)
	10	11.40	12	4896	5000

Step 5: Calculate the Runoff Reduction Volume for the Representative Storm, and calculate revised runoff parameters.

In this step, the representative storm identified in Step 3 (based on soil type or impervious cover and climate location) is calculated and used to adjust the CN (NRCS, 1986) and estimate the runoff reduction, as follows:

Step 5: Calculate the Runoff Reductiion Volume for the Reresentative Storm, and calculate a revised curve number for the treed area.	10. Runoff Reduction for the Representative Storm (cf)	11. Base CN	12. "Base" Runoff in the Area Beneath the Tree Canopy (cf)	13. Runoff for the Representative Storm (cf)	14. Runoff In Inches	15. Adjusted Curve Number
	7.5	70.95	16.37	8.92	0.0214	64.67

In Cell 10, the Runoff Reduction is calculated by multiplying the unit runoff reduction (Cell 5) by the representative storm depth (inches) (Cell 6).

$RR_{andhor} = (RR_{Tree\text{-}Unit})x(DBH)x(T)x(P_{representative})$

Where:

$RR_{representative}$ = runoff reduction volume for the representative storm (cf)

$RR_{Tree\text{-}Unit}$ = Tree and Region-specific unit runoff reduction (cf/in. rainfall/in. DBH)

T = Number of Trees

$P_{representative}$ = Representative Storm (inches) [from step 3]

- The "Base" CN using the representative storm is provided in Cell 11. The "base" CN is the value that would be used to predict runoff from the surface without trees present. Note that these curve numbers are adjusted based on the methods described in Woodward (2004) to account for smaller drainage areas.
- In Cell 12, this value is used to calculate the "Base" runoff, or the runoff that would have occurred without trees. The equation used to calculate runoff is:

$$R = \frac{\left(P - 0.05 \cdot \left(\frac{1000}{CN} - 10\right)\right)^2}{P + 0.95 \cdot \left(\frac{1000}{CN} - 10\right)} xA/12$$

Where:

R = Runoff Volume (cf)

P = Rainfall Depth (inches)
A = Area (sf) (in this case it is the area of the tree canopy)

CN = Curve Number
1/12 = Conversion Factor (Inches to Feet)

- In Cell 13, the runoff from the representative storm is calculated. This is simply the difference between the Base Runoff (Cell 12) and the Runoff Reduction (Cell 10).

- Cell 14 converts the runoff volume calculated in Cell 13 to a runoff depth in inches by dividing by the area (i.e., the area under the canopy) with the following equation:

  R(inches) = 12 x R(cf) x A (canopy area, ft^2)

- Finally, the equation for TR-55 is used to define the value of the adjusted curve number (Cell 15), with the following equation:

$$CN = \frac{100}{\left\lfloor 2xP + 19xR - \sqrt{361xR^2 + 80xPxR} + 1 \right\rfloor}$$

Where:

P = Precipitation Depth (Inches)
R = Runoff Depth (inches)

Step 6: Calculate "non-tree" runoff volumes at the site and canopy scales for the design storm

The Design Storm is defined by state or local regulations and represents the storm event that needs to be controlled. A typical value is the 90th percentile storm event, or 1”, and this is presented as an example for the user, but there is a wide range of storm events across states and local regulations. In this step, the user enters the depth of the Design Storm.

In Cell 17, the runoff equation (from Step 5) is used to calculate the runoff under the canopy, using the Base Curve Number from Cell 11.

In Cell 19, the average weighted CN for the entire site is calculated, which is then used to calculate the runoff for the entire site (Cell 20). This runoff volume is used to calculate the percent runoff reduction at the site level in the final step, but does not affect the absolute runoff reduction volume. Note that the site runoff volume may be calculated using a different methodology, such as a runoff coefficient method, in some municipalities.

Step 6: Calculate "Non-Tree" Runoff Volumes at the site and canopy scales for the Design Storm		90th Percentile Storm Event (for Guidance)	16. Design Storm (inches)	17. Runoff from the Area Below the Tree Canopy (cf)
		0.9	1	53.89
	Land Cover Type (Site Area)	18a-e. Site Areas (sf)	19. Site Curve Number	20. Site Level Runoff Without Trees (cf)
	Grass - HSG A		88.04	270.19
	Grass - HSG B			
	Grass - HSG C			
	Grass - HSG D	22000		
	Impervious Cover	22000		
	Total	44000		

Step 7: Calculate the runoff reduction volume for the design storm

The runoff from the area under the tree canopy using the Adjusted CN (from Cell 15 in Step 5) is calculated in this Step. The difference between this value and the Runoff Volume below the Tree Canopy (Cell 17) is equal to the runoff reduction volume that was achieved by tree planting.

Depending on the specific regulations, this may be the last step needed, as the Runoff Reduction Volume that can be achieved by the trees planted is provided. In many communities, this value alone can be used to document the extent to which trees provide runoff reduction for the design storm.

Step 7: Calculate the runoff reduction volume for the design storm	21. Runoff Volume for the Design Storm with Trees (cf)	22. Runoff Reduction Volume (cf)
	35.56	18.3

Step 8: Calculate the TN, TP and TSS reductions in urban runoff

In some municipalities, the regulations also tie the design storm to a particular pollutant removal. Thus, step 8 is provided to quantify pollutant removals for this storm event. In this step, the runoff volume calculated in Step 7 is multiplied by the default or user provided concentrations for total nitrogen (TN), total phosphorus (TP) and sediment (TSS) to estimate a load reduction for this runoff event. The equation is as follows:

$$LR_{runoff} = (RR_{Volume}) x C_{surface} x 6.24x10^{-5}$$

Where:

LR_{runoff} = surface runoff load reduction (lbs)
RRvolume = Runoff Reduction volume (cf)
$C_{surface}$ = surface runoff concentration (mg/L)
$6.24x10^{-5}$ = Conversion Factor

Default concentrations are provided in the calculation tool, but can be overridden by the user.

Step 8: Calculate the TN, TP and TSS reductions in urban runoff for the Design Storm (Cells 24a-c calculted from cell 22 and corresponding cells in 23a-c)	23a.TN Concentration (mg/L)	23b.TP Concentration (mg/L)	23c.TSS Concentration (mg/L)
	1.45	0.25	140
	24a.TN Load Reduction (lbs)	24b. TP Load Reduction (lbs)	24c.TSS Load Reduction (lbs)
	0.0017	0.0003	0.1601

Step 9: Represent reductions as percentages

This step calculates runoff and pollutant reductions as a percentage of the values without trees at the site and canopy scales. These percentages may be used to assist a manager in understanding the extent to which tree plantings achieved standards for the design storm.

Step 9: Represent as Percentages		% Reductions
	25. Canopy Scale	34.01%
	26. Site Scale	6.78%

References

Hynicka, J. and D. Caraco. 2017. *Relative and Absolute Reductions in Annual Water Yield and Non-Point Source Pollutant Loads of Urban Trees*. Crediting Framework Product #2 for the project Making Urban Trees Count: A Project to Demonstrate the Role of Urban Trees in Achieving Regulatory Compliance for Clean Water. Center for Watershed Protection, Ellicott City, MD.

Appendix A. Basic Tree Data and Unit Runoff and Leachate Reduction

TABLE A-1. UNIT RUNOFF REDUCTION FOR TREE TYPES IN EACH ZONE								
Zone	Tree Type	Canopy Area (sf)	DBH (inches)	Unit Runoff Reduction (cf/inch of DBH/inch of Precipitation) by Surface Type				
				Grass HSG-A	Grass HSG-B	Grass HSG-C	Grass HSG-D	Impervious
California Coast and Interior	BDL	1382.1	23.05	0.040	0.086	0.175	0.248	0.075
California Coast and Interior	BDM	766.3	16.40	0.056	0.105	0.209	0.290	0.120
California Coast and Interior	BDS	161.4	3.30	0.013	0.031	0.069	0.099	0.052
California Coast and Interior	CEL	660.5	21.80	0.050	0.064	0.127	0.181	0.084
California Coast and Interior	CES	280.6	11.70	0.030	0.052	0.106	0.150	0.076
Coastal Plain	BDL	2469.0	38.73	0.073	0.192	0.286	0.336	0.116
Coastal Plain	BDM	789.2	22.60	0.051	0.160	0.251	0.305	0.229
Coastal Plain	BDS	648.4	14.17	0.052	0.138	0.201	0.228	0.112
Coastal Plain	CEL	700.0	22.60	0.042	0.127	0.195	0.234	0.115
Coastal Plain	CES	22.1	3.80	0.009	0.026	0.041	0.050	0.032
Interior West	BDL	1830.2	28.20	0.005	0.027	0.092	0.265	0.374
Interior West	BDM	120.3	5.73	0.000	0.004	0.015	0.045	0.061
Interior West	BDS	515.0	14.00	0.001	0.013	0.046	0.123	0.189
Interior West	CEL	547.4	18.17	0.007	0.015	0.050	0.140	0.202
Interior West	CES	179.3	8.53	0.003	0.009	0.030	0.082	0.168
Lower Midwest	BDL	855.3	16.00	0.133	0.147	0.272	0.364	0.174
Lower Midwest	BDM	982.4	18.07	0.140	0.188	0.343	0.457	0.268
Lower Midwest	BDS	125.4	3.17	0.032	0.051	0.093	0.126	0.082
Lower Midwest	CEL	774.4	18.70	0.140	0.143	0.261	0.348	0.184
Lower Midwest	CES	339.8	13.30	0.079	0.107	0.202	0.272	0.245
Midwest	BDL	886.7	16.27	0.147	0.208	0.366	0.484	0.200
Midwest	BDM	940.3	17.30	0.139	0.271	0.486	0.647	0.300

TABLE A-1. UNIT RUNOFF REDUCTION FOR TREE TYPES IN EACH ZONE								
Zone	**Tree Type**	**Canopy Area (sf)**	**DBH (inches)**	**Unit Runoff Reduction (cf/inch of DBH/inch of Precipitation) by Surface Type**				
				Grass HSG-A	**Grass HSG-B**	**Grass HSG-C**	**Grass HSG-D**	**Impervious**
Midwest	BDS	300.7	8.03	0.086	0.138	0.240	0.313	0.150
Midwest	CEL	738.6	21.37	0.133	0.196	0.360	0.481	0.235
Midwest	CES	219.1	18.73	0.052	0.074	0.139	0.187	0.132
North	BDL	1411.8	22.97	0.016	0.106	0.231	0.337	0.417
North	BDM	90.5	6.17	0.002	0.016	0.035	0.051	0.054
North	BDS	481.9	13.53	0.009	0.060	0.128	0.183	0.193
North	CEL	590.5	19.60	0.009	0.056	0.122	0.177	0.230
North	CES	166.0	8.10	0.005	0.034	0.076	0.112	0.218
Northeast	BDL	489.6	11.40	0.210	0.151	0.261	0.343	0.211
Northeast	BDM	951.2	17.50	0.228	0.194	0.334	0.439	0.273
Northeast	BDS	242.1	6.40	0.130	0.102	0.170	0.221	0.130
Northeast	CEL	577.6	17.77	0.293	0.161	0.269	0.349	0.256
Northeast	CES	255.2	17.07	0.129	0.065	0.115	0.153	0.149
Pacific Northwest	BDL	814.3	15.80	0.047	0.078	0.152	0.218	0.160
Pacific Northwest	BDM	789.2	15.50	0.048	0.079	0.153	0.220	0.170
Pacific Northwest	BDS	105.7	2.55	0.022	0.040	0.078	0.111	0.106
Pacific Northwest	CEL	646.9	21.50	0.051	0.058	0.115	0.165	0.193
Pacific Northwest	CES	153.9	7.80	0.031	0.035	0.069	0.099	0.097
South	BDL	1779.8	31.20	0.259	0.323	0.508	0.636	0.325
South	BDM	969.6	17.87	0.222	0.246	0.381	0.473	0.169
South	BDS	575.2	12.70	0.077	0.135	0.212	0.265	0.110
South	CEL	899.8	25.40	0.195	0.174	0.275	0.341	0.127
South	CES	364.6	14.07	0.132	0.159	0.256	0.324	0.187
Southwest Interior	BDL	1024.8	18.53	0.030	0.044	0.102	0.213	0.340
Southwest Interior	BDM	183.9	7.83	0.004	0.015	0.034	0.073	0.085

TABLE A-1. UNIT RUNOFF REDUCTION FOR TREE TYPES IN EACH ZONE								
Zone	Tree Type	Canopy Area (sf)	DBH (inches)	Unit Runoff Reduction (cf/inch of DBH/inch of Precipitation) by Surface Type				
				Grass HSG-A	Grass HSG-B	Grass HSG-C	Grass HSG-D	Impervious
Southwest Interior	BDS	177.5	3.57	0.015	0.027	0.062	0.119	0.224
Southwest Interior	CEL	728.6	21.40	0.029	0.030	0.059	0.109	0.171
Southwest Interior	CES	239.8	10.10	0.027	0.018	0.042	0.088	0.168
Tropical	BDL	2030.2	35.70	0.071	0.265	0.406	0.498	0.138
Tropical	BDM	678.6	18.70	0.315	0.333	0.528	0.651	0.291
Tropical	BDS	127.3	5.30	0.081	0.123	0.190	0.233	0.071
Tropical	CEL	660.5	21.80	0.687	0.326	0.506	0.622	0.181
Tropical	CES	22.1	3.80	0.055	0.067	0.105	0.129	0.048

Appendix B. Methodology for Quantifying Runoff Reduction from a Design Storm

The methodology described in this document quantifies the benefits of tree planting for a specific storm event and is based upon the following:

1) The Unit Runoff Reduction Value from the Water Balance Model is expressed as a standardized unit reduction (in reduction per inch of rainfall per inch of tree DBH).
2) These unit values are not uniformly applicable across all storm events. In fact, it is expected to see a curve pattern with a peak performance at some storm event (See Discussion Below).
3) In order to convert the runoff reduction benefits at the annual scale to a particular design event, we need to adjust a runoff parameter (in this case, we use the Curve Number from TR-55, consistent with the Water Balance Model.
4) We adjust the curve number by identifying an "equivalent storm event." The equivalent storm is an event (expressed as a percentile), that can be used to adjust the curve number using the assumption that the unit runoff reduction (in inches/inch of rainfall/inch DBH) is applied to this event.
5) We select the appropriate equivalent storm by systematically selecting a storm event (as a percentile), adjusting the curve number using this event, and then using the adjusted curve number to reproduce the annual model results using the same rainfall record.

Bullet 2 is a key in the development of this approach. In the Water Balance Model (Hynicka and Caraco 2017), the runoff reduction from urban tree planting was modeled, accounting for evapotranspiration and interception in the leaf canopy, but also changes in the Curve Number based on TR-55. In order to translate the annual water balance model to an event-based runoff reduction crediting method, a new CN was needed to represent runoff at a different time step (event driven vs annual) for each of the different land cover types. As such, the approach taken identifies the storm that can be used to modify the curve number in a way that would produce the annual runoff reduction the Water Balance Model predicts. In addition to reflecting the curve number changes made in that model, it will also reflect the effects of evapotranspiration and interception that are explicitly included in the water balance model. This will provide consistency between the annual TMDL-based credit and the performance (event) based credit.

In order to identify the appropriate storm to translate the annual water balance model results to an event-based on performance standard approach, rainfall records were evaluated from all 31 cities included in the Water Balance Model, using the following steps. The analysis was conducted in R, a publicly available software, and the code is included at the end of this appendix.

1. Read in relevant data. These data include:
   a. Daily precipitation data for each city, corresponding to the model period (2009-2014).
   b. Tree Data including: Crown Area and Unit Runoff Reduction for each tree Type/region

2. Calculate the annual Runoff Reduction for each city-Tree Type combination. This value is determined as:

   $RR_{Annual} = P_{Annual} x RR_{Unit}$

   Where:

RR_{Annual} = Annual Runoff Reduction (cf/yr)
P_{Annual} = Annual Precipitation (inches/yr)
RR_{Unit} = Unit Runoff Reduction (cf/inch rainfall)

3. Identify various storm events (as a percentile) in each city's precipitation record. In this methodology, only runoff-producing storms (i.e., storms greater than 0.1" in depth) were included. For this analysis, we evaluated the 70th, 80th, and 90th percentile storm events.

4. Calculate the "Without Trees" runoff volume from each city/surface type combination for each potential representative storm. TR-55 was used to calculate these runoff volumes, with the following equation:

$$R_{no\ trees} = \frac{\left(P - 0.05 \cdot \left(\frac{1000}{CN} - 10\right)\right)^2}{P + 0.95 \cdot \left(\frac{1000}{CN} - 10\right)} xA/12$$

Where:
$R_{no\ trees}$ = Runoff Volume (cf)
P = Rainfall Depth (inches)
A = Area (sf) (in this case it is the area of the tree canopy)
CN = Curve Number
1/12 = Conversion Factor (Inches to Feet)

The CNs for the initial conditions (no trees) were based on open space, fair condition values. Reference values for turf grass were used in most regions, but in arid regions (Interior West and Southwest Interior), range curve numbers were used. (Table 3).

Table B-1. Base Curve Numbers by Climate and Soil Type/Surface

	Arid (Southwest Interior and Interior West)	Humid (Other Regions)
HSG A	49	55
HSG B	69	71
HSG C	79	81
HSG D	84	89
Impervious	98	98

These base CN values were first modified to be consistent with the CN calculations reported in Woodward (2003; Equation 9). This equation adjusts the curve number to account for the modified calculation of the S value.

$$CN_{adj} = \frac{100}{1.879 \times \left(\frac{100}{CN_{base}} - 1\right)^{1.15} + 1}$$

5. Calculate the Event Runoff Reduction (cf) from each combination as:

$RR = P x RR_{Unit}$

Where:

RR = Event Runoff Reduction (cf)

P = Event Precipitation (inches)

RR_{Unit} = Unit Runoff Reduction (cf/inch rainfall; this number is taken from the modeling results for each city).

6. Calculate the Runoff Volume *with trees* for each combination:

$R_{trees} = R_{no\ trees} - RR$

7. Convert the runoff volume to runoff depth in inches.

$R_{trees(inch)} = (R_{trees}) x 12 / A_{canopy}$

8. Find the Adjusted Initial Abstraction for the condition with trees present.

$$\text{Ia} = \frac{2 \times P + 19 \times R - \sqrt{361 \times R^2 + 80 \times P \times R}}{2}$$

Where:

Ia = Initial Abstraction (inches) (the Initial Abstraction is related to the curve number and is used to calculate the runoff volume).

P = Precipitation (inches)

R = Runoff (inches); equal to $R_{trees\text{-}inch}$

9. Find the total annual runoff estimated by applying the modified curve number (i.e., using the calculated Initial Abstraction),

$$R_{ann-est} = \sum_{i} \frac{(P_i - Ia)^2}{(P_i + 19 \times Ia) \times Y} \times \frac{A_{Canopy}}{12}$$

Where:

$R_{ann\text{-}est}$ = Estimated Annual Runoff (inches/year) from the rainfall record analysis
P_i = Precipitation Depth (inches) on Day i
Ia = Initial Abstraction (inches)
A_{canopy} = Area Beneath the Tree Canopy (sf)

10. Calculate the "Base" annual runoff volume by summing the runoff from each storm event (using the same equation used in Step 4 to find the equivalent representative storm base runoff volume).

11. The Calculated Estimated Annual Runoff Reduction is then calculated as the difference between the "Base" annual runoff (from step 10) minus the estimated annual runoff with trees (from step 10).

12. Determine the correct equivalent storm event.

If the correct equivalent storm is chosen, we would expect the estimated annual runoff reduction (from the rainfall record, calculated in Step 11) to match the annual runoff reduction method from the model results (Step 2).

For each storm event evaluated (70^{th}, 80^{th}, 90^{th} percentiles), the Mean Square Error statistic and a paired t-test were used to quantify the 90% confidence interval for the difference between the annual runoff volume predicted using the representative storm (method above) and the annual volume predicted by the Annual Water Balance Model. The summary statistics, along with the storm selected for each surface, are included in Table A-1. The shaded cells represent the percentile equivalent storm selected. Plots representing the agreement between the two values are included in Figures B1-B3.

Table B-2. Summary statistics for rainfall frequency distribution analysis.

		90% Confidence Interval for Prediction Error		
Percentile Equivalent Storm	**Surface**	**Low**	**High**	**Mean Standard Error**
70	Grass-HSG A	0.10	0.18	0.33
80	Grass-HSG A	-0.31	-0.07	0.90
90	Grass-HSGA	-0.02	0.02	0.15
70	Grass-HSG B	-0.53	-0.31	0.93
80	Grass-HSG B	-0.07	-0.04	0.13
90	Grass-HSG B	0.10	0.17	0.28
70	Grass-HSG C	-0.23	-0.13	0.38
80	Grass-HSG C	0.03	0.06	0.11
90	Grass-HSG C	0.17	0.28	0.45
70	Grass-HSG D	-0.10	-0.05	0.19
80	Grass-HSG D	0.10	0.15	0.25
90	Grass-HSG D	0.22	0.35	0.55
70	Impervious	0.12	0.18	0.26
80	Impervious	0.04	0.07	0.11
90	Impervious	-0.19	-0.10	0.34

Figure B-1. Estimated vs. Modeled Runoff Reduction using the 70th Percentile Representative Equivalent Storm

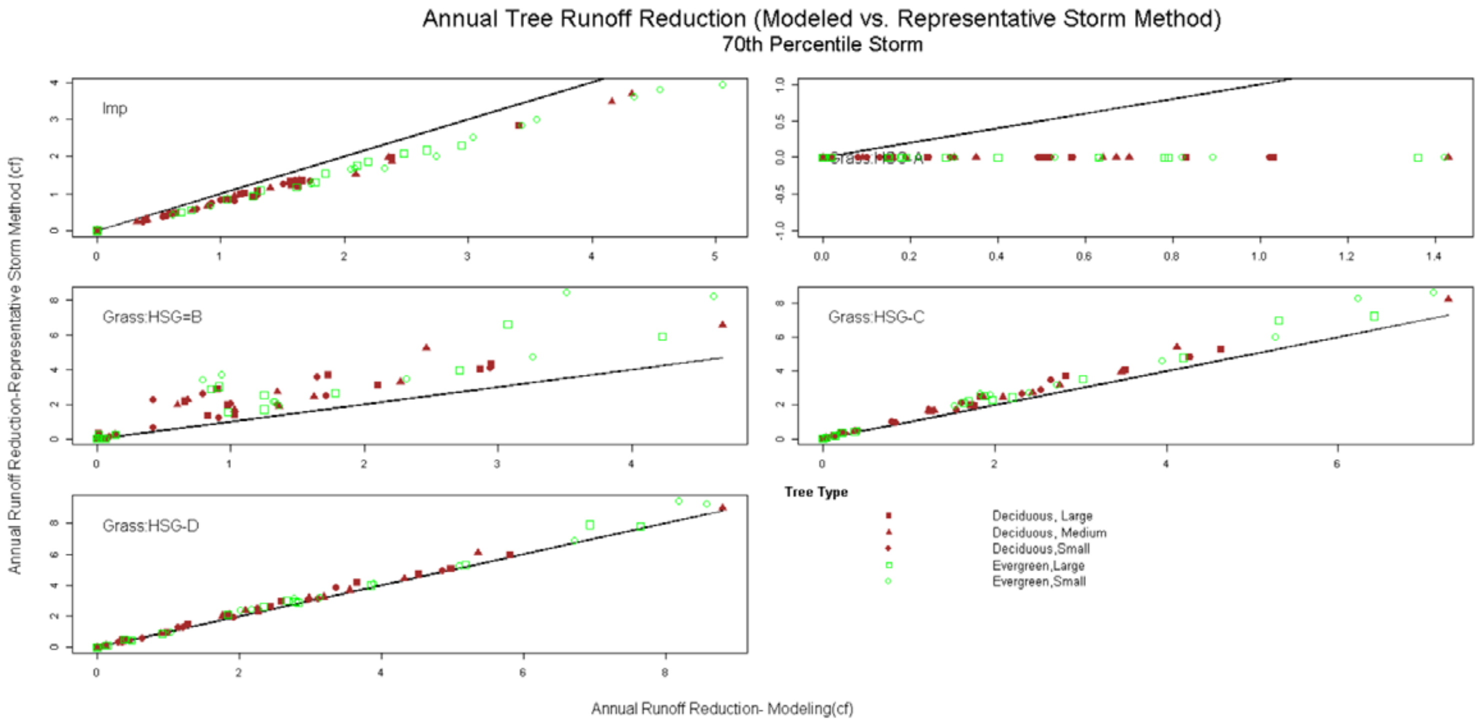

Figure B-2. Estimated vs. Modeled Runoff Reduction using the 80th Percentile Representative Storm.

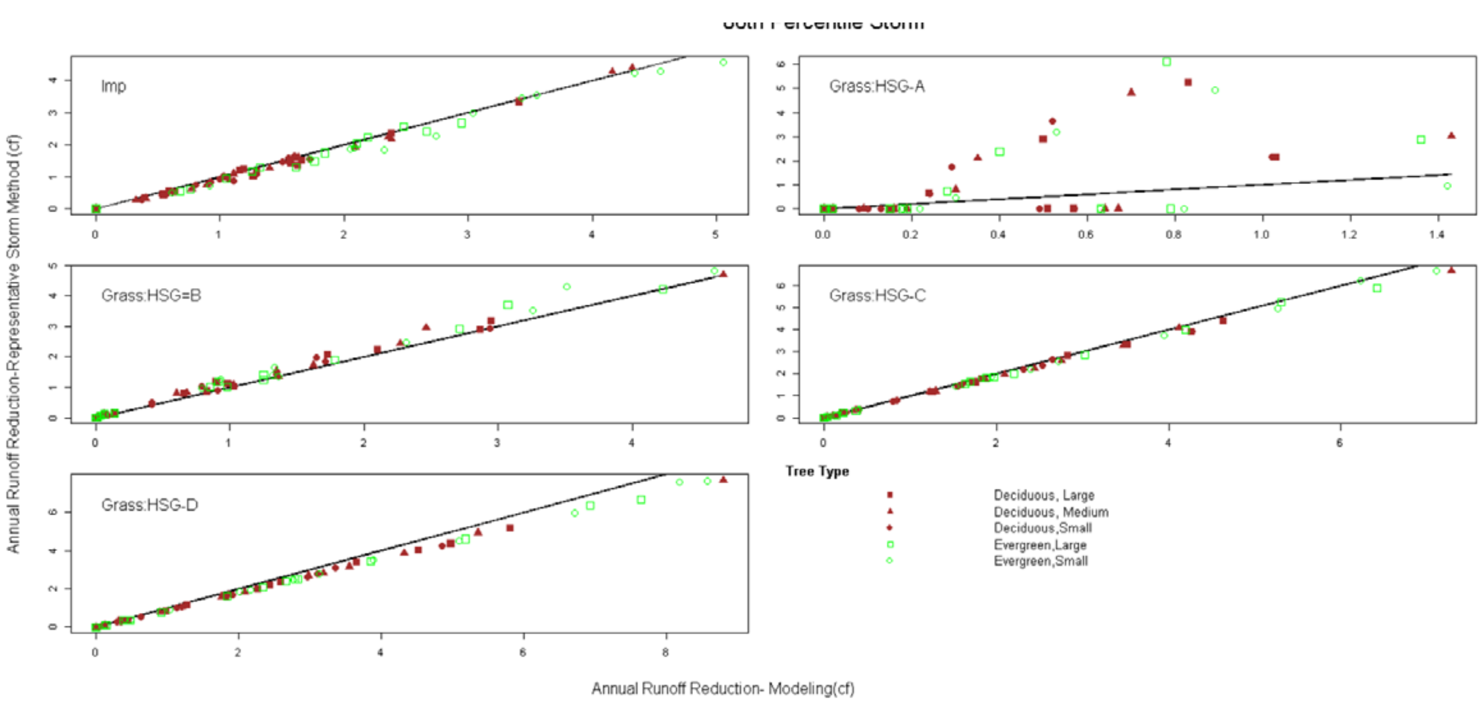

Figure B-3. Estimated vs. Modeled Runoff Reduction using the 90th Percentile Representative Storm.