Impacts of Urban Soil Compaction on Stormwater Runoff Volumes and BMP Sizing

Shirley E. Clark, PhD, PE, BC WRE, ENV SP, F ASCE

Distinguished Professor of Environmental Engineering

Bishwodeep Adhikari, PhD

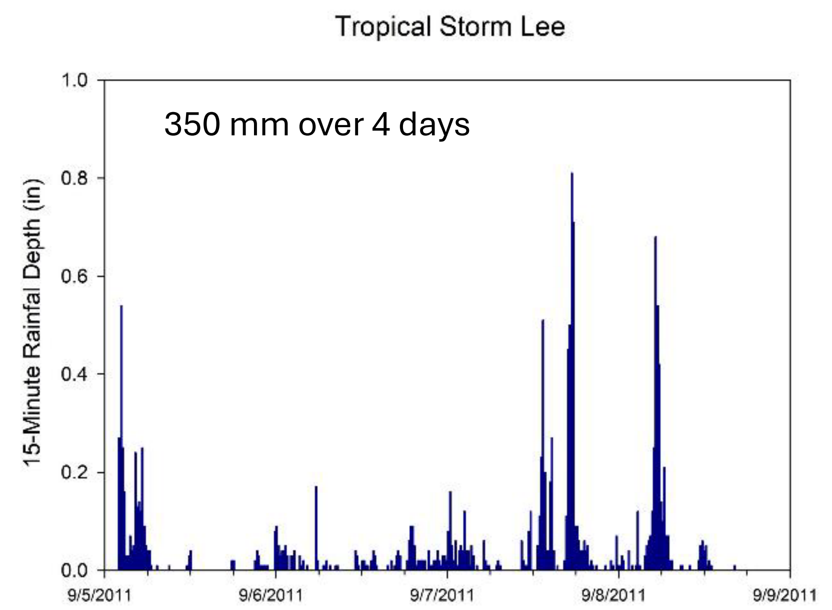
Assistant Professor of Environmental Engineering

Ghasem Razavi

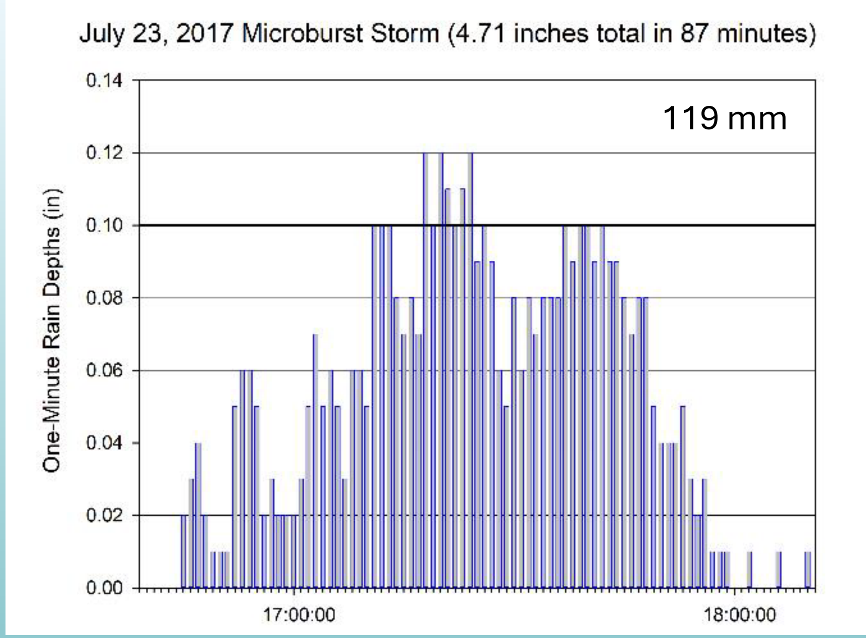
PhD Student

PennState Harrisburg

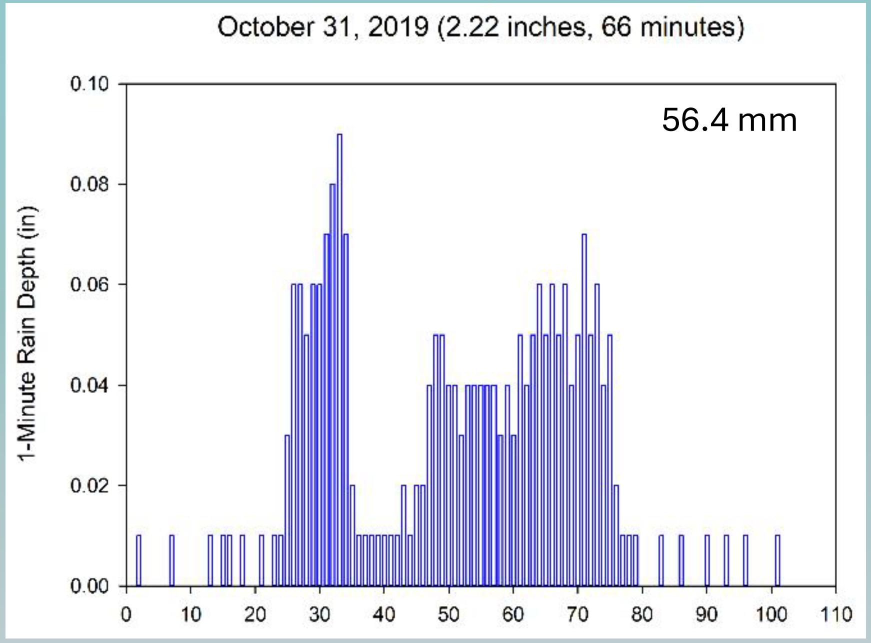
More Frequent Short-Duration, High-Intensity Storms



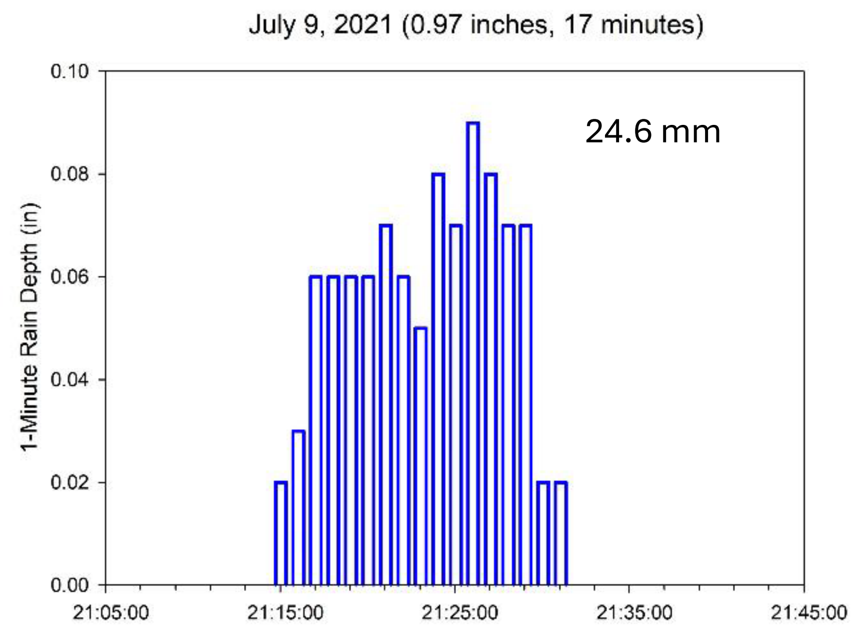
6 years



2 years, 3 months



1 year, 8 months



Flooding throughout Watershed during Microburst Storm of 4.71 inches in 85 minutes

(Photos by Borough residents and personnel)

Construction Procedure:

1. Clear Land and Grade
2. Compact Soils on Building Footprint and Staging/Working Areas
3. Add topsoil and Compact
4. Rototill to Unknown Depth
5. Plant Grass or Lay Sod

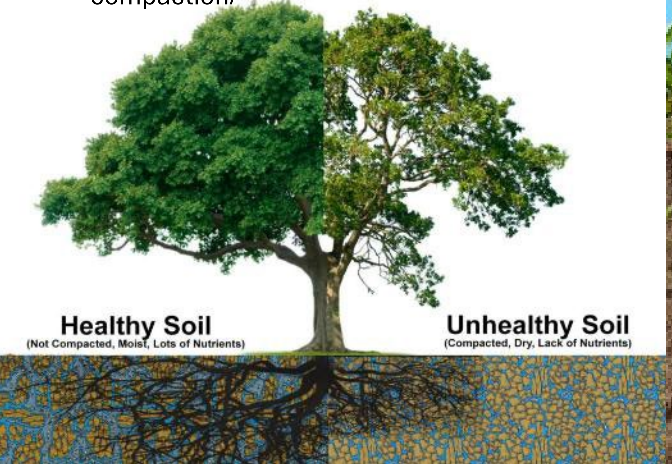
9 inches of soil water storage

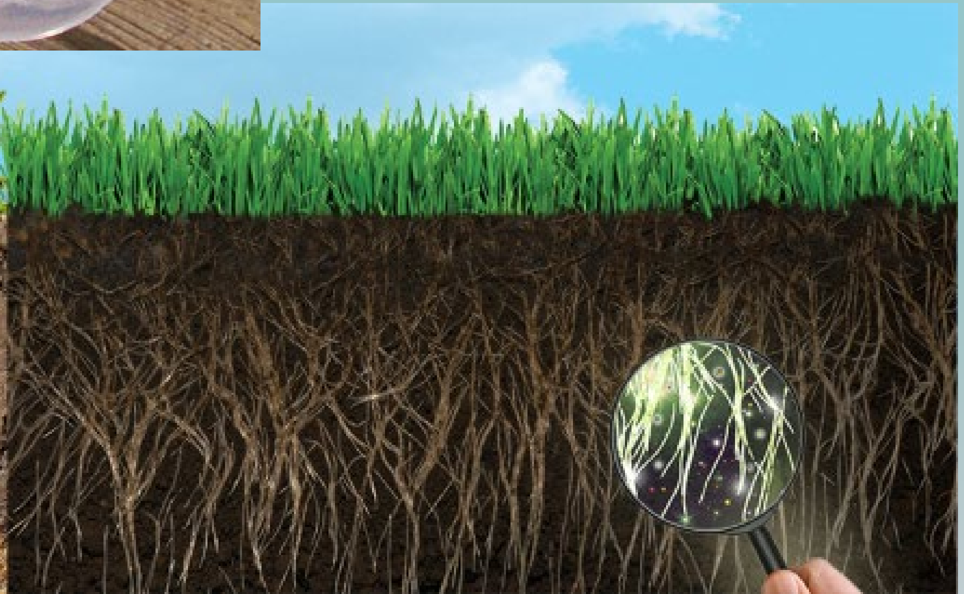
2 – 2.5 inches of soil water storage

Prince Georges Cty, MD photo

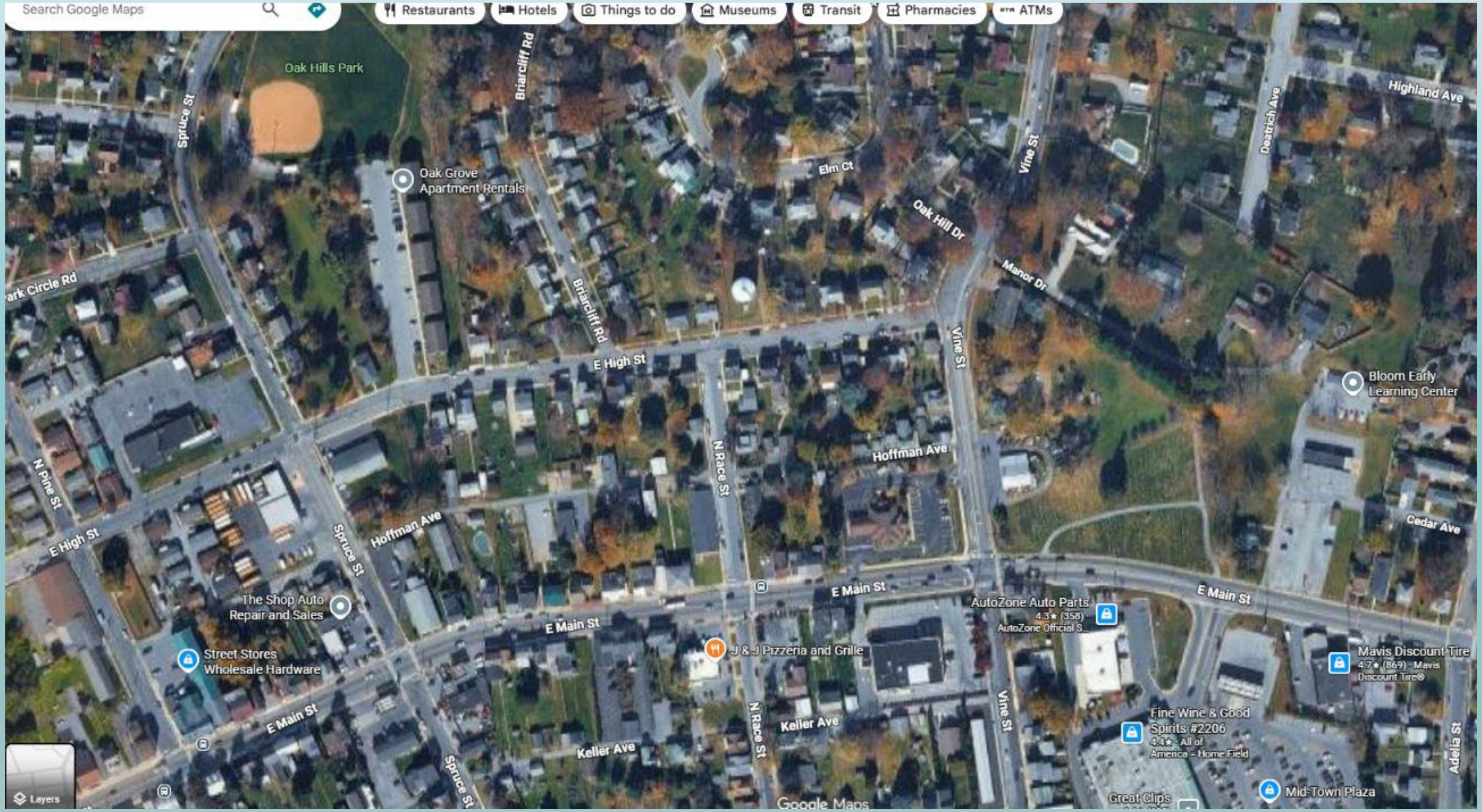
m/soil-compaction-problems-solutions.html

https://rtectreecare.com/soil-compaction/

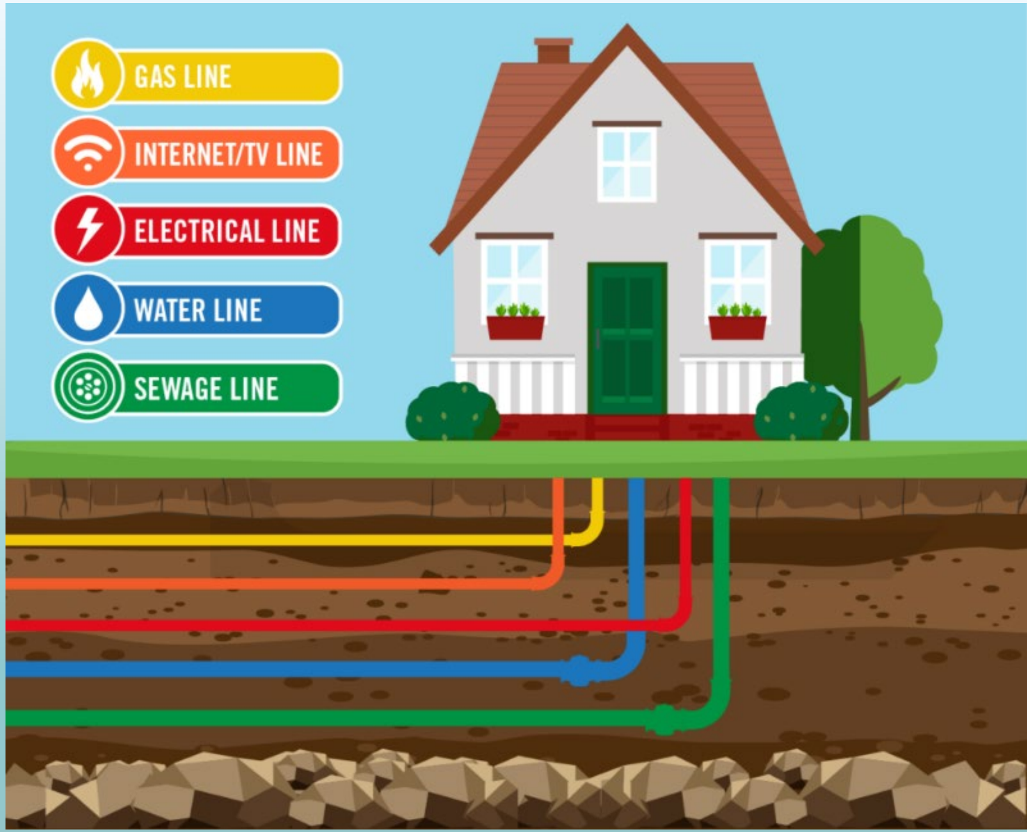




Challenge of Older Cities: Space for GSI



- New York City and Washington, DC: Median residential lot size of 2,700 sq ft with >50% impervious.
- Many newer homes, even on these small lot sizes, have gotten larger.
  - Washington, DC: Between 2010 and 2020, larger homes on median lot size of just 1,700 sq ft (94% lot usage).
- Philadelphia: Median residential lot size of approx. 1,100 sq ft.
- Baltimore:
  - Current: Rowhouse Districts permits lots down to 1,100 sq. ft. for rowhouses, while at least 2,500 sq. ft. for semi-detached developments.
  - Current: Detached/Semi-Detached require minimum lot sizes ranging from 3,000 sq. ft. to 5,000 sq. ft.
  - Historically, could be less than 1,000 sq ft to 2,500 sq ft in much of older sections of city

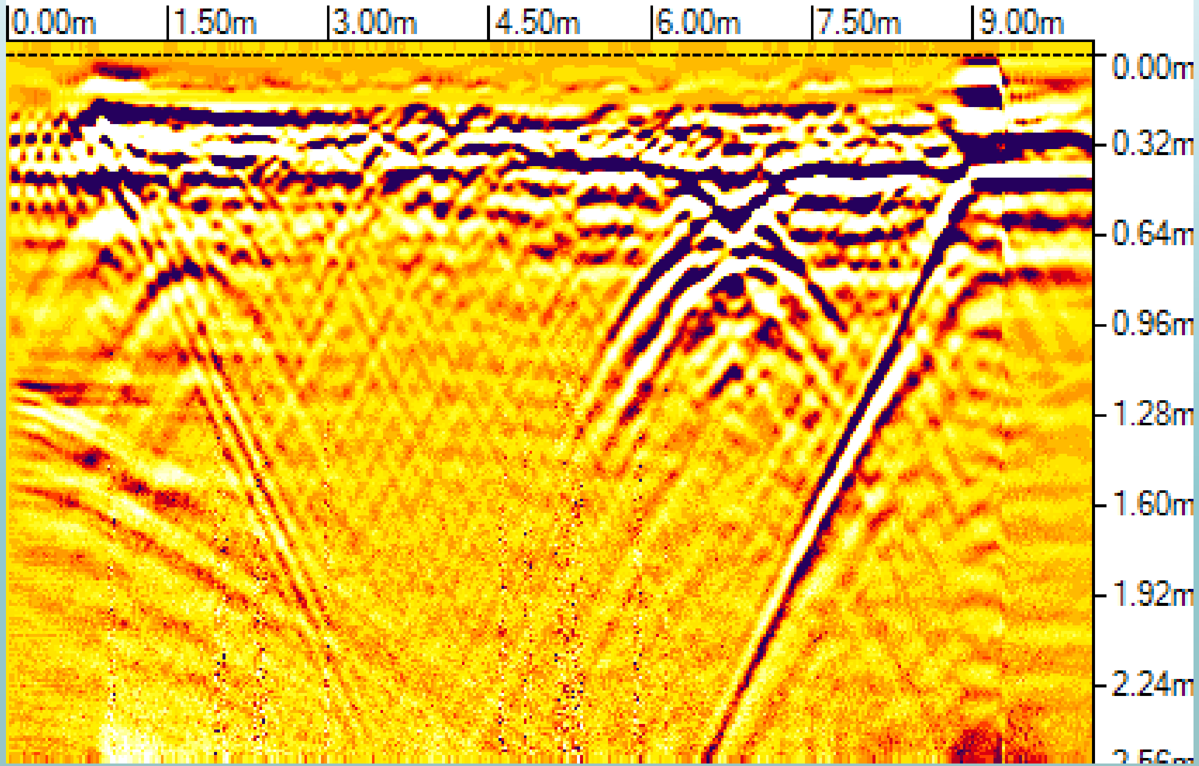


https://dpcoftexas.org/home-owners-and-811/

URBAN KARST BEHAVIOR

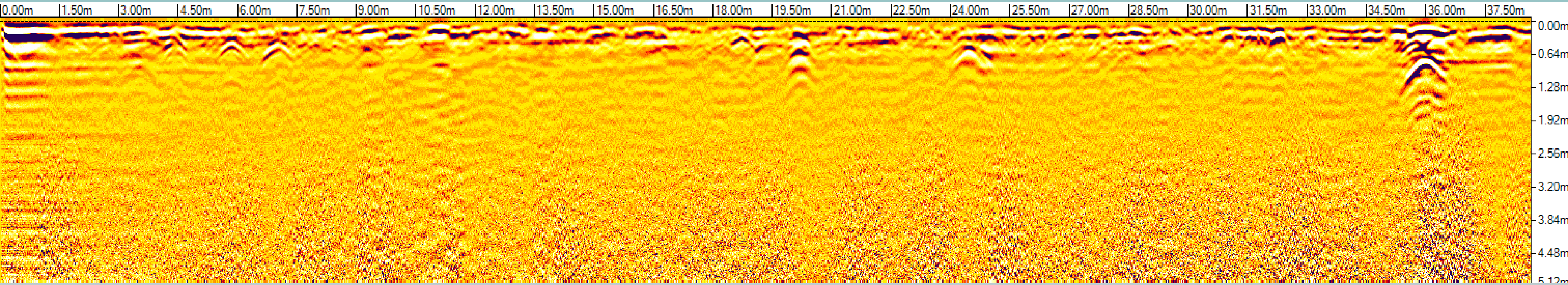
https://pipespy.com/blog/underground-utility-replacement/

Urban Soils Are Heterogeneous and Penetrated by Utilities

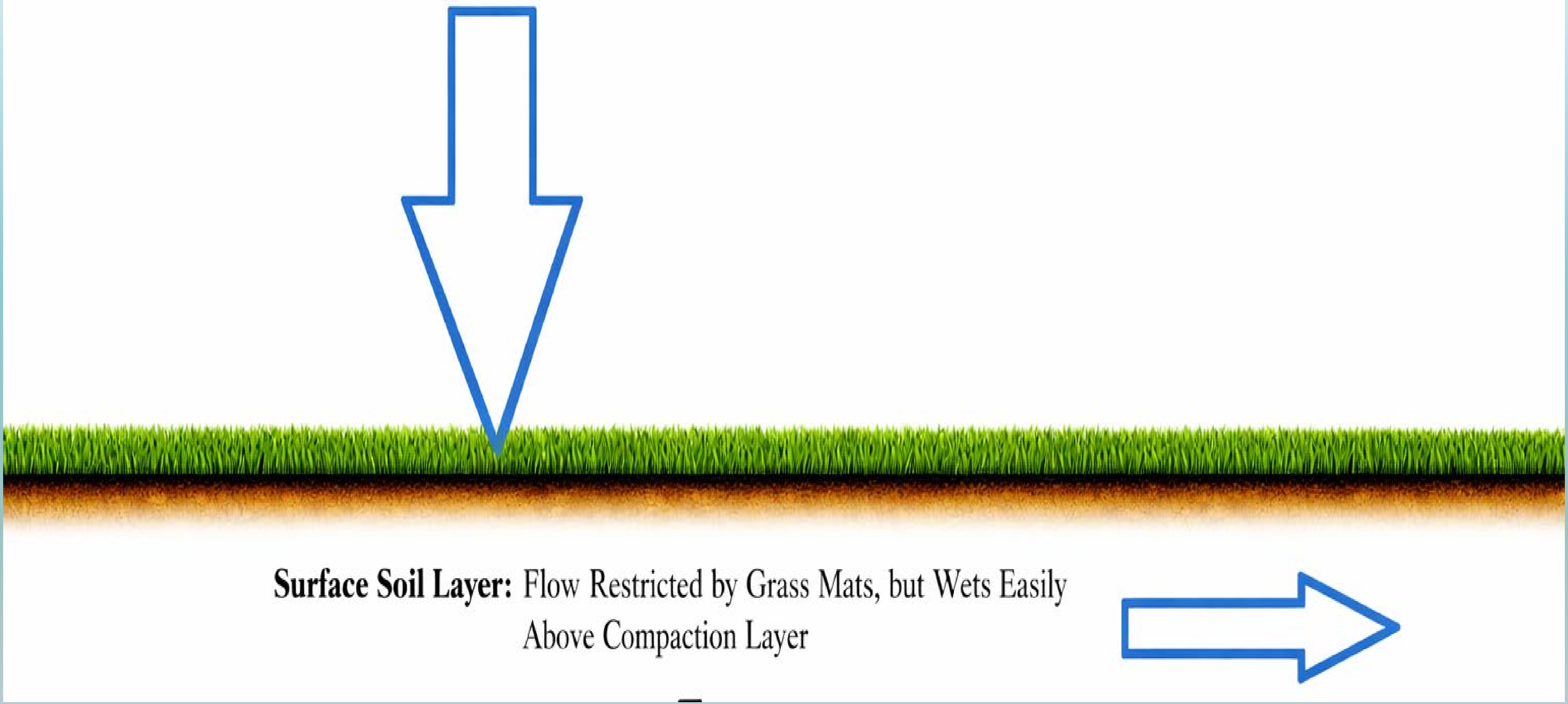


Under Pavement

Grass Area Behind Building

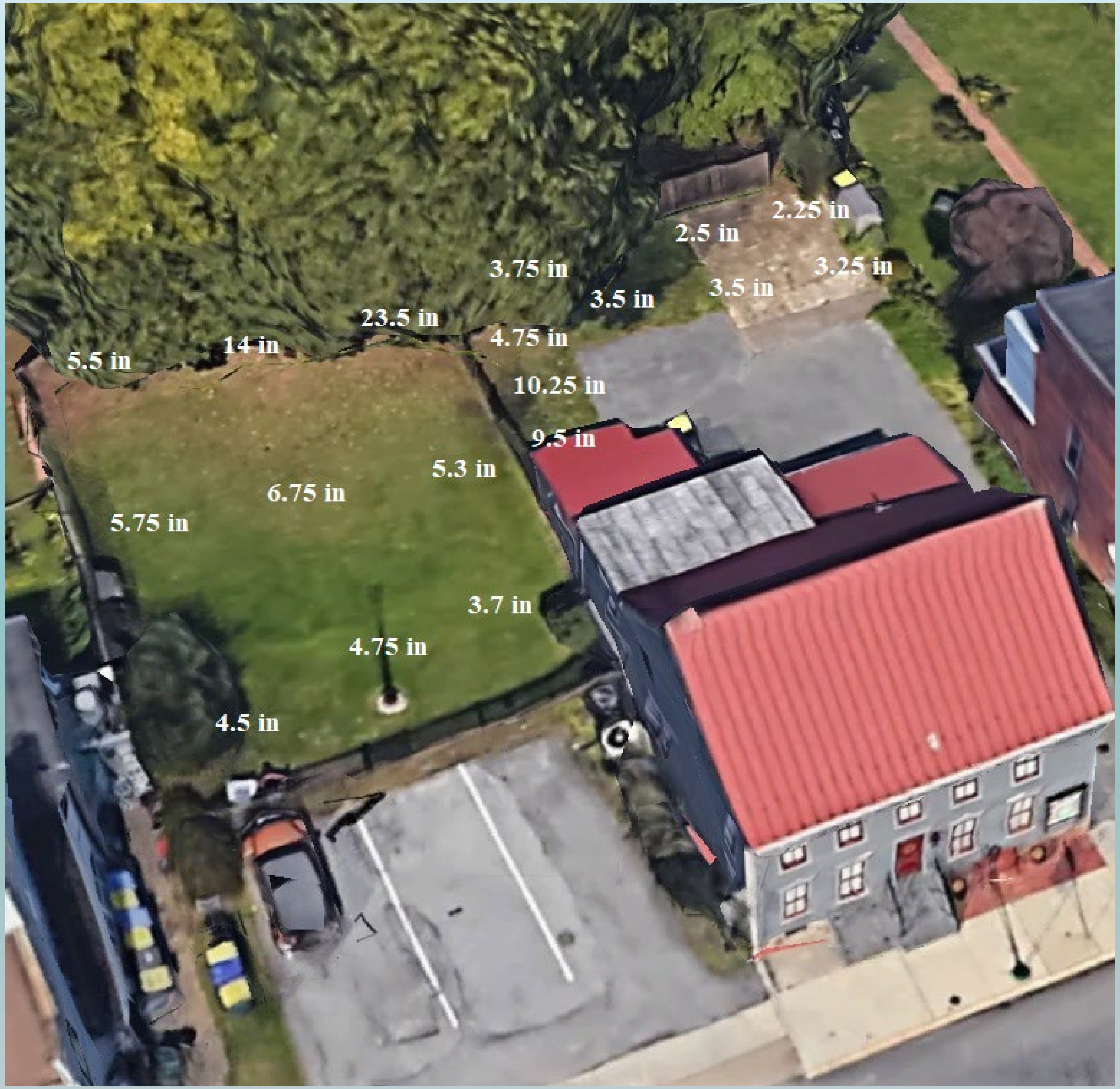


Where Does the Water Go?

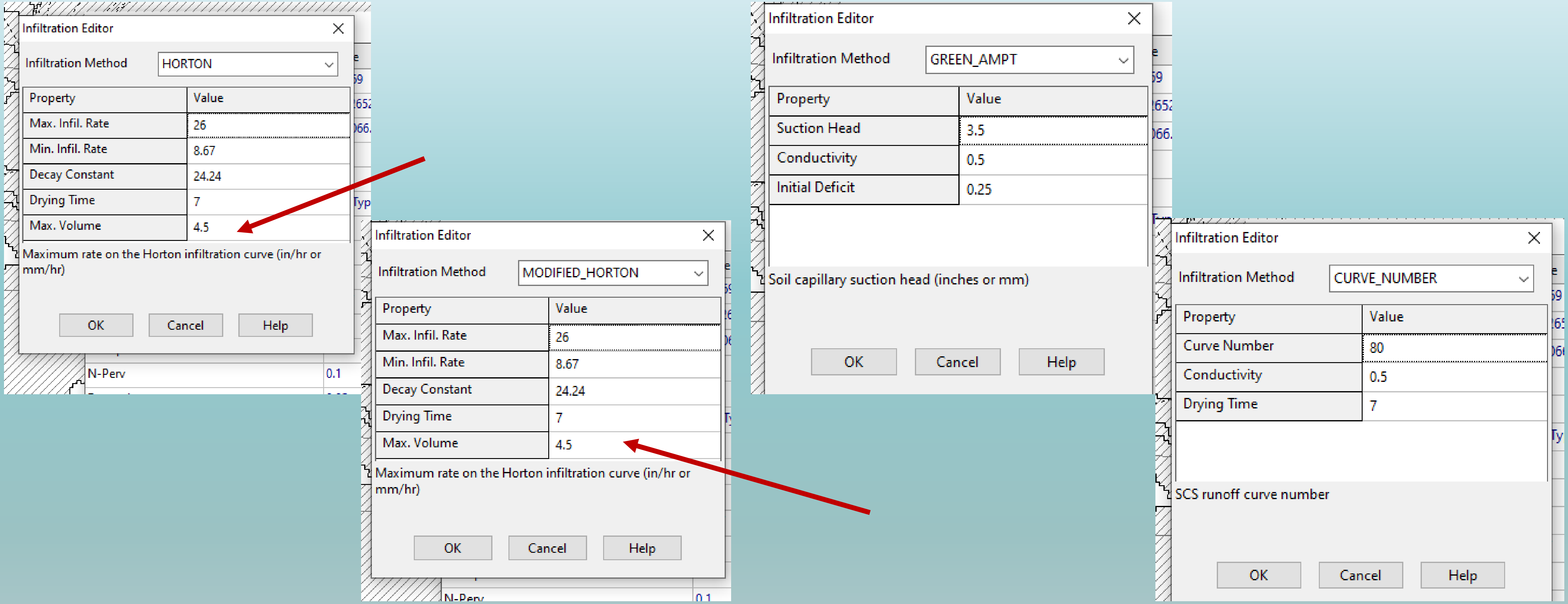


Compaction Depth

Depth to 2070 kPa (300 psi) resistance

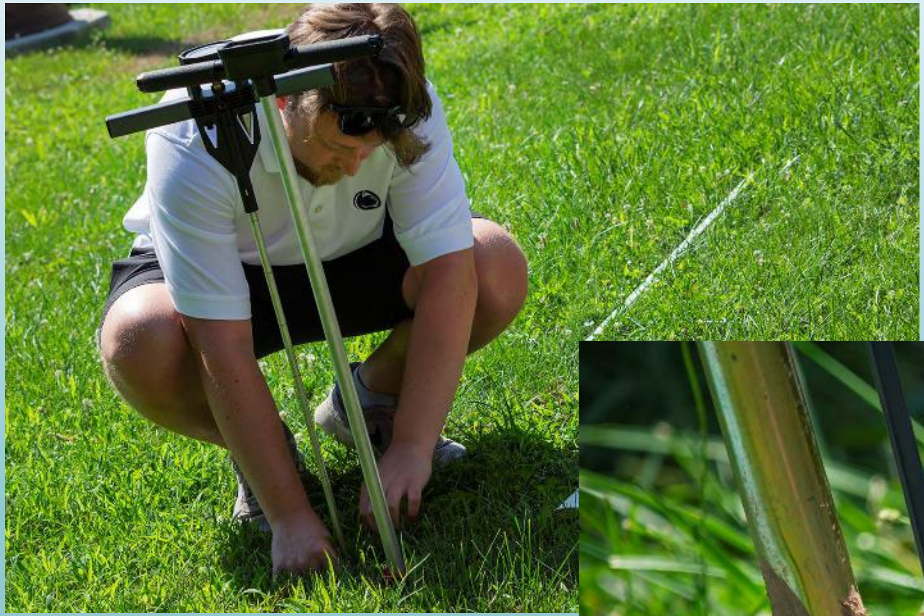


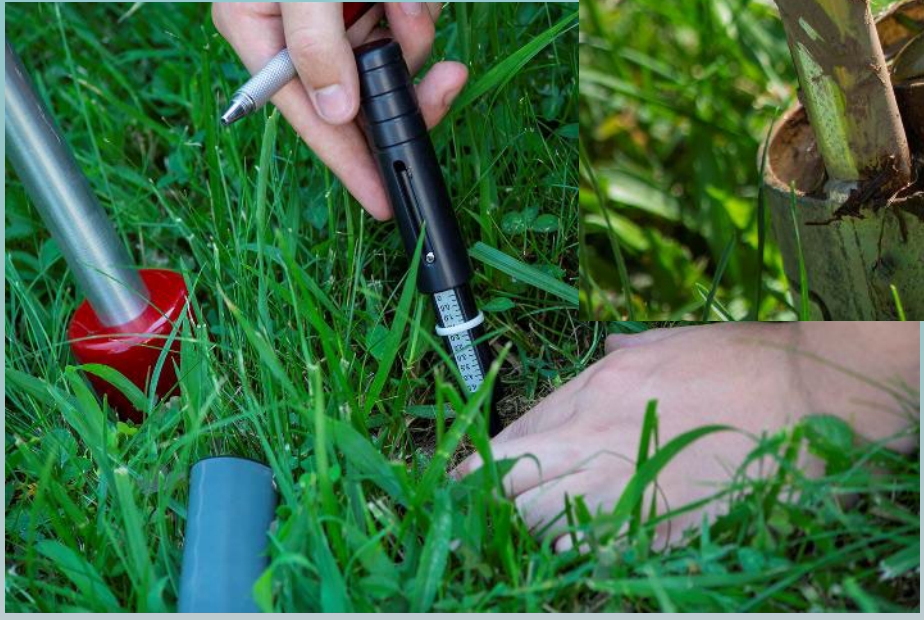
Comparison of SWMM Infiltration Choices



Horton is the only option that allows for a restrictive layer.

Compaction, Infiltration, Soil Moisture at Many Sites



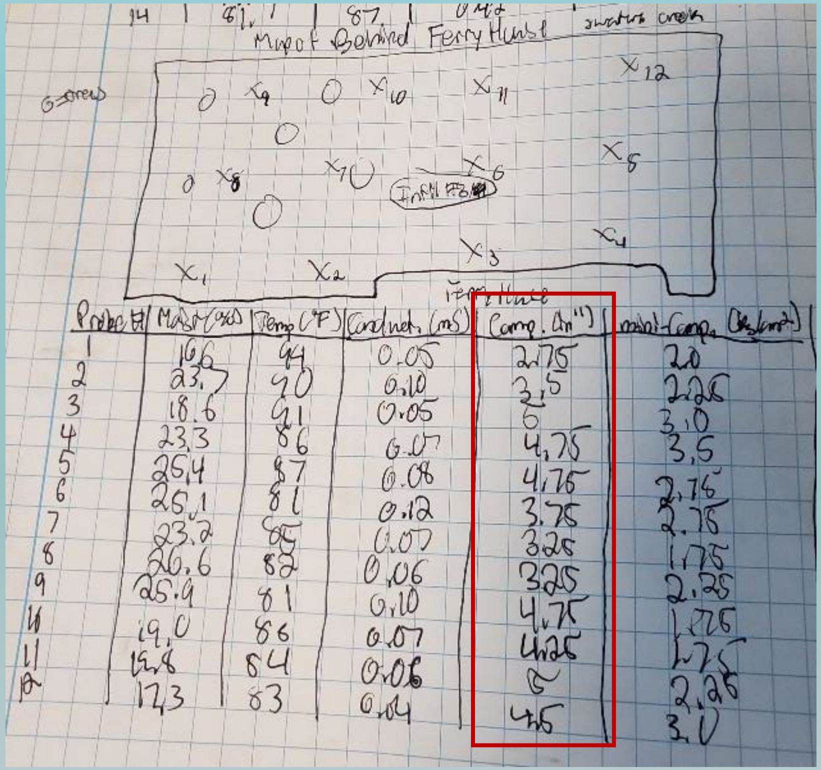


Procedure In the Field: Depth to Compaction Layer

Step 1. Insert cone penetrometer to depth where resistance is 300 psi.

Step 2. Measure the depth of penetration.

Step 3. Repeat in multiple locations at the site. Highlights variability (so can determine an average depth) and patterns (such as a leaky water line which increases compaction depth).



Probe #	Moist (%)	Temp (°F)	Conduct. (mS)	Comp. (in")	Comp. (lbs/in²)
1	16.6	94	0.05	2.75	2.0
2	23.7	90	0.10	3.5	2.25
3	18.6	91	0.05	6	3.0
4	23.3	86	0.07	4.75	3.5
5	25.4	87	0.08	4.75	2.75
6	25.1	81	0.12	3.75	2.75
7	23.2	85	0.07	3.25	1.75
8	26.6	82	0.06	3.25	2.25
9	25.9	81	0.10	4.75	1.25
10	19.0	86	0.07	4.25	1.75
11	15.8	84	0.06	6	2.25
12	17.3	83	0.04	4.5	3.0

Step 4. Dig small hole and collect soil sample.

Step 5. Add sand to graduated cylinder and fill hole (level to ground surface) with sand. Record volume.

DATA COLLECTED:

1. Compaction depth
2. Volume of sand required to fill hole

Soil sample collected and brought back to lab to weigh before and after drying at 103 – 105 C.

In the Field: Soil Characterization and Moisture Sensor Installation

Step 1. Dig hole and note any changes in soil profile.

Step 2. Note other observations (rock content, depth of roots, etc.).

Step 3. Insert soil moisture sensor per manufacturer's instructions.

Step 4. Measure depth of sensor installation.

DATA COLLECTED:

1. Sensor installation depth
2. Depth of roots and incongruities
3. Presence of rocks, etc.

First Step Calculations: Bulk Density, Porosity

Step 1. Calculate the bulk density of the soil sample.

Bulk Density, ρ_b:

$$\rho_b = \frac{Mass\ of\ oven\ dried\ soil}{Volume\ of\ sand\ that\ replaced\ soil}$$

Step 2. Calculate the total porosity.

Porosity, n:

$$n = 1 - \frac{\rho_b}{2.6\ \ g/cm^3}$$

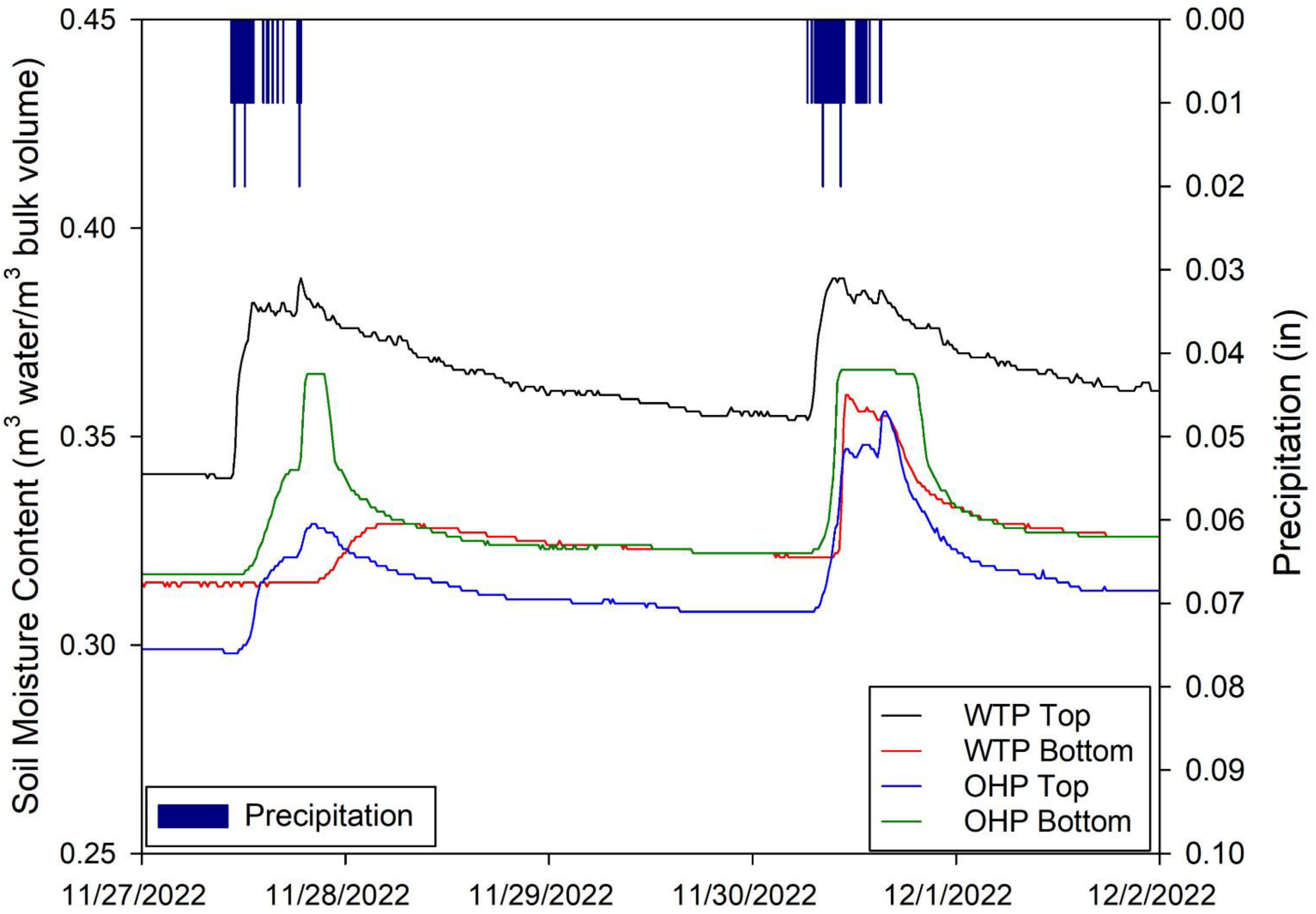
2.6 g/cm^3 is the approximate particle density for soil particles (range typically is 2.5 – 2.7 g/cm^3).

Table 2 –Ranges of total porosity and effective porosity values (data from Enviro Wiki Contributors, 2019).

Total and Effective Porosity		
	Total Porosity	**Effective Porosity**
Unconsolidated Sediments		
Gravel	0.25 – 0.44	0.13 – 0.44
Coarse Sand	0.31 – 0.46	0.18 – 0.43
Medium Sand		0.16 – 0.46
Fine Sand	0.25 – 0.53	0.01 – 0.46
Silt, loess	0.35 – 0.50	0.01 – 0.39
Clay	0.40 – 0.70	0.01 – 0.18

Step 3. Determine whether an assumption that effective porosity (n_e) = total porosity (n).

- If soil where sensor is installed was added on top of compaction layer to grow vegetation, this assumption should be reasonable.
- If sensor installed in compacted layer, use effective porosity from table for sand or silt (recommend 50-75% of max).



Soil Moisture Content (m³ water/m³ bulk volume)
Precipitation (in)
0.45
0.40
0.35
0.30
0.25
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
11/27/2022
11/28/2022
11/29/2022
11/30/2022
12/1/2022
12/2/2022
Precipitation
WTP Top
WTP Bottom
OHP Top
OHP Bottom

Impact of Shallow Compaction Layer

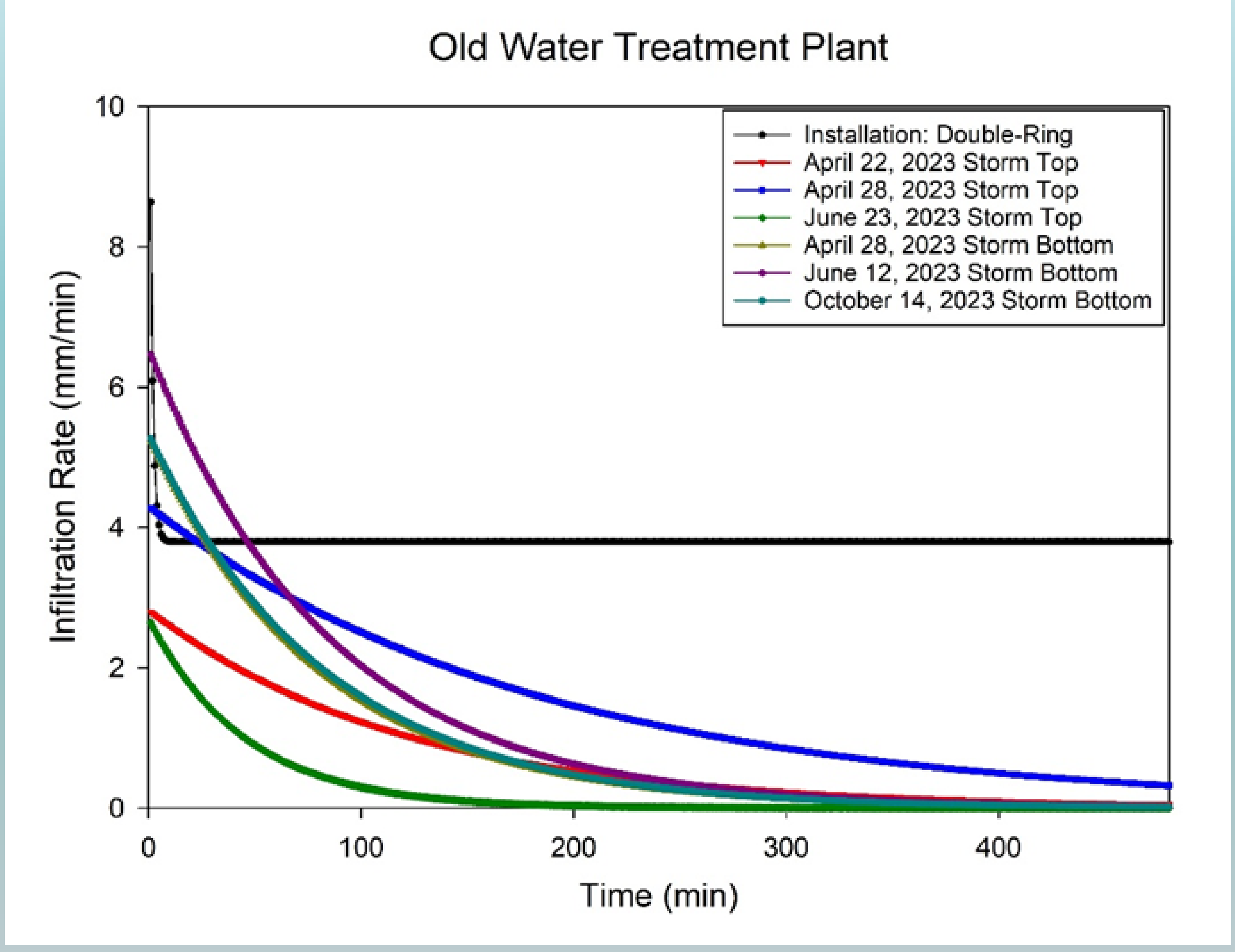
- Challenge: 3 to 6 inch soil depth layer difficult to install 2 soil moisture sensors with enough separation to get accurate depth measurements as a function of time.
- Solution: Compaction layer tell us the depth of bowl. Then:

F (total water infiltration) = [D (Depth to compaction layer)] [η_e (effective porosity)]

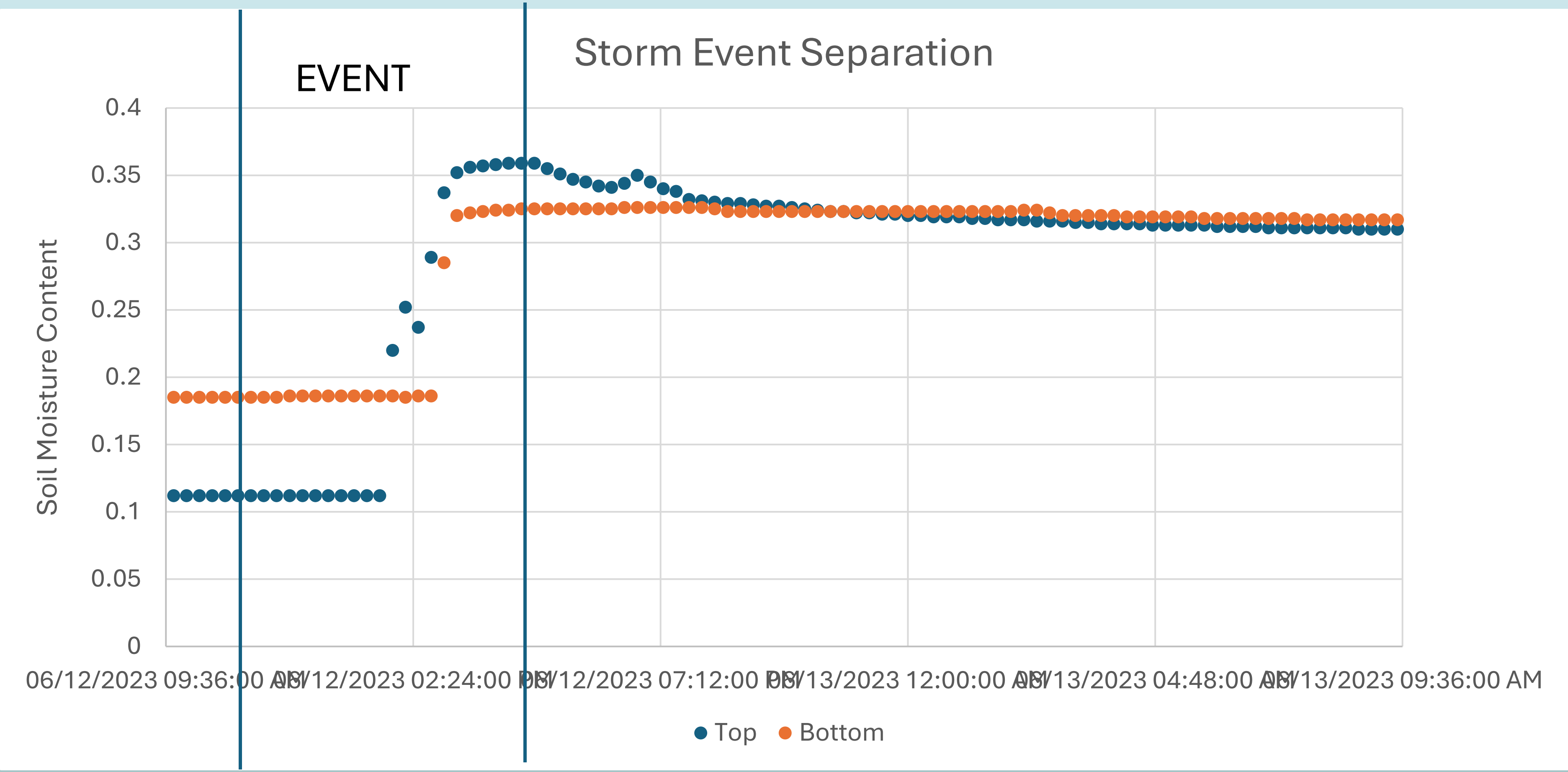
The modified Horton Equation becomes:

$$\frac{(fraction\ remaining\ to\ saturation)F}{\Delta t} = f_c + (f_0 - f_c)e^{-kt}$$

Site with Compaction Layer and "Interesting" Topsoil: Surface Double Ring Infiltrometer Not Reflective of Subsurface



Second Step Calculation:
Separating Soil Moisture Readings into Storm Events



Infiltration equations show that rate of infiltration decays over time. Soil moisture increases as water infiltrates with increases in soil moisture slowing over time.

Therefore, events to analyze are exponential growth sections of the curve.

Third Step: Modified Horton Equation Using Soil Moisture

Horton's Equation was selected because, in SWMM, Horton and Modified Horton are the only two infiltration equations where the maximum water storage volume can be entered as of this time.

Horton's Infiltration Equation:

$$f_p = f_\infty + (f_0 - f_\infty)e^{-k_d t}$$

where:

f_p = infiltration capacity into soil (ft/sec)

f_∞ = minimum or equilibrium value of f_p (at $t = \infty$) (ft/sec)

f_0 = maximum or initial value of f_p (at $t = 0$) (ft/sec)

t = time from beginning of storm (sec)

k_d = decay coefficient (sec^{-1}).

Third Step: Modified Horton Equation Using Soil Moisture

Horton's Infiltration Equation Modified Using Soil Moisture:

$$\frac{\left(\frac{\theta_s - \theta}{\theta_s - \theta_0}\right) D(n_e)}{\Delta t} = f_c + (f_0 - f_c)e^{-kt}$$

Where: θ_s = saturated soil moisture (maximum soil moisture for an event)

θ_0 = initial soil moisture (minimum soil moisture for an event)

θ = soil moisture at any time t

D = depth to sensor or depth to compaction layer

n_e = effective porosity

f_c = final infiltration rate (should be asymptotically approaching Ksat)

f_0 = initial infiltration rate

k = decay constant

t = time

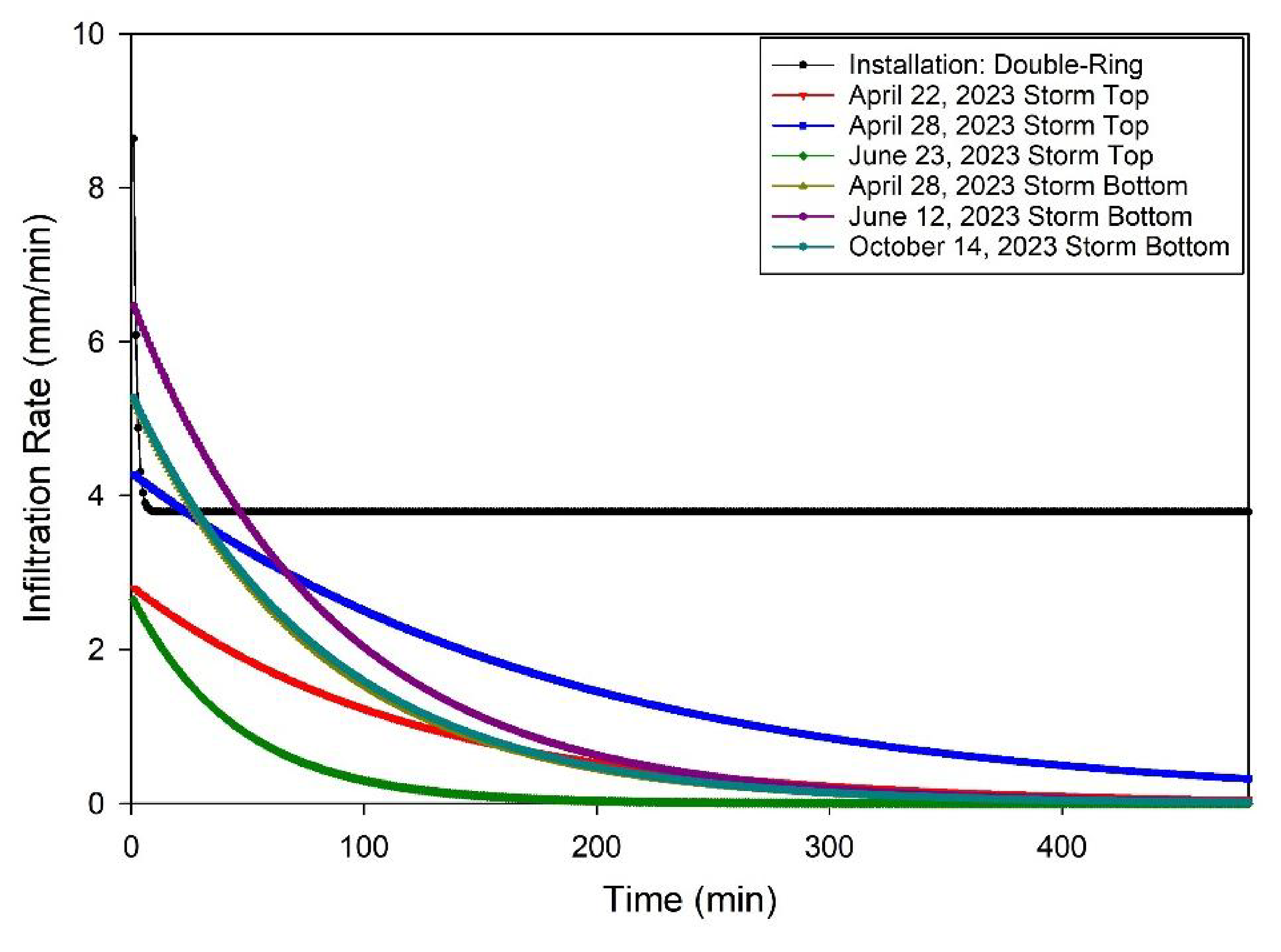
Left side of equation comes from sensors and field measurements.
Use nonlinear regression to calculate f_0, f_c, and k for use in SWMM.

RESULTS: Comparison to Double-Ring Infiltrometer

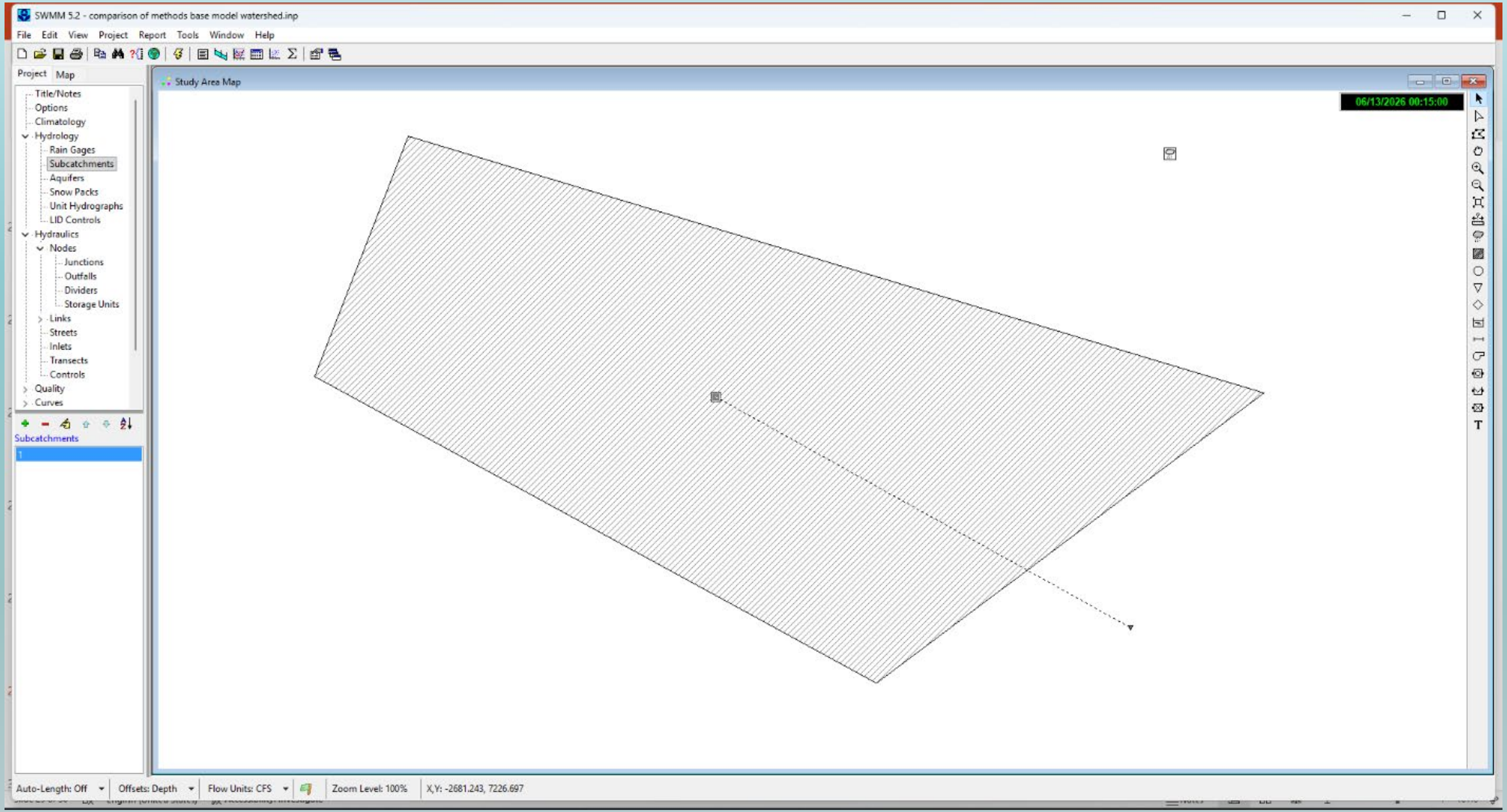
- Site: Upper and lower layer separated by compaction layer. Both layers are rocky with coal fragments.

- Double-ring infiltrometer on surface produces distinctly different results for f_c (the limiting infiltration rate). This is likely due to the heterogeneous nature of the soil layer.

- Analysis with soil moisture allows for replicate analysis and the sensors are installed in areas with less rocks and fractures in the soil. Rocks and fractures create preferential flow paths.



Translation to Curve Number Procedure



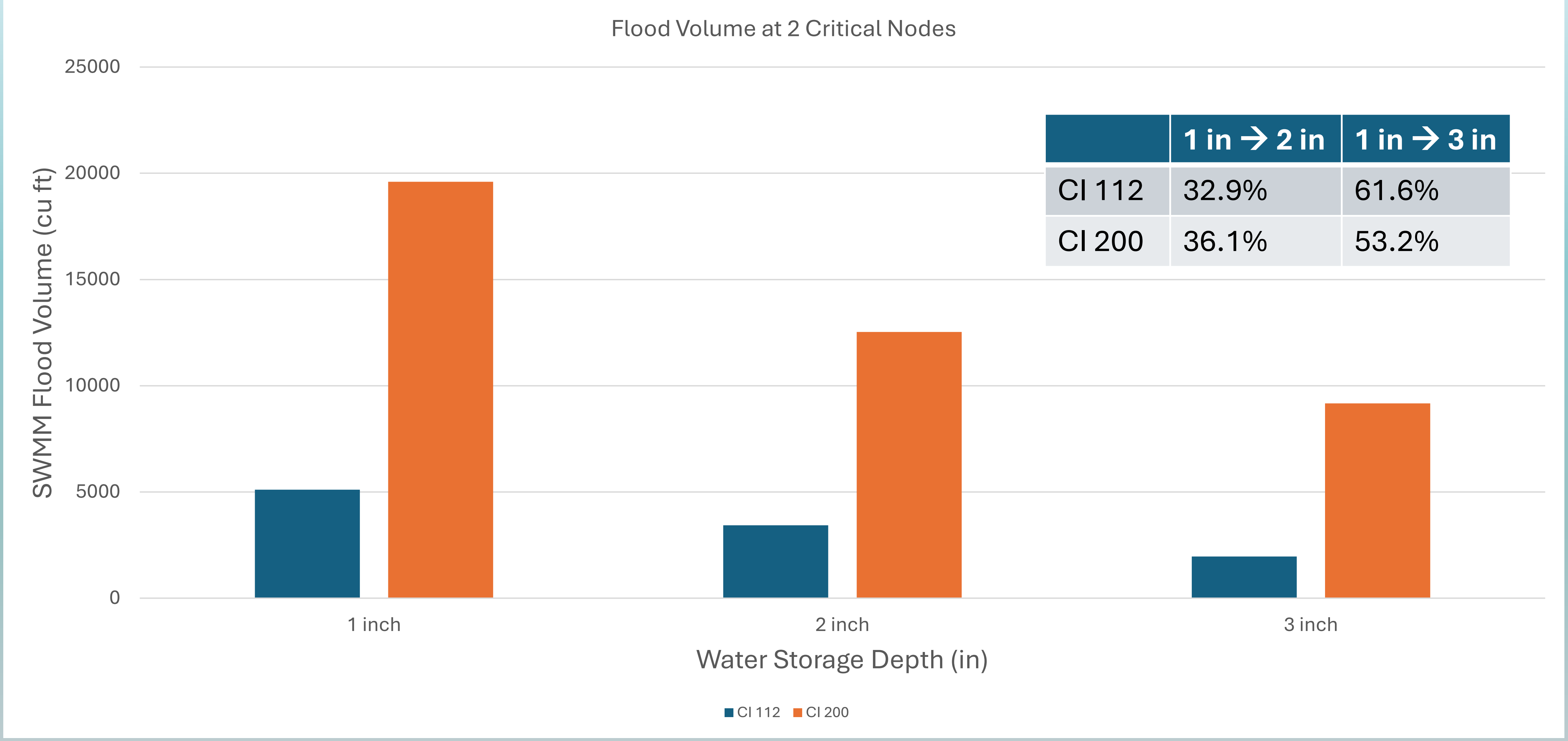
Horton Parameters for Stilson Loamy Sand

f_0 = 8.11 in/hr
f_c = 1.55 in/hr
k = 6.55 hr^{-1}

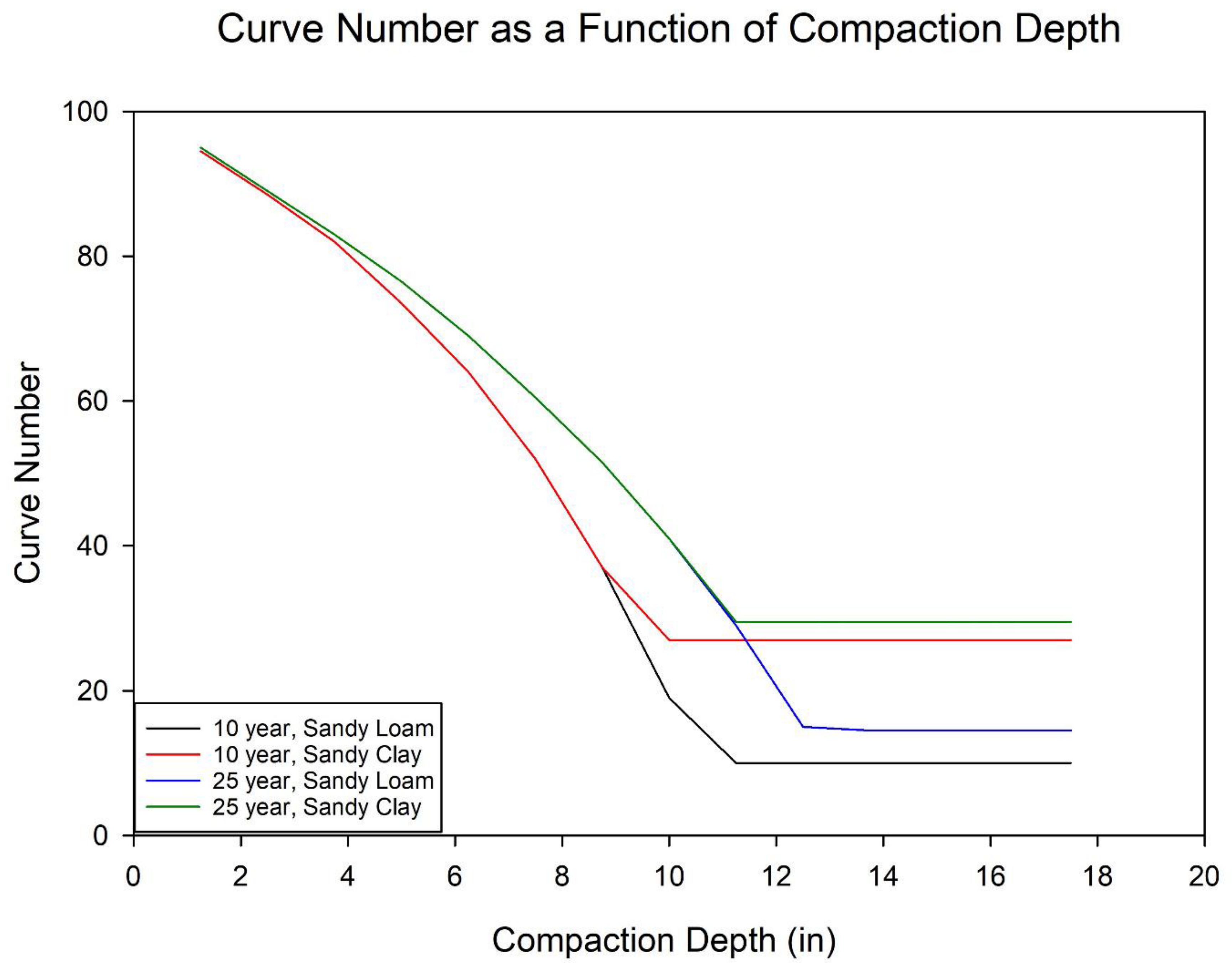
Horton Parameters for Sandy Clay (bare)

f_0 = 8.6 in/hr
f_c = 0.90 in/hr
k = 120 hr^{-1}

Impact of Shallow Restoration: Node Flood Volume



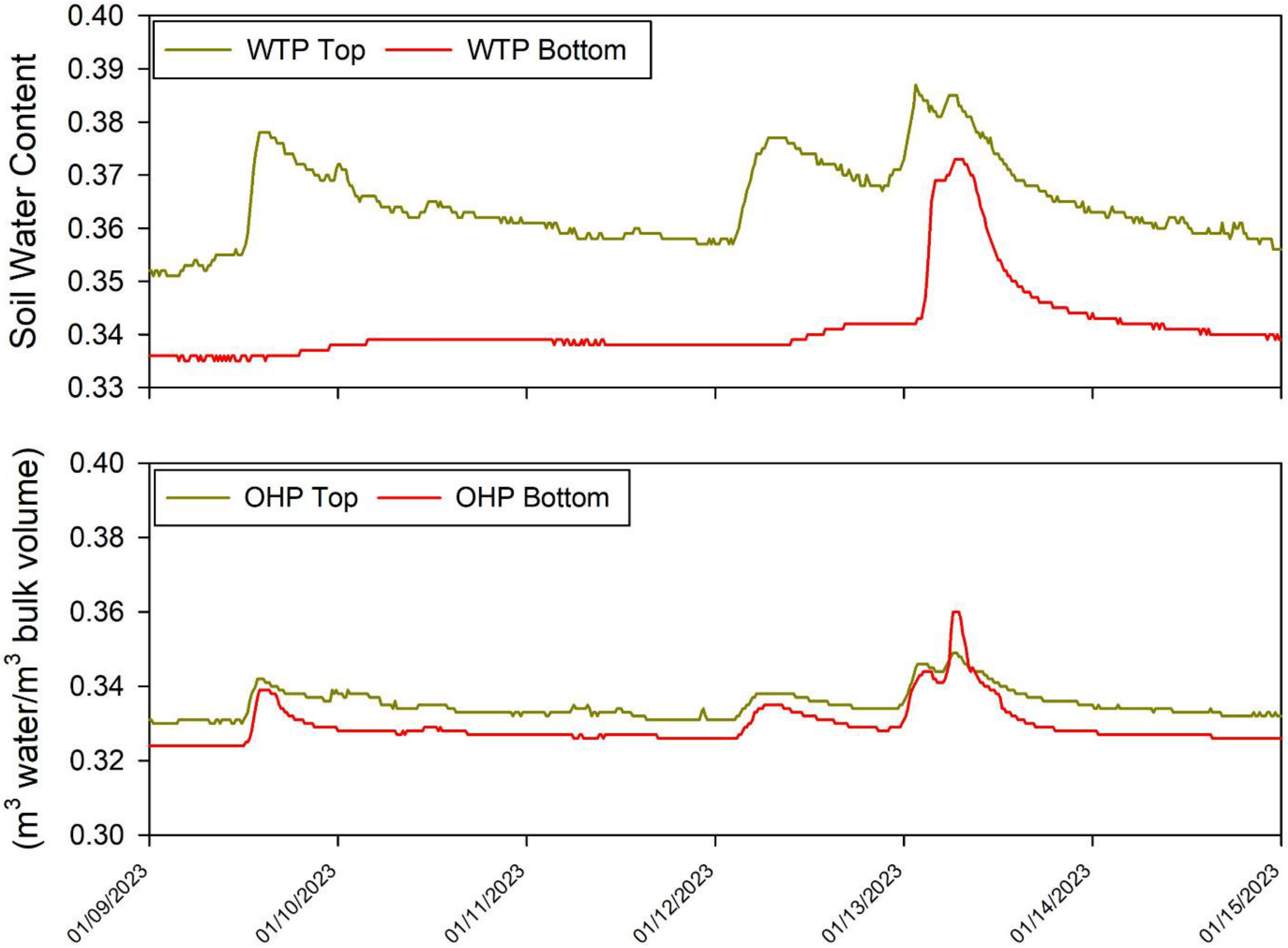
	1 in → 2 in	1 in → 3 in
CI 112	32.9%	61.6%
CI 200	36.1%	53.2%


Curve Number as a Function of Compaction Depth
Curve Number
Compaction Depth (in)
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20
10 year, Sandy Loam
10 year, Sandy Clay
25 year, Sandy Loam
25 year, Sandy Clay

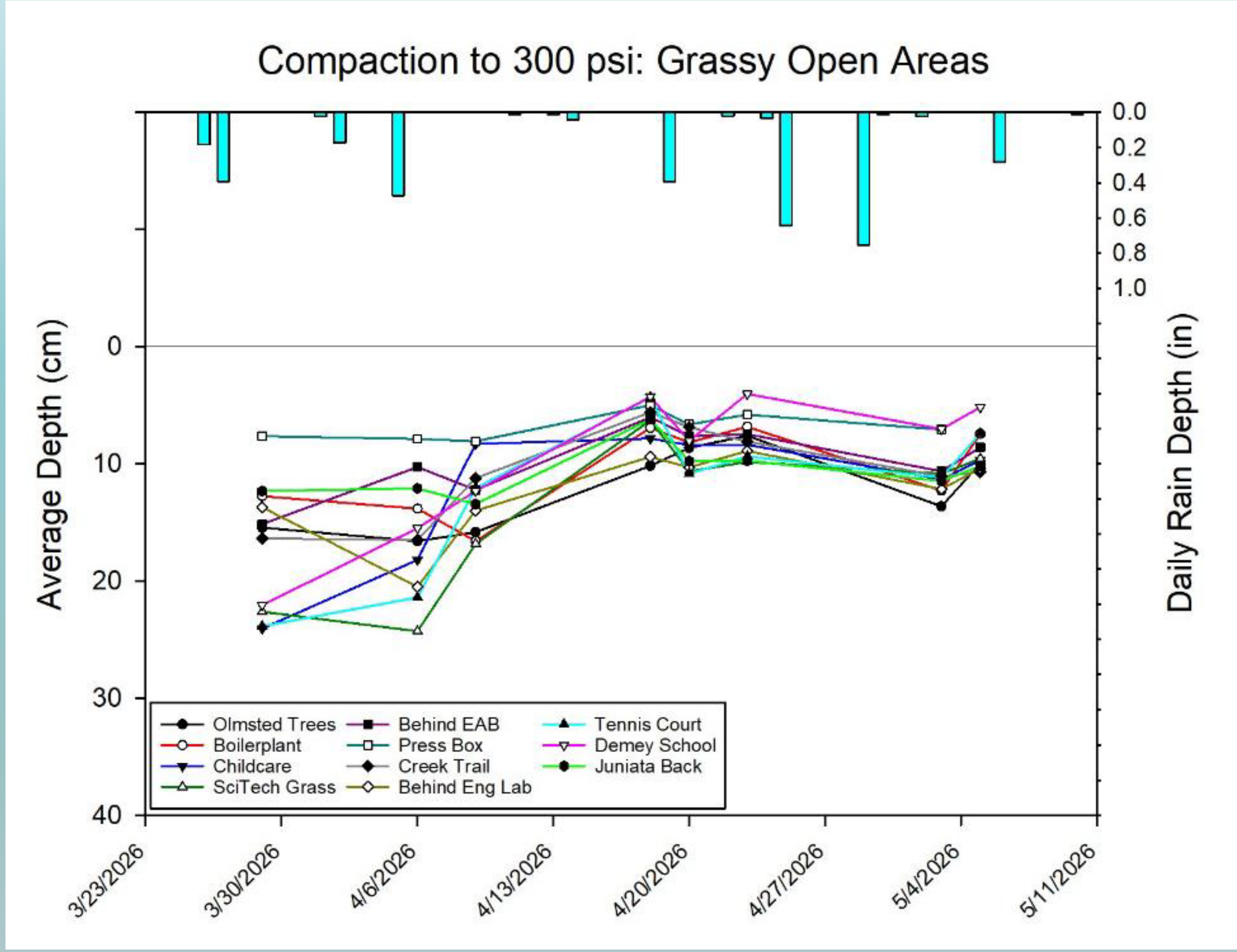
Next Challenge: Compaction Layer Appears to be Semi-Permeable

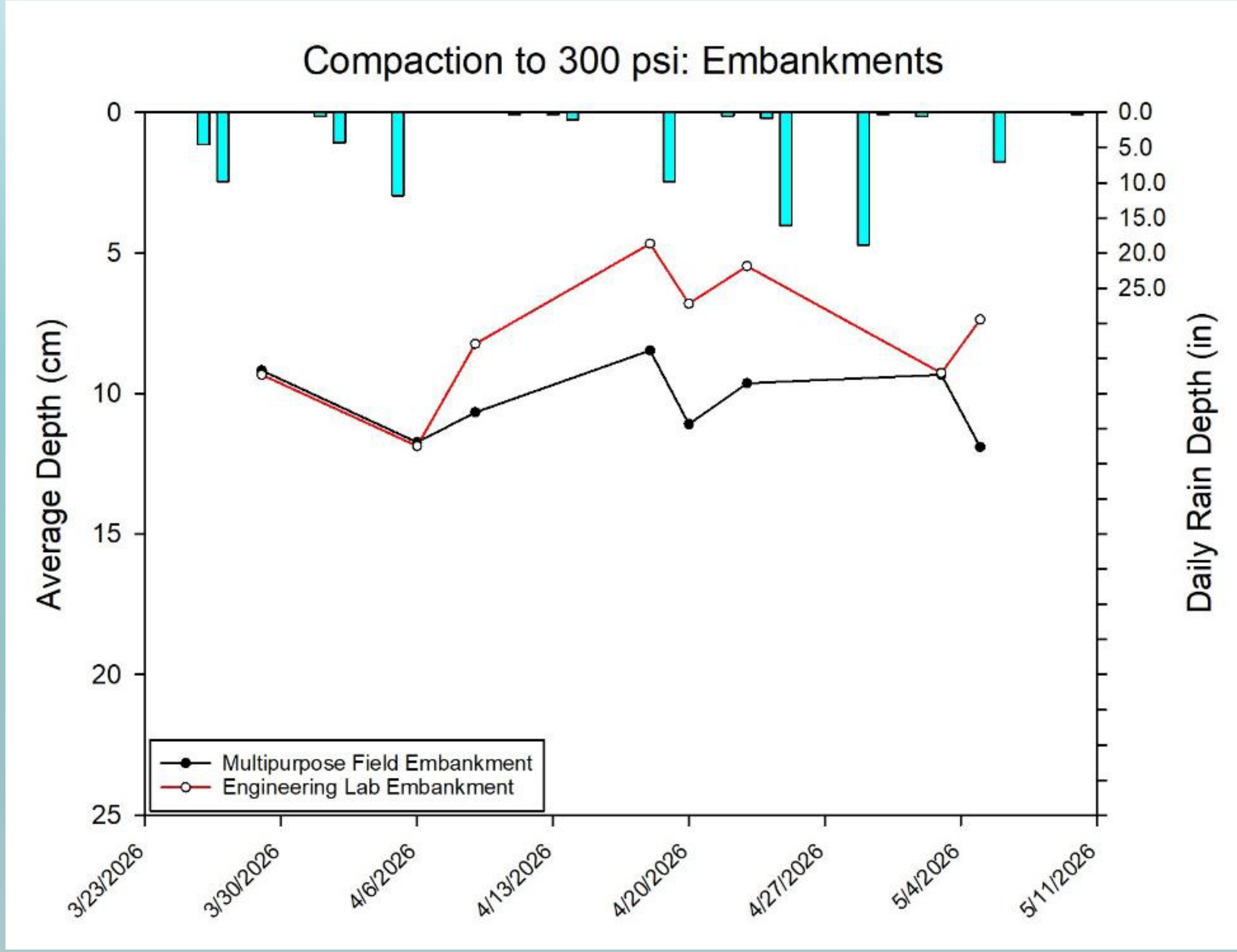
Approximate Location of Buried Stream

January 2023 Soil Moisture



Change in Compaction Depth as a Function of Antecedent Rainfall





Conclusions to Date

- Simplified field procedure for collecting data for following parameters:
  - Compaction depth
  - Double-ring infiltrometer (not required but will give information on rapidity of infiltration through surface mat)
  - Installation of sensor and collection of data
    - 15-minute data acceptable
  - Bulk density field measurement by replacing sample with sand
- Depth of soil water storage above compaction layer vital (3 inch: CN = 51/Runoff = 1.37 in **vs** 1 inch: CN = 88/Runoff = 3.14 in)
- Challenges are that the compaction layer likely is semi-permeable (barely permeable) – but SWMM is not

Impacts of Urban Soil Compaction on Stormwater Runoff Volumes and BMP Sizing

Translation Slides by
Kimberly Grove, Chief
Office of Research and Environmental Protection
Baltimore City DPW

Proposed SWM Regs WQ_v

Treat the specific runoff depth that corresponds to 90% of the average annal runoff.

Current

$$WQ_v = \frac{(1.0)(R_v)(A)}{12}$$ Eastern Rainfall Zone P = 1.0 inches of rainfall

where:
- WQ_v = water quality volume (in acre-feet)
- R_v = 0.05 + 0.009(I) where I is percent impervious cover
- A = area in acres*

Proposed:

$$WQ_v = \frac{Qi \times Ai}{12\ in/ft} + \frac{Qp \times Ap}{12\ in/ft} \qquad \text{(Equation 2.8)}$$

where:

Q_i = the direct runoff depth from the impervious area calculated based on a CN of 98 and a P of 1.0 inch or 1.5 inches, depending on the rainfall zone. Referring to Table 2.3, Q_i equals 0.79 inches for the Western Rainfall Zone and 1.28 inches for the Central/Eastern Rainfall Zone.

Q_p = the direct runoff depth from the pervious area calculated based on the weighted pervious CN and a P of 1.0 inch (Western Rainfall Zone) or 1.5 inches (Central/Eastern Rainfall Zone) as provided in Table 2.3 or calculated using Equations 2.1 and 2.2.

A_i = impervious area within the drainage area to the BMP

A_p = pervious area within the drainage area to the BMP

➢ Direct runoff depth (Q) is determined using the equations below:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{(Equation 2.1)}$$

and

$$S = \left(\frac{1000}{CN}\right) - 10 \qquad \text{(Equation 2.2)}$$

Based on $I_a = 0.2S$ and where:

I_a = initial abstraction (inches)
S = the potential maximum retention (inches) related to the CN through soil and cover conditions
Q = depth of runoff (inches)
P = depth of rainfall (inches) provided in Table 2.2 for the county where the project is located and the applicable design storm

HSG	CN
A	39
B	61
C	74
D	80
Imp. Area	98

Proposed SWM Method Only, P = 1"

WQ$_v$ for LOD = 1 ac, P = 1"
Prop HSG A (% Current)
Prop HSG D (% Current)

	Red Ex. A_i = 50% Pr. A_i = 40% $\Delta A_i < 0$ **431 CF** **612 CF**	**Red** Ex. A_i = 40% Pr. A_i = 40% $\Delta A_i = 0$ **574 CF** **756 CF**
New Ex. A_i = 39% Pr. A_i = 39% $\Delta A_i = 0$ **1,120 CF** **1,304 CF**	**New** Ex. A_i = 39% Pr. A_i = 40% $\Delta A_i > 0$ **1,148 CF** **1,330 CF**	**New** Ex. A_i = 39% Pr. A_i = 100% $\Delta A_i > 0$ **2,871 CF** **2,871 CF**

Does de-paving actually help?

USDA Soil Survey:
Urban Complex – HSG D

Grading Specifications:
Cut vs. Fill (compaction)

Geotechnical / Infiltration Test Requirements

Alternative BMP: Soil Restoration

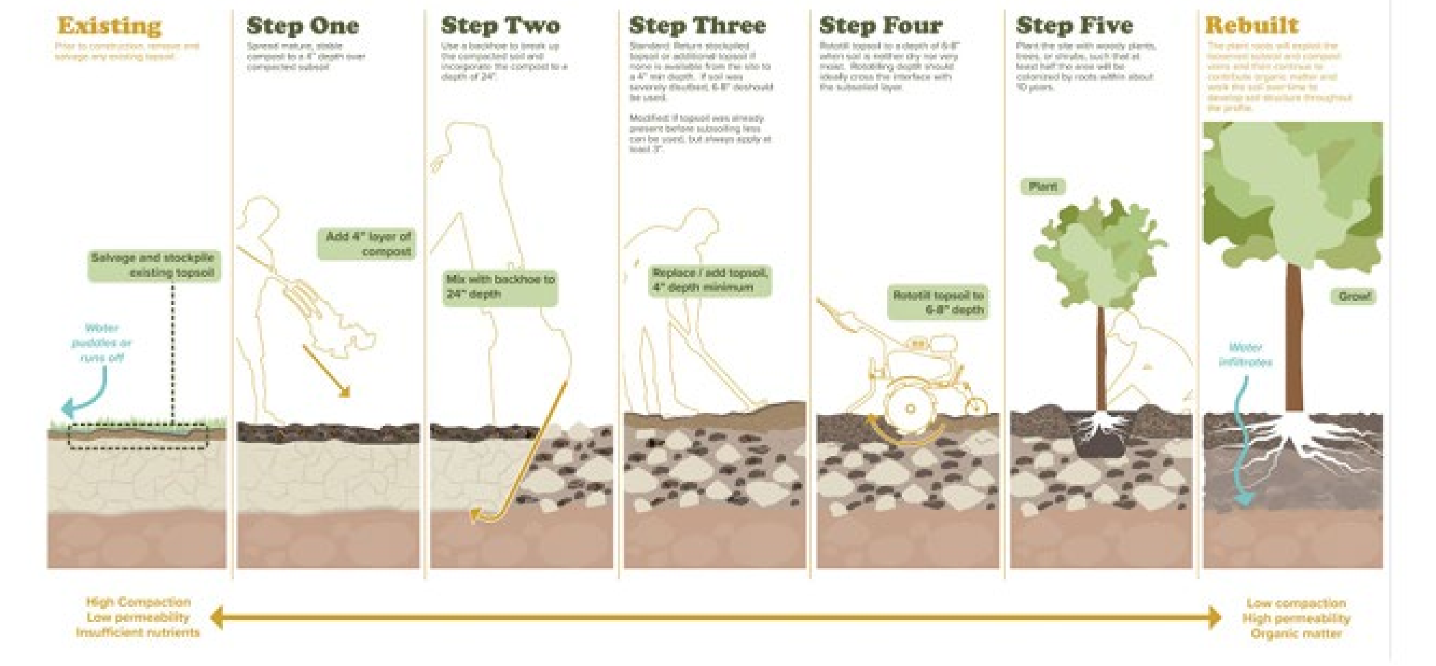


Figure 2. Soil Profile Rebuilding sequence. Source: Tree People Los Angeles

Table 14. Load Reductions and EIA$_f$ for Urban Soil Restoration

Level	Depth (inches)	Load Reduced (lbs/acre/yr)			EIA$_f$ per Acre of Soil Treatment
		TN	TP	TSS	
Compacted Pervious					
1	15	4.4	0.72	278	0.40
2	20	8.9	1.44	557	0.80
Impervious					
1	15	13.7	0.70	1,696	0.91
2	20	15.0	0.77	1,864	1.00

Soils where the depth to a water impermeable layer is less than 20 inches and/or the depth to the high water table is less than 24 inches are considered as hydrologic soil group (HSG) D when determining runoff characteristics. These soil characteristics are not available for the urban soil restoration credit. Appendix G provides the design criteria that must be met for each level of restoration.

Source: MDE, MS4 Accounting Guidance, 2021

Research findings: Shallow restoration of 3 to 5 inches can reduce runoff volumes 30%.

What does this mean for me?

- SWM BMP Regulatory Review
  - Field tests
  - Grading specifications
  - Underdrains
- MS4 Compliance Strategy:
  - Land Cover Conversion
  - Complete Streets
- City-wide Stormwater H & H Model
  - USDA Soil Survey Update
  - Flood Mgt: Soil vs. Structural Controls

Figure 5.14 Micro-Bioretention (Variation 1 - Parking Lot)