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MARYLAND DEPARTMENT
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RESEARCH REPORT

THE EFFECTIVENESS OF SOIL DECOMPACTION FOR STORMWATER MANAGEMENT

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FINAL REPORT

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16. Abstract

Compacted and highly disturbed urban soils are a pervasive feature of modern constructed landscapes. This research advances the integration of cost-effective practices that improve soil structure, restore infiltration, and reduce stormwater runoff to support soil decompaction and amendment as an approved stormwater BMP in the State of Maryland. To support the institutional acceptance of soil decompaction and amendment as an approved BMP, this project emphasized two primary complementary contributions: (1) a prototype BMP protocol for the practice, emulating the style of the State Stormwater Manual; and (2) supporting analysis for the consistent determination of a quantitative stormwater credit for decompaction and amendment. Observed soil moisture dynamics monitored in the field confirmed modeling predictions and represent a unique contribution of the research that enhances the credibility of our model-based approach for soil-specific site-specific stormwater credits. Soil decompaction and amendment can reduce costs for green asset maintenance while significantly expanding the opportunities for cost-effective stormwater management services from the pervious land uses in Maryland Department of Transportation State Highway Administration's (MDOT SHA) managed landholdings.

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Acronyms and Abbreviations

Cr	Runoff coefficient computed as the ratio of storm even precipitation to runoff
ECN	Effective curve number
JSON	JavaScript Object Notation
Ksat	saturated hydraulic conductivity
OM	organic matter
PET	potential evapotranspiration
PTF	Pedotransfer function
SWC	U.S EPA National Stormwater Calculator

Executive Summary

The Maryland Department of Transportation State Highway Administration (MDOT SHA) is interested in finding cost-effective solutions for stormwater management (SWM) of highway runoff in highly urban watersheds with limited right-of-way; reducing SWM facility maintenance costs; and reducing project right-of-way areas and costs for SWM. The Highway Hydraulics Division is interested in advancing soil decompaction and amendment as an innovative practice to achieve these goals. This research builds on prior collaborative research with UMBC that demonstrated dramatic infiltration increases in stabilized pervious landuses in the heavily compacted “pervious” footprint of the old MD Rt. 853 roadbed in Taneytown, MD [1, 2]. Given the positive results of that study, the Maryland Department of the Environment (MDE) built on this research to develop a formal protocol adding a soil restoration credit as an approved BMP in their 2020 MS4 guidance document. MDOT SHA is particularly interested in the potential use of the practice to enhance infiltration and runoff reduction.

This research developed a prototype protocol to support the institutionalization of soil decompaction and amendment as an approved stormwater BMP in the State of Maryland. The protocol can be used to develop a prototype specification, site-specific soil-specific stormwater credits, and establish requirements and procedures for inspection, acceptance, and maintenance. Performance monitoring data provided credible "ground truth" for the soil physics predictions used to quantify effective curve numbers that can be used to calculate a consistent quantitative stormwater credit for the practice.

Anticipated Benefits – Reducing stormwater runoff by reliably restoring infiltration on MDOT SHA’s pervious land holdings will lower the costs and accelerate stormwater compliance by reducing the number and size of stormwater management (SWM) facilities needed to meet SWM regulatory requirements. The results from this project advance the institutionalization of this innovative cost-effective practice by developing standard specifications and details for soil decompaction and amendment to guide design, specification, implementation, acceptance, inspection, and maintenance procedures for a new approved BMP. Collectively these elements support the institutional advancement of this practice as an approved BMP in the State of Maryland.

1. Introduction

Compacted and highly disturbed urban soils are a pervasive feature of modern constructed landscapes [3]. The standard practices for rapid vegetation establishment on sites associated with mass grading routinely result in a "pervious" landscape with impaired infiltration capacity in compacted soils that constrain plant root growth, reduce soil water holding capacity, and limit the reservoir of plant-available nutrients in the root zone. The lost hydrologic function of the pervious landscape can be reliably restored by renovating disturbed soil profiles through soil decompaction combined with aggressive organic compost amendment. We refer to this family of practices as *suburban subsoiling*, alluding to the adaptation of agricultural subsoiling technologies to disturbed compacted pervious landscapes in the urban-built environment. When properly planned and efficiently staged, this superior sustainable landscaping practice can be cost-effectively achieved through minor modifications to standard grading and landscaping practices. UMBC's subsequent work demonstrated a consistent modeling procedure to quantify the hydrologic services resulting from suburban subsoiling with a site-specific soil-specific effective curve number (ECN).

Prior work with MDOT SHA [1, 2] has documented the typical soil conditions resulting from standard construction specifications, and the dramatic improvements realized with suburban subsoiling. The project in Taneytown MD was selected as an AASHTO Sweet-16 high-value research project for 2016. UMBC's subsequent work demonstrated a consistent modeling procedure to quantify the hydrologic services resulting from suburban subsoiling with a site-specific soil-specific *effective curve number* (ECN).

To advance cost-effective stormwater management and superior sustainable landscaping in Maryland's transportation infrastructure, UMBC and MDOT SHA engaged in this collaborative research to demonstrate the *stormwater BMP credits* that can be reliably produced by institutionalizing standard methods and specifications for soil decompaction and amendment. This research is designed to advance the integration of new cost-effective practices and procedures that improve soil structure, restore infiltration, and reduce stormwater runoff as an approved stormwater BMP in the State of Maryland. Approval will result in reduced costs for green asset maintenance while significantly expanding the opportunities for cost-effective stormwater management services from the pervious landuses in MDOT SHA's managed landholdings.

2. Literature Review

Our previous research with MDOT SHA included an extensive literature review on soil properties, soil compaction and the risks, consequences and remediation of compaction [2]. We extend and update that literature review, concentrating on salient research supporting stormwater credits for soil decompaction and amendment, and advances in the potential application of decompaction and amendment to novel applications in the landscape.

Urban Soil Disturbance- The landmark work of Pitt et al. [4] and Gregory et al. [5] remain milestone papers characterizing the pervasive effects of soil compaction from routine construction practices on stormwater services of the urban pervious landscape. Perhaps most significant – and most overlooked in these papers- is the observation that most common practice makes the implicit assumption that urban pervious landuses retain the hydrologic characteristics of undisturbed soils reported in the National Cooperative Soil Survey. Recognition of the pervasive disturbance of urban soils is increasingly common. Schifman and Shuster [6] reported infiltration measurements from 12 cities were poorly represented in the SSURGO soils data base used in the National Stormwater Calculator (SWC). Herrmann et al. [3] similarly reported finding the consistent loss of soil horizons in urban soils from 12 different cities. This growing recognition has serious implications for our ability to accurately characterize and simulate runoff from disturbed compacted urban soils. Indeed, McGrane [7] described the hydrologic dynamics of infiltration in urban green spaces as "mere artefacts of anthropogenic modification". Voter and Loheide [8, 9] used detailed distributed parameter modeling to demonstrate the value of renovating compacted soils to reduce urban stormwater runoff at the parcel-scale, and spatially targeting soil renovation to maximize stormwater benefits.

Tillage and Compost Amendment - The combined benefits of decompaction or tillage plus compost amendment has been extensively documented in land reclamation and reforestation [10, 11]. The appreciation of its value in restoring urban soil function is growing in both scholarship and practice [12]. Work by Schwartz and Smith [1, 13] and Mohammadshirazi et al. [14, 15] have emphasized the practical benefits and pragmatic methods to mainstream this practice in urban and roadside [10, 16, 17] land development practices. The recent review by Kranz et al. [18] highlights much recent work as well as variability in nominal results [19], highlighting the need for standard BMP protocols to ensure predictable results from urban soil improvement practices implemented by practitioners.

The benefits of tillage and amendment have fostered the development of alternate innovative tillage practices designed specifically to reverse anthropogenic disturbance and compaction. Alternate practices range from complete cultivation and loose tipping [20, 21], to Cornell University's so-called "scoop and dump" method [22] which closely resembles complete cultivation. Along with alternate tillage practices, closer scrutiny of landscapes in the built environment have reinforced the value of tillage and compost amendment in the establishment of "low maintenance" turf (i.e. turf without regular supplemental inputs of irrigation and fertilizer).

Schmid et al. [23] showed that rapid vegetation establishment using standard methods (such as MDOT SHA specification 705 for vegetation establishment) can rapidly establish acceptable turf cover, but the shallow rooted turf established in relatively infertile fill material soon displays chlorosis and deteriorates to poor thin cover within just 1-2 years of establishment. In contrast, turf established with deep tillage and compost amendment developed denser deeper-rooted more verdant turf – results entirely consistent with our findings at our MDOT SHA Taneytown research site [2]. Our suburban subsoiling practice adapted agricultural subsoiling to disturbed compacted soil profiles in the built environment. Extensive experience in deep ripping agricultural soils usefully informed equipment choices and specifications for suburban subsoiling (including practical considerations spanning minimum equipment requirements to tractive force required to rip to a prescribed depths) and are usefully complied in [24].

Estimating Soil Hydraulic Properties- Assigning reliable credits for soil decompaction and amendment requires the ability to reliably predict the hydraulic characteristics of a decompacted and amended soil profile. Mass grading and standard construction activities that disturb and compact soil profiles in the built environment profoundly alter soil hydraulic characteristics by dramatically changing the pore size distribution throughout the soil profile. Menon et al. [25] used x-ray tomography to vividly capture the dramatic shift in pore size distribution among water stable aggregates resulting from modest compaction pressures. Their images showed how the largest interconnected pores (that disproportionately support infiltration) are the first pores eliminated under modest compaction energy. Using the Saxton-Rawls [26] Texture-Organic Matter (TeOM) pedotransfer function, we estimated that increasing the bulk density of an uncompacted soil by just 10% could result in more than a 65% reduction in infiltration rate – depending on the soil texture.

A diverse and growing set of pedotransfer functions have been developed to predict soil properties that are difficult to measure, from soil properties that are easy to measure [27, 28] leading in turn, to the evaluation of the accuracy of pedotransfer functions in novel environments – such as urban pervious landscapes [6, 29, 30]. Shuster et al. [31] and Schifman and Shuster [6] evaluated the use of the USDA SSURGO soils database, the National Stormwater Calculator, and the ROSETTA pedotransfer function to predict properties of urban soils from 12 cities, and urban demolition sites in Cleveland. Though unsurprising, their results emphasized the distinctive site-specific features of disturbed urban soils that do not readily lend themselves to statistical "space-for-time" sampling estimation; not all "urban" soils are created equal.

Infiltrating Run-on: Understanding infiltration on sloped surfaces and multi-layer soil profiles

Enhancing infiltration through soil decompaction and compost amendment has been considered by some practitioners as a practice that could be used to create small "hyperfunctional" pervious footprints, capable of receiving run-on from much larger surrounding drainage areas. This perspective resonates with traditional stormwater BMP designs for infiltration trenches, stormwater ponds and bioretention cells that combine temporary storage with engineered drainage to capture and treat runoff from surrounding drainage areas. In contrast to BMPs designed for stormwater storage and treatment, the desired endpoint for soil decompaction and amendment is to restore disturbed compacted soil profiles to a condition that nearly reproduces the natural infiltration capacity of an undisturbed (or minimally disturbed) soil profile. Consequently, soil decompaction and amendment does not employ grading to create shallow depressions for the temporary storage of run-on. The primary hydrologic benefit of decompaction and amendment derives from restoring infiltration rates close to those of an uncompacted soil profile, compared to the significantly lower infiltration otherwise realized in the compacted post-construction soil profile.

Understanding the extent and limitations of decompacted and amended soils to accept run-on requires an understanding of infiltration on sloped surfaces [32] as well as infiltration in multi-layer soil profiles [33]. Steeper slopes are generally expected to decrease ponding and increase overland flow velocities, reducing infiltration and limiting the effectiveness of treating run-on with decompacted and amended soils. However, the soil physics of decompacted and amended soil profiles also involves the hydraulics of two-layer – or multilayer- soil profiles.

Because current theory failed to adequately explain observed infiltration on sloped surfaces, Essig et al. [34] combined laboratory experiments and mathematical modeling to evaluate several hybrid schemes to reproduce and predict infiltration on sloped surfaces. Morbidelli et al. [35] examined run-on effects and infiltration on sloped surfaces using a tilting tank and rainfall simulator. They concluded the effect of run-on could be adequately represented by treating run-on as additional rainfall on the downstream infiltrating surface. Morbidelli et al [36] designed carefully controlled physical modeling experiments to try control for and resolve conflicting experimental results on the effect of slope on infiltration on bare soils and on grassy soils [37]. The state of the science, with rational explanations for some of the conflicting results in the literature and suggested steps for future research, are reviewed in Moribdelli et al [38]. An alternate conceptual approach to modeling infiltration on slopes considers the distribution of water velocity over the surface, with infiltration affecting the fraction of flow below a critical velocity [39].

Two-layer infiltration

The challenge of modeling and predicting infiltration in a two-layer (multilayer) soil profile has received considerable investigation [33]. Particularly relevant for urban pervious landuses are the solutions developed by Corradini and his colleagues for infiltration into a two-layer soil with a more pervious upper layer, and its extension to field-scale infiltration [40, 41]. The Corradini solution predicts infiltration with an effective conductivity, K_{eff}, which varies with the duration (depth) of infiltration. The Corradini solution for a two-layer soil is well approximated by an analytical expression for the effective saturated conductivity of a multi-layered soil based on Darcy's law. Application of Darcy's law and continuity to a multilayer soil profile admits the analytical solution of the effective saturated hydraulic conductivity as the inverse of the thickness-weighted average inverse conductivities of each soil layer, analogous to the flow of electrical current:

$$K_{eff} = \frac{(d_1 + d_2)}{\frac{d_1}{K_1} + \frac{d_2}{K_2}}$$

where d_i and K_i denote the thickness and saturated hydraulic conductivity of the i-th soil layer, respectively. From the analytical solution it is clear that the order of the soil layers in the *saturated soil profile* does not affect the solution. It follows that topsoiling, or the common practice of scarifying the surface of a compacted graded surface does not significantly improve the *saturated* hydraulic conductivity of the overall soil profile. The infiltration benefit from retaining a thin porous permeable surface layer is only relevant under unsaturated, or partially saturated conditions!

Corollary to this analytical solution is the dependence of K_{eff} on the *depth of saturation* – i.e. the depth of the (Green-Ampt) wetting front. Applying the layered effective conductivity solution to our "topsoiled" soil profile, we compute the effective Ksat as a function of the depth of the wetting front in Figure 1. The results in Figure 1 assume a one-meter soil column in which the top 5 cm of the profile are decompacted with Ksat = 5 cm/hr, and the remaining soil profile is compacted with Ksat = 0.05 cm/hr. Notice how rapidly the effective saturated conductivity decreases once the wetting front reaches the interface between the two layers. This simple example indicates how rapidly the infiltration capacity of a disturbed (e.g. "topsoiled") soil profile can change as the soil naturally oscillates between saturated and unsaturated conditions. Recognizing the importance of these processes in landscape-scale infiltration, we used a continuous soil physics model to simulate infiltration and the wetting drying dynamics of representative soil profiles in order to quantify the hydrologic consequences of soil compaction and the suburban subsoiling -decompaction and amendment- BMP. The following section discusses the consistent characterization of water movement through an idealized one-meter soil profile, forced by continuous meteorology.

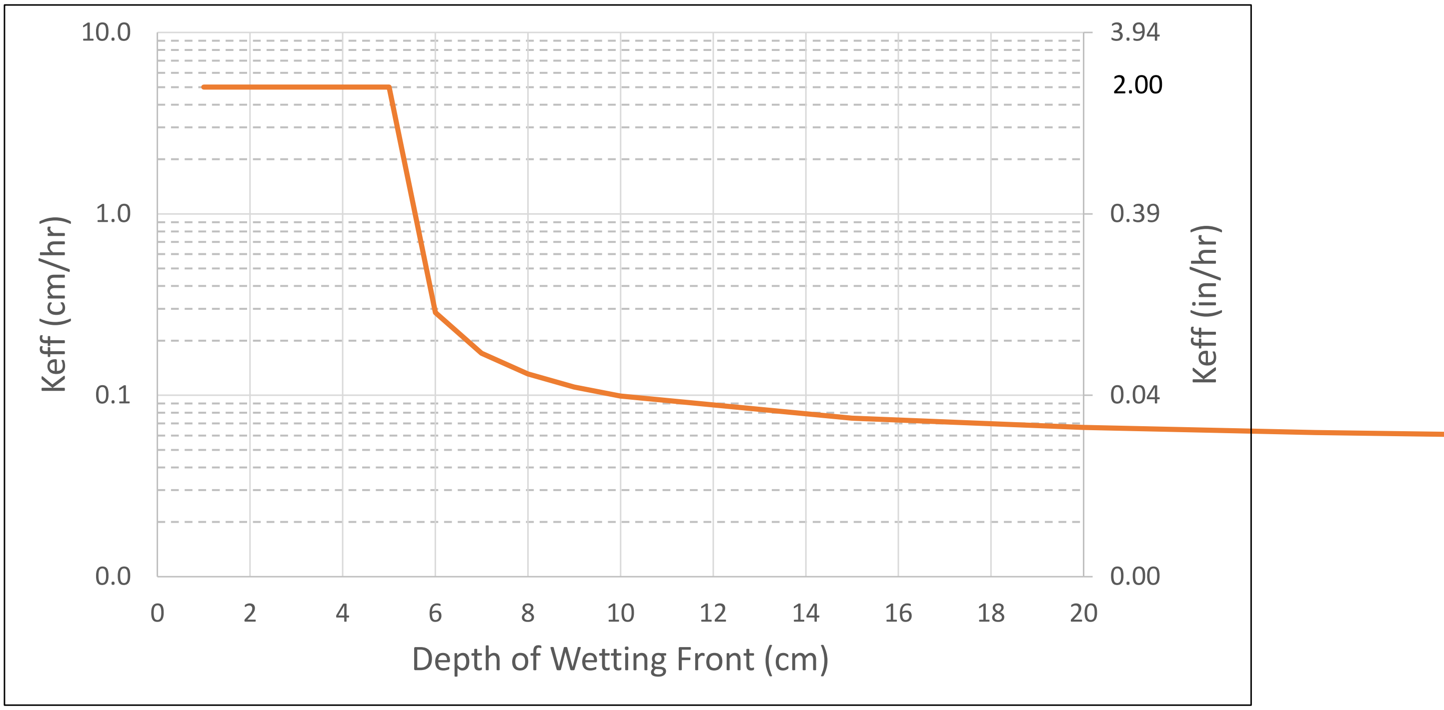

Figure 1 Effective conductivity of a two-layered soil as a function of the depth of saturation

3. Continuous Soil Moisture: Modeling and Monitoring

3.1 Simulated Soil Moisture

We extended our understanding of the hydraulics of infiltration through a layered soil profile through continuous simulation of the soil physics of water movement through a one-meter soil column, forced by time series of precipitation and potential evapotranspiration (PET). We force the model using continuous hourly meteorological data from the NASA POWER data stream to calculate Penman Monteith potential evapotranspiration (PET), and 15-minute precipitation data from the USDA Beltsville agricultural research station.

Uncompacted soil without vegetation

Soil parameters are derived from texture and bulk density using the Saxton-Rawls pedotransfer function (PTF), with the water characteristics curve parameterized by van Genuchten parameters estimated using the ROSETTA pedotransfer function. Water movement through the soil profile is resolved by numerically integrating the full Richards equation for each 15-min (precipitation) time step, through the entire one-meter soil column, with 1-cm vertical resolution. The soil moisture distribution at each time step can be plotted to show the evolution of the soil moisture profile throughout the year, as shown in Figure 2. The upper half of the Figure shows the depth of precipitation (blue) and runoff (red) events, as well as the seasonally varying depth of evaporation. The lower figure shows the vertical distribution of soil moisture throughout the year with 15-min resolution). The Figure shows the vertical distribution of soil moisture every 15-min for a typical year (just over 35,000 one-meter profiles).

The soil profile in Figure 2 represents an idealized uncompacted soil at native bulk density with no rooted vegetation. The absence of rooted vegetation means water can only leave the soil column via the slow diffusion driven process of surface evaporation, or drainage from the bottom of the profile. This one-year simulation shows the seasonal pattern of drying (from March to October) punctuated by rain events that recharge soil moisture due to infiltration. Note the events – characterized by dark blue vertical streaks- when the entire soil profile reaches saturated conditions. When the entire profile reaches saturation, water drains at the saturated hydraulic conductivity of the soil, Ksat. These events can be thought of as representing the recharge of deep soil moisture or groundwater. Note as well how the soil can dry out between significant rainfall events (e.g. in August) only to experience rapid wetting when the dry soil infiltrates and retains water during rain events. The simulation shows how the soil stays quite moist – nearly at field capacity- through the dormant season (from late fall to early spring) when days grow short and temperatures fall. For roughly half the year, evaporation is quite low, and soil moisture is held in soil micropores as tension water. Finally note that most of the precipitation during this simulation year was infiltrated, with a substantial fraction of annual precipitation returned to the atmosphere by evaporation or redistributed throughout the soil column. Note that only two rainfall events produced any significant runoff during this simulated year. As a one dimensional simulation we can only model infiltration excess overland flow, so the two precipitation events represent storms within which the precipitation rate within the storm exceeded the infiltration capacity of the soil.

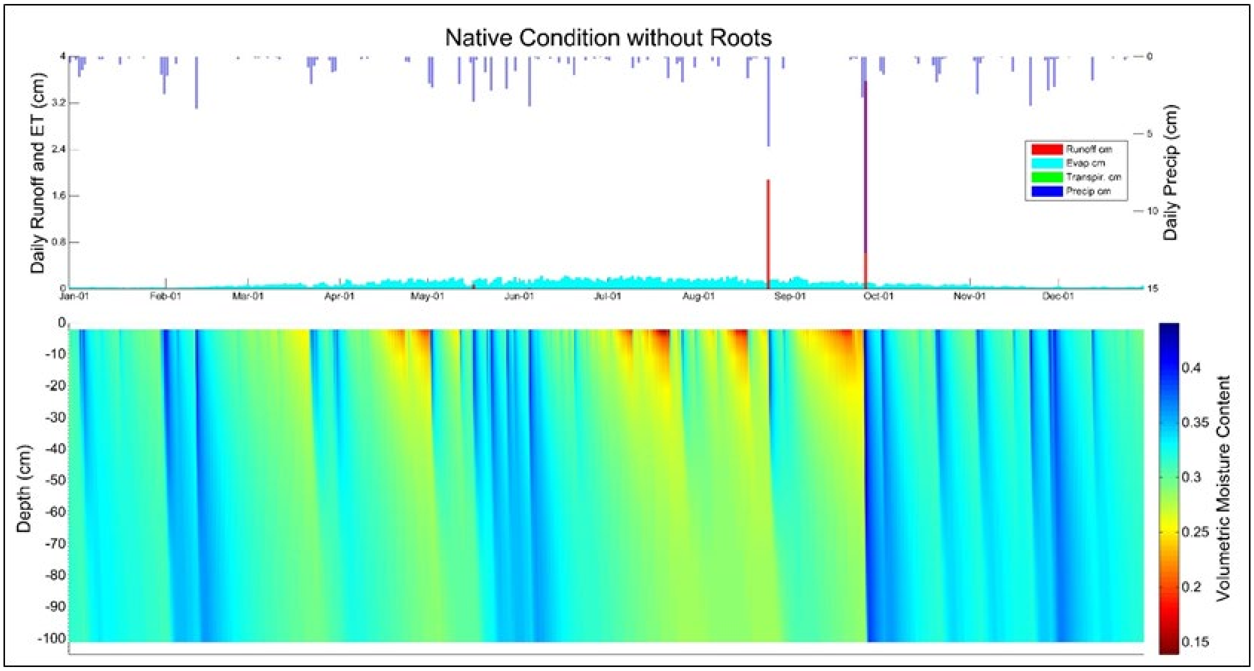

Figure 2 Soil Moisture for an uncompacted soil at native bulk density without rooted vegetation

<u>*Uncompacted soil profile with vegetation*</u>

The soil profile shown in Figure 3, simulates the same soil profile with the same meteorological forcing, in which we have also assumed vegetative cover with an active root mass throughout the top 20 cm of the soil profile. The same wetting and drying cycles can be seen on the event scale, as well as drying soil during the growing season and consistently moist soils during the dormant season. The principal difference in this second simulation is the action of plant roots in actively returning water to the atmosphere during the growing season through transpiration. In contrast to the slow diffusion limited drying from evaporation, plant roots are able to actively extract water from the entire 20 cm root zone, resulting in more rapid and intense drying of the root zone during the growing season, and the deeper propagation of that dry condition lower in the soil profile. Transpiration returns more water to the atmosphere than evaporation, and even reduces evaporation, by transpiring soil water that would otherwise have slowly evaporated in the absence of vegetation. Note the deeper more intense drying from transpiration makes it harder for this particular storm sequence to bring the soil profile to saturated conditions during the growing season, limiting recharge events during this simulated year to the dormant season. Yet, like the soil profile without vegetation, as days shorten and temperatures drop in the fall, the significant decline in evapotranspiration (ET) allows the soil profile to retain infiltrated rainfall, raising the soil moisture close to field capacity from late fall until early spring. With seasonally persistent high soil moisture, relatively small storms are able to bring the soil profile to saturated conditions, and we see several seasonal recharge events – all confined to the dormant season. Together these two continuous simulations provide a representative mental model for the dynamic seasonal patterns of wetting and drying that dominate the movement of water through the soil and the production of surface runoff from an idealized uncompacted one-meter soil profile.

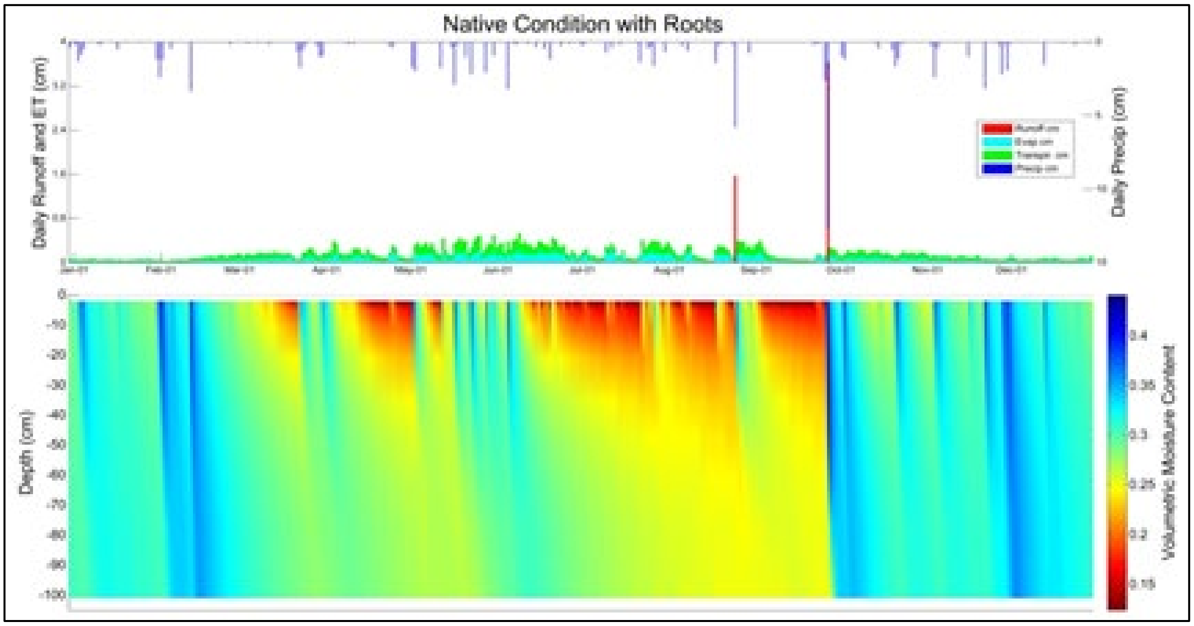

Figure 3 Soil moisture for an uncompacted vegetated soil profile at native bulk density with a 20-cm rootzone

Topsoiled soil profile

With these uncompacted soil profiles as reference points, we simulate an idealized "urban" soil profile resulting from mass grading, finished by spreading 10 cm of uncompacted topsoil over the compacted surface. We represent the "topsoiled" soil profile by assuming the top 10 cm of the profile are uncompacted, at native bulk density, with 3% organic matter (OM) (consistent with MDOT SHA topsoil specifications) and assume the rootzone of surface vegetation is confined to the top 10 cm of the soil profile. The remaining 90 cm of the one-meter soil profile is assumed to have been consolidated to a bulk density just 10% higher than native bulk density, with only 0.5% organic matter[1].

The same meteorological time series are used to force water movement through the topsoiled profile. The resulting difference in soil moisture may be attributed to the changes representing a topsoiled soil profile. This idealized profile typifies many disturbed compacted profiles we have seen in the field, and represents the type of post-construction conditions produced by current specifications and acceptance criteria for grading and vegetation establishment. Schwartz and Smith [13] described this style of land development as producing urban pervious landscapes that

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[1] 10% compaction with 0.5% OM was recommended as a representative for subgrade soils for urban BMPs by Jay Dorsey, Ohio DNR, based on subgrade measured infiltration measurements made in the field.

might best be described as grass growing in a thin veneer of topsoil on compacted fill. The simulated water movement through the topsoiled profile is shown in Figure 4.

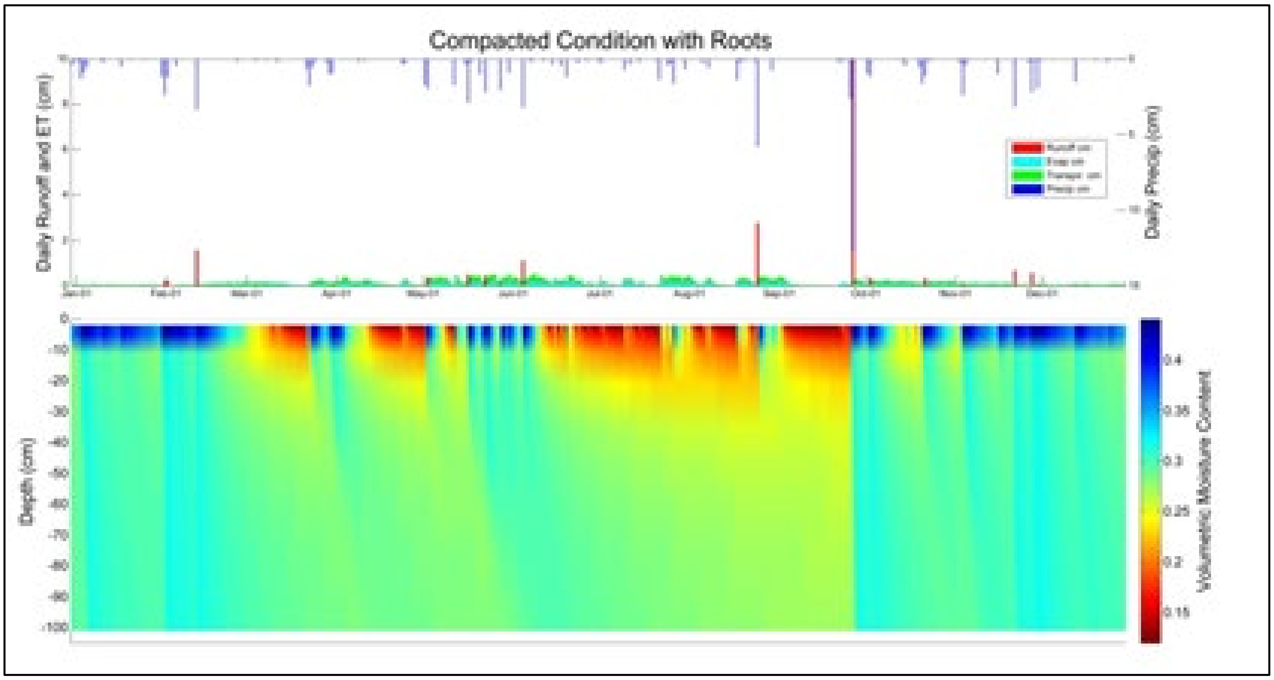

Figure 4 Topsoiled soil profile with 10 cm of uncompacted soil with 3% OM, over 90 cm of compacted soil with 0.5% OM

As with the uncompacted soil profiles, the topsoiled profile shows the seasonal pattern of drying between storms during the growing season and maintaining relatively high seasonal soil moisture during the dormant season. Plant roots in the 10 cm root zone rapidly return soil moisture to the atmosphere as transpiration, but the supply of plant available water for transpiration is limited by the depth of the rootzone and can be rapidly depleted between storm events, resulting in a significant decrease in net ET compared to the uncompacted soil profile. As well, rainfall readily infiltrates the 10 cm layer of uncompacted soil, but the relatively small increase in bulk density of the underlying soil is sufficient to significantly reduce conductivity and water movement into the lower soil profile. As a result, the rootzone is frequently brought to saturated conditions by even modest storms, but only a small fraction of the saturated soil water moves into the lower soil profile.

Notice that the entire soil profile *never* approaches saturated soil moisture contents at any time during the year – essentially eliminating deep recharge. The higher frequency of saturated surface conditions increases the frequency of runoff-producing conditions – when rainfall intensity exceeds the infiltration capacity of saturated surface soils with minimal drainage. As a result, the topsoiled profile realizes 12 runoff producing events during the simulated year – compared to just 2 runoff events on the uncompacted soil profile. Moreover, the topsoiled soil profile produces significantly more runoff from the two storms that produce runoff on the uncompacted profile. For example, the runoff from the October storm event is nearly three times greater (about 10 cm) than the runoff from the same event on the uncompacted profile.

Together these simulation results frame the dominant processes that are impaired by soil compaction and provide a framework to quantify both compaction and restoration of soil profile properties. Perhaps most interesting in the simulations is the consistent *prediction* that soil moisture should rise and stay high during the dormant season, and then transition seasonally to a much drier profile, with intermittent wetting and drying from significant storms during the growing season. We tested this prediction by installing two vertical nests of soil moisture sensors in test plots on the UMBC campus. Soil moisture monitoring conducted to test this prediction is described in the next section.

3.2 Soil Moisture Monitoring

The soil moisture dynamics predicted in the simulations described in the previous section, were monitored in the field for experimental plots on the UMBC campus. Soil moisture field dynamics were monitored by establishing two vertically nested arrays of METER TR-11 capacitance-based soil moisture sensors. The sensors were installed at approximate depths 4 inches, 9 inches, and 14 inches below the surface (Figure 5). All soil moisture sensors were hardwired to a Zentro ZL-6 data logger which recorded volumetric soil moisture content and soil temperature every 15 minutes, and uploaded the data to cloud-based storage on a custom reporting schedule defined to minimize power consumption for cellular communication, while ensuring no more than 12-hour latency in the data. The TR-11 soil moisture sensors were manually installed by pressing each sensor into the sidewall of a small soil trench excavated in each experimental plot.

Figure 5 Vertically nested soil moisture sensors

Beginning in late October 2020, soil temperature and soil moisture were monitored continuously at 15-minute time steps through the onset of summer in 2021. The data from one 3-sensor soil profile are shown in Figure 6.

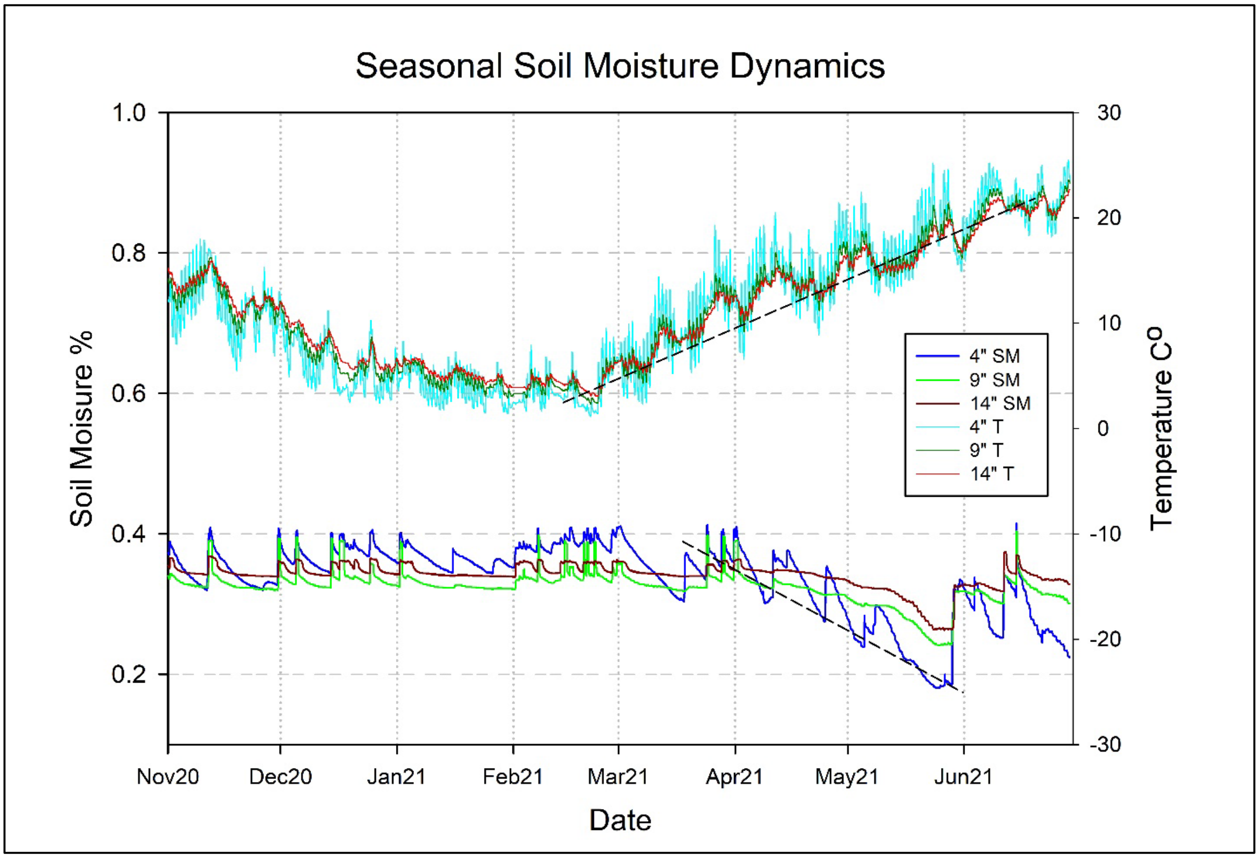

Figure 6 Soil Moisture and soil temperature for 2020-2021 fall-summer transition

The shallow (4") soil temperature data shows high short-term variability reflecting the diurnal cycle of air temperature. Most of this variability is essentially damped out in both the 9-inch and 14-inch temperature measurements. As soil temperatures cool during the onset of the dormant season, soil temperatures during winter of 2021 rarely rise above 5ºC. Seasonal warming of the soil begins in March 2021, with short term variability superimposed on the steady warming trend indicated by the upward sloped dashed line.

As predicted, the observed soil moisture remains consistently high during the dormant season, with considerable short-term excursions into saturated or near-saturated volumetric soil moisture (≥40%) in shallow (4") soil moisture during precipitation events. The minimal evapotranspiration during the dormant season allows soil moisture to remain uniformly high through March, with volumetric soil moisture remaining above 30% throughout the soil column. The soil moisture response to seasonal warming lags the steady seasonal increase in soil temperatures by 1-2 months, with significant initial drying of the upper soil beginning in April – moderated by seasonal rainfall. As vegetation becomes active and evapotranspiration increases, 4-inch soil moisture (which is sampling the rootzone) steadily decreases (punctuated by spring rainfall events). The seasonal drying response observed at a depth of 4-inches slowly extends to the deeper layers of the soil profile (below the shallow root zone) in late April and May, as day length continues to increase, temperatures continue to rise, and vegetation returns to seasonally high levels of growth and transpiration.

The seasonal soil moisture dynamics observed in our monitoring data are entirely consistent with the seasonal pattern of high soil moisture during the dormant season, transitioning into more dynamic wetting and drying during the growing season, predicted by our detailed one-dimensional soil profile simulations described in section 3.1. The persistence of dormant season soil moisture close to field capacity has significant implications for seasonal runoff. For example, reliance on the presumed infiltration services of urban pervious landuses during the dormant season for LID BMPs such as downspout disconnections may overestimate green infrastructure (GI) effectiveness without parallel efforts to improve and maintain urban soils (see, e.g. Voter and Loheide [8]). More generally, the persistence of high dormant-season soil moisture has not been widely considered in stormwater management and GI design. The identification of this phenomenon using continuous soil physics modeling is a unique contribution of this research. The validation of this prediction with our continuous monitoring data validates the predictive power of our modeling framework, and enhances the credibility of our physically-based modeling framework and its use to quantify the hydrologic credit for soil decompaction and amendment. The following section describes a consistent framework for quantifying site-specific soil-specific stormwater credits for soil decompaction and amendment.

4. Decompaction Credit

We build on the stormwater credit framework introduced by Schwartz and Smith [42], using continuous modeling with a 1-D soil physics model to simulate the hydrology of water movement through an idealized one-meter soil profile. Simulated rainfall-runoff results provide a consistent framework to characterize the dynamic rainfall-runoff response of the soil column as an estimated site-specific soil-specific ECN. Following [42], we consider reference soil profiles for (a) an uncompacted soil; (b) a "topsoiled" soil; and two variations of suburban subsoiling corresponding to deep ripping or deconsolidation to a depth of at least 20 inches combined with (c) incorporating 2-inches of surface applied compost throughout the top 6-inches of the soil profile (SS-6); and (d) incorporating 3-inches of surface applied compost throughout the top 9-inches of the soil profile (SS-9).

The endpoints for representative soil profile reference conditions are summarized in the following table. The following description is taken from Schwartz and Smith [2]

Table 1 Soil Profile Endpoints

Soil Profile Condition Endpoint	Description
1. Healthy Soil 5% OM	1 meter freely draining profile at native bulk density and 5% organic matter
2. Topsoiled Urban Soil 4"[2]	Top 4-inches at native bulk density and 3% organic matter, remainder of the column compacted 10% at 0.5% organic matter
3. 6-inch Suburban Subsoiling	Top 6-inches at native bulk density and 5% organic matter; 6-20 inches at native bulk density and 0.5% organic matter; remainder of profile compacted 10% at 0.5% organic matter
4. 9-inch Suburban Subsoiling	Top 9-inches at native bulk density and 5% organic matter; 9-20 inches at native bulk density and 0.5% organic matter; remainder of profile compacted 10% at 0.5% organic matter

For each soil *profile condition,* we modeled water movement through the soil profile by simulating infiltration and runoff processes for 10 standard 24-hour design storm depths[3]. The soil moisture condition of the soil column was initialized to a uniformly dry standard condition at the start of every simulation. For each storm, the 24-hour design storm depth was temporally

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[2] The topsoiled profile decompacted the top 4 inches of the profile with a single soil texture. Consequently, some of the higher clay textures were simulated with a "topsoil" with clay content that was too high to meet typical topsoiling specs. We retained the single texture assumption in these profiles for consistency. Even so, we recognize an alternate topsoiled configuration using any one of the acceptable textures in the top 4 inches would be more realistic. One of the modeling and real world challenges,, is characterizing the *very* broad range of textures that qualify as "topsoil".

[3] The design storms corresponded the 1,2,5,10,25,50,100,200,500 and 1000 year 24-hour precipitation depths.

distributed using the SCS Type II hyetograph[4], and applied in 6-minute time steps defining the time varying boundary condition at the top of the soil column. When the 6-minute rainfall intensity exceeds the instantaneous infiltration rate, any excess precipitation (representing infiltration excess overland flow) is tracked as runoff, resulting in a pair of simulated rainfall (P) runoff (Q) values for every storm event. These design storm simulations were, in turn, replicated for each of the 12 USDA texture categories, using the sand, silt, and clay contents of the centroid of each texture category polygon. An identically defined set of 120 simulations are repeated for each soil profile condition, enabling the representative hydrologic response of each soil profile condition to be compared for any texture[5]. To summarize the runoff characteristics of each soil profile condition, we used the 10 P-Q pairs to estimate an Effective Curve Number (ECN) for each soil texture centroid, along with a runoff coefficient, C_r, computed as the mean ratio of event precipitation to simulated storm runoff. The runoff characteristics of each soil profile condition are summarized in the ECN table, Table 2, and can be represented graphically by plotting smoothed interpolated ECN contours on the soil texture ternary diagram (see Ch. 7).

Table 2 Effective Curve Number (ECN) table by texture for "topsoiled" and decompacted and amended soil profiles.

	Topsoiled 10 cm		SS 6-inch		SS 9-inch		ΔQ TS - SS6	
TEXTURE	ECN	Cr	ECN	Cr	ECN	Cr	1-yr 2.69 in	2-yr 3.25 in
Clay	93	0.89	88	0.82	88	0.81	0.35	0.38
Clay Loam	91	0.87	72	0.56	71	0.54	1.19	1.38
Loam	73	0.54	60	0.38	55	0.35	0.43	0.57
Loamy Sand	56	0.36	38	0.15	38	0.14	0.14	0.29
Sand	36	0.13	30	0.08	30	0.08	0.00	0.00
Sandy Clay	94	0.95	79	0.72	73	0.64	1.06	1.19
Sandy Clay Loam	88	0.82	72	0.50	72	0.49	0.89	1.05
Sandy Loam	70	0.53	50	0.24	49	0.23	0.50	0.71
Silt	86	0.80	58	0.41	52	0.38	1.20	1.50
Silty Clay	89	0.84	76	0.60	76	0.58	0.81	0.94
Silty Clay Loam	88	0.83	67	0.52	64	0.48	1.14	1.37
Silty Loam	87	0.81	62	0.45	56	0.42	1.19	1.46

The ECN values in Table 2 are limited to single-texture profiles and provide reasonable initial endpoints for the continuum of soil profile conditions found in the field. Although the soil physics modeling used to derive these ECNs can be performed on more complex soil profiles as well, the variation of conditions experienced in the field is virtually limitless. For this reason, we examined alternate methods that might be used by MDOT SHA designers and contractors to

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[4] NOAA Precipitation Atlas 14 introduced refined storm hyetographs with finer spatial resolution than the NRCS Type II hyetograph. The NOAA Type B and C hyetographs are recommended for eastern and western Maryland. The Type II hyetograph is bounded by the small differences between the NOAA Type B and C hyetographs. For this reason, the Type II hyetograph was judged to provide a good representation of the mean 24-hour design storm, and was used exclusively in the work reported here.

[5] We limit the use of the Saxton-Rawls PTF to soil textures with no more than 60% clay, reflecting the under-representation of the high clay textures in the pedons used to estimate the pedotransfer function.

extend the reference points in the ECN table to other soil profiles. The following section describes the use and limitations of the US EPA National Stormwater Calculator for this purpose.

5. US EPA National Stormwater Calculator

The US EPA National Stormwater Calculator (SWC) is an online tool developed to support site-specific decision making for stormwater BMPs. The SWC provides an integrated web-based interface enabling site selection and analysis of stormwater runoff changes accompanying land transformation and the use of green infrastructure best management practices (BMPs) to control stormwater runoff. The SWC provides a convenient integrated interface to draw upon national databases of landuse, soil characteristics, and hydrometeorological data to drive site-specific continuous hydrologic modeling, and the analysis of results. Full details & documentation can be found online at: https://www.epa.gov/water-research/national-stormwater-calculator#capabilities. To evaluate the potential use of the EPA SWC for crediting Suburban Subsoiling, we compared our detailed evaluation of hydrologic characteristics and ECN at MDOT SHA's Taneytown research site [1] with characteristics estimated using SWC.

SWC analysis of Taneytown Site
Using the web-based version of the EPA SWC the user can select the site interactively, registering the associated geospatial data layers. Figure 7 shows the location map for the MDOT SHA Taneytown site. The study area, consisting of the old roadbed of MD Rt. 853 and the adjoining construction staging area are shown in Figure 8

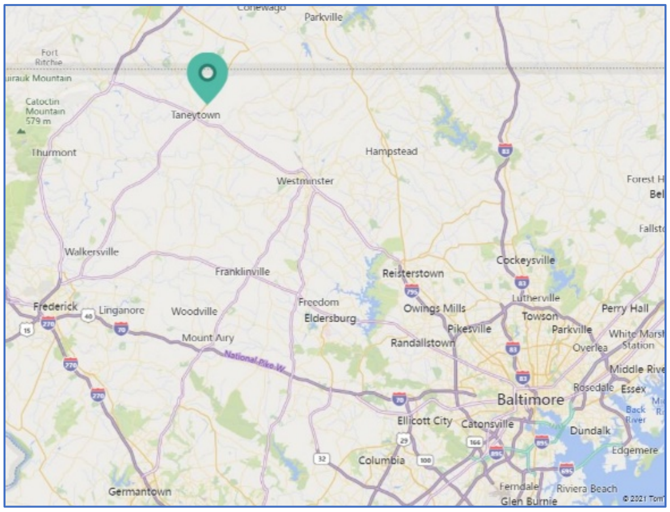


Figure 7 Location Map

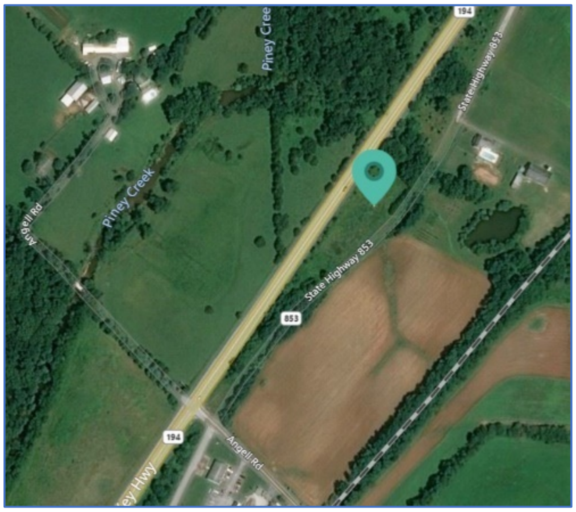


Figure 8 Taneytown Site

Accepting the site-specific soil data from the SWC's linked geospatial data layers assigns the site a sandy-loam soil texture with moderate runoff potential, and hydraulic conductivity of 0.092 in/hr, with moderately flat topography (5% slope). SWC gives a choice of NOAA precipitation and weather stations data to force the hydrologic calculations. We selected the closest station, Emmitsburg 2 SE for both. For the Emittsburg station, approximately 35 years of hourly data are available beginning 1 January 1970. Average annual precipitation and evapotranspiration for the period of record are 45.35 inches and 0.19 inches, respectively. The current volunteer vegetation on the site was assigned to the SWC "meadow" vegetation category. None of the available climate change scenarios or BMP treatment options available in the SWC were selected. With these default characteristics, we simulated 20 years of hourly precipitation to produce default baseline hydrologic characteristics for the "pre-treatment" conditions of the site.

We also simulated the pre-treatment baseline condition of the Taneytown site using our field data from the site [1], with a mean Ksat of 0.04 in/hr, and the mean Ksat of the subsoiled plots of 8.7 in.hr. The simulated rainfall-runoff events using field-observed soil parameters are displayed in Figure 9. The relatively high observed mean Ksat of 8.7 in/hr reported in Schwartz and Smith [1] was observed after only 3 months of settling. As a more conservative estimate of the long-term infiltration capacity after decompaction and amendment, we assumed a *default* post-treatment infiltration rate of only 3.0 in/hr (derived using the Saxton-Rawls pedotransfer function) along with the SWC *default* infiltration rate of 0.092 in/hr. Simulated rainfall runoff events using these estimated *default* conditions are compared and shown in Figure 10.

Event precipitation-discharge (P-Q) data simulated by the SWC can also be used to estimate the ECN for each simulated condition. As an example, representative events selected from Figure 9 and Figure 10 give approximate CN values for the baseline and current condition data in each Figure, and are summarized in Table 3.

	1. SWC Default	2 Settled (est) Decompacted	3. Obs (pre-treatment)	4. Obs. Post-treatment
Drainage Rate (in/hr)	0.092	3	0.04	8.7
Av Annual P (in)	42.77	42.77	42.77	42.77
An Av Q (in)	4.76	2.23	8.45	2.23
Ann days P	73.35	73.35	73.35	73.35
Ann days Q	3	1.55	6.2	1.55
smallest P w/ Q	0.84	1.74	0.6	1.74
Largest P w/o Q	1.7	1.73	1.45	1.73
Max P retained	2.29	3.1	1.66	3.1
Estimated ECN	78	63	86	60

Table 3 Taneytown Hydrologic Characteristics estimated with US EPA National Stormwater Calculator

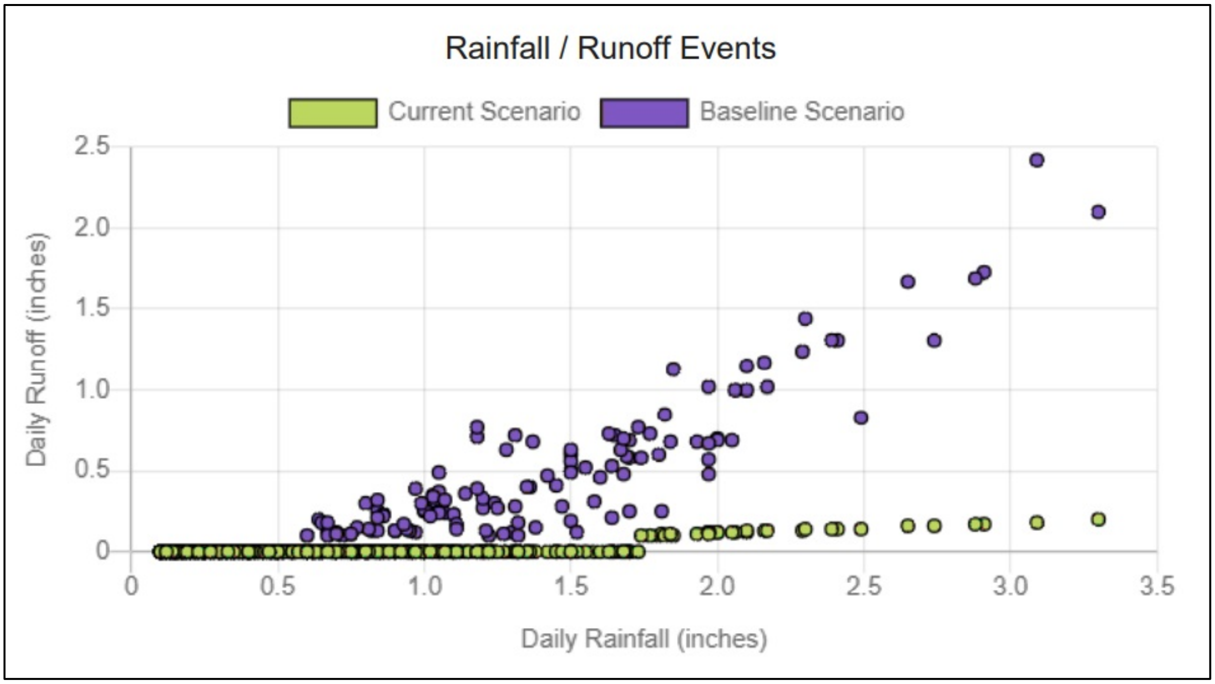


Figure 9 SWC event simulation using observed Ksat data. Baseline is pretreatment, current scenario is after suburban subsoiling

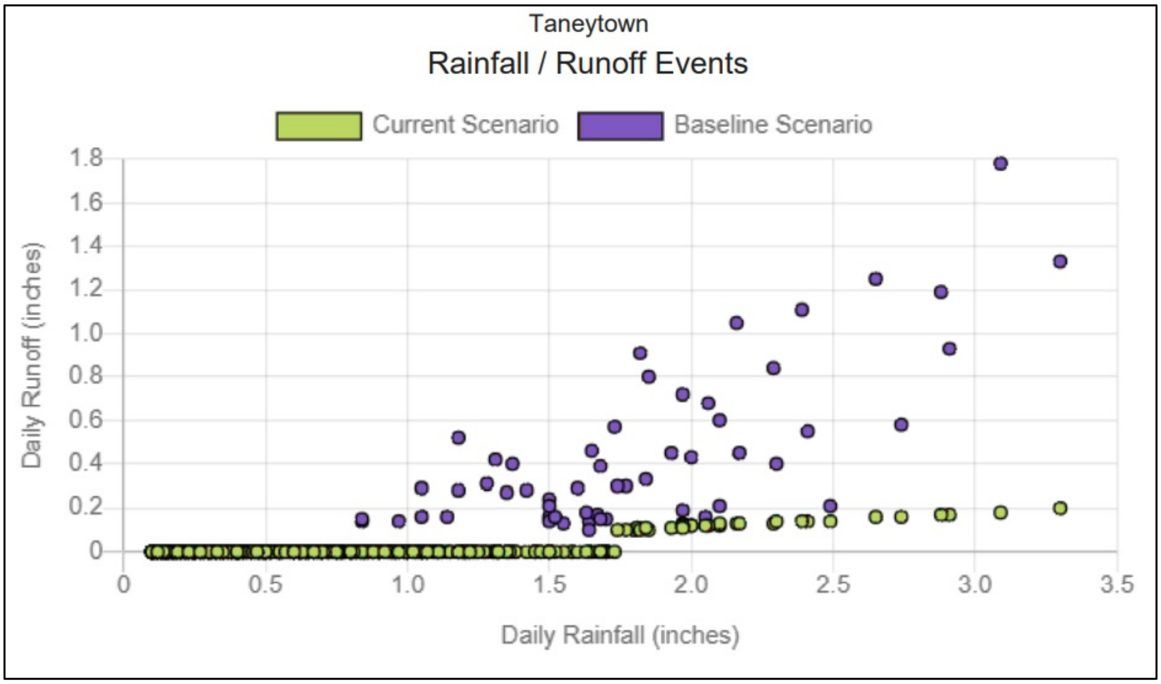


Figure 10 SWC event simulation using default Ksat. Baseline is pretreatment, current scenario assumes Ksat = 3.0 in/hr.

The ECNs in Table 3 are calculated as the mean event CN for a representative sample of the 20 year simulation results shown in Figures 9 and 10. A more consistent estimate can be derived by using all the simulated events and estimating the ECN as a least squares fit of the CN equation (as in Schwartz and Smith [1]). To automate this procedure, we developed a workflow that enabled us to scrape the full set of event P-Q data from the EPA SWC website in JSON format. The JSON file was decoded in R using the **rjson** package [43] and used to produce ECN estimates using all SWC simulated events. The ECN estimates were not significantly different, although using all available events made the least-squares estimates more consistent and reproducible, as expected. Scraping and decoding SWC event simulation data to derive consistent ECN estimates is eminently feasible and enhances the practical application of SWC results. We discussed the possibility of adding the simple derived ECN product with US EPA SWC technical support. Though sympathetic to the usefulness of this change EPA indicated they had no plans to add this capability in the foreseeable future. Alternatively, though beyond the scope of this project, the process could be automated in a complete R script that could be developed for SWC users in future work.

Note that the difference in runoff statistics between the field-observed post-treatment condition (Ksat =8.7 in/hr) and the conservative estimate (Ksat = 3 in/hr) does *not* lead to a *significant difference* in the runoff summary statistics shown in Table 3. This reflects the fact that, on an average annual basis, the vast majority of storm events are readily infiltrated under either soil condition. In part this reflects the highly skewed nature of the daily rainfall distribution at the Emmitsburg (and most other) precipitation gauges (for example a storm depth of 2.91 inches would be expected to be exceeded only once in 2.5 years). In contrast, the estimated runoff prior to decompaction and amendment is *significantly underestimated* by the SWC. In part, this is due to the SWC's use of nominal soil properties retrieved from the National soil database which typically reflect undisturbed soil pedons that were sampled during the original development of the National Cooperative Soil Survey. It is well known that the information in the national soil data base cannot reliably predict the hydraulic properties of disturbed soils.

The biased error introduced by using national soil databases to represent *in situ* conditions on disturbed graded sites is manifested in the difference between the site-specific drainage rate selected by the SWC (Ksat = 0.092 in/hr) compared the values observed on the site prior to decompaction and amendment (Ksat = 0.04 in/hr) reported in Schwartz and Smith [1].

6. Site Screening

Site screening was originally envisioned to identify a site for implementation and monitoring in Phases II and III of the project. Initially, screening efforts planned to use detailed BMP site assessment reports already prepared by MDOT SHA contractors. None of these data and reports were made available for screening. Without the benefit of these prior investigations, screening activity was delayed, and re-envisioned with the development of more generic simple screening criteria, such as screening for disturbed compacted sites with access that would not require traffic control, and sites with relatively low public access to limit the risks of vandalism to installed monitoring equipment.

Other screening criteria included soil profiles that maximize transferability and relevance for developing the BMP protocol. For example, sites in poorly drained coastal plain marine silty clays would have limited value for validating a BMP protocol for disturbed compacted piedmont sites, etc. We sought sites that clearly manifested typical disturbed compacted conditions that result from mass grading and standard land transformation practices. In addition we wanted to consider sites that were large enough to allow effective efficient operation of ripping and tillage equipment. No other specific minimum or maximum size requirements inherently constrain site selection, other than budget limitations. Although specific slope constraints have not yet been specified for the practice, we expected site selection would avoid steep slopes (e.g. requiring slopes < 5%) to avoid unnecessary expenses for non-representative conditions or other idiosyncratic conditions that would require non-standard methods or yield non-transferable results.

To maximize project success, we emphasized screening for sites that would minimize the need for traffic control during construction - *especially* during performance monitoring. As well, screening would similarly avoid sites that may contain construction debris or other challenging "fill" that would constrain ripping and spading equipment. Landuse and landcover for preferred sites favors "permanent" stabilized turf, meadow, and open space landuses in areas designated to support permanent activities that minimize recompaction risk (e.g. no overflow parking areas). Beyond these physical attributes, sites should minimize run on. Soil decompaction BMPs restore landscape infiltration services, separate and distinct from infiltration-based BMPs that are designed to capture and infiltrate runoff from large contributing drainage areas in engineered structures with small footprints that *require* significant storage of off-site run-on. This is a key feature distinguishing soil decompaction and amendment from the use of engineered soil media in, e.g., bioretention structures. Sites should minimize the exposure to other idiosyncratic site-specific conditions that might increase site preparation costs without adding to the knowledge and information generated from the site. The overarching goal considered for site selection was to identify representative sites that would cost-effectively generate the most useful data and information to advance BMP approval by the State of Maryland. Without access to any of the comprehensive data or screening work previously performed by MDOT SHA contractors, we nevertheless identified a candidate site with desirable features for an implementation site.

The site, shown in Figure 11, adjoins the I-70 Security Square park and ride. The site provides easy access and parking for field vehicles without requiring traffic control. Local topography and landuse strongly indicates the site was cleared and mass graded with standard methods used for I-70 highway construction, suggesting significant cut-and-fill mass grading. The open space landuse provides an ideal site for the operation of ripping and tillage equipment without the need to avoid tree plantings. As MDOT SHA Phase I priorities changed during the study, no further screening or site investigation activities were pursued. The following section presents the final BMP protocol for soil decompaction and amendment developed during this Phase I research project.

Figure 11 Security Square I-70 Park and Ride candidate site

7. BMP Protocol for Soil Decompaction and Amendment

Specification: Soil decompaction and amendment – Suburban Subsoiling.

Suburban Subsoiling (soil decompaction and amendment) refers to the adaptation of agricultural subsoiling practices to disturbed compacted soil profiles found in the built environment.

Mass grading and soil disturbance from modern construction practices result in the wholesale disruption of natural soil profiles. Consequently, the landscapes developed using these practices are often characterized by "pervious" land uses with low infiltration capacity and shallow-rooted vegetative cover growing in a thin veneer of topsoil over dense compacted infertile fill. Suburban subsoiling can cost-effectively restore sustainable infiltration, drainage, and soil ecosystem processes in the pervious landscape.

The restoration of infiltration and drainage emphasizes restoration of the structure and function of the *soil profile* by combining decompaction of dense compacted soil to a depth of at least 20-inches, with the uniform incorporation of 2-3 inches of compost throughout the top 6-9 inches of the soil profile. Together, soil decompaction and compost amendment can renovate disturbed compacted soil profiles and restore sustainable hydrologic function with infiltration capacities close to those of an uncompacted soil.

Applications

- Decompaction and amendment are best considered an *at-source practice for reducing runoff* to address ESD criteria by restoring sustainable infiltration capacity to disturbed compacted pervious land uses in the built environment. Decompacted soil profiles are vulnerable to re-compaction. For this reason, suburban subsoiling is most applicable to pervious areas that are expected to be free from recompaction risks (such as vehicle traffic, overflow parking, etc.) under the long-term site activities anticipated for the stabilized site.
- Suburban subsoiling restores infiltration and drainage by combining deep ripping and aggressive compost incorporation to reestablish porous permeable organic-rich soil profiles and the soil ecosystem processes that recycle organic nutrients and maintain soil structure.

Performance

- When designed according to the guidance presented below suburban subsoiling can restore soil infiltration capacity to rates close to those of uncompacted soils at "native bulk density". For design and crediting purposes, the hydrologic characteristics of pervious land uses treated with suburban subsoiling can be characterized by an effective curve number (ECN), enabling runoff calculations using familiar Curve Number hydrology methods. Runoff characteristics of pervious land uses renovated with suburban subsoiling will vary with the texture and initial bulk density of the soil profile, and the depths of ripping (decompaction) and compost amendment. The effective curve number (ECN) of the decompacted and amended area will therefore vary with site-specific conditions and implementation. Site-specific ECN can be estimated from soil texture using diagrams (see Figure 12 and Figure 13), or planning level tables (see Table 4) specific to the selected depth of decompaction and amendment selected.

Constraints

- **Location:** The size, distribution, and ultimate use of unpaved surfaces within a project should be considered early in the Environmental Site Design planning process. Suburban subsoiling is best suited for pervious areas that do not require load bearing strength, or where significant vehicle traffic or other compressive loads are not expected under long-term expected usage patterns.

- **Underground Utilities:** Decompaction using deep ripping (or excavation - for complete cultivation) must account for underground utilities. Site planning for greenfield construction may efficiently constrain all underground utility lines to designated rights-of-way or utility corridors, from which suburban subsoiling is excluded *a priori*. Retrofit applications should review historical construction plans, check with Miss Utilities, and may need to pre-screen the site using a private utility locator, in order to avoid potential damage to underground utilities that have not opted in to Miss Utilities.

- **Construction Debris:** Soil on cut-and-fill sites (e.g. beneath impervious area removal projects) or demolition sites (such as residential parcels where structures have been razed) may contain large stones, sizable pavement fragments, tree stumps, and other construction debris that can snag and damage ripping and tillage equipment. If significant debris is present within the top 2 feet of the soil, excavation and replacement with a select fill may be required to provide a surface layer that can be decompacted and amended with suburban subsoiling.

- **Area** – Run-on from adjacent drainage areas should be limited or avoided in design. Suburban subsoiling restores near-natural infiltration capacity to pervious land uses with disturbed compacted soil profiles. Decompaction and amendment are best considered as an *at-source practice for reducing runoff* to address ESD criteria. Suburban subsoiling should not be viewed as a BMP that creates "excess" infiltration capacity in small footprints that can treat substantial runoff redirected from large contributing drainage areas. Run-on changes the frequency depth and duration of inundation, altering the wetting and drying characteristics that maintain soil structure and soil ecosystem processes of the soil profile. As the contributing area draining to decompacted areas increases, the dynamic soil processes that maintain soil structure may be degraded, reducing the long-term effectiveness and expected lifespan of the practice.

- **Deconsolidation Methods -** The choice of deconsolidation methods may also vary with the size or configuration of the site. Ripping is appropriate and efficient for larger contiguous areas that can be easily treated with parallel passes of tillage equipment, and are long enough to allow ripping blades to reach their full design depth on each parallel pass. For smaller irregularly shaped sites, alternate decompaction methods such as complete cultivation (e.g. using a mini-excavator) or loose tipping (to replace stripped and stored topsoil) may be required (see Appendix A).

- **Integrated site planning** – Suburban subsoiling is not suitable for areas that will be subject to frequent recompaction stresses, such as overflow parking areas, that increase the risk of recompaction. Alternate technologies such as structural soils [44] or cribbed systems [45] are available to establish pervious land uses with both higher permeability and load-bearing strength – albeit at significantly greater cost.

- **Soils -** Because suburban subsoiling restores infiltration capacity close to natural uncompacted soils, the greatest stormwater benefit from the practice is likely to come from soils capable of supporting significant infiltration rates that are also susceptible to significant compaction. Sandy soils can maintain high infiltration rates (for stormwater purposes) even with compaction. Uncompacted clay soils have low infiltration rates – even at native bulk density. Expected *changes* in runoff from implementing suburban subsoiling can be computed using standard curve number methods to support value engineering decisions on the site-specific use of the practice.

- **Hotspot Runoff:** Suburban Subsoiling restores infiltration and drainage of disturbed compacted soil profiles and should not be used to improve the infiltration capacity of pollutant hotspots – i.e. areas with elevated loads of hydrocarbons, trace metals, road salt, or other toxicants, because infiltrating stormwater with higher concentrations of stormwater contaminants may contaminate groundwater.

- **Operation:** Decompacted and amended soils are susceptible to recompaction, especially under high soil moisture conditions. Individual landowners need to be educated to ensure appropriate use and maintenance of restored areas (e.g. soil moisture limits for the operation of mowing equipment) to preserve the long-term performance of the practice. Applications should be limited to locations for which the stabilized site is not expected to receive vehicle traffic or other loads that could recompact the soil profile.

Design Guidance

- Pre-treatment site conditions (e.g. soil texture, bulk density) of the soil profile should be determined to assess the suitability and cost-effectiveness of Suburban Subsoiling. Cone penetrometer profiles taken under consistent moisture conditions provide an effective assessment of the depth and extent of compaction and disturbance. Cone penetrometer profiles are most easily taken during the dormant season from late fall to early spring (when seasonal evapotranspiration is at a minimum) roughly two-days after a soaking rain, to approximate soil moisture at field capacity.

- **Decompaction** – The goal of decompaction is to break up dense massive structureless compacted soil that limits drainage and resists penetration and mixing by tillage implements. On dry compacted soil profiles, rotary tillers and spaders may be unable to penetrate these dense soils, much less incorporate compost to specified depths. Deep ripping following agricultural subsoiling practices [24] can provide cost-effective deconsolidation if suitable equipment is available and can be effectively operated within the site footprint. Alternate methods of decompaction (Appendix A) are available for small or irregular footprints. Agricultural subsoiling requirements for deep ripping typically recommend at least 35-75 HP *per shank* depending on the depth of ripping and the bulk density and moisture content of the soil profile. Weill [24] described the salient features of subsoiling:

> **"Deep** ***ripping (deep tillage) involves the use of strong deep working tines that penetrate the compacted soil and mechanically break up and shatter the soil hard pan.***
>
> ***For deep ripping to be effective:***
>
> - ***The ripping tines must be able to penetrate to the minimum specified depth of deconsolidation***
> - ***Soil must be moist enough to allow penetration of the ripping tines but not so moist that the tines cause smearing without fracturing and shattering the soil."***

Additional technical details on subsoiling (including tine spacing, use of winged tines, etc.) can be found in Weill [24].

- **Compost Amendment** – Compost adds organic matter to decompacted soil supporting the reestablished soil ecosystem. One-time addition of compost with active vegetative cover can jump-start a self-sustaining soil ecosystem that processes and recycles organic carbon and nutrients, and supports soil aggregation and soil structure that maintains infiltration and oxygen diffusion. New soil pores are opened each year as senescent roots die, decay, and recycle their organic nutrients and carbon, even as new roots are developing and modifying the soil in spring and fall.
    - *Compost characteristics* may be tested using US Compost Council test protocols (see: https://agsci.psu.edu/aasl/compost-testing). In addition to standard landscaping specifications for low soluble salts, near-neutral pH, and relatively high organic matter content, mature vegetative composts are the preferred input for suburban subsoiling. Composts from biosolids and manure generally have higher phosphorous content and may not be able to meet standards for "low-P compost". In addition to low salts, key tests for maturity include respiration rate – to select mature to very mature compost in which inorganic nitrogen represents < 0.1% TN. Similarly, bioassay testing should be conducted to evaluate phytotoxicity. Preference for mature vegetated compost favors organic amendments with nutrient content in less mobile organic forms, minimizing the risks of nutrient leaching from adding organic matter to restore soils.
      Incorporation rate: Compost amendment for suburban subsoiling targets a final amended soil with 2:1 (by volume) soil to compost ratio, operationalized as the incorporation of 2 inches of surface applied compost mixed throughout the top 6 inches of the soil after incorporation; or incorporation of 3 inches of compost throughout the top 9-inches of soil. Without decompaction or soil deconsolidation (as in Complete Cultivation) most rotary tillers will not be able to achieve this depth of incorporation and complete mixing of surface applied compost.

Reference ECNs

To help provide consistent quantitative guidance for stormwater planning, the effective curve number (ECN) of soil profiles for key reference conditions has been computed for each texture in the USDA soil texture triangle. These values are displayed as ECN contours (or isoquants) superimposed on the texture diagrams in Figures 1-3. Results for representative texture categories are also summarized in Table 1.

We consider two reference conditions: (1) an <u>uncompacted</u> one meter soil profile at "native bulk density" with 5% organic matter; and (2) a "<u>topsoiled</u> soil profile" in which we assume the top 10 cm have been replaced with uncompacted soil with 3% organic matter, and the remaining 90 cm of the profile consists of disturbed compacted soil with bulk density 10% greater than the native bulk density, with organic matter content of only 0.5%.

From Figure 1, an uncompacted loam (with about 40% sand and 15% clay is estimated to display an ECN of about 53. The ECN for a clay loam (30% sand and 35% clay) is approximately 60.

Uncompacted Soil

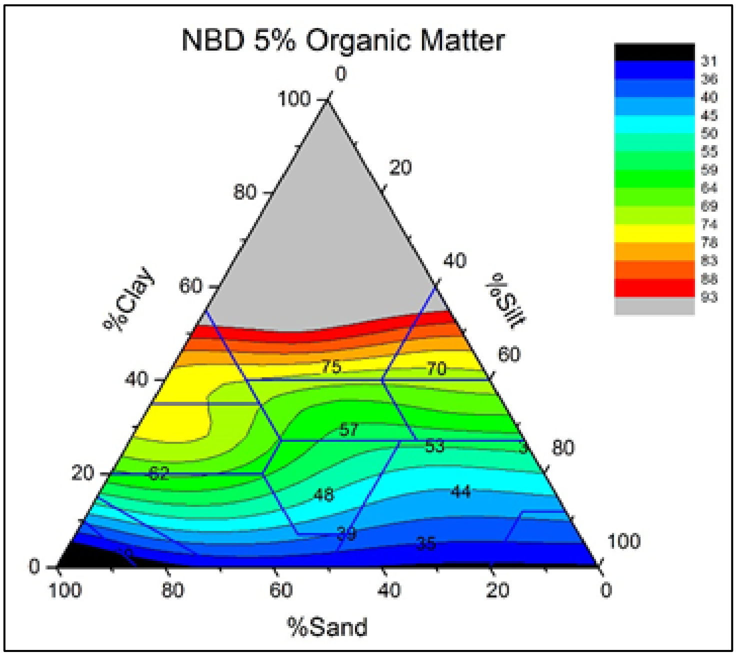


Figure 1 Reference ECN for an uncompacted soil (native bulk density with 5% OM)

Table 1 summarizes the ECN for the centroid of each texture class for the topsoiled or "compacted" soil profile, as well as the ECNs for topsoiled profiles that have been decompacted and amended with Suburban Subsoiling using both 2 inches of compost incorporated to a depth of 6 inches (SS6) and 3 inches of compost incorporated to a depth of 9 inches (SS9). The resulting ECNs for these two variations on suburban subsoiling are displayed in Figure 2 and 3 and summarized in Table 4.

Compacted profile after Suburban Subsoiling with 2 inches of compost incorporated to 6-inches

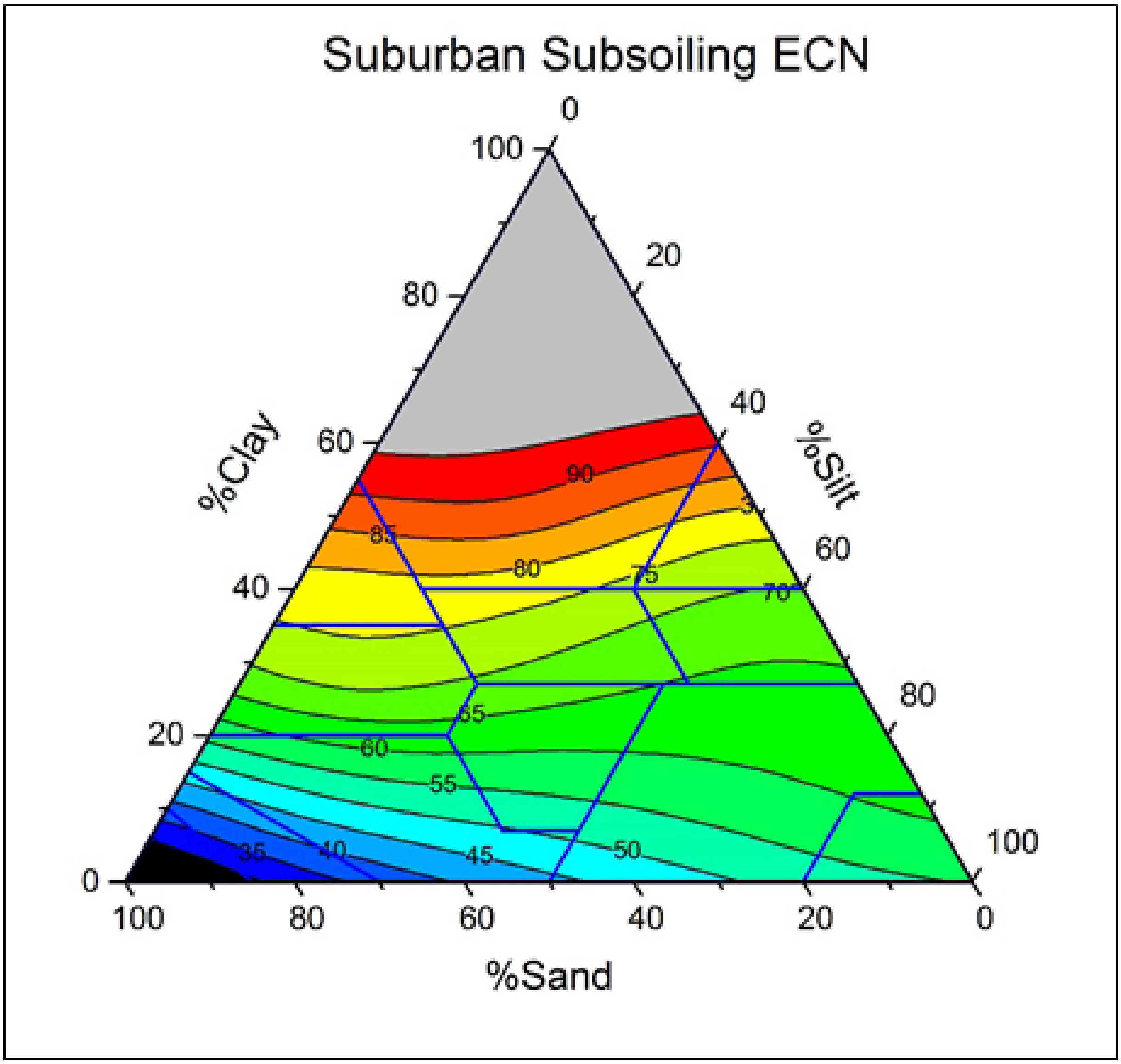


Figure 2 ECN for Suburban Subsoiling of compacted profile 2 inches compost

Compacted profile after suburban subsoiling with 3 inches of compost incorporated to 9 inches

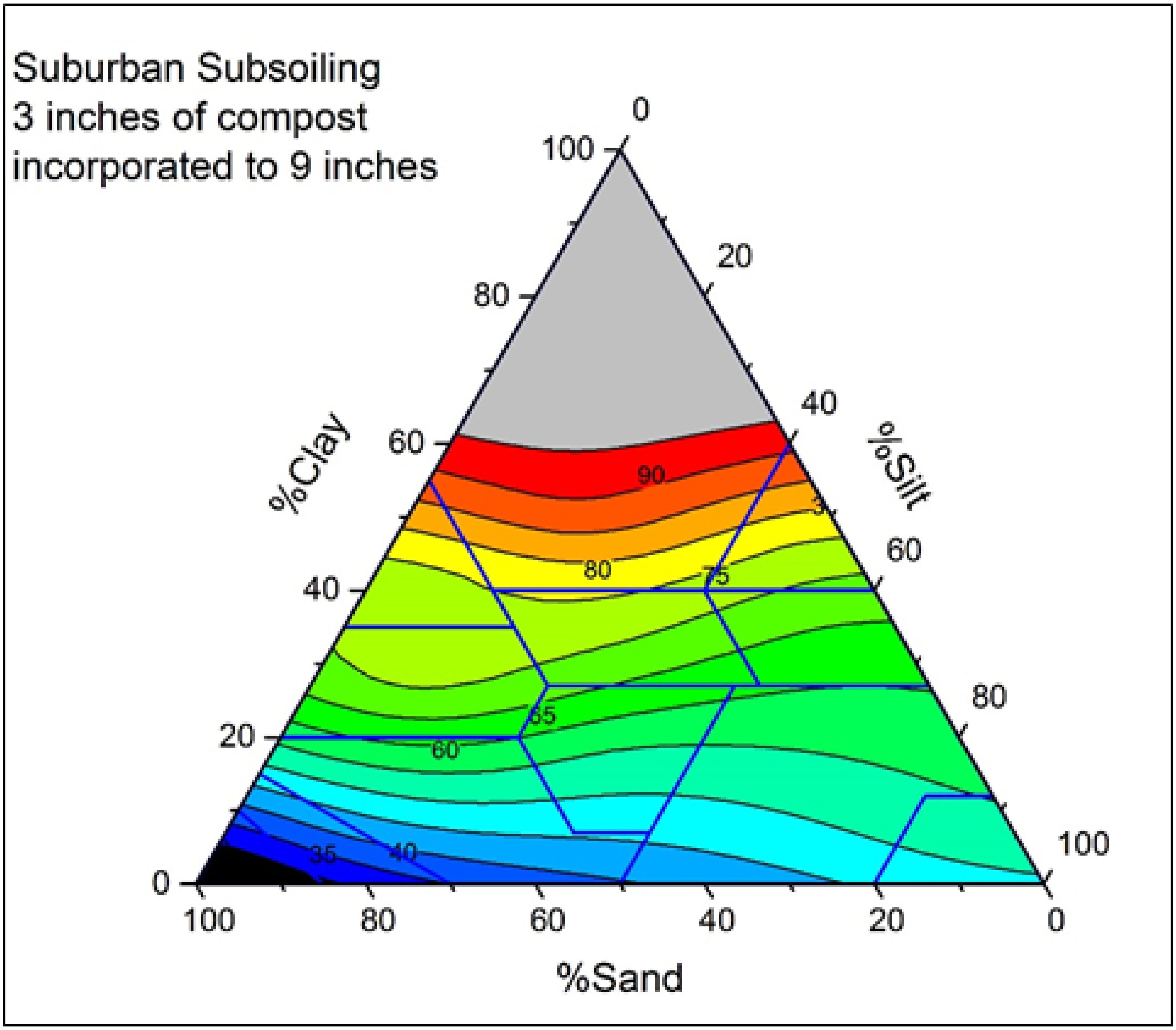


Figure 3 ECN for Suburban Subsoiling of topsoiled profile incorporating 3-inches of compost throughout the top 9 inches of the soil profile.

ECN Performance Table

Table 4 ECN and Cr by texture for "Topsoiled" profile (TS) and Suburban Subsoiling (SS) with 6-inch and 9-inch depths of compost incorporation

	Topsoiled 10 cm		SS 6-inch		SS 9-inch		ΔQ (in) TS - SS6	
TEXTURE	ECN	Cr	ECN	Cr	ECN	Cr	1-yr storm 2.69 in	2-yr storm 3.25 in
Clay	93	0.89	88	0.82	88	0.81	0.35	0.38
Clay Loam	91	0.87	72	0.56	71	0.54	1.19	1.38
Loam	73	0.54	60	0.38	55	0.35	0.43	0.57
Loamy Sand	56	0.36	38	0.15	38	0.14	0.14	0.29
Sand	36	0.13	30	0.08	30	0.08	0.00	0.00
Sandy Clay	94	0.95	79	0.72	73	0.64	1.06	1.19
Sandy Clay Loam	88	0.82	72	0.50	72	0.49	0.89	1.05
Sandy Loam	70	0.53	50	0.24	49	0.23	0.50	0.71
Silt	86	0.80	58	0.41	52	0.38	1.20	1.50
Silty Clay	89	0.84	76	0.60	76	0.58	0.81	0.94
Silty Clay Loam	88	0.83	67	0.52	64	0.48	1.14	1.37
Silty Loam	87	0.81	62	0.45	56	0.42	1.19	1.46

Table 4 summarizes the ECN by soil texture for an idealized topsoiled soil profile (TS) before and after suburban subsoiling with compost incorporation to depths of 6 inches (SS6) and 9 inches (SS9). The last two columns of the table summarize the estimated runoff reduction (in) from implementing SS6 on the TS soil profile for the 1-year and 2-year design storms. Average runoff coefficients (Cr) are computed as an average ratio of event rainfall-to-runoff over a range of historical storm depths. Runoff coefficients can also be computed for individual design storms, using standard CN runoff computations.

Although suburban subsoiling may be implemented on any compacted soil profile, the practice may be most cost-effective for soil textures for which significant runoff reduction can be expected from restoring compacted soil profiles. Expected runoff reductions from SS6 are tallied for the 1-year or 2-year design storm in Table 4. The runoff reduction expected from decompacting and amending compacted clay soils is relatively small and may not be cost-effective. Similarly, the *increased* runoff from compacted Loam, Loamy Sand, and true Sand soils is relatively low, similarly reducing the cost effectiveness of *runoff reductions* realized from

Suburban Subsoiling. From the planning-level results in Table 4, significant design storm runoff reductions (approximately 0.8-1.5 inches) are most likely for soil profiles with Clay Loam, Sandy Clay, Sandy Clay Loam, Silt, Silty Clay, Silty Clay Loam and Silty Loam soil textures.

Construction Criteria

- Soil profiles can be deconsolidated by multiple passes with deep ripping blades. If ripping in multiple parallel passes, sufficient area should be reserved to allow equipment to turn. Ripping blades should be extracted from soil before turning. The start of the next ripping pass should allow sufficient distance for blades to fully penetrate the profile to the specified ripping depth.
- The soil profile must be moist enough to allow penetration of the ripping tines but not so moist that the tines cause smearing without fracturing and shattering the soil.
- Dry soils require more powerful equipment and may require multiple passes at progressive depths in order to fully deconsolidate the soil profile down to the minimum specified ripping depth.
- Surface soils should be dry enough to avoid significant rutting or excessive wheel slippage. Final surface variation after deconsolidation or ripping should establish a relatively uniform surface for compost application.
- Compost may be surface applied and spread using a calibrated spreader, broadcast spread using a conveyor application system, or spread with a bulldozer using fine grading methods to ensure uniform depth of coverage.
- Compost shall be incorporated with tillage equipment capable of achieving uniform incorporation with a 2:1 (by volume) soil-to-compost ratio within the specified depth of incorporation. On dense compacted soil profiles, typical rotary tillers used to prepare planting beds will not be able to achieve this depth of incorporation without first completely deconsolidating the *in situ* soils as, e.g., in complete cultivation.

Deconsolidating Rough Graded Areas

- **Notification and Evaluation**. The Contractor shall notify the Engineer at least 48-hours prior to starting the ripping work and ensure the appropriate tools are available to measure ripped soil depth and resistance for compliance with specifications. The Engineer will evaluate prepared surfaces to ensure rough-graded conditions reflect lines, grades, and elevations in the Contract Documents and soil moisture conditions for deconsolidation. Soils to be deconsolidated should be sufficiently dry to avoid clumping during deconsolidation. Subsoiling shall not be performed when soil is wet.

- **Soil Deconsolidation**. The rough-graded area shall be subsoiled/ripped to a minimum depth of 20 in. Subsoiling is to be accomplished by pulling the subsoiler (ripper) across the surface in one direction followed by pulling the subsoiler in an approximately perpendicular direction. This process will be repeated until full deconsolidation is achieved. Plows, discs and excavator buckets should not be used for subsoil work. If a subsoiler/ripper is not practical for smaller areas, the Contractor may use a ditch witch-type excavator or alternate methods described in Appendix A. Deconsolidated soil shall be loose and well mixed, and any remaining soil clumps or rocks over two inches in diameter shall be removed from the surface area.

- **Testing Deconsolidated Soils. The Contractor shall perform the required tests as detailed in this section**. Deconsolidation efforts shall be considered complete upon successful testing of work area. Penetrability of soils shall achieve pressure less than 1,400 kPa (200 psi) down to a 20 in. depth. Tests shall be taken in equal spacing across work area at a rate of not less than one test per 1,000 square feet (three tests minimum). Testing shall be witnessed by the Engineer and test results recorded with test locations shown on a sketch of the work area.

Placing and Integrating Compost

- **Grading and Surface Preparation**. Grading in preparation for the placement of compost will be conducted to provide a relatively uniform surface without sharp local undulations to ensure the uniform thickness of surface-applied compost. *Placing, Spreading, and Incorporating Compost*. The compost will be placed and spread evenly over the work area to achieve a uniform thickness of 2(3) inches over the graded subsoil. The entire work area shall be thoroughly tilled to mix compost throughout the top 6(9) inches of the soil profile. Upon achieving a fully mixed soil condition, the work area should be final graded to a relatively uniform surface suitable for the establishment of permanent vegetative cover.

- **Retesting in Acceptance of Completed Work**. The Engineer shall review the finished conditions to determine that a deconsolidated soil condition exists and compost is fully integrated into topsoil.

- **Protection of Deconsolidated Soils**. The Contractor shall ensure the work area of deconsolidated soils shall be protected from reconsolidation throughout site stabilization. Retesting of soils is to occur as outlined above in ***Testing Deconsolidated Soils***. The Contractor will be required to re-loosen any reconsolidated areas to the satisfaction of the Engineer at no additional cost.

Inspection

Regular inspections shall be made during the following stages of construction:

- During deconsolidation
- During compost placement
- During compost incorporation
- During seeding or hydroseeding
- Upon completion of final grading and establishment of permanent stabilization

Maintenance Criteria

Under normal anticipated use, areas treated with suburban subsoiling require normal maintenance for any vegetated area (e.g. routine mowing for areas stabilized with turf grass), and routine visual inspection to assure persistence of uniform healthy cover without bare spots or invasive weeds, and absence of any evidence of recompaction (e.g. surface pooling of rainwater, evidence of rutting from vehicle tracks, etc.). Routine mowing should be scheduled and coordinated with the owner to avoid high soil moisture conditions (to avoid recompaction risks) or wet turf (to avoid leaving "clumps" of wet clippings on the turf that will shade and eventually smother turf, creating bare spots for weed colonization). As a self-sustaining system, clippings from routine mowing (preferably with a mulching mower) can be returned to the turf.

Seasonal inspections with a cone penetrometer may be used to identify any areas with significant indications of a significant increase in compaction. Areas displaying evidence of modest recompaction may be renovated with deep tine hollow core aeration and top dressing with sand or a sand-compost mixture. If significant recompaction is discovered, every effort should be made to identify and eliminate the source of recompaction. Although hollow core aeration can mitigate the effects of modest compaction, recurring activities that consistently recompact the soil (especially under high moisture conditions) may result in a level of compaction that can only be mitigated by repeating Suburban Subsoiling.

Soil Decompaction and Amendment BMP Protocol

Appendix A.

Alternate Decompaction Methods

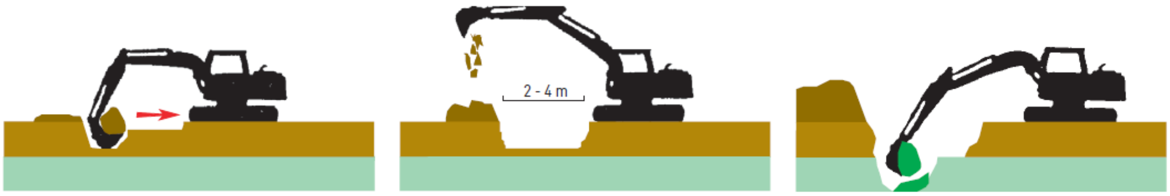
Complete Cultivation

Complete Cultivation was developed by British Forest Research [46] to remediate dense compacted soils on reclamation sites. Moffat and Boswell [47] found decompaction with complete cultivation was sustained over multiple years compared to shorter-lived decompaction with industrial ripping alone. More sustainable decompaction realized significantly higher survival, vigor and growth of reforested trees planted after complete cultivation [48].
When implemented with a rubber track mini-excavator, we found complete cultivation to be a feasible and highly effective method for deconsolidation of compacted soil profiles on smaller urban-suburban footprints where size, irregular shapes, and underground utilities make the use of deep ripping equipment infeasible.

Reynolds [46] found the "profile-strip" method to be the most versatile and cost-effective method of complete cultivation. As depicted in Figure 4, the profile is completely deconsolidated in two lifts, maintaining the relative positions of the upper and lower soil layers after cultivation. The excavator backs across the site to complete each adjoining "strip" so that the deconsolidated soil never experiences any vehicle traffic, thereby avoiding recompaction.

Deconsolidation reduces the bulk density of soils so final settled profiles can be expected to have slightly higher surface elevations than the compacted pre-deconsolidation soil surface. For open space areas this surface elevation change may be inconsequential. If deconsolidation and amendment is performed on soils adjoining pavement, walking paths or other fixed infrastructure, some material may need to be removed to match the surface elevation of the settled decompacted soil to the original adjoining pavement elevations.

Typical construction practices would simply roll the soil surface to match the final design elevations. This recompaction would obviously defeat the purpose of the practice. Since the upper soil layers contain the greatest biological activity, soil removed to match finished surface elevations should be taken from the bottom of the profile. To guide practitioners the nomographs in Figure 5 provide (a) the target surface elevation of unconsolidated (but unsettled) soil after cultivation and (b) the thickness of (compacted) soil that should be removed from the bottom of the profile to allow deconsolidated soil to settle back to the initial surface elevation. The nomographs are parameterized by the initial (compacted) bulk density of the soil, the expected final (post-settlement) bulk density of the soil, and the soil bulking factor (quantifying the increase in the volume of unconsolidated soil before settlement).



1. Strip top layer. This may be accomplished in two or more passes 15 to 25 cm in thickness depending on friability. Cultivate in an arc to a final working width of between 7 to 8 metres.

2. Place the spoil in front of the void. Drop material from height to further assist the break up. Large lumps may require further breaking up at this stage. Repeat (1) until final working width of between 2 to 4 metres is accomplished.

3. On completion of working width the next stage can be started. Cultivate second layer to required depth. If friable this may be broken up by simply lifting and raking the spoil. Long teeth on the bucket can assist in the breaking up process.

4. If material is not friable, scrape in 15 to 25 cm layers; lift and drop to assist break up. Spoil is replaced directly into the bottom of the void. Cultivate entire working length lifting spoil and dropping to increase the cultivating effect.

5. Move machine forward and pull top layer into void. Level off and move back 3 to 4 metres. Repeat (1) through (5) until strip complete.

6. The finished profile.

Figure 4 Complete Cultivation

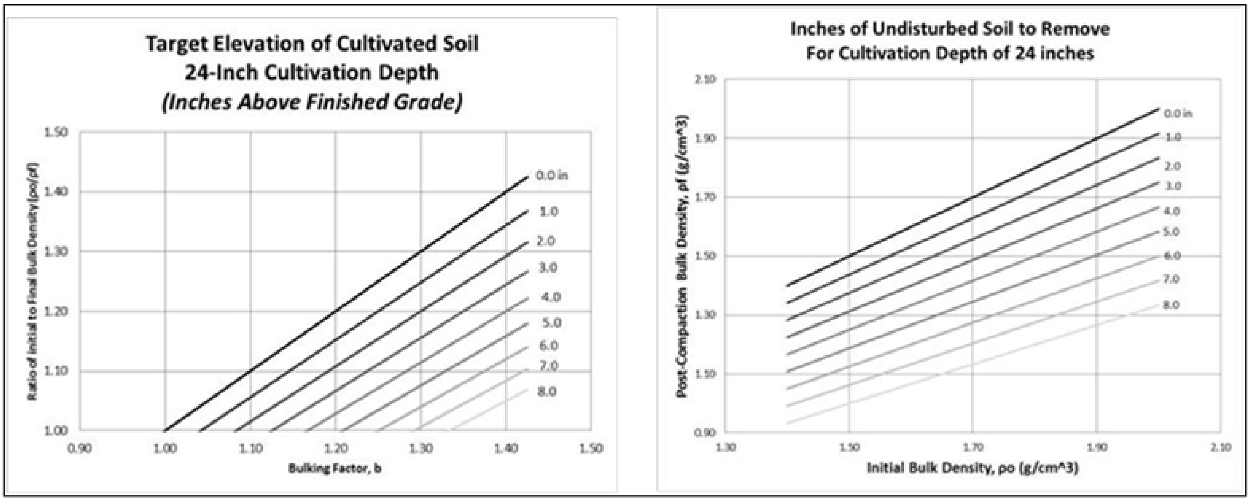


Figure 5 Nomographs for final soil elevation and depth of uncompacted soil to be removed in order to enable settled deconsolidated soil to match initial surface elevations

Loose Tipping

Loose tipping refers to a family of practices for placing stripped or stockpiled soils to avoid recompaction by avoiding equipment operation on the unconsolidated placed soil. Significant variation in loose tipping methods have developed, reflecting variations in removal and replacement of stripped soil versus reconstructing a multi-layer soil profile with topsoil placed over subsoil, which has in turn been placed over soil-forming materials [48]. Loose tipping is implemented by placing each layer in strips, with an excavator operating on adjoining overburden to avoid compacting placed material. Unconsolidated amended soil may also be replaced without recompaction using an automated belt system (sometimes referred to as a soil slinger or telebelt) to shoot a stream of deconsolidated soil onto a ripped and graded subsoil surface.

Where soil stripping, stockpiling, and replacement is specified, advantages of loose tipping include:

- Loose tipping produces a more open, less dense soil structure with low root impedance and higher infiltration
- A loose profile of any desired thickness can be produced in a one-pass operation
- No need for ripping or decompaction operations
- Loose tipping is more easily monitored, and provides greater opportunity to remove stone and obstructions
- Improved vegetation establishment reduces cost of repair, replacement, and maintenance.

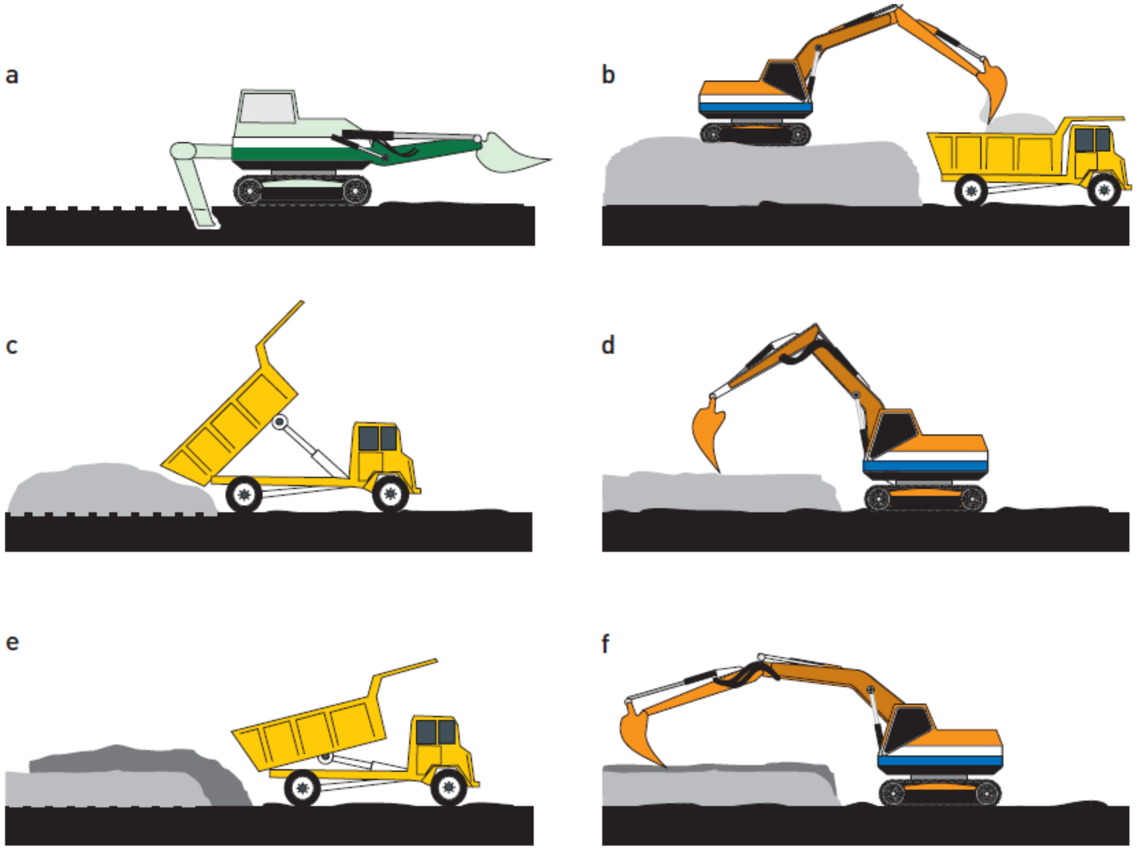


Figure 6 Loose Tipping

Figure 7 Non-contact placement of unconsolidated soil with a soil slinger

Soil Decompaction and Amendment Protocol

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Conclusion

Compacted and highly disturbed urban soils are a pervasive feature of modern constructed landscapes. The standard practices for rapid vegetation establishment on sites associated with mass grading routinely result in a "pervious" landscape with impaired infiltration capacity that constrains plant root growth, reduces soil water holding capacity, and limits the reservoir of plant-available nutrients in the root zone. The lost hydrologic function of the pervious landscape can be reliably restored by renovating disturbed soil profiles through soil decompaction combined with aggressive organic compost amendment. When properly planned and efficiently staged, this superior sustainable landscaping practice can be cost-effectively implemented through minor modifications to standard grading and landscaping practices.

This research advances the integration of cost-effective practices and procedures that improve soil structure, restore infiltration, and reduce stormwater runoff to support an approved stormwater BMP in the State of Maryland. To support the institutional acceptance of soil decompaction and amendment as an approved BMP, this project emphasized two primary complementary contributions: (1) a prototype BMP protocol for the practice, emulating the style of the State Stormwater Manual; and (2) supporting analysis for the consistent determination of a quantitative stormwater credit for decompaction and amendment.

The complete BMP protocol is contained in Chapter 7, and may be used as a standalone document to develop specifications for construction, construction inspection and acceptance, and maintenance. The stormwater credit built on previous work by Schwartz and Smith [1, 13, 42, 49] emphasizing the consistent use of a soil physics model to simulate soil water movement linked to site-specific characteristics of the soil profile. Continuous simulation with high resolution (15-minute) precipitation data enabled us to quantify the site specific rainfall-runoff characteristics of urban soil profiles as an effective curve number (ECN). The soil physics modeling also made strong predictions about the seasonal dynamics of soil moisture profiles on disturbed and decompacted soil profiles.

Real-time soil moisture monitoring verified the model-predicted dynamics of seasonal soil moisture profiles. The monitoring-modeling results highlighted the persistently high soil moisture (and runoff potential) from urban pervious landuses during the dormant season (from late fall to early spring). The consistency of observations with model predictions has significant implications for the design of green infrastructure, and substantially enhanced the credibility of our modeling framework for quantifying stormwater credits as a site-specific ECN.

Because dynamic soil physics modeling is currently beyond the core skill set of most stormwater practitioners, representative ECNs for archetype soil profile conditions were summarized in both graphical and tabular form, for use as a convenient design aid for practitioners. We also explored the use of the US EPA National Stormwater Calculator (SWC) as an alternative tool to derive a consistent stormwater credit for soil decompaction and amendment. SWC provides a well-conceived user interface that links site-specific soil, topography, landuse, and hydrometeorological data from standard national geospatial databases, to support rainfall runoff analysis (including green infrastructure effectiveness) for site-specific stormwater management.

SWC includes the capacity to simulate daily rainfall-runoff events – which can, in turn, be used to derive a simulation specific ECN – just as we do with our 1-D soil physics modeling. A more detailed analysis of SWC results showed how the use of soil properties from the SSURGO database introduced overly optimistic estimates of pervious landuse infiltration into the SWC simulations. As well, a comparison of SWC rainfall runoff simulations with our soil-physics-based simulations found that the SWC results consistently underestimated runoff. Beyond the failure to account for disturbed compacted urban soil profiles (not captured in SSURGO) we found the use of hourly precipitation data (used in SWC simulations) consistently underestimated runoff – thereby overestimating the effectiveness of green infrastructure. Although SWC could be used to derive consistent site specific ECNs, the consistent biases introduced through the use of SSURGO soil characteristics and hourly precipitation would need to be addressed with a bias correction before these results could be used for regulatory credit. The analysis and development of such bias correction procedures is an area of ongoing research, but was beyond the scope of the Phase I research reported here.

Soil decompaction and amendment can reduce costs for green asset maintenance while significantly expanding the opportunities for cost-effective stormwater management services from the pervious landuses in MDOT SHA’s managed landholdings. Soil physics modeling provided a consistent reproducible framework to quantify soil decompaction benefits and quantify restored hydrologic services as an effective curve number. The Phase I results reported here provided a prototype protocol and an initial framework for quantifying BMP credits and institutionalizing soil decompaction and amendment as an approved stormwater BMP in Maryland.

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