FHWA-NJ-2023-004

EVALUATION OF COEFFICIENT RELATED TO RUNOFF FROM ROADWAY PROJECTS

FINAL REPORT

March 2023

Submitted by

Qizhong (George) Guo
Professor

Robert Miskewitz
Research Professor

John Hencken
Research Associate

Lin Zheng, Diego Meneses
Graduate Students

Center for Advanced Infrastructure and Transportation (CAIT)
Rutgers, the State University of New Jersey
100 Brett Road
Piscataway, NJ 08854

Priscilla Ukpah
NJDOT Research Project Manager

In cooperation with
New Jersey Department of Transportation
Bureau of Research
And
U. S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA NJ-2023-004	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Evaluation of Coefficient Related to Runoff from Roadway Projects	**5. Report Date** March 2023 **6. Performing Organization Code**
7. Author(s) Qizhong (George) Guo, Robert Miskewitz, John Hencken, Lin Zheng, Diego Meneses	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Advanced Infrastructure and Transportation (CAIT) Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854	**10. Work Unit No.** **11. Contract or Grant No.** 20-60161
12. Sponsoring Agency Name and Address Federal Highway Administration (SPR) 1200 New Jersey Avenue, SE Washington, DC 20590 New Jersey Department of Transportation (SPR) 1035 Parkway Avenue, P.O. Box 600 Trenton, NJ 08625.0600	**13. Type of Report and Period Covered** Final Report, March 12, 2020 - March 10, 2023 **14. Sponsoring Agency Code** FHWA, NJDOT

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

New Jersey Department of Transportation (NJDOT) is required to quantify and mitigate the stormwater impacts of certain roadway projects. Acceptable runoff calculation methods include the Natural Resources Conservation Service Method and the Rational Method. Existing coefficients are often insufficient for representing land treatments utilized in roadway design but have never been investigated before. The objective of this project was to develop new curve numbers (CNs) for four land treatments, which included: (1) bare soil, (2) gravel, (3) vegetation, and (4) porous hot mix asphalt (HMA). To achieve this objective, laboratory studies were conducted to measure rainfall, runoff, and infiltration for these four land treatments. Each land treatment was tested as a composite column, where the treatment was installed on top of subsoil. The subsoils utilized in this project had ten different hydraulic conductivities, covering all four Hydrologic Soil Groups, A, B, C and D, that may be encountered at NJDOT roadway projects. The rainfall and runoff data were collected and analyzed to quantify CNs for the four land treatments under laboratory conditions. Laboratory derived CNs were then applied to the field conditions and compared with the established CNs of corresponding land treatments. CNs for bare soil and vegetation agreed well with the existing values, CNs of gravel were significantly smaller than the existing values, and CNs of porous HMA were not established prior to this project and were not available for comparison. The CNs developed from this project can be used to quantify runoff from these four land treatments for any rainfall events.

17. Key Words Runoff, curve number, runoff coefficient, NRCS Method, Rational Method, hydraulic conductivity, land treatment, porous asphalt, curve fitting	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 125	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors wish to acknowledge the efforts of New Jersey Department of Transportation (NJDOT) Bureau of Research under the direction of the Project Manager, Ms. Priscilla Ukpah, NJDOT Bureau of Research, Ms. Amanda Gendek, Manager of NJDOT Bureau of Research, and NJDOT BLAES Hydrology & Hydraulics including the valuable guidance from Ms. Sandra Blick and Mr. Sean Henry. The authors would like to thank Mr. Thomas Decker, Ms. Kyrra Mosley, and Mr. Ben Morales from Jacobs Engineering Group Inc. and Ms. Theresa O'Reilly, Ms. Meg Iannacone, Ms. Chun-Ti Huang, and Ms. Deidra Valianti from BEM Systems Inc. for their valuable inputs. Additionally, the authors would like to acknowledge Mr. Zikai Zhou and Ms. Mariah Diaz for the initial literature search as well as Dr. Nenad Gucunski and Mr. Sharef Farrage for access and use of the Soil Mechanics Laboratory. Moreover, the authors would like to acknowledge the Rutgers Center for Advanced Infrastructure and Transportation (CAIT) including the administrative support of Ms. Samantha Bartley, Mr. Sherif Stephan, and Ms. Azam Kalantari for their help and assistance during this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Stormwater management plays an increasingly important role in the design of roadway projects. New Jersey Department of Transportation (NJDOT) is required to assess and mitigate the stormwater runoff impacts of certain roadway projects. Quantification of runoff is typically conducted using well established rainfall-runoff models that are widely accepted. Two acceptable runoff quantification methods outlined in N.J.A.C. 7:8-5.7 “Calculation of stormwater runoff and groundwater recharge” include the Natural Resources Conservation Service (NRCS) Method and the Rational Method. They have been applied in many roadway projects throughout New Jersey and beyond and proved to successfully predict runoff with acceptable accuracy. An agency may need to reconstruct unpaved areas within the Right of Way (ROW), median, and/or under guiderails in roadway projects by applying land treatments. Surface materials that have recently been utilized by NJDOT under and adjacent to guiderails include gravel, vegetation, porous hot mix asphalt (HMA), etc. To current methods for runoff calculation, these materials along with their in-situ configurations are new and unique. The increased use of these land treatments prompted a demand for further evaluation of the applicability of the current methods for runoff calculation, especially for land treatments that were not examined before for the runoff calculation methods (e.g., porous HMA, etc.). Particularly, in the current methods for runoff calculation, the existing coefficients are often insufficient for representing land treatments utilized in roadway design but have never been investigated before. Therefore, there is a need to evaluate and develop new coefficients for these new land treatments. The objective of this NJDOT-sponsored research project was to develop new curve numbers (CN) for these land treatments: (1) bare soil, (2) gravel, (3) vegetation, and (4) porous hot mix asphalt (HMA). To achieve this objective, measurements of rainfall and runoff were conducted in the laboratory for these four land treatments. The NJDOT construction specifications for the land treatments were followed in the design of laboratory setup. Each land treatment was tested as a composite column, where the treatment was installed on top of specific subsoils. The subsoils utilized in this project had ten different hydraulic conductivities, covering all four Hydrologic Soil Groups A, B, C, and D, that may be encountered at NJDOT roadway projects. Measurements of rainfall, infiltration, and runoff were collected and analyzed to quantify CNs for the four land treatments under laboratory conditions. Laboratory derived CNs were then applied to NJDOT field conditions and compared with established CNs of corresponding land treatments, where available, in the NRCS Technical Release 55 (TR-55). CNs for bare soil and vegetation agreed well with existing values, CNs of gravel were significantly smaller than existing values, and CNs of porous HMA were not established prior to this project and were not available for comparison. The CNs developed during this project can be used to predict quantity of runoff from these four land treatments for any given storm events.

BACKGROUND

Stormwater management plays an increasingly important role in the design of roadway projects. New Jersey Department of Transportation (NJDOT) is required to quantify and mitigate the stormwater impacts of certain roadway projects. The methods for runoff calculations for all NJDOT projects that require New Jersey Department of Environmental Protection (NJDEP) Stormwater Permits are outlined in N.J.A.C. 7:8-5.7 “Calculation of stormwater runoff and groundwater recharge”. (1) Runoff calculations are currently performed using the National Resources Conservation Service (NRCS) Method at N.J.A.C. 7:8-5.7(a)1i and Rational and Modified Rational Method at N.J.A.C. 7:8-5.7(a)1ii in this guidance. They are both based upon the application of a runoff coefficient that is applied to determine the relative contribution of a land treatment to the runoff. The runoff coefficient is specified as Curve Number (CN) in the NRCS Method and as Runoff Coefficient (C) in the Rational Method. Both methodologies apply rainfall-runoff models that are well defined, developed, and accepted throughout the industry. They have been employed at many sites throughout New Jersey and throughout the United States, successfully to estimate the quantity of runoff that results from a particular storm. These current methods are based on observations of rainfall-runoff curves for various land treatments and watershed characteristics. However, existing coefficients are often insufficient for representing land treatments utilized in roadway design but have never been investigated before. Therefore, for proper use and application of these current methods, there is a need to obtain runoff-related coefficients for these land treatments.

OBJECTIVES

The objective of this NJDOT-sponsored research project was to evaluate and develop new CNs for the NRCS Method. The following four land treatments within the Right of Way (ROW), median, and/or under guiderails were evaluated, which included (1) bare soil, (2) gravel, (3) vegetation, and (4) porous hot mix asphalt (HMA). The new CNs were quantified for a series of hydraulic conductivities, typical of NJDOT roadway projects. According to the New Jersey Stormwater Best Management Practices Manual (BMP manual), "the classification of Hydrologic Soil Group (HSG) is in accordance with the NRCS National Engineering Handbook, Part 630 – Hydrology (NEH), Chapter 7 Hydrologic Soil Groups, January 2009." (2) Table 7-1 of NEH Chapter 7 lists the criteria for assignment of HSG, which varies with "saturated hydraulic conductivity", "depth to water impermeable layer", and "depth to high water table". (3) To facilitate the applications of results from this project, the research team correlated CNs with HSGs and the new CNs were assigned for each hydrologic soil group A, B, C and D.

INTRODUCTION

Evaluation of the impacts of runoff from roadway projects is essential to certain roadway projects. Runoff calculations are currently performed using the NRCS Method and Rational Method. These two methods, accepted as standard operation procedures in the Stormwater Management rules at N.J.A.C. 7:8-5.7, are well-defined and widely accepted runoff modeling methodologies. They have been applied in many roadway projects throughout New Jersey and beyond and proved to successfully predict runoff with acceptable accuracy. An agency may need to reconstruct the unpaved areas within the Right of Way (ROW), median, and/or under guiderails in roadway projects by applying land treatments. Surface materials that have recently been employed by NJDOT include gravel, vegetation, porous HMA, etc. To current methods for runoff calculation, these materials along with their in-situ configurations are new and unique. Despite the increased use of these land treatments, their true applicability to current methods for runoff calculation still needs further evaluation, especially for land treatments that were never examined before (e.g., porous HMA, etc.). A research project is critical to validate existing coefficients and quantify new coefficients to determine runoff from different land treatments utilized in roadway design. This study was intended to evaluate and develop coefficients for runoff analysis to reflect conditions associated with roadway projects. To achieve the objective of this research, first an extensive literature search and review was conducted for the existing laboratory testing and field monitoring methodologies and results. The literature did not reveal data that could be directly used or adopted. Then laboratory tests were designed and implemented using the hydrology apparatus available at Rutgers University’s Fluid Mechanics Laboratory under controlled rainfall conditions. The NJDOT construction specifications for the land treatments were followed in the design of laboratory setup. The hydrology apparatus was used to quantify the infiltration and runoff for roadway-related land treatments (i.e., bare soil, gravel, vegetation, and porous HMA) under a prescribed set of rainfall intensities and time intervals. The research methods and a series of empirical equations, curves, and tables were developed and shared with the NJDOT’s Technical Advisory Panel (TAP) for guidance and enhancement. Recommendations and guidelines for the use of new runoff-related coefficients were developed and presented. The use of new runoff-related coefficients, upon acceptance by hydrology and stormwater professionals as well as approval by regulatory agencies, will provide scientifically defensible runoff estimates for these land treatments.

SUMMARY OF THE LITERATURE REVIEW

The research team conducted an extensive and detailed literature search and review of hydrologic analysis for the four land treatments including bare soil, gravel, vegetation, and porous HMA. Methodologies for determining runoff based on the NRCS Method and Rational Method were assessed, with proposed modifications to the NRCS runoff methodologies included. Runoff-related coefficients established by federal and local agencies were identified and listed. Runoff-related coefficients quantified by other researchers through laboratory testing, field monitoring, mathematical modeling, and/or regression analysis were found and summarized. Existing datasets in the literature and the International Stormwater BMP Database with 700 existing studies including some for green infrastructure measures were also evaluated. NJDOT specifications were also investigated for construction requirements for all four land treatments, with which test conditions used within viable literature studies were compared. The literature did not reveal data that could be directly used or adopted due to the discrepancy in field conditions between existing studies and NJDOT specifications.

NRCS Method and Rational Method for Hydrologic Analysis

The two methods for runoff calculation, the NRCS Method and the Rational Method, outlined in N.J.A.C. 7:8-5.7 “Calculation of stormwater runoff and groundwater recharge”, are discussed below.

NRCS Method

The Curve Number Method for prediction of runoff is based upon the observation that the amount of runoff expected from a given watershed is equal to the quantity of rainfall, minus any losses to the system from surface retention/abstraction or infiltration. The method was first presented in the NRCS National Engineering Handbook, Section 4, Hydrology. (3) It was later updated as Technical Release 55 (TR-55) to encompass urban lands. (4) It is a methodology that was originally created in the 1950s and has continued to be used to the present. It has been updated many times. (See references 4, 5, 6, and 7.) The most recent update was proposed by an ASCE-WERI Task Committee in 2017 but it is not yet adopted by NRCS. (8) The basis of the methodology is as follows:

$$Q = \frac{(\mathrm{P}-I_a)^2}{(P-I_a)+S} \qquad P \geq I_a \tag{1}$$

$$Q = 0 \qquad P < I_a \tag{2}$$

$$I_a = 0.2S \tag{3}$$

where Q = Runoff (in)

P = Rainfall (in)

S = Potential maximum retention after runoff begins (in)

I_a = Initial Abstraction (in)

This original model estimated that the initial abstraction (I_a) had a value of 0.2S. Recently, a new equation has been proposed in draft form in the ASCE-WERI Task Committee guidance. (8) The update has been proposed to reflect that $I_a = 0.05S$, which will directly impact the runoff result. It is important to note that this guidance is new and has yet to be adopted by NRCS.

To use either value of the initial abstraction (I_a), it is necessary to determine the value of S. S is a site-specific variable that can be estimated as a function of the watershed conditions. This includes the characteristics of the land surface, slope, and soil condition. These characteristics are then used to determine a CN by the equation:

$$CN = \frac{1000}{S+10} \tag{4}$$

where CN = Curve number

The CN is then used to describe the runoff from a watershed as a function not only of the surface, but also the rainfall depth.

The plot shown in figure 1 presents the rainfall-runoff relationships for a variety of CNs from 40 to 100. (9) 40 is typical of vegetated areas with soils that have relatively high hydraulic conductivities. 100 is a completely impervious surface that has no storage capabilities. Typically, paved areas will have a CN of 98 to reflect the fact that water can be retained on the surface or lost due to evaporation.

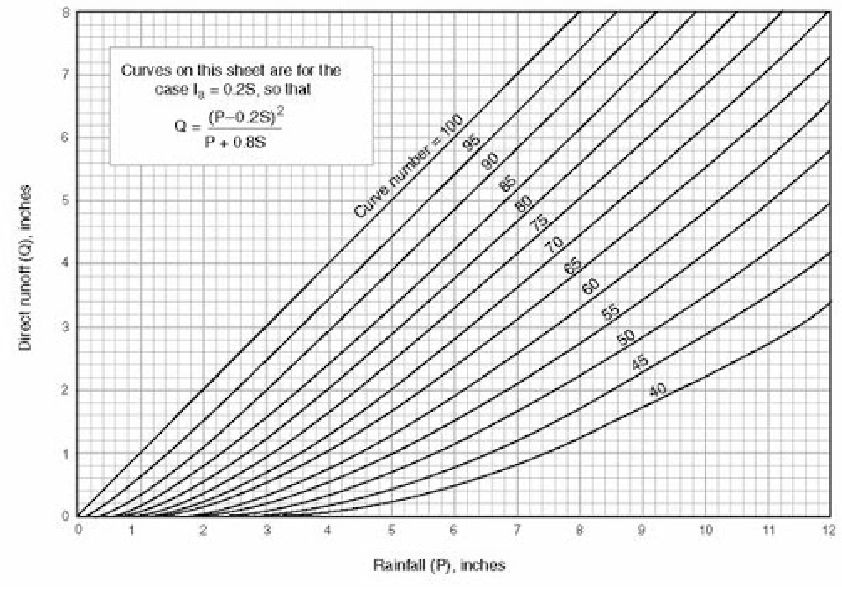
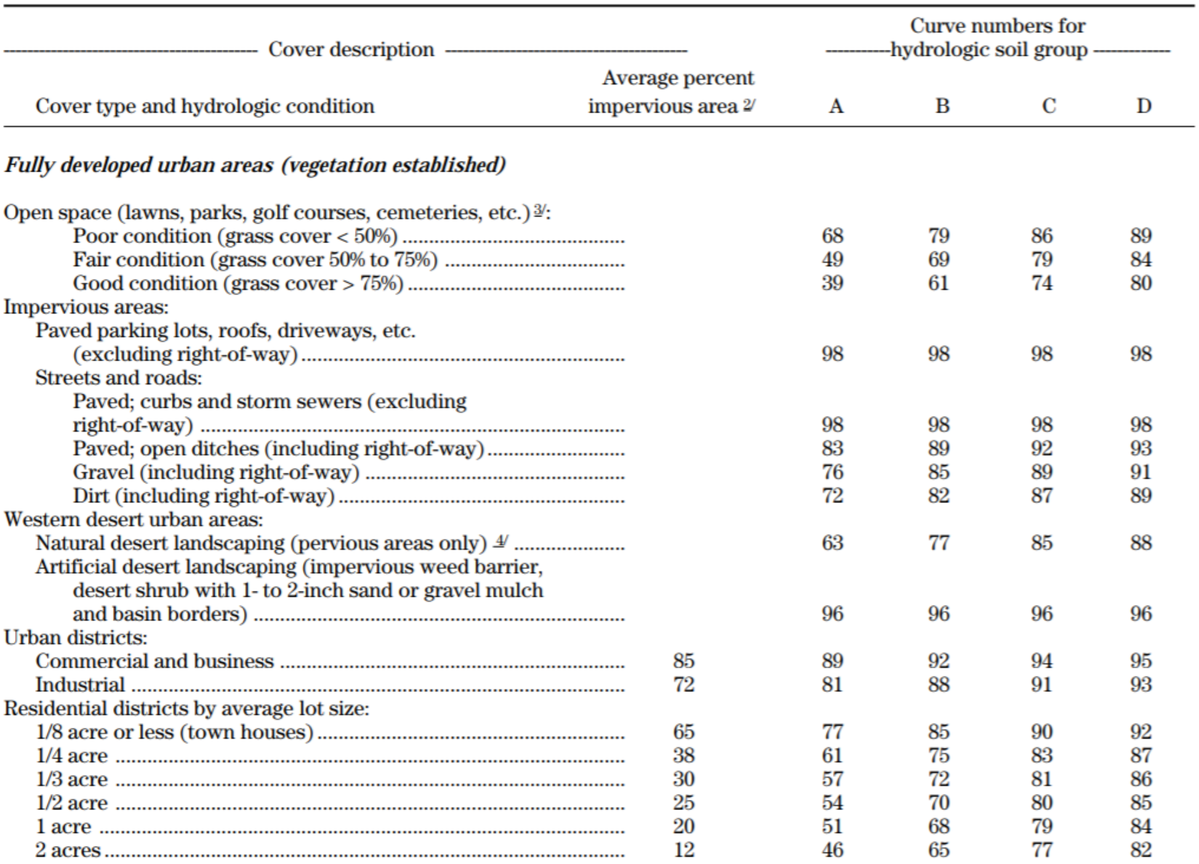


Figure 1. Rainfall-Runoff Relationships for CN 40 through 100

These curves were developed through intensive observations over the past 70 years. In each update of the method (1986, 1997, 2004, 2009), CN values have been updated and validated, and new land treatments have been added. (See references 4, 5, 6, and 7.)

Development of CNs for new land treatments will require a procedure based upon previous developments, those of existing land treatments. This procedure should be the application of a wide range of rainfall depths to a well characterized surface and quantification of runoff depths. Characterization of the surface will include information regarding the surface characteristics (e.g., soil, gravel, vegetation, green infrastructure, etc.), surface morphology (e.g., slope, undulations, etc.), and the underlying soil characteristics (e.g., soil texture, antecedent runoff condition (ARC), etc.). The equations presented above are then fit to the data to provide statistically defensible estimates of CN values for specific surface types. This procedure can be used for laboratory measurements, in-situ experiments, and reanalysis of existing measurements. The newly calculated CNs should be statistically defensible values that can accurately represent field conditions for old and new land treatments commonly utilized in New Jersey. Existing CN values are readily available in tabular form in TR-55 as shown in table 1. (4)

Table 1 - Runoff CNs for Urban Areas



Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

During the latest proposed TR-55 update, CNs for low impact development land treatments were included in the guidance. (8) These included green roofs and permeable pavement over hydrologic soil group (HSG) subbases. CNs for green roofs (table 2) were found to be a function of depth of the planting media based upon work completed by Fassman-Beck et al. (10)

Table 2 - Green Roof CNs

Depth of Planting Media (in)	2	3	4	6	8
CN	92	89	84	80	70

CNs were also proposed for porous concrete pavement (table 3) based upon the work of Schwartz and other sources. (11) They assumed there is adequate positive drainage within the pavement conditions. If there is no positive drainage, the CN is equal to fallow or bare soil.

Table 3 - Permeable Pavement CNs

Subbase (inches)	HSG B	HSG C	HSG D
6	69	79	90
9	53	57	70
12	32	46	62

Both tables were developed from observed data.

Rational Method

The Rational Method (and later the Modified Rational Method) for calculating runoff is applicable for small (< 200 acres) watersheds. (12,13) In practice, it is typically used for watersheds not greater than 20 acres. (14) In its most simplistic form, runoff peak rate is calculated as the product of the rainfall intensity, the area, and a “runoff coefficient”.

$$Q_p = CiA \tag{5}$$

where Q_p = Peak rate of runoff (ft^3/s)

C = Runoff coefficient

i = Rainfall intensity (in/h)

A = Area of watershed/catchment (acre)

The runoff coefficient is a dimensionless constant that describes the potential runoff based on surface types, slopes, and underlying soil conditions. The actual numerical value of the runoff coefficient is:

$$C = \frac{R}{P} \tag{6}$$

where R = Total depth of runoff (in)

P = Total depth of precipitation (in)

Specific values identified in N.J.A.C. 7:8-5.7(a)1i by the State of New Jersey and further described in the NJDOT Drainage Design Manual are tabulated in table 4. (15) For comparison, existing runoff coefficient values readily available from other sources are included in table 5, which shows runoff coefficient values for more land treatments. These values have been developed through laboratory and field measurements.

Table 4 - Recommended Coefficient of Runoff Values for Various Selected Land Uses

Land Use	Description	Hydrologic Soils Group			
		A	B	C	D
Cultivated Land	without conservation treatment	0.49	0.67	0.81	0.88
	with conservation treatment	0.27	0.43	0.67	0.67
Pasture or Range Land	poor condition	0.38	0.63	0.78	0.84
	good condition	---	0.25	0.51	0.65
Meadow	good condition	---	---	0.41	0.61
Wood or Forest Land	thin stand, poor cover, no mulch	---	0.34	0.59	0.70
	good cover	---	---	0.45	0.59
Open Spaces, Lawns, Parks, Golf Courses, Cemeteries Good Condition Fair Condition	grass cover on 75% or more	---	0.25	0.51	0.65
	grass cover on 50% to 75%	---	0.45	0.63	0.74
Commercial and Business Area	85% impervious	0.84	0.90	0.93	0.96
Industrial Districts	72% impervious	0.67	0.81	0.88	0.92
Residential Average Lot Size (acres)	average % impervious				
1/8	65	0.59	0.76	0.86	0.9
1/4	38	0.29	0.55	0.7	0.8
1/3	30	---	0.49	0.67	0.78
1/2	25	---	0.45	0.65	0.76
1	20	---	0.41	0.63	0.74
Paved Areas	parking lots, roofs, driveways, etc.	0.99	0.99	0.99	0.99
Streets and Roads	paved with curbs & storm sewers	0.99	0.99	0.99	0.99
	gravel	0.57	0.76	0.84	0.88
	dirt	0.49	0.69	0.80	0.84

Table 5 - Values of Runoff Coefficient (C) for Rational Method

Land Use	C	Land Use	C
		Agricultural land:	
		Bare packed soil	
		*Smooth	0.30 - 0.60
		*Rough	0.20 - 0.50
Residential:		*Cultivated rows*	
Single-family areas	0.30 - 0.50	*Heavy soil, no crop	0.30 - 0.60
Multi units, detached	0.40 - 0.60	*Heavy soil, with crop	0.20 - 0.50
Multi units, attached	0.60 - 0.75	*Sandy soil, no crop	0.20 - 0.40
Suburban	0.25 - 0.40	*Sandy soil, with crop	0.10 - 0.25
		Pasture	
		*Heavy soil	0.15 - 0.45
		*Sandy soil	0.05 - 0.25
		Woodlands	0.05 - 0.25
		Lawns:	
		Sandy soil, flat, 2%	0.05 - 0.10
Business:		Sandy soil, avg., 2-7%	0.10 - 0.15
Downtown areas	0.70 - 0.95	Sandy soil, steep, 7%	0.15 - 0.20
Neighborhood areas	0.50 - 0.70	Heavy soil, flat, 2%	0.13 - 0.17
		Heavy soil, avg., 2-7%	0.18 - 0.22
		Heavy soil, steep, 7%	0.25 - 0.35
Industrial:		***Streets:***	
Light areas	0.50 - 0.80	Asphaltic	0.70 - 0.95
Heavy areas	0.60 - 0.90	Concrete	0.80 - 0.95
		Brick	0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

Source: http://abe-research.illinois.edu/courses/tsm352/lectures/runoffcoeffs.html.
Note: The designer must use judgement to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes, and dense vegetation should have the lowest "C" values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the highest "C" values.

The methodology for development of these C values is similar to the methodology described for the NRCS CN values in the previous section. Observations of rainfall and resulting runoff are collected from a well described surface under a wide range of storms events. The ratio of the runoff depth to rainfall depth will then be calculated using a statistically rigorous procedure to predict the C value for that surface. This methodology was employed by Fassman-Beck et al. for the development of runoff coefficients for green roof installations. (16) Data was compiled from several sites throughout the world under various operating parameters. The results generally indicated that the calculated runoff coefficients decreased with larger substrate depth and increased with higher rainfall intensity. As expected with in-situ field studies, Fassman-Beck's study showed significant site-to-site variation of runoff coefficients.

Construction Specifications and Materials

The four land treatments to be characterized with values for C and CN are land treatments that NJDOT has recently been employing. Therefore, to address stormwater runoff calculations associated with NJDEP Stormwater Permits, scientifically defensible values of C and CN must be developed for all potential conditions in which these land treatments may be used. A summary of the NJDOT specifications for each land treatment is presented in table 6. References and specifications are described in detail in table 13 in appendix A.

Table 6 - Specifications of NJDOT Land Treatment (Summary)

Land Treatment	Layer	Gradation (Nominal Size)	Depth (in)	Compaction	Notes
Porous HMA	Porous Hot Mix Asphalt (HMA)	3/8" / 3/16"	4 / 6	95-97% of theoretical max density	/
	Aggregate Base	3/4"	< 8 (per lift)	Q >= 0.36	
	Subsoil	/	/	>= 95% of max density	
Vegetation	Topsoil	/	4	/	Vegetation coverage >= 95%
	Scarified Subsoil		12		
	Subsoil		/	>= 95% of max density	
Bare Soil with Polyester Matting *	Polyester Matting	/	> 0.25	/	/
	Subsoil		/	>= 95% of max density	
Gravel	Broken Stone	2″	4	/	/
	Subsoil	/	/	>= 95% of max density	

* The scope of the project was changed after the literature review phase. The land treatment of "bare soil with polyester matting" was changed to "bare soil" as recommended by NJDOT.

Existing Values of Curve Number and Runoff Coefficient

The research team extensively reviewed existing literature from databases including Web of Science, Engineering Village, Transportation Research Record, Google Scholar, and China National Knowledge Infrastructure for studies that present CN and C values for land treatments that are similar to the four land treatments to be studied in this project. There is a large existing body of literature for CN and C values. Values of runoff-related coefficients for these four land treatments are summarized below. Tables listing runoff-related coefficient information and test conditions in all existing studies are presented in appendix B. International Stormwater BMP Databases were evaluated available rainfall-runoff databases and were presented in appendix C.

Bare Soil with Polyester Matting

Polyester matting is a material typically used to cover bare soil to avoid soil erosion in unvegetated areas. The matting is a composite of polyester base fiber and vinyl chloride resin with a minimum thickness of 1/4 in. According to roadway design manuals, the range of runoff coefficient is about 0.2-0.4. A large amount of in-lab and on-site experiments of various geotextiles including polyester matting have been conducted, showing that natural geotextiles have similar effect on runoff reduction as compared to synthetic geotextiles. The runoff coefficient (table 14 in appendix B) was quantified to be from 0.0041 to 0.91 and 17-66 percent runoff reduction was observed with different coverage percentages, slopes, rainfall durations, and rainfall intensities. However, it was found that under extreme conditions such as steep slope (10 percent) or long ramp (10 m), runoff coefficients might become significantly higher or lower than normal. It should be noted that the scope of the project was changed after the literature review phase. The land treatment of “bare soil with polyester matting” was changed to “bare soil” as recommended by NJDOT.

Gravel

Gravel land treatment is applied in roadway design to keep even the runoff discharged from roads and provide a skid-resistant surface for safety. Research has been conducted under lab and field conditions studying the hydrologic characteristics of gravel areas. Results showed that runoff coefficients (table 15 in appendix B) varied from 0.15 to 0.80. The wide range of runoff coefficients indicates the sensitivity of the gravel land treatment to external conditions.

Vegetation

Vegetative strips or grass swales are commonly constructed in the median of highways to capture and treat surface runoff. The hydrologic performance of different vegetative types has been investigated by researchers. Wide ranges of runoff-related coefficients (table 16 in appendix B) were found, including 0.02-0.98 for runoff coefficient, 36-94 for CN, and 5-60 percent for runoff reduction, depending on rainfall, subsoil condition, slope, antecedent runoff condition, vegetation coverage, etc. As a result, some researchers suggested that runoff-related coefficients for vegetation land treatment need to be calibrated site by site to obtain accurate runoff predictions.

Porous HMA

Porous HMA is an open-graded material designed to intercept runoff from roadways with a hydraulic conductivity that is significantly greater than conventional HMA. A wide range of runoff-related coefficients were observed in studies with different conditions, including rainfall, pavement depth, porosity of storage layer, subsoil infiltration, and temporal variation. Ranges of runoff-related coefficients (table 17 in appendix B) are 0.001 to 1.0 for runoff coefficients, 44-97 for CN, and 25.0-97.6 percent for runoff reduction of porous HMA as compared to conventional dense-graded (impermeable) pavement.

Investigation of Studies with Similar Conditions as NJDOT Specifications

NJDOT specifications were investigated and requirements for each land treatment were presented in an earlier section. Among all studies mentioned above, those which have similar or different conditions as NJDOT specifications are indicated in table 14, 15, 16, and 17 in appendix B. To focus on studies of greater interest to this project, box plots showing runoff-related coefficient distributions of all land treatments from studies with similar test conditions as NJDOT specifications are included as figure 2 and figure 3. In figure 2, CN distributions of only porous HMA and vegetation were plotted because studies that report CN of bare soil and gravel were not found.

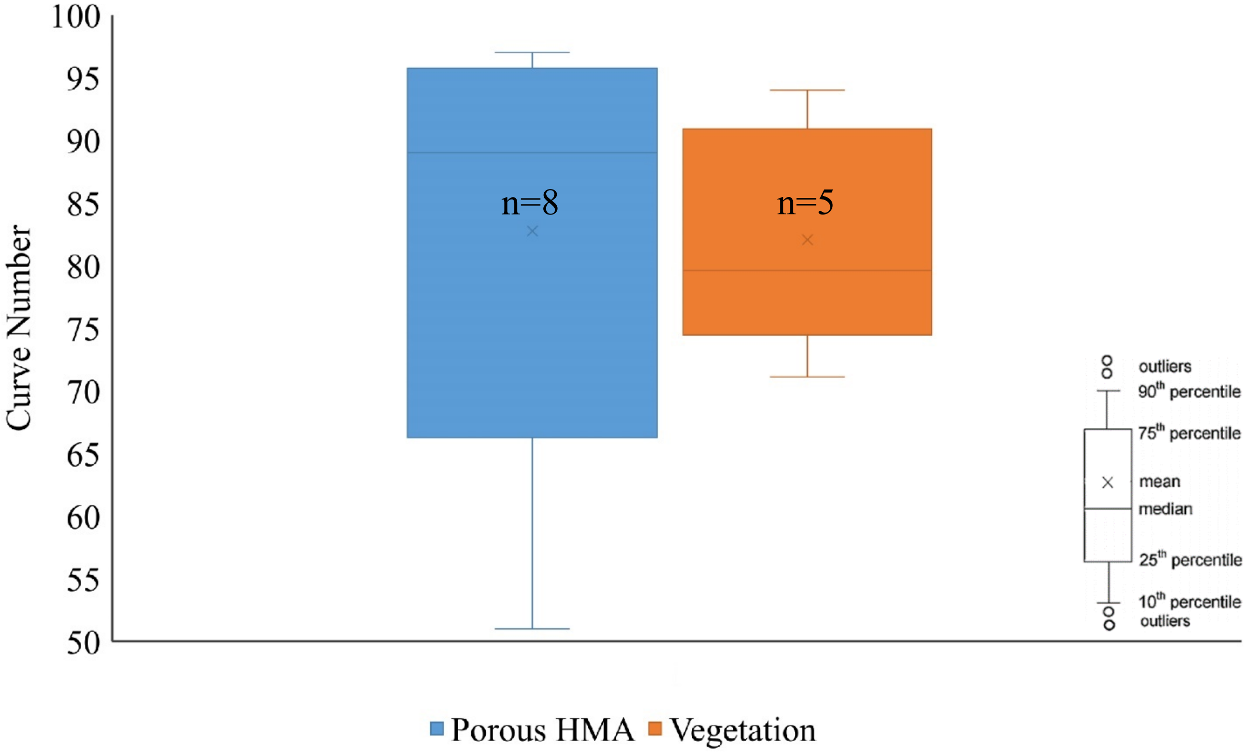


Figure 2. CN Distribution of Porous HMA and Vegetation
(n is number of data points)

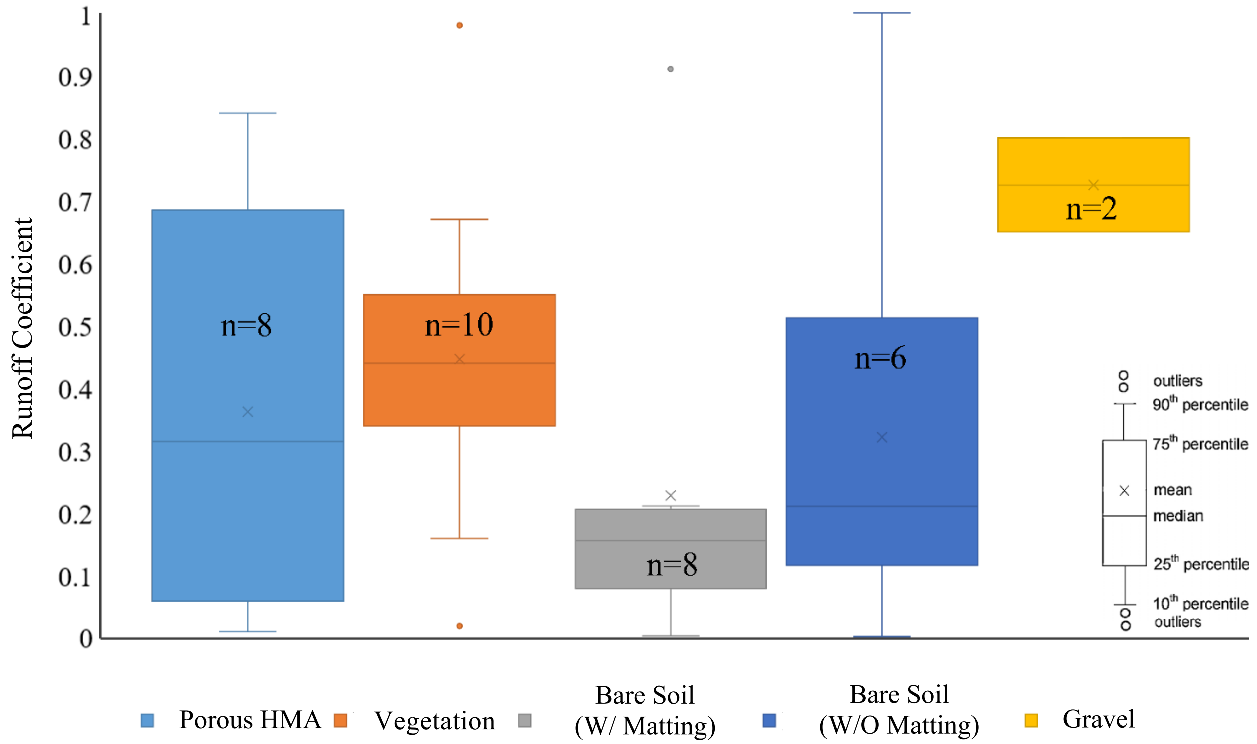


Figure 3. Runoff Coefficient Distribution of Five Land Treatments
(n is number of data points)

After excluding studies which had conditions different from standard NJDOT conditions, the ranges of the runoff-related coefficients for each of the four land treatments either become narrower or remain unchanged compared to the total range. For porous HMA, an increase in the lower bound of CN is attributed to the removal of a research site with a gravel layer over 10 inches thick, subsoil of HSG A, as well as underdrain systems; excluding a study of a traditional asphalt road covered with porous HMA decreases the upper limit of runoff coefficient from 1.0 to 0.84. In terms of vegetation, the increase in CN lower bound can be explained by the exclusion of studies without test conditions provided. As for gravel, the lower limit of runoff coefficient increases because of the removal of a study analyzing the hydrologic performance of soil-gravel mixture, which has a different structure from gravel land treatment.

However, the runoff-related coefficients from studies with similar conditions as NJDOT specifications still show large variations. For porous HMA, the large ranges of rainfall-related coefficients mainly result from a significant deviation of rainfall depths ranging from 0.39 to 34.4 in. For vegetation, the variability of rainfall, slope, vegetation coverage, antecedent runoff condition, and HSG can explain the wide ranges of runoff-related coefficients. For example, with soil moisture content ranging from 0.20-0.30 cm^3/cm^3 and slope ranging from 5 to 15 degrees, the runoff coefficient of the same site varied from 0.02 to 0.55; with other variables equal, rainfall of 2.0 to 4.9 in and vegetation coverage of 0 to 100 percent led to runoff coefficient variation of 0.02 to 0.7 and 0.38 to 0.98, respectively; differences in slope, rainfall, and HSG explained the wide range of CNs. (See references 17, 18, 19, 20, and 21.) In terms of bare soil with polyester matting, the wide range of the runoff coefficients can be attributed to site and plot characteristics of various field sites and the use of different geotextiles; the extremely low runoff coefficient (0.0041) was calculated from a study conducted on a site over an entire year with relatively small cumulative rainfall (24.4 in annually), good subsoil condition (HSG B), and a rather long runoff travel distance (10-m ramp). As for gravel, the effect of rainfall depth on runoff coefficients was found to be significant: runoff coefficients varied from 0.65 to 0.80 with rainfall depths varying from 0.3 to 0.5 in. (22) It is worth noting that even though the number of studies of gravel with similar conditions was very limited (only one), the result (runoff coefficient of 0.65 to 0.80) is reliable and helpful. This is because the study was conducted by the University of Washington and Washington State Department of Transportation, with similar test conditions as expected in New Jersey.

Runoff coefficients for bare soil with and without matting were searched and reviewed (figure 3). Runoff coefficients of bare soil areas with matting (0.0041 to 0.91 for the total range, 0.080 to 0.21 for the middle half range, the range of 25 percent to 75 percent of the distribution of a dataset) are lower than the range of bare soil areas without matting (0.0033 to 1.0 for the total range, 0.12 to 0.51 for the middle half range) as shown in figure 3. This is due to the runoff reduction effect of matting. The wide range can also be attributed to variability in site conditions and matting type. It should be noted that the lower limits of bare soil both with and without matting are from the same study, and there is no significant difference between these two runoff coefficients due to high variation of testing conditions and low sample count included in the test. (23) Besides, the upper bound of runoff coefficient of bare soil areas without matting is calculated from the conclusion that upper bound of runoff coefficient of bare soil areas with matting is 0.91, and the matting has an average runoff reduction rate of 46 percent compared to uncovered surfaces. (24)

To compare values obtained from NJDOT specifications and studies that have similar conditions, box plots showing comparison of runoff-related coefficients between referenced research and NJDOT specifications are included as figure 4 and figure 5. It should be noted that comparison is presented in the plots only when values are available both in studies and specifications. The comparison indicates that C values obtained from research on vegetation generally agree with existing values in NJDOT manuals and the obtained CN values generally agree with existing values in NRCS TR-55 referred to in NJDOT manuals. The significant discrepancy between runoff coefficients of bare soil from studies and NJDOT specifications as well as the lack of results for porous HMA and gravel emphasize the necessity of this project.

The literature search showed that this research project is of great importance to validate existing values and obtain new values of CN and C for the four proposed land treatments. Furthermore, during lab and field tests, a careful control of variables (e.g., rainfall intensity, rainfall duration, hydraulic conductivity, etc.) must be applied for a better understanding of their independent effects, and these values should be carefully designed for higher result repeatability and accuracy.

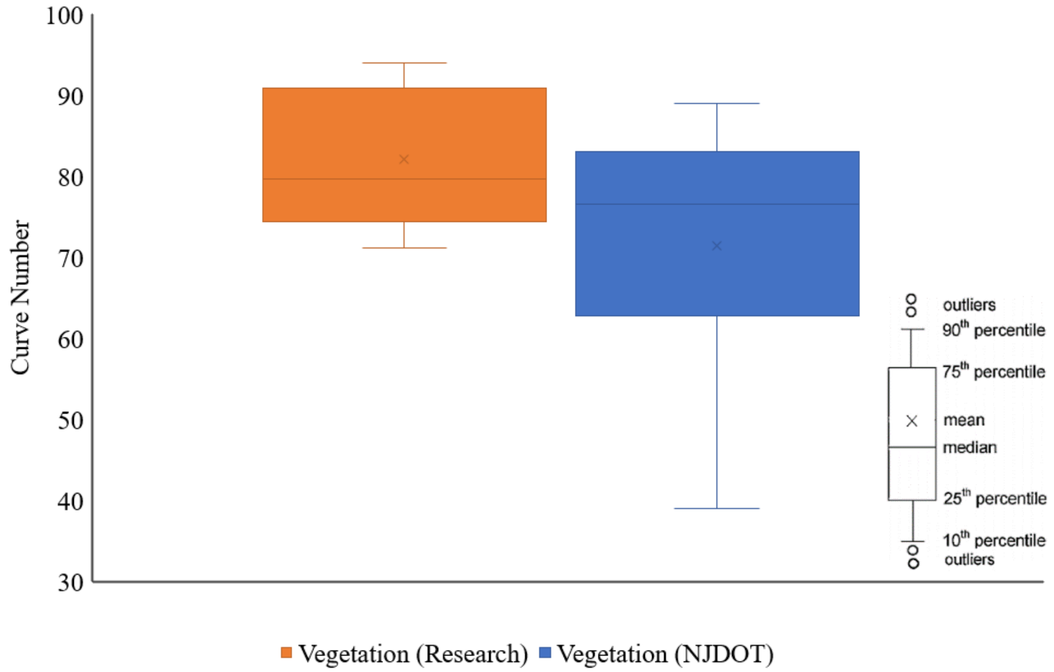


Figure 4. CN Comparison of Vegetation Land Treatments Between Referenced Research and NJDOT Specifications

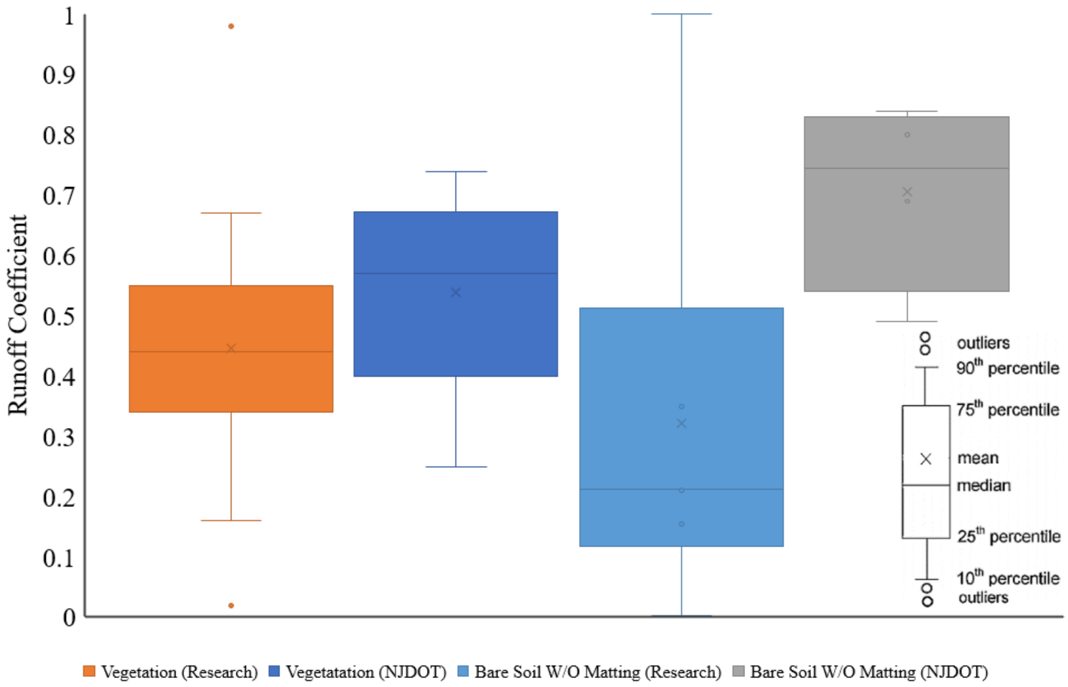


Figure 5. Runoff Coefficient Comparison of Two Land Types Between Referenced Research and NJDOT Specifications

Lab-Testing and Field-Testing Settings and Conditions

To better understand how tests were conducted in referenced studies, lab-testing and field-testing settings and conditions are presented below.

Lab-Testing Setup

The testing method presented by Yang et al. represents the typical lab-testing settings and conditions of research on soil hydrologic analysis. (25) A large-scale soil column apparatus was employed in this study. The major instruments for the soil column apparatus consisted of a tensiometer-transducer system, data acquisition system, time-domain reflectometry, and electronic weighing balance. The schematic diagram of the infiltration column apparatus is presented in figure 6. Results suggest that this soil column apparatus is capable of performing comprehensive infiltration studies and infiltration behavior of any soil configuration (single, two-layered, or multilayered soil) can be studied using this apparatus for different infiltration rates.

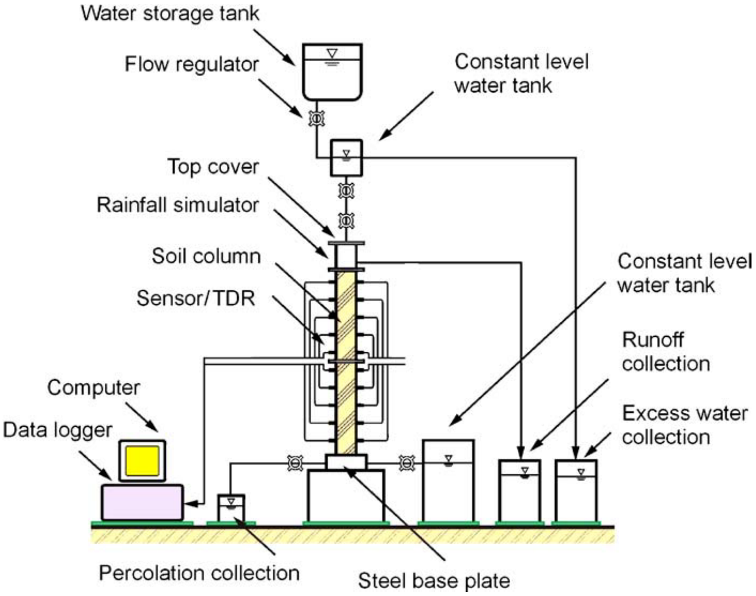


Figure 6. Schematic Diagram of Infiltration Column Apparatus (25)

Field-Testing Setup

The testing method of a project conducted by the University of Washington and Washington DOT represents the typical field-testing settings and conditions of research on runoff from road shoulders (figure 7). (22) Different types of shoulder materials (e.g., gravel, porous asphalt, etc.) were tested. Runoff from the road flowed onto the shoulder test sections and was collected in a stormwater collection system at the base through slot drains installed at the edge of the test sections. Pipes were attached to the outlet of each drain and directed the runoff into flow splitters. Rectangular PVC gutter material was used to convey the sampled stormwater from the flow splitter vein to an enclosed sampling container for volume monitoring. Similarly, Barrett, M. E. had a collection system installed along the edge of pavement and the runoff was routed to an H-flume, where runoff rates were recorded and water quality samples were collected using an automatic sampler (figure 8). (26)

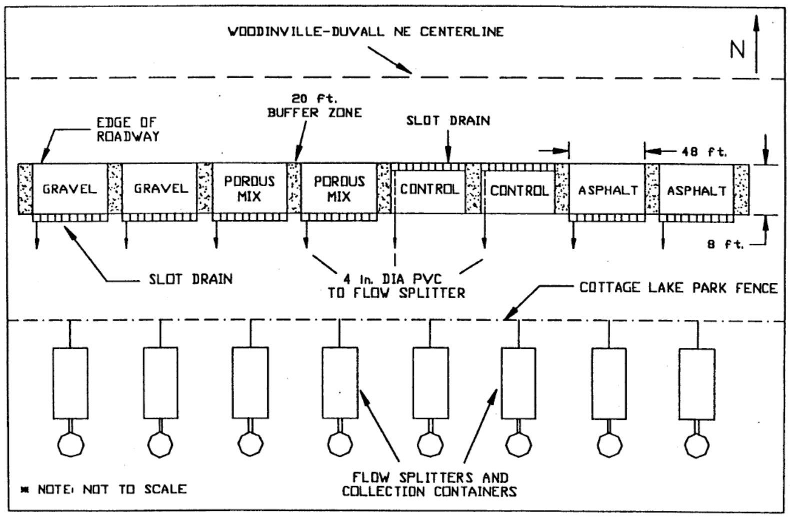


Figure 7. Plan View of Road Shoulder Test Sections and Stormwater Runoff Collection System (22)

Figure 8. Photograph of Installed Sampler at Edge of Pavement (26)

To summarize, the methods and data obtained from the literature review have helped identify independent factors (e.g., rainfall intensity, rainfall duration, soil permeability, land cover type) that would affect runoff-related coefficients and would guide further the research design.

SUMMARY OF THE WORK PERFORMED

This section summarizes the work performed and results obtained, including laboratory setup, sample preparation, laboratory experiments, laboratory test results, data processing and analysis, and data analysis results.

Laboratory Setup

A laboratory setup was developed and implemented following the typical lab-testing design found in the literature review. This setup helped achieve the objective of this project: to evaluate and develop coefficients for runoff analysis that can reflect conditions associated with roadway projects.

Soil Column Apparatus

The soil column apparatus (figure 9 and figure 10) consisted of an acrylic cylinder with an internal diameter of 6 in and a length of 12 in. The wall thickness of the cylinder was 0.25 in, being rigid enough to reduce deformation of the soil column during compaction. The top of the column was covered with a piece of cotton pad with a diameter of 6 in and a thickness of 0.5 in to evenly distribute rainfall falling on the soil surface, dissipate excessive impact of artificial raindrops, and minimize evaporation from the soil. A plastic ring (runoff collection ring) was attached to the exterior of the cylinder surrounding the top edge. A piece of tube was connected to the opening at the lower end of the ring. The bottom of the cylinder was covered by a No. 200 metallic mesh (opening size: 0.0029 in). The mesh was secured by a 3/8-in width hose clamp and the gap between the cylinder and the mesh was sealed with waterproof tape to prevent water leakage. The metallic mesh was intended to provide the conditions of free drainage and structural support of soil.

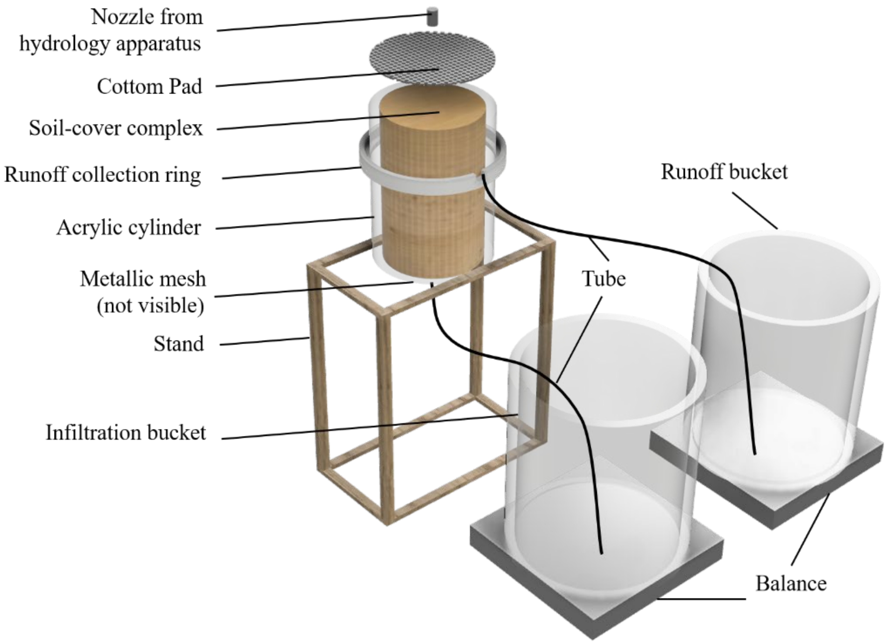


Figure 9. Sketch of Instrumental Setup

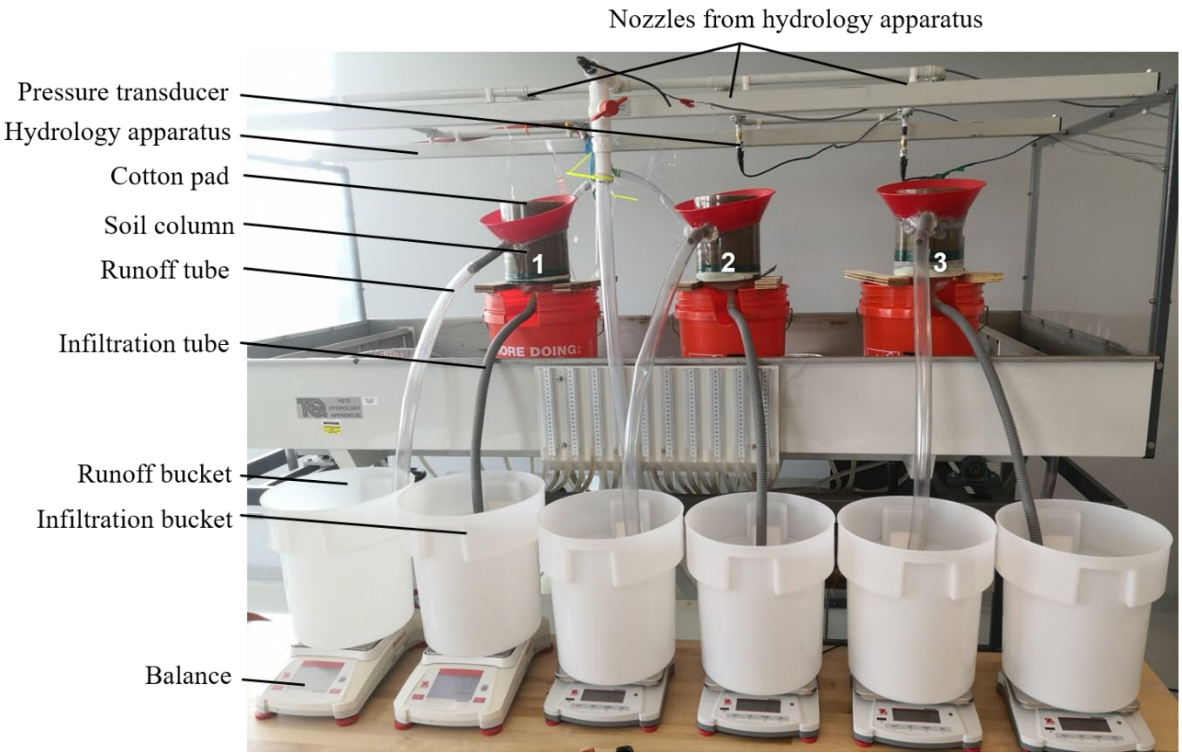


Figure 10. Photo of Instrumental Setup

Water Flow System

The water flow system for the experiments included three parts: (1) rainfall simulation, (2) runoff quantification, and (3) infiltration quantification. The first part, rainfall simulation, was conducted using a hydrology apparatus (TQ Group, model H313) (figure 11) inside the Fluid Mechanics Laboratory. The apparatus is composed of a metal frame which holds a rectangular stainless-steel tank, with a catchment area of 21.54 ft^2 (2 m^2) and a reservoir tank. Above the catchment area, a manifold with three spray nozzles simulates different rainfall intensities. One pressure transducer (Walfront LLC) was connected to the manifold to monitor the rainfall intensity. A pump was used to take water from the reservoir and continuously feed the overhead nozzles.

Second, runoff was collected using the runoff collection ring described in the previous section. Water that did not penetrate the soil column became runoff which would flow over the exterior of the cylinder to be collected in the ring, and would ultimately flow into a runoff collection bucket.

Third, as shown in figure 9 and figure 10, the soil column was placed over a stand that collected infiltration exiting from the bottom (or called exfiltration). The infiltration was then diverted to the infiltration collection bucket through a tube. Both runoff and infiltration collection buckets were placed on balances (OHAUS Corp., model Navigator NVT12000) that continuously recorded mass values to achieve the quantifications of runoff and infiltration.

Figure 11. Photo of Hydrology Apparatus

Data Acquisition System

The pressure transducer and balances were connected to a data logger (CAMPBELL SCIENTIFIC, INC., model CR1000) and a personal computer (figure 12). Pressure and mass value were recorded on the hard drive of the computer at a time interval of 1 minute.

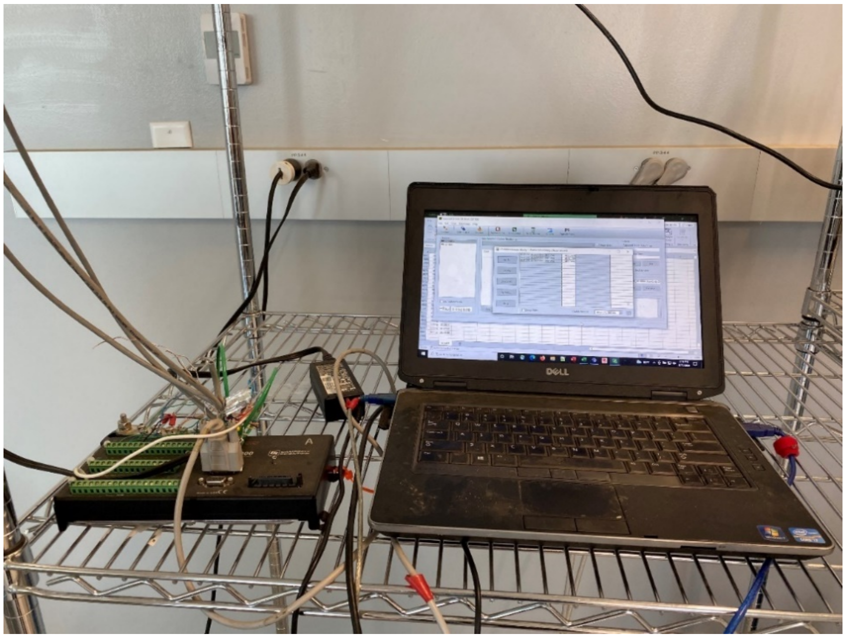


Figure 12. Photo of Data Acquisition System

Sample Preparation

This section describes the preliminary procedures for raw materials and preliminary testing of samples prior to experiments.

Raw Soil Processing

The raw soil (figure 13) was obtained from a NJDOT certified local quarry (EME Corp.) in New Egypt, New Jersey. This material was utilized in the experiments, so that the physical and chemical characteristics of natural soil were well represented in lab. The quarry soil was oven dried at 110 ± 5°C for 24 hours following the Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (ASTM D2216-19). Then the soil was and sieved with No. 4 mesh (opening size: 0.187 in) to remove large particles (e.g., roots, non-organic material). Following the Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (ASTM D2974), the raw soil was ashed in a furnace and the organic content was calculated by the weight difference before and after. The organic content was less than 1 percent (with an average value of 0.889% from the three samples, 0.835%, 1.000%, and 0.833%, respectively). The grain size analysis was conducted by the research team following the Standard Test for Particle-Size Analysis (ASTM D422) and the soil contained 15.3 percent of coarse sand, 69.5 percent of fine sand, and 15.2 percent of silt and clay. The soil was classified as clayey sand (ASTM D2488).

Figure 13. Photo of Soil Sourced from the Quarry

Subsoil Preparation

The subsoils were prepared by mixing the raw soil with washed sand (washed with water to remove dust, clay, salt, and silt), and mineral filler (finely ground mineral powders with the same diameter range as silt and clay) in a ratio of 55:35:10 (mass-based). Sand and mineral filler were obtained from a NJDOT certified local quarry (Trap Rock Industries, LLC) in Kingston, New Jersey. The subsoils were produced to mimic the physical and chemical characteristics of natural soils for roadway projects and the properties of natural and laboratory soils are shown in appendix D. The properties of subsoils included hydraulic conductivity, porosity, bulk density, field capacity, and organic content and the values quantified for subsoils are shown in appendix E.

Hydraulic Conductivity-Bulk Density Relationship Determination

Subsoils were produced for a total of 10 hydraulic conductivities covering 4 HSGs typical of subsoil conditions in New Jersey. Hydraulic conductivities of the subsoils were found to be related to bulk densities of the subsoil. (27) In this project, different hydraulic conductivities were realized by different bulk densities. The bulk density to match the desired hydraulic conductivity was first estimated from the soil compositions and targeted hydraulic conductivities using an available computer program (Rosetta) for estimating soil hydraulic parameters. (27) The subsoil would then be loaded into a permeameter with a mass value calculated by the estimated bulk density and the hydraulic conductivity was measured following the ASTM Standard D5856: Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter. This standard test method is typically used to measure hydraulic conductivity of (porous/semi-porous) soil samples. If the measured soil hydraulic conductivity was larger than the desired hydraulic conductivity, more soil was added and compacted into the permeameter to increase the bulk density (while keeping the soil composition the same) and decrease the hydraulic conductivity, and vice versa. This process was done for all 10 hydraulic conductivities and a hydraulic conductivity-bulk density relationship was determined. This relationship was used as guidance in the construction of soil columns with all 10 subsoil hydraulic conductivities.

Land Treatment Preparation

The land treatments selected for this research project were designed to match current standards utilized in New Jersey by NJDOT as summarized in table 6. Four land treatments were tested: (1) bare soil, (2) gravel, (3) vegetation, and (4) porous HMA. Following the Roadway Design Manual and the Standard Specifications for Road and Bridge Construction, the depth of gravel, vegetation, and porous HMA under guiderail was set as 4 in for consistency. (15,28) For the bare soil land treatment, the top 4 in of land treatment was constructed with the same soil mix as the subsoil. For the gravel land treatment (figure 14 (a)), crushed aggregate (Aggregate No.3) obtained from Trap Rock Industries, LLC was used. (28) For the vegetation land treatment (figure 14 (b)), Kentucky Bluegrass sod obtained from The Yard LLC Topsoil & Mulch Depot was used. (28) The 1-in-thick sod was nurtured on topsoil with a depth of 3 in for 1 month following standard protocols and recommendations from the supplier to allow necessary root growth. For the porous asphalt land treatment (figure 14 (c)), cylindrical porous Hot Mix Asphalt (HMA) gyratory samples with a diameter of 6 in and a depth of 4 in were manufactured at Rutgers CAIT Asphalt Pavement Lab. The mix design utilized to manufacture the HMA met the requirements of the Open-graded Friction Course in the Updated Standard Specifications for Road and Bridge Construction 2007. (29) The land treatments utilized in the experiments represented well the physical and chemical characteristics of land treatments applied in field conditions for roadway projects.

(a) Gravel (b) Vegetation (c) Porous HMA

Figure 14. Pictures of (a) Gravel, (b) Vegetation, and (c) Porous HMA

Soil Column Construction

The processed subsoil was loaded and compacted to the desired mass (calculated by the bulk density related to the desired hydraulic conductivity) in 2-in increments. The compaction was performed by a hammer compactor with a mass of 5.5 lb, a drop of 12 in, and a diameter of 2 in (a standard soil compaction hammer). The hammer compactor was dropped at a level of 12 in for 7 times per increment, with a total effort of 14,120 ft-lb/ft^3. The same amount of compaction was applied to each layer until reaching a depth of 8 in with the desired mass of soil (to reach the targeted bulk density) compacted in the column. The masses of the soil columns were measured and recorded to calculate the bulk density of the subsoil. A total of three soil columns were created as replicates per hydraulic conductivity.

After the subsoil was constructed, 4 in of land treatments (i.e., bare soil, gravel, vegetation, porous HMA) were placed on top, making a total depth of 12 in. The design of soil columns with different land treatments is shown in figure 15.

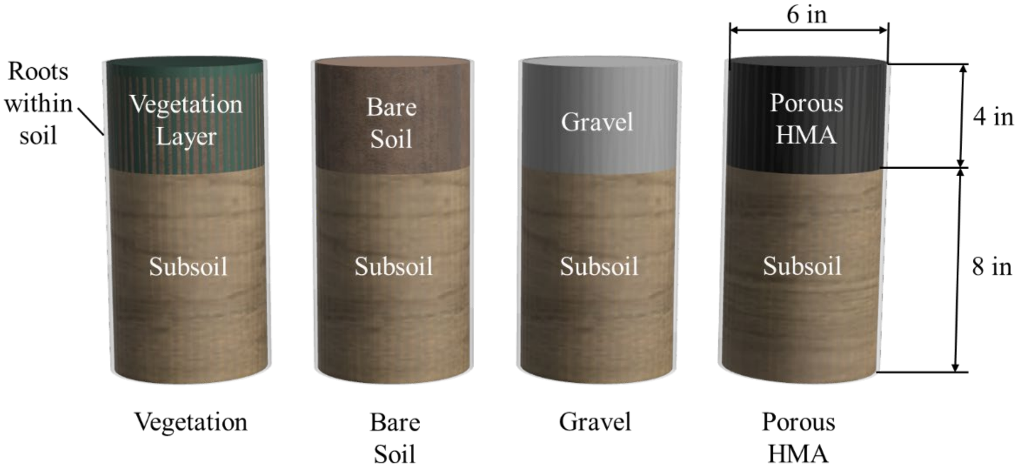


Figure 15. Sketch of Soil Columns with Different Land Treatments

Soil Column Prewetting

After being constructed, soil columns were fully saturated for 240 minutes. The stabilization of infiltration rate over time indicated the saturated status of the soils. Afterwards, soil columns were gravitationally drained for 2 days to ensure that the water content of the soil reached field capacity. (30) Test results of soil water content following ASTM Standard D5856 (appendix F) showed that field capacity was reached after 2 days. Soil columns were weighed once reached field capacity. The 4-in land treatment layer of gravel, vegetation, and porous HMA were fully saturated and gravitationally drained for 2 days to reach field capacity. The masses of both statuses were measured and monitored, and the differences (ΔM) were used to calculate the drainable porosity (i.e., porosity – field capacity) of land treatments.

Sample Property Measurement

The bulk density, porosity, and field capacity of subsoils were calculated as follows: (30)

$$\rho_b = \frac{M_d}{V_b} \tag{7}$$

$$\eta = 1 - \frac{\rho_b}{\rho_{particle}} \tag{8}$$

$$\text{Field Capacity} = \frac{M_f - M_d}{V_b} \tag{9}$$

where ρ_b = Bulk density (g/cm^3)

M_d= Mass of dry subsoil (after construction and before prewetting) (g)

V_b = Volume of dry subsoil (cm^3)

η = Porosity of subsoil

$\rho_{particle}$= Particle density (g/cm^3). The particle densities of the subsoils were measured to be 2.674, 2.681, and 2.660 g/cm^3, respectively, following ASTM D7263-21 and averaged value was 2.671 g/cm^3

M_f = Mass of subsoil at field capacity (g)

The drainable porosity of each land treatments was calculated as follows:

$$\eta_e = \frac{\Delta M}{\rho_w V} \tag{10}$$

where η_d = Drainable porosity of land treatments

ΔM = Mass difference between saturation and field capacity (g)

ρ_w = Density of water. 1.00 g/cm^3 under lab conditions

V = Volume of land treatments (cm^3)

The drainable porosity of gravel, vegetation, and porous HMA were measured to be 0.41, 0.20, and 0.11, respectively.

Laboratory Experiments

Measurements of rainfall and runoff were conducted at the laboratory for the four land treatments within the Right of Way (ROW), median, and/or under guiderails, which included (1) bare soil, (2) gravel, (3) vegetation, and (4) porous hot mix asphalt (HMA). Each land treatment was tested as a composite column, where the treatment was positioned above the subsoil. Each land treatment was prepared according to the specifications provided by NJDOT. The subsoils utilized in this experiment were prepared to simulate those typically found within the State of New Jersey, with ten different hydraulic conductivities covering hydrologic soil groups A, B, C, and D. The rainfall covered a full range of intensities and depths, from very small to very large storms (up to 24-h 100-year storm), encountered in the State of New Jersey. (31) The laboratory tests simultaneously and continuously measured surface runoff and subsurface infiltration for each soil column as well as the rainfall intensity.

Laboratory Test Matrix

The subsoils utilized in this experiment were prepared to simulate those typically found within the State of New Jersey, with ten different hydraulic conductivities. Four rainfall intensities were simulated to cover the full range of depths and intensities typically encountered in the State of New Jersey. The shortest duration of rainfall was set to 120 minutes (2 hours) and the longest duration was set to 240 minutes (4 hours). The laboratory test matrix is shown in figure 16.

Land Treatment	Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Rainfall Duration (h)
Bare Soil	10.0	9.0	Varies from
Grave	8.0	4.0	2 to 4
Vegetation	6.0	1.0	
Porous HMA	5.5	0.3	
	4.0		
	2.0		
	1.5		
	1.0		
	0.5		
	0.1		

Figure 16. Laboratory Test Matrix

Laboratory Instrument Calibration

The calibration was conducted in three steps. First, the flow capacity of the spray nozzles was assessed. The nozzles were able to produce rainfall intensities from 0.2 to 26.0 in/h, large enough to simulate the 100-year storm of short duration (for the duration of 6 minutes, the rainfall intensity for the 100-year storm is about 10.0 in/h in New Jersey). (31) Second, a preliminary test was carried out to assess the stability of rainfall intensity over time. Rainfalls were simulated for 30 minutes for three times at rainfall intensities of 9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0, 0.5, and 0.3 in/h, respectively. The test concluded that the rainfall intensity could be maintained steadily over time, with a maximum percentage difference of ± 0.9 percent/h in rainfall intensity. Third, a calibration curve was obtained to relate the voltage outputs of the pressure transducer to rainfall intensities. The calibration curve (figure 35 in appendix G) was obtained by plotting voltage readings versus corresponding rainfall intensities manually measured during the preliminary test. The balances, with a resolution of 0.1 g, were factory-calibrated and installed on a steady and level platform. The calibration and inspection report is attached as figure 36 in appendix H. The mass of the buckets was tared before experiments.

Laboratory Test Procedure

In each laboratory experiment, one soil column, along with two replicates were tested under one rainfall intensity. This set of soil columns represented one subsoil hydraulic conductivity and one land treatment. The same laboratory test procedure was followed for all tests proposed in the laboratory test matrix (figure 15). The laboratory tests were conducted following the steps below:

1. At the beginning of each laboratory experiment, the water system flow was turned on and adjusted to the desired rainfall intensity for 30 minutes to achieve steady inflow.
2. The masses of soil columns (gravitationally drained for 2 days after being saturated) were measured and recorded, and field capacities were calculated.
3. Soil columns were then placed on the test stands under each spray nozzle.
4. Rainfall was simulated until both rates of runoff and infiltration of the soil column remained steady (with a percentage difference in flow rate per unit cross-sectional area lower than 5 percent/minute) for 120 minutes.
5. Once the rainfall stopped, runoff and infiltration rates were continuously recorded until the relative percentage difference was lower than 5 percent/minute.
6. After being tested in one experiment, soil columns became saturated and would be gravitationally drained for 2 days to ensure that the water content of the soil reached field capacity. Then, these columns were ready for the next test with a different rainfall intensity. A total of four tests with different rainfall intensities were conducted using the same soil composite columns. After the four tests for one land treatment were finished, the land treatment would be removed and the subsoil would be reused. The subsoil was then loaded with a new land treatment and went through the aforementioned procedure in “soil column prewetting”.

The experiments were carried out at water temperature of 23.0 ± 1.0 °C. The evaporation and interception of the soil columns were estimated to be minimal and thus neglected. This was due to the cotton pad placed on top of the soil column that greatly limited evaporation without intercepting rainfall. Surface depression on top of the soil column was observed to be minimal and thus neglected. This was because no ponding occurred on the surface of soil columns during laboratory experiments.

Laboratory Test Results

Pressure readings from the pressure transducer, connected to the manifold, were recorded by the data acquisition system every minute. Rainfall intensity was converted from pressure values by the calibration curve of the pressure transducer (figure 35 in appendix G). Infiltration and runoff masses were recorded at 1 minute interval. The water temperature in the laboratory apparatus was monitored and recorded at 23.0 ± 1.0 °C (where density of water is 1.00 g/cm^3). The infiltration and runoff volumes were calculated by dividing the mass by the density of water. Infiltration and runoff flow rates per unit cross-sectional area were calculated by dividing the volume increase of water every minute by the cross-sectional area (28.27 in^2) of the soil column. An example of the time variations of flow rate per unit cross-sectional area (in/h) of runoff, infiltration, and rainfall from a soil column experiment (land treatment of bare soil, subsoil hydraulic conductivity of 1.5 in/h, rainfall intensity of 4.0 in/h) is shown in figure 17.

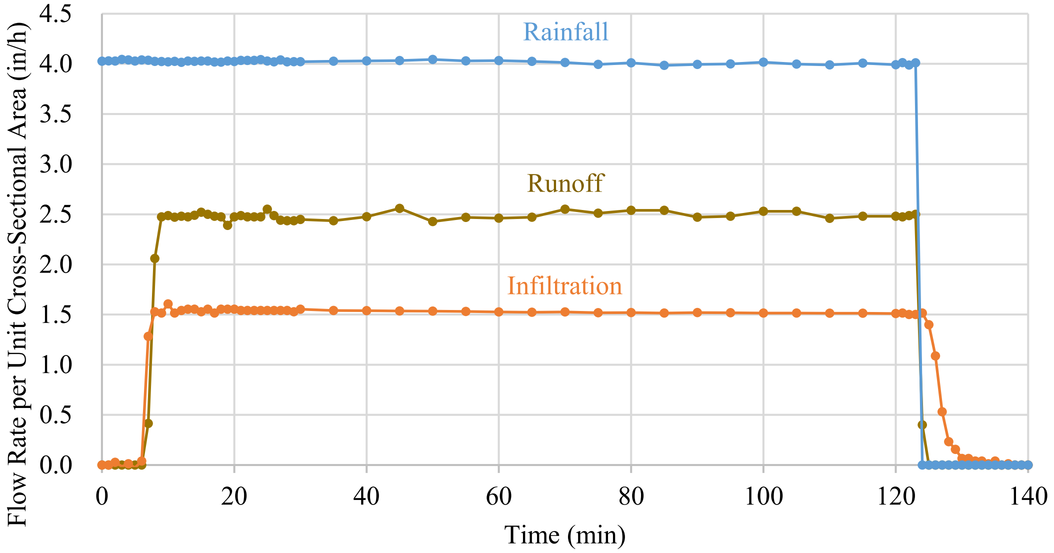


Figure 17. Time Variations of Runoff, Infiltration, and Rainfall

As the soil column reached saturation, the infiltration rate became steady and was recorded. When the steady state was achieved, the soil column was saturated and there was no water ponding on top of the land treatment. This steady infiltration rate is thus the hydraulic conductivity of the entire soil column. The hydraulic conductivity of the composite soil column (land treatments plus subsoils) was named as the "composite hydraulic conductivity" in this research project. The composite hydraulic conductivity is equal to the product of subsoil hydraulic conductivity and hydraulic gradient along the subsoil depth. The hydraulic gradient was quantified by the hydraulic head difference divided by the depth of the subsoil (length of the vertical flow path). The relationships are expressed by the equations below:

$$K_{sat-Comp} = \frac{dh}{dl} \times K_{sat-Base} \tag{11}$$

$$\frac{dh}{dl} = \frac{\Delta h}{\Delta l} \tag{12}$$

where $K_{sat\text{-}comp}$ = Composite hydraulic conductivity (in/h)

$K_{sat\text{-}Base}$ = Subsoil hydraulic conductivity (in/h)

$\frac{dh}{dl}$ = Hydraulic gradient

Δh = Hydraulic head difference along the subsoil column (in), Δh = 12 in in this study

Δl = Depth of the subsoil (in), Δl = 8 in in this study

All conditions of land treatment, soil hydraulic conductivity, and rainfall intensity under which the laboratory tests were conducted are shown in table 7. The test conditions followed the test matrix in figure 15 as close as possible.

Table 7 - Laboratory Test Conditions

Bare Soil		Gravel		Vegetation		Porous HMA	
Composite Hydraulic Conductivity (in/h) **	Rainfall Intensity (in/h) ***	Composite Hydraulic Conductivity (in/h) **	Rainfall Intensity (in/h) ***	Composite Hydraulic Conductivity (in/h) **	Rainfall Intensity (in/h) ***	Composite Hydraulic Conductivity (in/h) **	Rainfall Intensity (in/h) ***
0.11 ± 0.02	9.04 ± 0.05	0.18 ± 0.02	8.61 ± 0.10	0.20 ± 0.03	8.64 ± 0.02	0.20 ± 0.02	8.27 ± 0.03
	3.96 ± 0.07		4.25 ± 0.03		4.02 ± 0.02		3.89 ± 0.02
	1.00 ± 0.02		1.49 ± 0.01		1.51 ± 0.01		1.53 ± 0.02
	0.51 ± 0.01 *		1.04 ± 0.02 *		1.02 ± 0.01 *		1.05 ± 0.02 *
0.37 ± 0.03	8.95 ± 0.13	0.49 ± 0.05	9.03 ± 0.03	0.41 ± 0.04	9.02 ± 0.12	0.44 ± 0.07	9.03 ± 0.02
	4.03 ± 0.12		4.04 ± 0.03		3.98 ± 0.05		3.96 ± 0.03
	1.06 ± 0.11		1.49 ± 0.01		1.98 ± 0.06		2.50 ± 0.00
	0.54 ± 0.10 *		1.03 ± 0.04 *		1.02 ± 0.08 *		1.06 ± 0.06 *
0.87 ± 0.12	8.62 ± 0.21	1.50 ± 0.02	9.01 ± 0.02	1.49 ± 0.03	9.02 ± 0.01	1.51 ± 0.02	8.94 ± 0.07
	4.37 ± 0.09		3.95 ± 0.04		4.01 ± 0.01		3.99 ± 0.02
	1.43 ± 0.09		3.45 ± 0.03		2.57 ± 0.04		2.57 ± 0.05
	1.03 ± 0.10 *		0.95 ± 0.05 *		1.03 ± 0.03 *		1.02 ± 0.10 *
1.59 ± 0.09	9.15 ± 0.11	2.21 ± 0.07	9.01 ± 0.02	2.01 ± 0.03	8.71 ± 0.21	2.11 ± 0.04	8.94 ± 0.07
	8.20 ± 0.10		4.02 ± 0.02		3.95 ± 0.07		3.99 ± 0.02
	4.04 ± 0.03		3.43 ± 0.09		2.52 ± 0.02		3.50 ± 0.03
	2.13 ± 0.08		1.05 ± 0.15 *		1.03 ± 0.05 *		1.04 ± 0.10 *
2.01 ± 0.06	9.00 ± 0.00	3.05 ± 0.14	9.07 ± 0.04	2.98 ± 0.31	8.97 ± 0.05	2.73 ± 0.16	8.52 ± 0.20
	4.22 ± 0.04		5.03 ± 0.08		6.00 ± 0.02		4.97 ± 0.05
	7.06 ± 0.09		3.92 ± 0.11		4.02 ± 0.02		3.97 ± 0.02
	2.49 ± 0.02		1.04 ± 0.11 *		0.98 ± 0.03 *		1.03 ± 0.10 *
4.09 ± 0.06	9.02 ± 0.02	6.49 ± 0.22	8.95 ± 0.32	6.37 ± 0.12	9.02 ± 0.25	6.65 ± 0.04	9.23 ± 0.02
	8.09 ± 0.10		8.03 ± 0.01		8.07 ± 0.30		8.10 ± 0.00
	5.02 ± 0.02		7.00 ± 0.01		7.09 ± 0.03		7.35 ± 0.10
	4.02 ± 0.05 *		3.99 ± 0.14 *		4.03 ± 0.11 *		4.05 ± 0.05 *
5.52 ± 0.05	8.74 ± 0.21	8.49 ± 0.19	9.07 ± 0.01 *	8.57 ± 0.15	9.02 ± 0.02 *	8.45 ± 0.14	9.03 ± 0.04 *
	8.00 ± 0.00						
	7.02 ± 0.04						
	5.50 ± 0.11 *						
5.92 ± 0.05	9.01 ± 0.01	8.99 ± 0.15	8.99 ± 0.01 *	9.03 ± 0.16	9.01 ± 0.02 *	9.05 ± 0.16	9.02 ± 0.05 *
	8.05 ± 0.04						
	7.09 ± 0.04						
	6.02 ± 0.03 *						
8.05 ± 0.06	9.01 ± 0.02	10.06 ± 0.15	8.97 ± 0.12 *	10.13 ± 0.15	9.03 ± 0.05 *	10.05 ± 0.10	9.09 ± 0.06 *
	8.02 ± 0.03 *						
10.02 ± 0.05	9.03 ± 0.03 *	No test	No test	No test	No test	No test	No test

* No runoff was observed during laboratory tests. ** The composite hydraulic conductivities are presented by the arithmetic means and standard deviations of three replicates for up to four rainfall intensities. *** The rainfall intensities are presented by the arithmetic means and standard deviations of three replicates.

In table 7, under each land treatment, each row represents one test (i.e., one soil column replicate under one rainfall intensity). Note there were three replicates of the soil column. Initially, a total of 160 test conditions were intended to be performed according to the lab test matrix in figure 15, but only a total of 113 tests were actually conducted. When a soil column did not produce runoff under a certain rainfall intensity over 2 hours in the laboratory test matrix, the lower rainfall intensities were not tested. For example, the soil column with land treatment of bare soil and hydraulic conductivity of 8.0 in/h did not produce runoff under the rainfall intensity of 8.0 in/h. Therefore, the other lower rainfall intensities proposed in the matrix (i.e., 4.0, 1.0, and 0.3 in/h) were not tested. The 113 test scenarios that were conducted are listed in table 7. For each test, time-varied flow rates per unit cross-sectional area (in/h) of runoff, infiltration, and rainfall were measured and recorded at a 1-minute interval.

Data Processing and Analysis

This section presents how the data obtained from laboratory tests was prepared, processed, and analyzed.

Data Preparation

A dataset consists of one soil column of one land treatment subjected to four rainfall intensities. Each dataset contains up to 16 data points configured as 1 land treatment, 1 hydraulic conductivity, 1 soil column, up to 4 rainfall intensities, and up to 4 time intervals under 1 rainfall intensity. Each data point corresponds cumulative runoff depth to cumulative rainfall depth at a certain time interval in the format of a data point (rainfall depth, runoff depth). The configuration of a dataset (land treatment of bare soil, subsoil hydraulic conductivity of 2.0 in/h, soil column replicate #1) is shown in table 8. Cumulative depths were calculated by dividing the cumulative volume of water at a certain time interval by the cross-sectional area (28.27 in^2) of the soil column. Data with operational error was removed, and the corresponding test was repeated.

Table 8 - Dataset Configuration (land treatment of bare soil, subsoil hydraulic conductivity of 2.0 in/h, soil column replicate #1)

Rainfall Intensity (in/h)	Time Interval (minute)	Rainfall Depth (in)	Runoff Depth (in)
9.0	30	4.52	3.34
	60	9.04	6.84
	90	-	-
	120	-	-
7.0	30	3.50	2.44
	60	7.01	4.94
	90	-	-
	120	-	-
4.0	30	2.02	0.92
	60	4.04	2.04
	90	6.06	3.15
	120	8.08	4.26
2.1	60	2.10	0.01
	90	3.15	0.05
	120	4.20	0.10
	150	5.25	0.16

The data truncation rules were as follows:

1. Data points at four time intervals were taken every 30 minutes after runoff occurred. For example, if runoff occurred at minute 34, data points would be taken at minutes 60, 90, 120, and 150.
2. Cumulative rainfall depth shall not exceed 10.0 in (i.e., New Jersey 24-hour rainfall depth during 100-year storm). (31)

Data Analysis Methods

Four data analysis methods were investigated in this project, including (1) the original NRCS Method, (2) the current simplified NRCS Method (TR-55) with I_a = 0.2S, (3) the proposed simplified NRCS Method with I_a = 0.05S, and (4) the Rational Method. (See references 3, 8, 12, and 4.)

In the original NRCS Method, the initial abstraction was related to the impact of rainfall intensity. (3) By contrast, the initial abstraction was assumed to be linearly related to the potential maximum retention by a factor of 0.2 in the current simplified NRCS described in TR-55. (4) Data analysis results from this research project indicate that the original NRCS Method has a better statistical performance and can be used to provide a more accurate runoff prediction. However, the original NRCS Method is much more complicated to apply than the simplified NRCS method as input of the rainfall intensity will be additionally needed. Therefore, the original NRCS Method is not recommended for the calculation of runoff in stormwater management. As explained above, the original NRCS Method does not set the initial abstraction (I_a) as a ratio of the potential maximum retention after runoff begins (S), but the simplified NRCS Method does. The simplified NRCS (where I_a is set to 0.2S) is the current standard NRCS method. The original NRCS Method is presented in appendix I.

An update to the original NRCS Method has been proposed by an ASCE-EWRI Task Committee to reflect that I_a = 0.05S. (8) It is important to note that the update of I_a = 0.05S is new and has yet to be adopted by NRCS that is a national technical assistance provider. The simplified NRCS Method with the update of I_a = 0.05S was also investigated in this project and found to have a statistical performance that is similar to the current simplified NRCS Method where I_a was set to be 0.2S. The results of the investigation are presented in appendix J.

In the main body of this report, the Rational Method and the current simplified NRCS Method outlined in the TR-55 are presented and discussed. (12,4)

Rational Method

The method of least squares was applied for data analysis to calculate runoff coefficients. This is a statistical procedure to find the best fit for a set of data points by minimizing the sum of residuals of points from the plotted curve. A predicted runoff depth was calculated by an observed rainfall depth and an assumed C value:

$$C_{fit} = \frac{\mathrm{R_{pre}}}{P_{obs}} \qquad (13)$$

where R_{pre} = Predicted runoff depth (in)

P_{obs} = Observed rainfall depth (in)

C_{fit} = Runoff Coefficient to be fitted

One C value was assumed to calculate the R_{pre} values of all data points within a dataset. The coefficient of determination (R^2) of the dataset was calculated by: (32)

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(R_{obs_i} - \overline{R_{obs}}\right)\left(R_{pre_i} - \overline{R_{pre}}\right)}{\sqrt{\sum_{i=1}^{n}\left(R_{obs_i} - \overline{R_{obs}}\right)^2 \sum_{i=1}^{n}\left(R_{pre_i} - \overline{R_{pre}}\right)^2}}\right]^2 \tag{14}$$

where R_{obs} = Observed runoff depth (in)

$\overline{R_{obs}}$ = Arithmetic mean of observed runoff depths (in)

R_{pre} = predicted runoff depth (in);

$\overline{R_{pre}}$ = arithmetic mean of predicted runoff depths (in)

The solver function in Microsoft Excel was applied to maximize the R^2 of the dataset (i.e., minimizing the sum of residuals of data points from the P-R_{pre} curve) by varying the C. The best fit of C was obtained when the maximal R^2 was reached.

The coefficients of determination (R^2) of the precipitation-runoff (P-Q_{pre}) curve shall meet the statistical requirement for acceptance (i.e., $R^2 = 0.60$, performance evaluation criteria of "satisfactory"). (32) An example of bare soil land treatment with subsoil hydraulic conductivity of 1.5 in/h is included as figure 18 to illustrate the data analysis method (i.e., calculation of individual runoff coefficient and individual R^2 values) for one soil column.

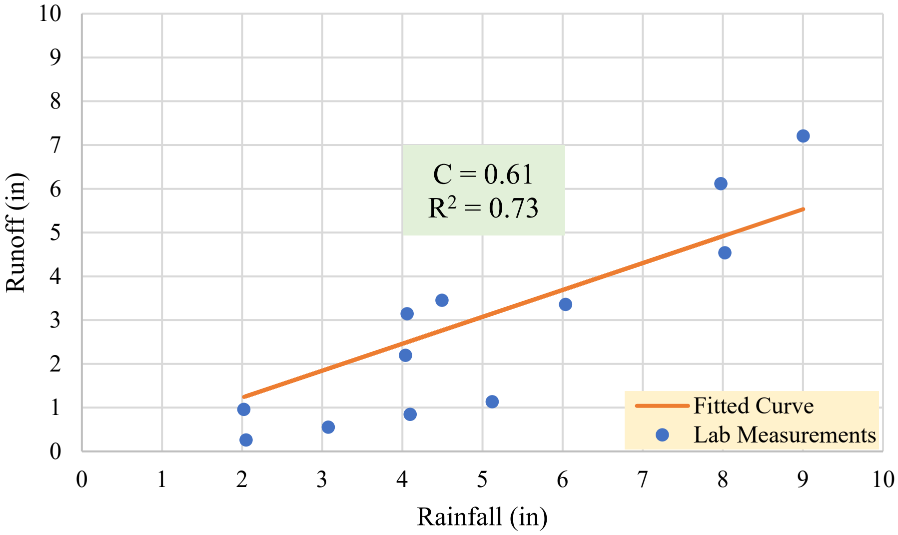


Figure 18. Data Analysis using Rational Method (land treatment of bare soil, subsoil hydraulic conductivity of 1.5 in/h, soil column replicate #2)

NRCS Method

The method of least squares was applied for data analysis to fit CNs. For each soil column (combination of a subsoil and a land treatment), a predicted runoff depth was calculated by an observed rainfall depth and an assumed S value with the current simplified NRCS (i.e., TR-55) equation:

$$\mathrm{Q_{pre}} = \frac{(P_{obs} - 0.2S_{fit})^2}{P_{obs} + 0.8S_{fit}} \tag{15}$$

where Q_{pre} = Predicted runoff depth (in)

P_{obs} = Observed rainfall depth (in)

S_{fit} = Potential maximum retention after runoff begins (in) to be fitted

One S value was assumed to calculate Q_{pre} values of all data points within a dataset. The coefficient of determination (R^2) of the NRCS Runoff Equation was calculated by:

$$\mathrm{R^2} = \left[\frac{\sum_{i=1}^{n}\left(\mathrm{Q_{obs_i}} - \overline{\mathrm{Q_{obs}}}\right)\left(\mathrm{Q_{pre_i}} - \overline{\mathrm{Q_{pre}}}\right)}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{Q_{obs_i}} - \overline{\mathrm{Q_{obs}}}\right)^2 \sum_{i=1}^{n}\left(\mathrm{Q_{pre_i}} - \overline{\mathrm{Q_{pre}}}\right)^2}}\right]^2 \tag{16}$$

where Q_{obs} = Observed runoff depth (in)

$\overline{Q_{obs}}$ = Arithmetic mean of observed runoff depths (in)

Q_{pre} = predicted runoff depth (in);

$\overline{Q_{pre}}$ = arithmetic mean of predicted runoff depths (in)

The solver function in Microsoft Excel was applied to maximize the R^2 of the dataset (i.e., minimizing the sum of residuals of data points from the P-Q_{pre} curve) by varying the S. The best fit of S was obtained when the maximal R^2 was reached. The best fit of CN was calculated from the best fit S by the established NRCS relation presented above as equation 4:

$$\mathrm{CN} = \frac{1000}{S_{fit} + 10} \tag{17}$$

where CN = Curve number

S_{fit} = Fitted potential maximum retention after runoff begins (in)

The coefficients of determination (R^2) of the precipitation-runoff (P-Q_{pre}) curve shall meet the statistical requirement for acceptance (i.e., $R^2 = 0.60$, performance evaluation criteria of “satisfactory”). An example of bare soil land treatment with subsoil hydraulic conductivity of 1.5 in/h is included as figure 19 to illustrate the data analysis method (i.e., calculation of individual CN and individual R^2 values) for one soil column.

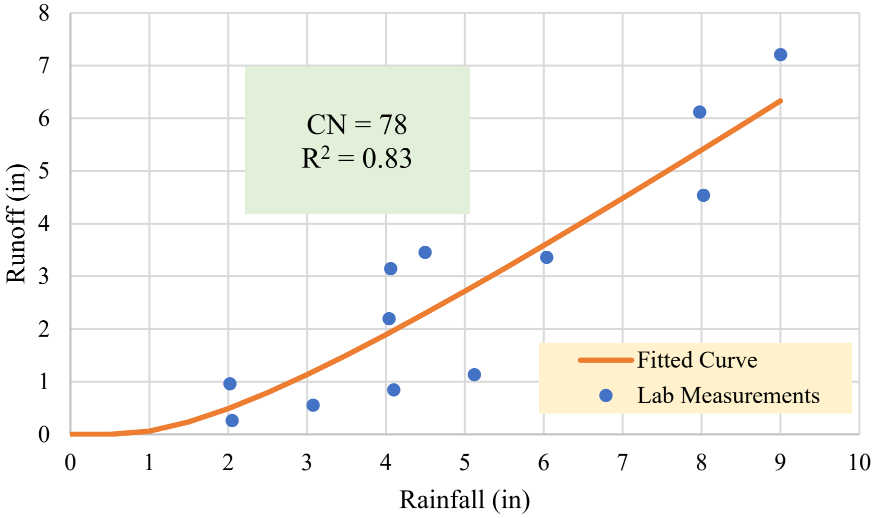


Figure 19. Data Analysis Using NRCS Method (land treatment of bare soil, subsoil hydraulic conductivity of 1.5 in/h, soil column replicate #2)

All the above-fitted individual CNs of bare soil, gravel, vegetation, and porous HMA are tabulated in table 9 and plotted versus composite hydraulic conductivities. The composite hydraulic conductivity is the measured infiltration rate at steady state (after the soil saturation) as shown in figure 17. A regression analysis (curve fitting) was conducted for each land treatment by using the trendline tool in Microsoft Excel. The exponential function was selected as the model for curve fitting because it had the best fit to the data points. The coefficients of determination (R^2) of the CN-composite hydraulic conductivity curve were calculated by the equation below and shall meet the statistical requirement for acceptance (lower limit of 0.60).

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(CN_{fit_i} - \overline{CN_{fit}}\right)\left(CN_{pre_i} - \overline{CN_{pre}}\right)}{\sqrt{\sum_{i=1}^{n}\left(CN_{fit_i} - \overline{CN_{fit}}\right)^2 \sum_{i=1}^{n}\left(CN_{pre_i} - \overline{CN_{pre}}\right)^2}}\right]^2 \quad (18)$$

where CN_{fit} = Fitted individual CN

CN_{pre} = CN predicted by the fitted curve

$\overline{CN_{fit}}$ = Arithmetic mean of fitted CNs for all the individual soil columns

$\overline{CN_{pre}}$ = Arithmetic mean of predicted CNs for all the individual soil columns

Runoff predictions were plotted versus runoff observations of all datasets and the Nash–Sutcliffe Efficiency Coefficient (NSE) of each land treatment was calculated by: (33)

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs_i} - Q_{pre_i})^2}{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q_{obs}})^2} \tag{19}$$

where Q_{obs} = Observed runoff depth (in)

Q_{pre} = Predicted runoff depth (in)

$\overline{Q_{obs}}$ = Arithmetic mean of observed runoff depths (in)

The NSE shall meet the statistical requirements for acceptance (0.64, the lower limit of a good fit). (33)

Furthermore, the three soil columns in one test (running simultaneously under the same test conditions) could be treated as replicates rather than as individual samples as done above. An uncertainty analysis for the treatment as replicates was conducted and shown in appendix K.

Data Analysis Results

Data analysis results are presented below for the Rational Method and the NRCS Method.

Rational Method

R^2 values of fitted runoff coefficient for individual soil column of all tested soil hydraulic conductivities and land treatments are listed in table 9. The ranges of R^2 values for bare soil, gravel, vegetation, and porous HMA are 0.52-0.68, 0.37-0.82, 0.50-0.92, and 0.52-0.97, respectively. The coefficients of determination (R^2) had the lowest value of 0.37 when runoff coefficients were fitted, which is far from meeting the statistical requirements for acceptance (0.60). This result points out the limitations in the Rational Method and thus its low accuracy in runoff prediction. Therefore, this method is not recommended for stormwater management design by agencies and their consultants and no further data analysis was conducted.

Table 9 - R^2 Values of Fitted Runoff Coefficient for Individual Soil Column of All Tested Soil Hydraulic Conductivities and Land Treatments

Soil Column Replicate #	Targeted Subsoil Hydraulic Conductivity (in/h)	Bare Soil		Gravel		Vegetation		Porous HMA	
		Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2
1	0.1	0.11	0.96	0.18	0.81	0.20	0.91	0.20	0.95
2			0.96		0.82		0.91		0.94
3			0.96		0.79		0.91		0.95
1	0.5	0.37	0.92	0.49	0.74	0.41	0.92	0.44	0.95
2			0.91		0.74		0.90		0.97
3			0.90		0.65		0.91		0.95
1	1.0	0.87	0.87	1.50	0.69	1.49	0.69	1.51	0.79
2			0.90		0.65		0.70		0.80
3			0.88		0.67		0.71		0.80
1	1.5	1.59	0.73	2.21	0.50	2.01	0.50	2.11	0.68
2			0.72		0.48		0.51		0.68
3			0.67		0.44		0.55		0.70
1	2.0	2.01	0.58	3.05	0.40	2.98	0.67	2.73	0.63
2			0.59		0.41		0.64		0.70
3			0.56		0.37		0.52		0.65
1	4.0	4.09	0.57	6.49	0.49	6.37	0.48	6.65	0.52
2			0.53		0.47		0.57		0.55
3			0.52		0.51		0.57		0.59
1	5.5	5.52	0.71	No runoff		No runoff		No runoff	
2			0.75						
3			0.76						
1	6.0	5.92	0.72						
2			0.67						
3			0.73						
1	8.0	No runoff							
2									
3									
1	10.0								
2									
3									
Range of R^2	/	0.52 - 0.96		0.37 - 0.82		0.50 - 0.92		0.52 - 0.97	

NRCS Method

The CN and R^2 values of fitted CNs for individual soil columns of all tested soil hydraulic conductivities and land treatments are listed in table 10. The curve fitting plots used to calculate these R^2 values are presented in appendix L. The ranges of R^2 values for bare soil, gravel, vegetation, and porous HMA are 0.61 to 0.98, 0.62 to 0.97, 0.61 to 0.99, and 0.60 to 0.99, respectively. All R^2 values are higher than or equal to the lower limit of 0.60.

Table 10 - CN and R^2 Values of Fitted CN for Individual Soil Column of All Tested Soil Composite Hydraulic Conductivities ($K_{sat\text{-}comp}$) and Land Treatments

Soil Column Replicate #	Targeted Subsoil Hydraulic Conductivity (in/h)	Bare Soil			Gravel			Vegetation			Porous HMA		
		$K_{sat\text{-}comp}$ (in/h)	CN	R^2	$K_{sat\text{-}comp}$ (in/h)	CN	R^2	$K_{sat\text{-}comp}$ (in/h))	CN	R^2	$K_{sat\text{-}comp}$ (in/h)	CN	R^2
1	0.1	0.12	95	0.98	0.18	79	0.96	0.20	87	0.98	0.17	92	0.99
2		0.09	94	0.98	0.19	79	0.97	0.21	87	0.99	0.22	91	0.99
3		0.11	95	0.98	0.17	78	0.95	0.20	87	0.98	0.20	91	0.99
1	0.5	0.39	91	0.95	0.45	74	0.93	0.37	86	0.98	0.41	89	0.99
2		0.32	92	0.96	0.53	73	0.86	0.46	86	0.98	0.41	90	0.99
3		0.36	91	0.96	0.48	73	0.94	0.40	85	0.98	0.50	89	0.99
1	1.0	0.90	86	0.95	1.53	64	0.84	1.46	69	0.85	1.52	75	0.91
2		0.72	87	0.94	1.50	64	0.80	1.51	69	0.85	1.52	75	0.91
3		0.98	86	0.95	1.50	66	0.87	1.51	69	0.87	1.50	74	0.91
1	1.5	1.65	76	0.78	2.12	55	0.69	2.03	61	0.70	2.12	67	0.79
2		1.50	78	0.83	2.21	54	0.66	1.99	62	0.72	2.12	67	0.79
3		1.62	77	0.82	2.28	54	0.62	2.01	62	0.75	2.10	67	0.80
1	2.0	2.00	72	0.65	3.06	50	0.65	2.90	59	0.74	2.65	62	0.64
2		2.03	71	0.66	2.87	51	0.64	2.66	61	0.77	2.85	65	0.75
3		1.98	71	0.68	3.20	48	0.64	3.34	53	0.61	2.68	64	0.69
1	4.0	4.04	61	0.80	6.36	36	0.85	6.46	37	0.71	6.62	38	0.60
2		4.16	60	0.77	6.67	34	0.88	6.39	39	0.77	6.69	41	0.60
3		4.05	60	0.77	6.46	36	0.89	6.26	41	0.81	6.62	42	0.62
1	5.5	5.55	52	0.61	No runoff			No runoff			No runoff		
2		5.50	54	0.67									
3		5.49	54	0.68									
1	6.0	5.93	49	0.64									
2		5.92	50	0.63									
3		5.96	49	0.63									
1	8.0	No runoff											
2													
3													
1	10.0												
2													
3													
Range of R^2	/	0.61 - 0.98			0.62 - 0.97			0.61 - 0.99			0.60 - 0.99		

The fitted CNs versus measured composite hydraulic conductivity of the four land treatments are presented below. The CNs for the individual test column of bare soil (figure 20), gravel (figure 21), vegetation (figure 22), and porous HMA (figure 23), respectively, are plotted versus the measured composite hydraulic conductivity. The measured composite hydraulic conductivity (the steady infiltration rate) varied slightly over the testing duration (e.g., over 2 hours) under different rainfall intensities (up to four) and were averaged before the regression analysis. The coefficients of determination ranged from 0.97 to 0.99 and met the statistical requirements for acceptance (lower limit of 0.60). These results indicate that there is an exponential relationship between CN and hydraulic conductivity.

The current practice of CN selection is relating one CN to one hydrologic soil group, which covers a wide range of hydraulic conductivities in most cases. This is essentially a many-to-one relationship, where several elements from the domain (i.e., various hydraulic conductivities from one soil group) correspond to a single element in the codomain (i.e., CN). The uncertainty due to the fact that one soil group covers a wide range of hydraulic conductivities will inevitably lead to errors in runoff prediction. As pointed out by Hawkins (2009), runoff calculation is more sensitive to the choice of CN than it is to the precision of the input rainfall P. (9) By contrast, the exponential equations obtained in this research established a one-to-one relationship between CN and hydraulic conductivity. As a result, a more realistic CN can be selected based on the actual hydraulic conductivity (when available), and a more accurate runoff prediction can be expected.

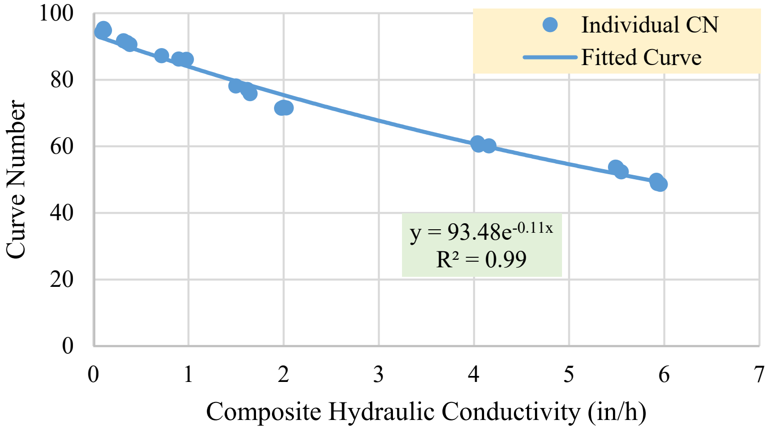


Figure 20. Relationship Between CN and Composite Hydraulic Conductivity of Bare Soil

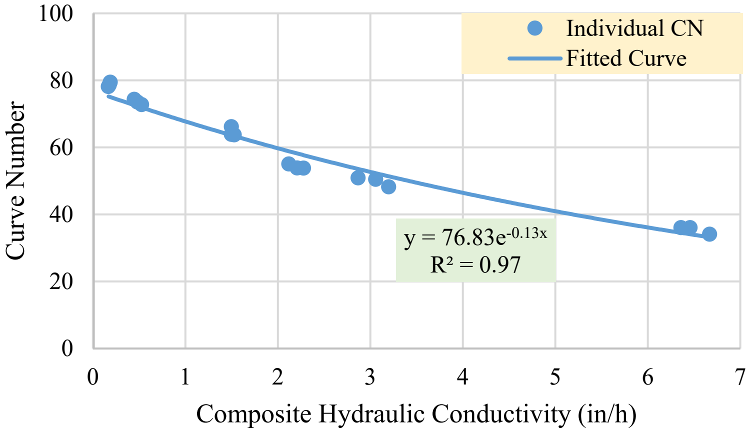


Figure 21. Relationship Between CN and Composite Hydraulic Conductivity of Gravel

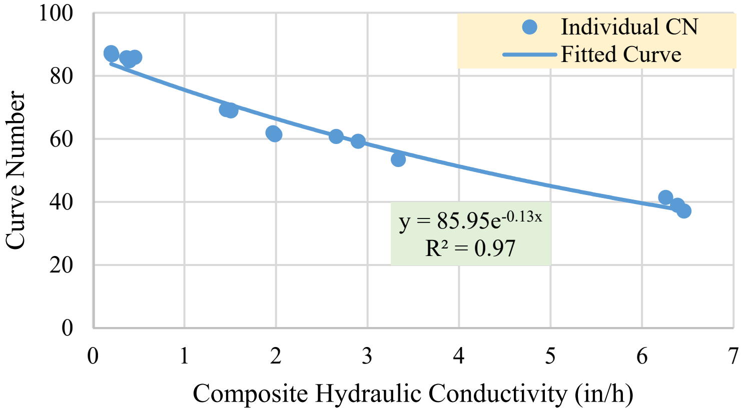


Figure 22. Relationship Between CN and Composite Hydraulic Conductivity of Vegetation

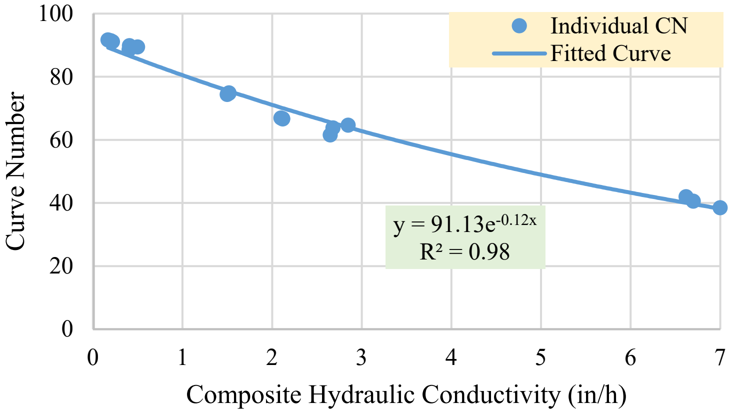


Figure 23. Relationship Between CN and Composite Hydraulic Conductivity of Porous HMA

Runoff predicted by the NRCS Method are compared to runoff observed in laboratory experiments. This comparison helped to determine how representative the NRCS Method is of the rainfall-runoff measurements. NSE values were calculated by equation 16 to statistically quantify this representativeness. NSE values are shown for bare soil (figure 24), gravel (figure 25), vegetation (figure 26), and porous HMA (figure 27), respectively. The NSE ranged from 0.88 to 0.93 and met the statistical requirements for acceptance (lower limit of 0.64). It should be noted that each point in the plots represents one "data point" defined earlier in section "Data Preparation".

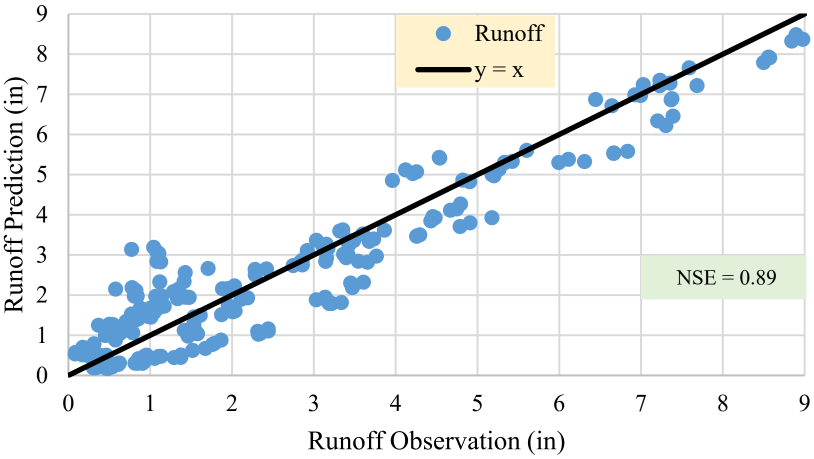


Figure 24. Comparison Between Runoff Prediction and Observation of Bare Soil

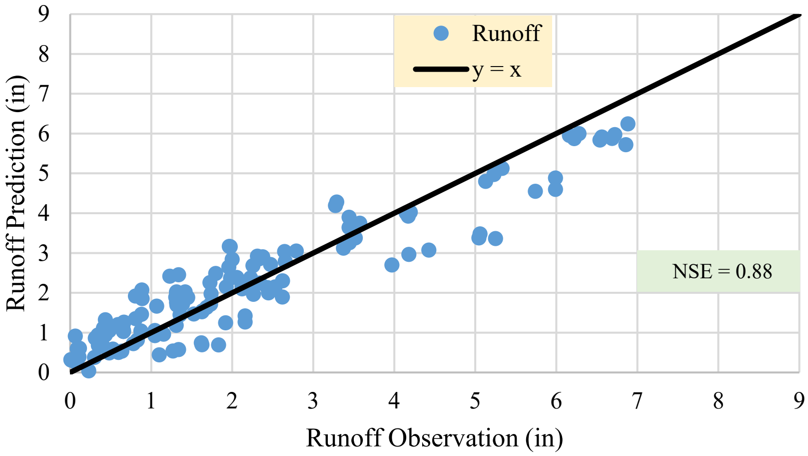


Figure 25. Comparison Between Runoff Prediction and Observation of Gravel

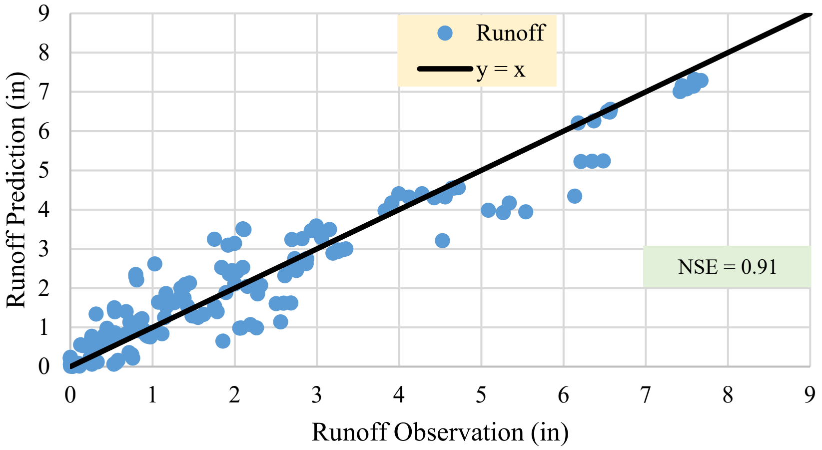


Figure 26. Comparison Between Runoff Prediction and Observation of Vegetation

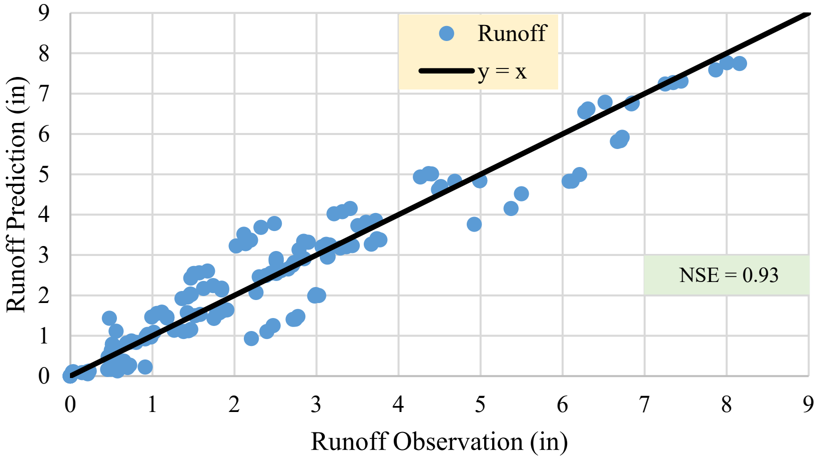


Figure 27. Comparison Between Runoff Prediction and Observation of Porous HMA

Translation of Lab Results to Field Applications

The field conditions should be the same or close to the laboratory testing conditions when applying the results obtained from the laboratory directly to the actual field. The laboratory-test design in this research project reflects typical field conditions (subsoils and land treatments) found throughout the State of New Jersey. However, there are two laboratory conditions that may deviate significantly from the field conditions. First, the laboratory tests were conducted in a vertical soil column without lateral flow. Therefore, to apply the laboratory results, infiltration in the field should be one-dimensional and vertical with negligible lateral flow. Second, the laboratory tests were conducted with the height of subsoil column of 8 in that is equivalent to depth to the groundwater table of 8 in from the bottom of the land treatment layers. The tested groundwater table was much shallower than those typical in the field. The initial abstraction was fully reached in every laboratory test as the subsoil was fully saturated and the steady infiltration was achieved (figure 17). That is, the 8-in height of the subsoil columns in the laboratory was sufficient to simulate the initial abstraction in the field. However, the hydraulic gradient imposed on the subsoil test column in the laboratory after the initial abstraction was reached (after the soil was saturated) was significantly larger than that in the field with much deeper groundwater tables. Direct translations in this regard were made (below) for applications of CNs obtained from the laboratory tests to field conditions.

According to equation 11, the composite hydraulic conductivity of a soil column is equal to the product of hydraulic gradient and subsoil hydraulic conductivity. In field conditions, depth to the groundwater table is usually deeper than 40 in. The hydraulic gradient of the composite soil column is close to 1.0. For example, according to equation 12, the hydraulic gradient is equal to 1.1 when depth of the land treatment is 4 inches and depth of the subsoil is 40 inches ((40+4)/40 = 1.1) and can be idealized as 1.0, as shown in figure 28. Therefore, in field conditions, composite hydraulic conductivities are equal to subsoil hydraulic conductivities. To validate this translation, a 44-in-high soil column was employed to evaluate CNs of four land treatments under the condition of large depth to groundwater table. Results (presented in appendix M) agreed well with the derivation.

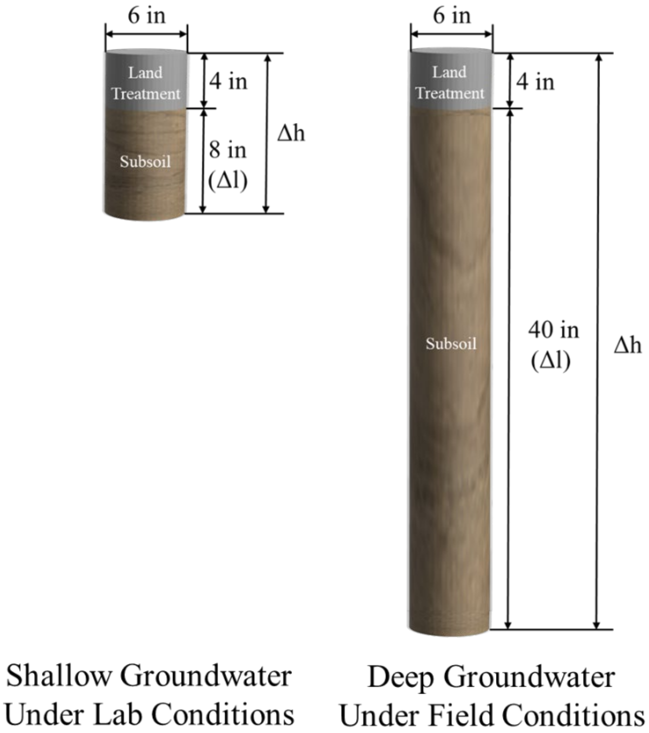
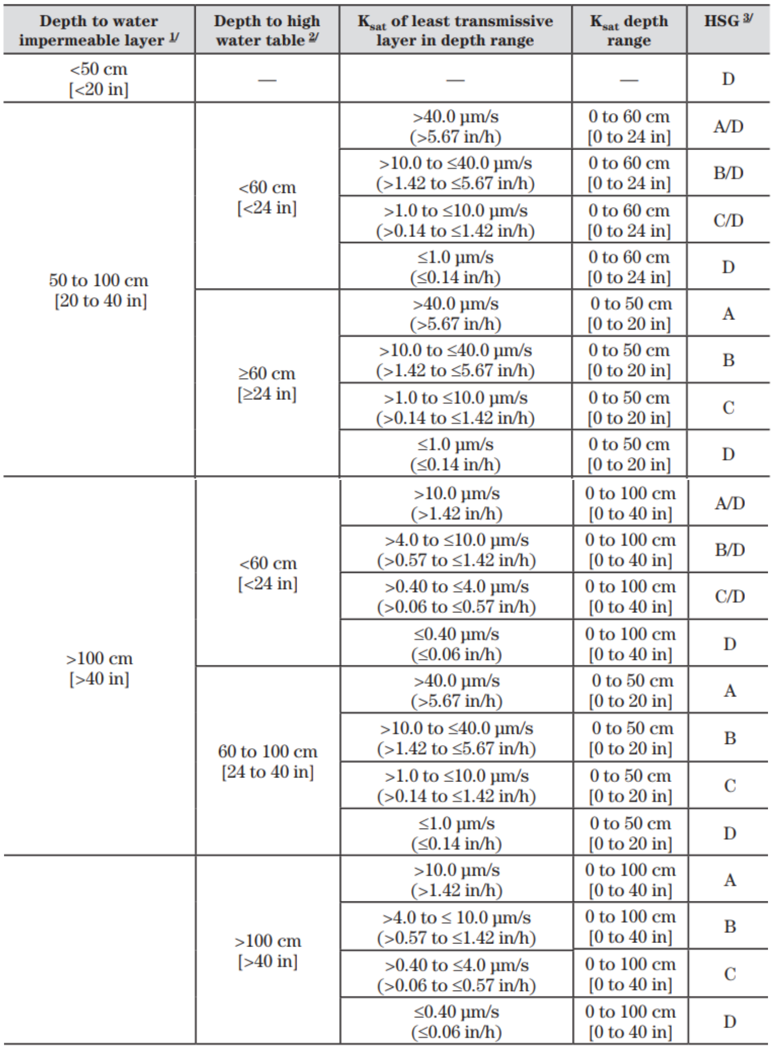


Figure 28. Translation of Results from Shallow Groundwater Table to Deep Groundwater Table in Subsoils

Therefore, in this section, the equation of CN versus composite hydraulic conductivity obtained in the data analysis was translated to the equation of CN versus subsoil hydraulic conductivity for field application.

In Table 7–1 Criteria for assignment of hydrologic soil group (table 11) in the National Engineering Handbook, Section 4, Hydrology, “Depth to Water Impermeable Layer”, “Depth to High Water Table”, and “saturated hydraulic conductivity” determine the hydraulic conductivity criteria for assignment of HSG. (7)

Table 11 - Criteria for assignment of hydrologic soil group (HSG) (7)



Depth to water impermeable layer [1/]	Depth to high water table [2/]	K_{sat} of least transmissive layer in depth range	K_{sat} depth range	HSG [3/]
<50 cm [<20 in]	—	—	—	D
50 to 100 cm [20 to 40 in]	<60 cm [<24 in]	>40.0 μm/s (>5.67 in/h)	0 to 60 cm [0 to 24 in]	A/D
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 60 cm [0 to 24 in]	B/D
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 60 cm [0 to 24 in]	C/D
		≤1.0 μm/s (≤0.14 in/h)	0 to 60 cm [0 to 24 in]	D
	≥60 cm [≥24 in]	>40.0 μm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 μm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
>100 cm [>40 in]	<60 cm [<24 in]	>10.0 μm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A/D
		>4.0 to ≤10.0 μm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B/D
		>0.40 to ≤4.0 μm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C/D
		≤0.40 μm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D
	60 to 100 cm [24 to 40 in]	>40.0 μm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 μm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
	>100 cm [>40 in]	>10.0 μm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A
		>4.0 to ≤ 10.0 μm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B
		>0.40 to ≤4.0 μm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C
		≤0.40 μm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D

The depth to the groundwater table is commonly larger than 40 in under the field conditions. In addition, according to Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer (ASTM D3385-18), infiltration rate should be tested when the water table is lower than 100 cm (39.4 in, approximately 40 in). Therefore, condition of deep groundwater table (depth to groundwater table (DTGT) > 40 in) was selected to be the condition for the assignment of hydrologic soil group in the CN curves and tables. In this case, HSG A/B, B/C, and C/D are differentiated by hydraulic conductivities of 1.42, 0.57, and 0.06 in/h.

Application CN curves of bare soil (figure 29), gravel (figure 30), vegetation (figure 31), porous HMA (figure 32), and the four land treatments combined (figure 33) are plotted versus subsoil hydraulic conductivity along with hydrologic soil group where applicable, respectively. It is recommended to select CNs through the measured in-situ hydraulic conductivity from the CN-hydraulic conductivity relationships presented for four different land treatments in figures 33 or regression equations 20, 21, 22, and 23, respectively.

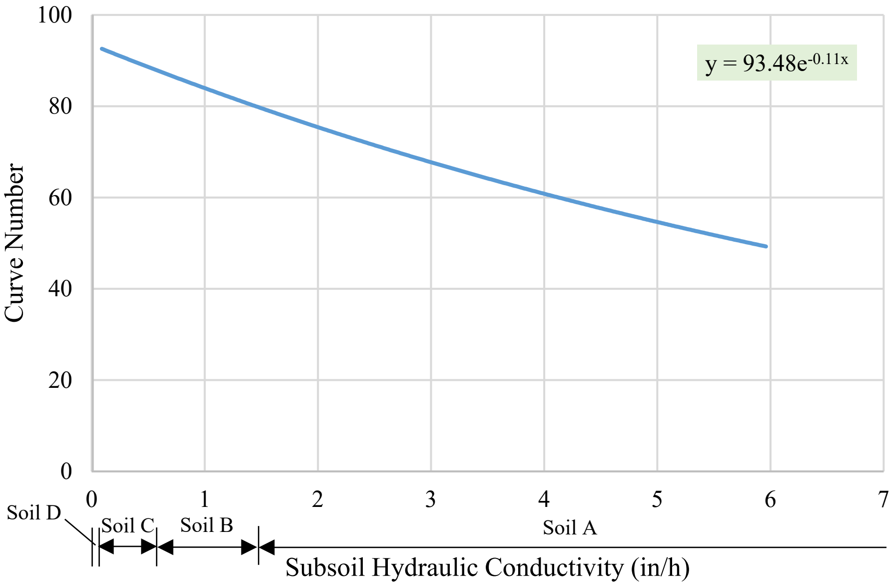


Figure 29. Application Curve for CN of Bare Soil (Depth to Groundwater Table > 40 in)

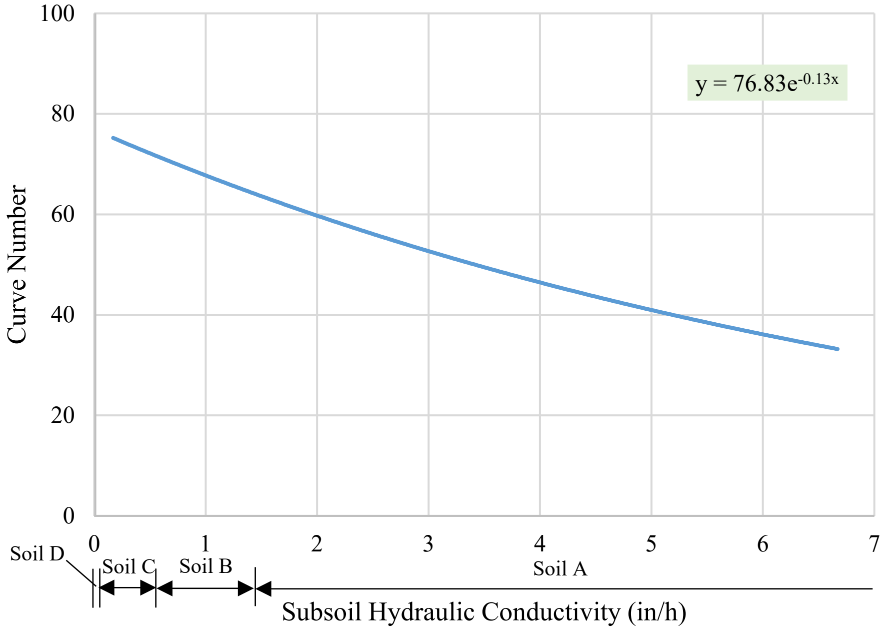


Figure 30. Application Curve for CN of Gravel (Depth to Groundwater Table > 40 in)

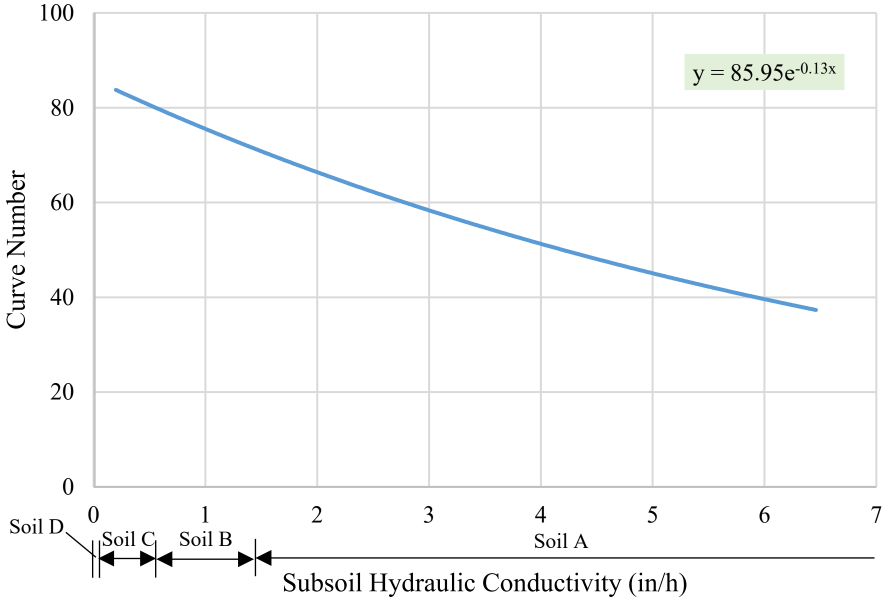


Figure 31. Application Curve for CN of Vegetation (Depth to Groundwater Table > 40 in)

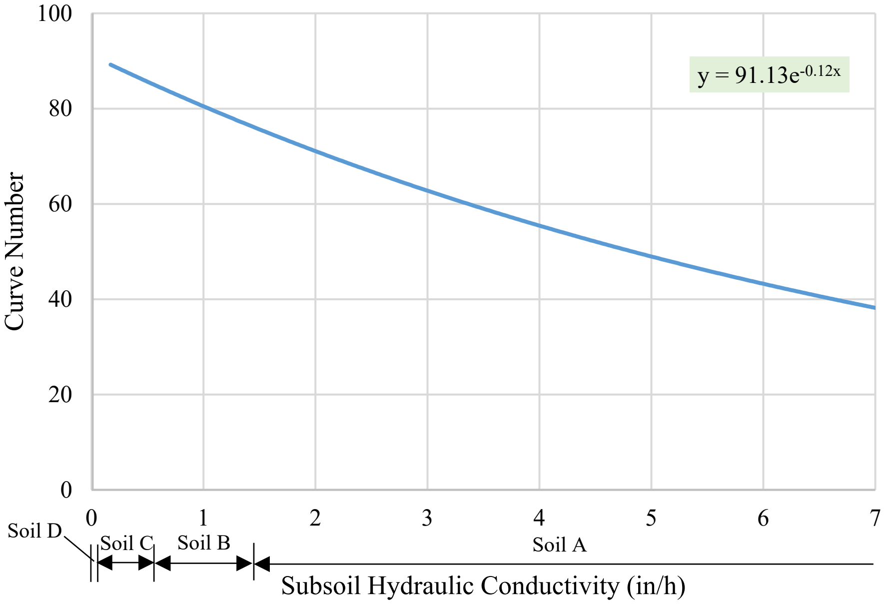


Figure 32. Application Curve for CN of Porous HMA
(Depth to Groundwater Table > 40 in)

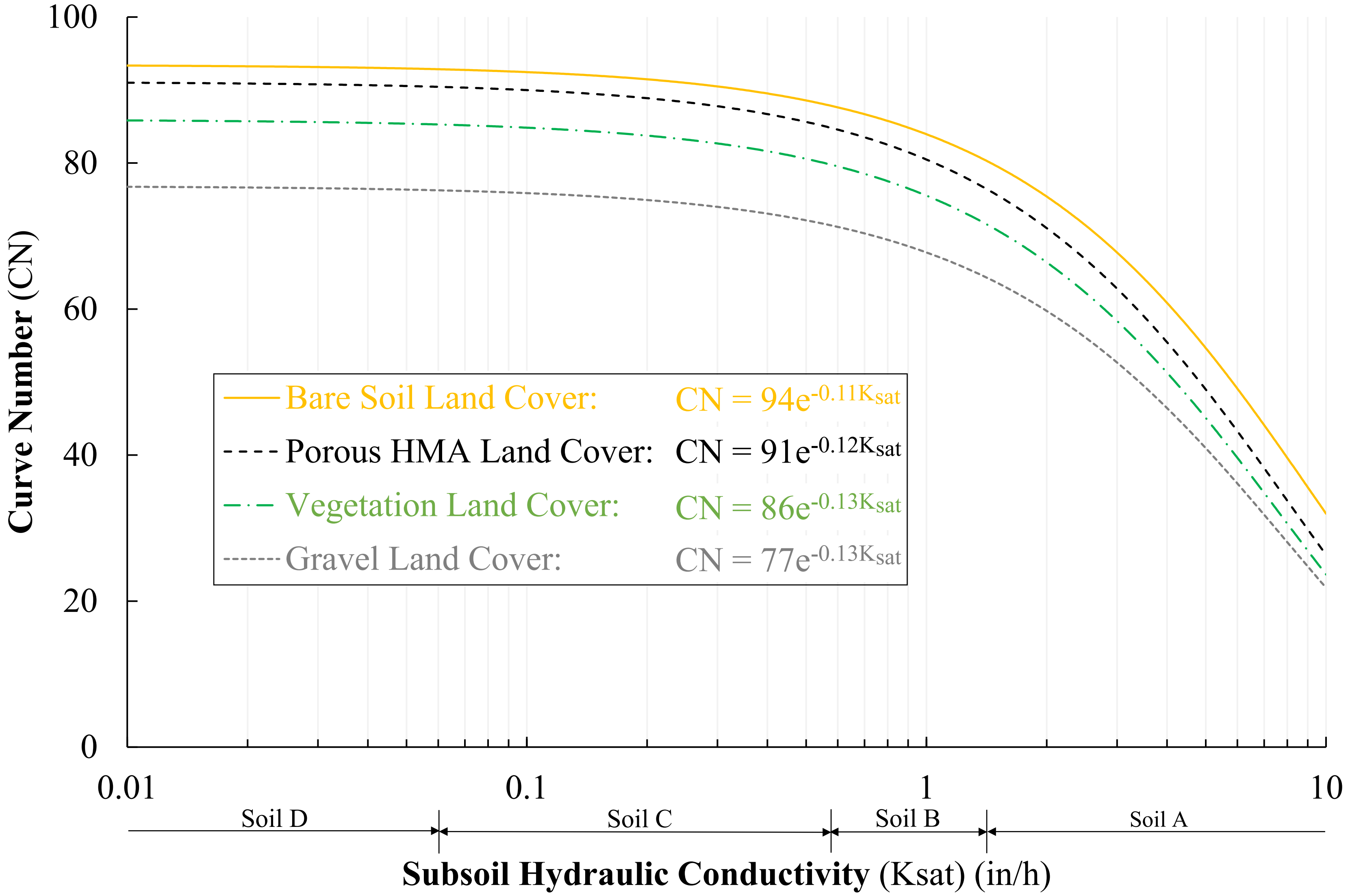


Figure 33. Application Curves and Equations for CN of Bare Soil, Gravel, Vegetation, and Porous HMA (Depth to Groundwater Table > 40 in)

The regression equations for the relationships between curve number (CN) and saturated hydraulic conductivity of subsoil (K_s) for bare soil, gravel, vegetation, and porous HMA land treatments (depth to groundwater table > 40 in):

Bare soil land cover: $CN = 94\, e^{-0.11\, K_s}$ (20)

Gravel land cover: $CN = 77\, e^{-0.13\, K_s}$ (21)

Vegetation land cover: $CN = 86\, e^{-0.13\, K_s}$ (22)

Porous HMA land cover: $CN = 91\, e^{-0.12\, K_s}$ (23)

where CN = Curve number

K_s = Saturated hydraulic conductivity of subsoil (in/h)

Table 12 - Comparison of Established and Fitted Curve Numbers

Hydrologic Soil Group (Depth to Groundwater Table > 40 in)	Hydraulic Conductivity (in/h)	Bare Soil		Gravel		Vegetation		Porous HMA	
		TR-55 for *Dirt* (NRCS 1986)	Rutgers Research Results	TR-55 (NRCS 1986)	Rutgers Research Results	TR-55 for *Lawns (Fair Condition)* (NRCS 1986)	Rutgers Research Results	TR-55 (NRCS 1986)	Rutgers Research Results
A	>1.42	72	<79	76	<64	49	<72	Not Available	<76
B	0.57-1.42	82	79-87	85	64-72	69	72-80		76-85
C	0.06-0.57	87	87-92	89	72-76	79	80-86		85-90
D	<0.06	89	>92	91	>76	84	>86		>90

Fitted CNs of bare soil, gravel, vegetation, and porous are compared in table 12 to established CNs of dirt (including right-of-way), gravel (including right-of-way), open space (lawns, fair condition), and porous HMA, respectively, found in the Natural Resources Conservation Services (NRCS) Technical Release 55 Method (TR-55). (4)

As can be seen from table 12 above, the CNs for bare soil and vegetation are similar to the established CNs for dirt (including right-of-way) and open space (lawns, fair condition) in TR-55, respectively. The CNs for gravel are significantly smaller than the established CNs for gravel (including right-of-way) in TR-55. The CNs for porous HMA were obtained from the research project but are not available in TR-55 for comparison.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to evaluate and develop curve numbers (CNs) for the Natural Resources Conservation Service (NRCS) Method and runoff coefficients (C) for the Rational Method. The following four land treatments within the Right of Way (ROW), median, and/or under guiderails were evaluated, which included (1) bare soil, (2) gravel, (3) vegetation, and (4) porous hot mix asphalt (HMA). A total of 113 soil column tests were conducted at the laboratory under various conditions of land treatment, subsoil hydraulic conductivity, rainfall intensity, and rainfall time interval. Measurements of rainfall, runoff, and infiltration were obtained, processed, and analyzed to quantify runoff-related coefficients. Laboratory results were translated to the conditions in the field (e.g., depth to the groundwater table larger than 40 inches), and the translated results were compared with established CNs of corresponding land treatments, where available, in NRCS TR-55. Based on the results of this project, the following conclusions and recommendations can be provided:

- Literature review found a significant variation in existing runoff-related coefficients. These coefficients varied by conditions such as rainfall intensity, rainfall duration, soil hydraulic conductivity, and our laboratory design has addressed these variable conditions.
- A lab-testing setting (i.e., soil column apparatus) was successfully designed and applied for research on soil hydrologic analysis. The results suggest that this soil column apparatus can be utilized to perform comprehensive rainfall-runoff studies, and runoff and infiltration behaviors of any permeable land treatments can be studied using this apparatus for different subsoil hydraulic conductivities.
- A data processing and analysis procedure (i.e., data truncation, regression analysis, uncertainty analysis) was successfully developed and applied for research on soil hydrologic analysis. The results suggest that this procedure can be used to perform comprehensive analysis of any rainfall-runoff data.
- Translation of CNs derived from the laboratory testing results to field applications was justified and is scientifically defensible.
- CNs for the NRCS Method were established for the four land treatments (i.e., bare soil, gravel, vegetation, and porous HMA) with 10 different subsoil hydraulic conductivities. Comparing with established CNs of corresponding land treatments, where available, in NRCS TR-55, CNs of bare soil and vegetation agreed well with existing values, CNs of gravel were significantly smaller than existing values, and CNs of porous HMA provided new data to this land treatment for which values were never established before.
- Exponential relationships were found between CNs and subsoil hydraulic conductivities for the four land treatments. These relationships enable a more accurate selection of CN based on the specific subsoil hydraulic conductivity. The introduction of this relationship reduces uncertainty in CNs by the fact that soil groups A, B, and C correspond to a wide range of subsoil hydraulic conductivities.
- The difference in CNs among land treatments is due to the variation in effective storage depths within land treatment layers. A larger effective storage depth can lead to a larger runoff reduction and a lower CN.

- The original NRCS Method has a better statistical performance and can be used to provide a more accurate runoff prediction compared to the current simplified NRCS Method. However, it is much more complicated to apply than the current simplified NRCS method as input of the rainfall intensity will be additionally needed. A relationship between initial abstraction and rainfall intensity excess over subsoil hydraulic conductivity was found. An initial abstraction model for gravel, vegetation, and porous HMA were also established. The relationship and model should be used if the original NRCS Method is applied.
- The current simplified NRCS Method with a proposed update of $I_a = 0.05S$ has a statistical performance that is similar to the current simplified NRCS Method where I_a was set to be 0.2S.
- The Rational Method has significant uncertainties in runoff quantification and cannot meet common statistical requirements for acceptance.

IMPLEMENTATION AND TRAINING

The research methods and the developed empirical equations, curves, and tables were shared with the NJDOT's Technical Advisory Panel (TAP).

The research methods and findings will be presented at the NJDOT Virtual Research Showcase Lunchtime Edition on April 26, 2023. The abstract was submitted and accepted for the presentation.

The research methods and findings will be presented during the Curve Number Hydrology Session at the ASCE-EWRI World Environmental and Water Resources Congress 2023 in Henderson, Nevada on May 26, 2023. The abstract was submitted and accepted for the presentation.

REFERENCES

1. New Jersey Department of Environmental Protection, *N.J.A.C. 7:8, Stormwater Management*. NJDEP, Trenton, 2020.
2. New Jersey Department of Environmental Protection, *NJ Stormwater Best Management Practices Manual.* NJDEP, Trenton, 2021.
3. Natural Resources Conservation Service, *National Engineering Handbook*. NRCS, Washington, D.C., 1969.
4. Natural Resources Conservation Service. *Urban Hydrology for Small Watersheds. Technical Release No. 55 (TR-55)*. NRCS, Washington, D.C, 1986.
5. Natural Resources Conservation Service, *National Engineering Handbook*. NRCS, Washington, D.C., 1997. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=18380.wba
6. Natural Resources Conservation Service, *National Engineering Handbook*. NRCS, Washington, D.C., 2004. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17758.wba
7. Natural Resources Conservation Service, *National Engineering Handbook*. NRCS, Washington, D.C., 2009. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22526.wba
8. Natural Resources Conservation Service, *Executive Summary to the Curve Number Update Project*, NRCS, Washington, D.C., 2017. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=41604.wba
9. R. H. Hawkins, D. E. Ward, D. E. Woodward, and J. A. Van Mullem. *Curve number hydrology: State of the Practice*. ASCE, Reston, 2009.
10. E. Fassman-Beck, W. Hunt, R. Berghage, D. Carpenter, T. Kurtz, V. Stovin, and B. Wadzuk. “Curve Number and Runoff Coefficients for Extensive Living Roofs.” *Journal of Hydrologic Engineering*, Vol. 21 No. 3, (March 2016).
11. S. S Schwartz. “Effective Curve Number and Hydrologic Design of Pervious Concrete Storm-Water Systems.” *Journal of Hydrologic Engineering*, Vol. 15 No. 6, (June 2010), pp 465–474.
12. H. Poertner. *Practices in Detention of Urban Stormwater Runoff*. APWA Special Report No. 43. American Public Works Association, 1974.
13. T. J. Mulvaney. “On the use of self-registering rain and flood gauges.” *Transactions of the Institution of Engineers, Ireland*, Vol. 4 No. 2, (1850), pp 1–8.
14. New Jersey Department of Agriculture, *Standards for Soil Erosion and Sediment Control in New Jersey*. NJDA, Trenton, 1999.
15. New Jersey Department of Transportation. *Roadway Design Manual*. NJDOT, Ewing, 2015.
16. E. Fassman-Beck, W. Hunt, R. Berghage, D. Carpenter, T. Kurtz, V. Stovin, and B. Wadzuk. “Curve Number and Runoff Coefficients for Extensive Living Roofs.” *Journal of Hydrologic Engineering*, (March 2016), Vol. 21 No. 3.
17. Y. Li, C. Li, W. Mu, J. Liu, and D. Yan. “Analysis of Bare Soil and Grassland Rainfall-runoff Experiment in Different Slope Gradient and Antecedent Soil Moisture Content.” (in Chinese with English abstract) *Science Technology and Engineering*, Vol. 17 No. 14, (May 2017), pp 45-53.

18. Y. Xu, X. Xu, T. Yu, and Y. Zhang. “Factor Analysis of Runoff Coefficient Subjected to Heavy Rainfall on Urban Lawns with Backfill Soil.” (in Chinese with English abstract) *Journal of Soil and Water Conservation*, Vol. 28 No. 6, (December 2014), pp 82-87.
19. S. Wu, J. Xie, Z. Wang, and S. Wang. “Runoff Coefficient Forecasting of Greenbelt Based on ε- support Vector Regression.” (in Chinese with English abstract) *Journal of Shenyang Agricultural University*, Vol. 38 No. 1, (February 2007), pp 102-105.
20. M. Huang, J. Gallichand, Z. Wang, and M. Goulet. “A modification to the Soil Conservation Service curve number method for steep slopes in the Loess Plateau of China.” *Hydrological Processes*, Vol. 20 No. 3, (February 2006), pp 579-589.
21. S. P. Kakuturu, M. B. Chopra, M. Hardin, and M. P. Wanielista. “Runoff Curve Numbers for Simulated Highway Slopes under Different Slope, Soil-Turf, and Rainfall Conditions.” *Journal of Hydrologic Engineering*, Vol. 18 No. 3, (March 2013), pp 299–306.
22. M. S. St. John and R. R. Horne. *Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity*. Report WA-RD 429.1. Washington State Department of Transportation, 1997.
23. K. Davies, M. A. Fullen, and C. A. Booth. “A pilot project on the potential contribution of palm-mat geotextiles to soil conservation.” *Earth Surface Processes and Landforms*, Vol. 31 No. 5, (April 2006), pp 561-569.
24. T. Smets, J. Poesen, R. Bhattacharyya, M. A. Fullen, M. Subedi, C. A. Booth, A. Kertész, Z. Szalai, A. Toth, B. Jankauskas, G. Jankauskiene, A. Guerra, J. F. R. Bezerra, Z. Yi, M. Panomtaranichagul, C. Bühmann, and D. G. Paterson. “Evaluation of biological geotextiles for reducing runoff and soil loss under various environmental conditions using laboratory and field plot data.” *Land Degradation & Development*, Vol. 22 No. 5, (October 2011), pp 480–494.
25. H. Yang et al. “A Soil Column Apparatus for Laboratory Infiltration Study.” *Geotechnical Testing Journal*, Vol. 27 No. 4, (June 2004), pp 347-355.
26. M. E. Barrett. “Effects of a Permeable Friction Course on Highway Runoff.” *Journal of Irrigation and Drainage Engineering*, Vol 134 No. 5, (October 2008), 646–651.
27. M. G. Schaap, F. J. Leij, and M. Th. van Genuchten. “ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions” *Journal of Hydrology,* Vol. 251 No. 3-4, (October 2001), pp 163-176.
28. New Jersey Department of Transportation, *Standard Specifications for Road and Bridge Construction*. NJDOT, Ewing, 2019.
29. New Jersey Department of Transportation. *Updated Standard Specifications for Road and Bridge Construction 2007*. NJDOT, Ewing, 2007.
30. Natural Resources Conservation Service. *Soil Quality Physical Indicator Information Sheet Series*. NRCS, Washington D. C., 2008. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053288.pdf
31. New Jersey Department of Environmental Protection. *NJ Stormwater Best Management Practices Manual, Chapter 5*. NJDEP, Trenton, 2021.
32. D. N. Moriasi, M. W. Gitau, N. Pai, and P. Daggupati. “Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria.” *Transactions of the ASABE*, Vol. 58 No. 6, (December 2015), pp 1763-1785.
33. D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. “Model Evaluation Guidelines for Systematic Quantification of Accuracy in

Watershed Simulations.” *Transactions of the ASABE*, Vol. 50 No. 3, (March 2007), pp 885-900.

34. M. Smithson, *Confidence Intervals*. SAGE, New York, 2003.
35. Natural Resources Conservation Service, *National Engineering Handbook, Chapter 10, ASCE-ASABE Proposed CN Update*. NRCS, Washington, D.C., 2017. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=41607.wba
36. W. S. Gosset. “The probable error of a mean” *Biometrika*, Vol. 6 No. 1, (March 1908), pp 1-25.
37. Minnesota Pollution Control Agency, *Minnesota Stormwater Manual: Soil water storage properties*. MPCA, St Paul, 2022. https://stormwater.pca.state.mn.us/index.php?title=Soil_water_storage_properties
38. Soil Lab Modules. *Soil bulk density*. 2022. https://labmodules.soilweb.ca/soil-compaction-bulk-density

APPENDIX A SPECIFICATIONS OF NJDOT LAND TREATMENT

Table 13 – Specifications of NJDOT Land Treatment

Land Use	Layer	Gradation (Nominal Size)	Depth (in)	Compaction	Notes
Porous Pavement	Porous HMA (1)	3/8” / 0.187” (1,2)	4 (3) / 6 (3,4)	95-97% of theoretical max density (5)	/
	Aggregate base (6,7)	3/4”	< 8 (per lift) (8)	Q >= 0.36 (9)	
	Subsoil	/	/	>= 95% of max density (10)	
Vegetated	Topsoil (11)	/	4 (12,13)	/	Vegetation coverage >= 95% (15)
	Scarified subsoil		12 (14)		
	Subsoil		/	>= 95% of max density (10)	
Unvegetated	Polyester matting (16)	/	> 0.25 (16)	/	/
	Subsoil		/	>= 95% of max density (10)	
Gravel	Broken stone (Aggregate No.3) (17,18)	2″	4 (3)	/	/
	Subsoil	/	/	>= 95% of max density (10)	

Reference	Specification	Page	Section	Subsection
(1)	NJDOT 2019	299	608	608.02.01
(2)	NJDOT 2019	392	902	Table 902.02.03-1
(3)	NJDOT 2015	8-19	8.3.5	Table 8-5
(4)	NJDOT 2016	56	CD-606-5.4	Figure Type D
(5)	NJDOT 2019	394	902	Table 902.02.04-1
(6)	NJDOT 2019	142	302	302.02.01
(7)	NJDOT 2019	385	901	Table 901.10.01-1, Table 901.10.03-1
(8)	NJDOT 2019	142	302	302.03.01
(9)	NJDOT 2019	143	302	302.03.01
(10)	NJDOT 2019	139	203	203.03.02-B-2-b
(11)	NJDOT 2019	496	917	Table 917.01-2
(12)	NJDOT 2019	365	803	803.03.01
(13)	NJDOT 2016	61	CD-608-1.1	/
(14)	NJDOT 2019	365	804	804.03.01
(15)	NJDOT 2019	368	806	806.03.01-E
(16)	NJDOT 2019	516	919	919.15
(17)	NJDOT 2019	300	608	608.03.03
(18)	NJDOT 2019	378	901	Table 901.03-1
2015:	Roadway Design Manual			
2016:	Standard Construction Details			
2019:	Standard Specifications for Road and Bridge Constructions			

APPENDIX B RUNOFF-RELATED COEFFICIENTS OBTAINED FROM LITERATURE REVIEW

Table 14 – Runoff-Related Coefficients for Bare Soil with Polyester Matting

Source	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Runoff Coefficient	CN	Test conditions (Similar with DOT tests?)
Bhattacharyya et al. 2010	Bare soil with different geotextiles	/	Average 66% reduction	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting
Code for outdoor drainage engineering, 2006	Bare soil	/	0.25-0.35	/	Conditions unknown
Davies et al. 2006	Palm-mat geotextiles	D	0.0041	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting
Luo et al. 2013	Non-woven fabrics	/	0.19	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting
	Shade net		0.14		
	Straw mats		0.06		
Shao et al. 2013	Bare soil with jute mat	/	Average 62.1% reduction	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting
	Bare soil with polyester mat		Average 57.7% reduction		
	Bare soil with polyester net		Average 16.6% reduction		

Source	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Runoff Coefficient**	**CN**	**Test conditions (Similar with DOT tests?)**
Smets et al. 2011	Bare soil with four different geotextiles	/	Average 46% reduction	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting
Specifications for Drainage Design of Highway, 2012	Bare soil	/	0.40-0.65 (fine soil) 0.10-0.30 (coarse soil)	/	Conditions unknown
Urban Roadway Design Handbook, 1985	Bare soil	/	0.30	/	Conditions unknown
Yue et al. 2015	Vegetation carpet	/	0.239-0.537	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting

Table 15 – Runoff-Related Coefficients for Gravel

Source	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Runoff Coefficient**	**CN**	**Test conditions (Similar with DOT tests?)**
Code for outdoor drainage engineering, 2006	Gravel	/	0.40-0.50	/	Conditions unknown
Gilbert and Clausen 2006	Gravel pavement	B	0.02	/	Different conditions: Gradation does not follow DOT requirement
Kang et al. 2016	Gravel with soil	A	0.15-0.68	/	Similar conditions: limited effect on hydrologic performance due to the gravel layer depth deviation
NRCS 1986	Gravel pavement	A	/	76	Conditions unknown
		B		85	
		C		89	
		D		91	
Specifications for Drainage Design of Highway, 2012	Gravel	/	0.40-0.60	/	Conditions unknown
St. John and Horner 1997	Gravel pavement	A/B	0.65	/	Similar conditions: gradation does not follow DOT requirement
			0.8		
Urban Roadway Design Handbook, 1985	Gravel	/	0.45	/	Conditions unknown

Table 16 – Runoff-Related Coefficients for Vegetation

Source	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Runoff Coefficient**	**CN**	**Test conditions (Similar with DOT tests?)**
Backstrom 2002	Grass swale	/	0.34-0.67	/	Similar conditions: soil and coverage conditions unknown
Battiata et al. 2010	Dry swale	/	40-60% reduction	/	Similar conditions: soil and coverage conditions unknown
Code for outdoor drainage engineering, 2006	Grass	/	0.10-0.20	/	Conditions unknown
Fu et al. 2013	Grass	A	/	35.7	Conditions unknown
		B		73.8	
Huang et al. 2006	Grass	A	/	71.1-87.8	Similar conditions: limited effect on hydrologic performance due to the small coverage deviation
Kakuturu et al. 2013	Turf covered soil	A/B	/	79.6	Similar conditions: soil and coverage conditions unknown
		B/C		94	
Li et al. 2008	Grass	A	/	73.56	Conditions unknown
Li et al. 2017	Grass	B	0.02-0.55	/	Similar conditions: soil and coverage conditions unknown
Lian et al. 2020	Grass	B	/	94.73	Conditions unknown
				71.88	
				64.07	
				64.16	
Luo et al. 2002	Grass	A	/	77.8	Similar conditions: soil and coverage conditions unknown
Rushton 1999	Grass swale	A	0.16-0.35		Similar conditions: soil and coverage conditions unknown

Source	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Runoff Coefficient	CN	Test conditions (Similar with DOT tests?)
Sample et al. 2001	Grass swale	A	/	46	Conditions unknown
		B		65	
		C		77	
		D		82	
Specifications for Drainage Design of Highway, 2012	Grass	/	0.40-0.65	/	Conditions unknown
Stagge 2006	Grass swale	/	46-54% reduction	/	Similar conditions: soil and coverage conditions unknown
Urban Roadway Design Handbook, 1985	Grass	/	0.15	/	Conditions unknown
Wu et al. 2007	Grass	A	0.40-0.98	/	Similar conditions: soil conditions unknown
Xu et al. 2014	Grass	B	0-0.44	/	Similar conditions: soil and coverage conditions unknown
Zhu et al. 2003	Grass	A, B, C, D	0.13-0.33	/	Different conditions: vegetation coverage lower than required

Table 17 – Runoff-Related Coefficients for Porous HMA

Source	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Runoff Coefficient**	**CN**	**Test conditions (Similar with DOT tests?)**
Abbott and Comino-Mateos 2003	Porous block	/	0.67	/	Different conditions
Barrett 2008	Porous friction course	/	1.0	/	Different conditions
Battiata et al. 2010	Permeable pavement	/	45-75% reduction	/	Test conditions unknown
Bean et al. 2007	Concrete grid paver	A	/	77-91	Similar conditions: limited effect on hydrologic performance due to the porous pavement depth deviation
	Porous concrete			80	
	Permeable interlocking concrete paver			44	
	Permeable interlocking concrete paver			73	
Cheng et al. 2019	Permeable interlocking concrete paver and porous asphalt	/	0.23-0.84	/	Similar conditions: limited effect on hydrologic performance due to the porous pavement depth deviation
Code for outdoor drainage engineering 2006	Porous pavement	/	0.85-0.95	/	Conditions unknown

Source	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Runoff Coefficient	CN	Test conditions (Similar with DOT tests?)
Collins et al. 2008	Concrete grid paver	D	0.36	/	Different conditions
Collins et al. 2008	Porous concrete	D	0.56	/	Different conditions
	Permeable interlocking concrete paver		0.34		
	Permeable interlocking concrete paver		0.62		
Drake et al. 2014	Permeable interlocking concrete paver	D	0.57	/	Different conditions
Dreelin et al. 2006	Grassy paver	B	0-0.26 (Average 0.1)	/	Different conditions
Fassman and Blackbourn 2010	Permeable interlocking concrete paver	/	0.29-0.67	/	Different conditions
Feng et al. 2019	Porous asphalt	/	0.011-0.671	/	Similar conditions: limited effect on hydrologic performance due to the porous pavement depth deviation
Gilbert and Clausen 2006	Permeable interlocking concrete paver	B	0.4	/	Different conditions

Source	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Runoff Coefficient	CN	Test conditions (Similar with DOT tests?)
James and Thompson 1997	Permeable interlocking concrete paver	/	0.38	/	Different conditions
Jayasuriya and Kadurupokune 2007	Turf cell	/	0.4-0.5	/	Different conditions
Legret and Colandini 1999	Porous asphalt	/	0.033	/	Different conditions
Li et al. 2018	Porous asphalt	/	0.07-0.29	/	Different conditions
Mahmoud et al. 2020	Permeable interlocking concrete paver	D	0.18	/	Different conditions
Martin and Kaye 2014	Porous pavement	/	/	/	Different conditions
Pagotto 2000	Porous friction course	/	0.98	/	Different conditions
Pratt et al. 1995	Permeable concrete block pavement	/	0.34-0.45	/	Different conditions
Roseen et al. 2012	Porous asphalt	C	0.75	/	Different conditions
Sample et al. 2001	Permeable pavement	A	/	70	Similar conditions: limited effect on hydrologic performance due to the small pavement gradation deviation
		B		80	
		C		85	
		D		87	
Schwartz 2010	Porous pavement	/	/	/	Different conditions

Source	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Runoff Coefficient**	**CN**	**Test conditions (Similar with DOT tests?)**
Specifications for Drainage Design of Highway 2012	Porous pavement	/	0.95	/	Conditions unknown
St. John and Horner 1997	Porous asphalt	A/B	0.12	/	Different conditions
			0.4		
Urban Roadway Design Handbook 1985	Porous pavement	/	0.9	/	Conditions unknown

APPENDIX C RAINFALL-RUNOFF DATABASES OBTAINED FROM LITERATURE REVIEW

Table 18 – Rainfall-Runoff Database(s) for Bare Soil with Polyester Matting

Source	Location	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Rainfall Depth/ Volume Data Available?	Runoff Depth/ Volume Data Available?	Other Data Available ?	Test conditions (Similar with DOT tests?)
Guo et al. 2019	Inner Mongolia, China	Vegetation carpet	A	Rainfall Volume	Runoff Volume	/	Similar conditions: other types of matting with the same hydrologic performance as polyester matting

Table 19 – Rainfall-Runoff Database(s) for Gravel

Source	Location	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Rainfall Depth/ Volume Data Available?	Runoff Depth/ Volume Data Available?	Other Data Available ?	Test conditions (Similar with DOT tests?)
Zhu and Shao 2006	Beijing, China	Gravel with Soil	A	Rainfall Volume	Runoff Volume	/	Similar conditions: gravel layer depth unknown

Table 20 – Rainfall-Runoff Database(s) for Vegetation

Source	Location	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Rainfall Depth/ Volume Data Available ?	Runoff Depth/ Volume Data Available ?	Other Data Available ?	Test conditions (Similar with DOT tests?)
International Stormwater BMP Database, 1994b	Austin, TX 78701	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage less than DOT requirement
International Stormwater BMP Database, 1999	Vista, CA 92008, US	Grass swale	/	Yes	Yes	Yes	Similar conditions: soil and coverage conditions unknown
International Stormwater BMP Database, 2001	Orange, CA, US	Grass strip	B	Yes	Yes	Yes	Similar conditions: soil and coverage conditions unknown
International Stormwater BMP Database, 2001b	San Onofre, CA 92054, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage does not follow DOT requirement
International Stormwater BMP Database, 2001c	Yorba Linda, CA 92870, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage does not follow DOT requirement
International Stormwater BMP Database, 2001d	Orange, CA, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage does not follow DOT requirement
International Stormwater BMP Database, 2001e	Orange, CA, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage does not follow DOT requirement

Source	Location	Land Cover	Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)	Rainfall Depth/ Volume Data Available ?	Runoff Depth/ Volume Data Available ?	Other Data Available ?	Test conditions (Similar with DOT tests?)
International Stormwater BMP Database, 2007	Moreno Valley, CA 92553, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage does not follow DOT requirement
International Stormwater BMP Database, 2007b	Murrieta, CA 92562, US	Grass strip	C	Yes	Yes	Yes	Different conditions: vegetation coverage DOT requirement
International Stormwater BMP Database, 2007c	Auckland, ZZ, NZ	Bioswale	/	Yes	Yes	Yes	Similar conditions: soil and coverage conditions unknown
International Stormwater BMP Database, Alta Vista Planned Unit Development	Austin, TX 78757	Grass Swale	/	Yes	Yes	Yes	Different conditions: vegetation coverage less than DOT requirement
Luo et al. 1990	Shanxi, China	Grass	A	Yes	Yes	/	Different conditions: vegetation coverage does not follow DOT requirement
Zhu et al. 2003	Fujian, China	Grass	A, B, C, D	Yes	Yes	/	Different conditions: vegetation coverage does not follow DOT requirement

Table 21 - Rainfall-Runoff Database(s) for Porous HMA

Source	**Location**	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Rainfall Depth/ Volume Data Available ?**	**Runoff Depth/ Volume Data Available ?**	**Other Data Available ?**	**Test conditions (Similar with DOT tests?)**
International Stormwater BMP Database, 1994	Lakewood, CO 80215, US	Permeable pavement	C	Yes	Yes	Yes	Similar conditions: pavement conditions and gravel depth unknown
International Stormwater BMP Database, 2003	Swansboro, NC 28584	Permeable pavement	A	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2005	Lakewood, CO 80215, US	Porous concrete	C	Yes	Yes	Yes	Similar conditions: pavement conditions and gravel depth unknown
International Stormwater BMP Database, 2006	Auckland, NZ	Porous pavement – Modular blocks	/	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2006b	Kinston, NC 28501, US	Permeable concrete	/	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2009	Fort Collins, CO 80524	Permeable pavement	B	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2010	Benson, NC 27504, US	Open graded asphalt friction course	/	Yes	Yes	Yes	Similar conditions: limited effect on hydrologic performance due to the porous pavement depth deviation

Source	**Location**	**Land Cover**	**Soil Type (Hydrologic Soil Group and/or Hydraulic Conductivity)**	**Rainfall Depth/ Volume Data Available ?**	**Runoff Depth/ Volume Data Available ?**	**Other Data Available ?**	**Test conditions (Similar with DOT tests?)**
International Stormwater BMP Database, 2010b	Durham, NH 3824, US	Pervious concrete	/	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2010c	Benson, NC 27504, US	Pervious concrete	/	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2012	Perkins Township, OH 44870	Permeable pavement	D	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, 2012b	Lakewood, CO 80215	Slotted concrete	/	Yes	Yes	Yes	Different conditions
International Stormwater BMP Database, LakewoodPC	Lakewood, CO 80215, US	Permeable pavement	/	Yes	Yes	Yes	Different conditions: gravel gradation does not follow DOT requirement
Qin 2017	Beijing, China	Porous concrete	B	Yes	Yes	/	Different conditions

APPENDIX D SOIL PROPERTIES OF NATURAL AND LABORATORY SOILS FOR COMPARISON

Table 22 - Soil Properties of Natural and Laboratory Soils for Comparison

Soil Group	Porosity		Field Capacity		Drainable Porosity*		Bulk Density (g/cm^3)	
	Natural (37)	Lab	Natural	Lab	Natural	Lab	Natural	Lab
A	0.43-0.45	0.48±0.05	0.09-0.17	0.20±0.02	0.26-0.35	0.28±0.05	1.00-1.80 (38)	1.39±0.14
B	0.47-0.50	0.41±0.01	0.25-0.32	0.20±0.01	0.19-0.22	0.21±0.01		1.57±0.02
C	0.40-0.49	0.40±0.01	0.25-0.33	0.21±0.01	0.17-0.18	0.18±0.01		1.60±0.03
D	0.43-0.51	0.38±0.01	0.30-0.37	0.22±0.01	0.14-0.16	0.16±0.01		1.66±0.02

*Drainable porosity = porosity – field capacity

APPENDIX E PROPERTIES OF SUBSOILS USED IN LAND TREATMENT TESTS

Table 23 - Properties of Subsoils Used in Bare Soil Land Treatment Tests

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Bare Soil	1	0.14	9.1	81	18	1	1.68	0.37	0.23
		0.12	4.0						0.22
		0.11	1.0						0.22
		0.12	0.5						0.23
	2	0.11	9.0	81	18	1	1.67	0.37	0.23
		0.07	4.1						0.22
		0.09	1.0						0.22
		0.09	0.5						0.21
	3	0.13	8.9	81	18	1	1.62	0.39	0.21
		0.12	3.9						0.22
		0.10	1.0						0.22
		0.11	0.5						0.22
	1	0.42	9.1	81	18	1	1.59	0.40	0.20
		0.37	4.0						0.21
		0.40	1.2						0.22
		0.39	0.5						0.21
	2	0.31	8.8	81	18	1	1.62	0.39	0.21
		0.35	4.2						0.21
		0.33	1.0						0.20
		0.32	0.5						0.22
	3	0.39	9.0	81	18	1	1.68	0.37	0.21
		0.36	3.9						0.22
		0.36	1.0						0.21
		0.36	0.5						0.22
	1	1.0	8.6	81	18	1	1.58	0.40	0.19
		0.9	4.3						0.19
		0.9	1.5						0.20
		0.9	1.0						0.20
	2	0.7	8.4	81	18	1	1.62	0.39	0.20
		0.7	4.3						0.19
		0.7	1.3						0.20
		0.7	1.0						0.21
	3	1.0	8.9	81	18	1	1.54	0.42	0.20
		0.9	4.5						0.20
		1.0	1.5						0.21
		1.0	1.1						0.19

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Bare Soil	1	1.5	9.0	81	18	1	1.53	0.42	0.17
		1.5	8.1						0.17
		1.5	4.0						0.18
		1.5	2.1						0.17
	2	1.6	9.3	81	18	1	1.52	0.43	0.17
		1.7	8.2						0.17
		1.7	4.1						0.17
		1.6	2.1						0.17
	3	1.6	9.0	81	18	1	1.53	0.42	0.18
		1.7	8.3						0.16
		1.7	4.0						0.17
		1.7	2.3						0.16
	1	2.0	9.0	81	18	1	1.44	0.46	0.21
		2.0	4.2						0.21
		2.0	7.2						0.21
		2.1	2.5						0.23
	2	2.1	9.0	81	18	1	1.54	0.42	0.23
		2.0	4.2						0.22
		2.0	7.1						0.22
		2.0	2.5						0.22
	3	2.0	9.0	81	18	1	1.52	0.43	0.23
		2.1	4.1						0.21
		1.9	7.0						0.23
		2.0	2.5						0.22
	1	4.0	9.1	81	18	1	1.31	0.50	0.19
		4.1	8.2						0.20
		4.1	5.0						0.20
		4.0	4.0						0.21
	2	4.2	9.0	81	18	1	1.29	0.51	0.19
		4.2	8.0						0.20
		4.2	5.1						0.19
		4.2	4.0						0.19
	3	4.1	9.0	81	18	1	1.39	0.48	0.21
		4.1	8.0						0.20
		4.1	5.0						0.20
		4.1	4.0						0.21

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Bare Soil	1	5.6	8.5	81	18	1	1.27	0.52	0.22
		5.6	8.0						0.23
		5.6	7.0						0.22
		5.5	5.5						0.21
	2	5.5	9.0	81	18	1	1.22	0.54	0.22
		5.5	8.0						0.22
		5.6	7.0						0.23
		5.5	5.5						0.22
	3	5.5	8.8	81	18	1	1.24	0.53	0.22
		5.5	8.0						0.22
		5.6	7.0						0.21
		5.5	5.5						0.21
	1	5.9	9.0	81	18	1	1.14	0.57	0.20
		6.0	8.1						0.20
		5.9	7.1						0.21
		6.0	6.1						0.21
	2	5.9	9.0	81	18	1	1.20	0.55	0.21
		5.9	8.0						0.20
		5.9	7.2						0.20
		5.9	6.0						0.21
	3	5.9	9.0	81	18	1	1.26	0.53	0.22
		6.0	8.1						0.20
		5.9	7.1						0.21
		5.9	6.0						0.21
	1	8.0	9.1	81	18	1	1.15	0.56	0.22
		8.0	8.0						0.22
	2	8.1	9.0	81	18	1	1.14	0.57	0.22
		8.1	8.1						0.21
	3	8.0	9.0	81	18	1	1.20	0.55	0.21
		8.0	8.0						0.20
	1	10.0	9.1	81	18	1	1.21	0.54	0.21
	2	10.0	9.0	81	18	1	1.18	0.55	0.20
	3	10.0	9.0	81	18	1	1.13	0.57	0.20

Table 24 - Properties of Subsoils Used in Gravel Land Treatment Tests

	Test Condition			Subsoil Property					
Land Treatment	Core #	Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Gravel	1	0.20	8.5	81	18	1	1.65	0.38	0.23
		0.17	4.3						0.21
		0.17	1.5						0.22
		0.18	1.0						0.22
	2	0.21	8.7	81	18	1	1.68	0.37	0.23
		0.19	4.2						0.21
		0.17	1.5						0.22
		0.19	1.0						0.22
	3	0.20	8.6	81	18	1	1.67	0.37	0.22
		0.18	4.3						0.22
		0.14	1.1						0.23
		0.17	1.0						0.23
	1	0.43	9.0	81	18	1	1.60	0.39	0.21
		0.47	4.1						0.20
		0.44	1.5						0.20
		0.45	1.0						0.22
	2	0.47	9.0	81	18	1	1.62	0.39	0.22
		0.54	4.0						0.20
		0.59	1.5						0.21
		0.53	1.0						0.21
	3	0.45	9.1	81	18	1	1.60	0.40	0.22
		0.50	4.1						0.20
		0.50	1.5						0.21
		0.48	1.0						0.22
	1	1.5	9.0	81	18	1	1.55	0.42	0.20
		1.5	4.0						0.21
		1.5	3.4						0.20
		1.5	1.0						0.20
	2	1.5	9.0	81	18	1	1.54	0.42	0.20
		1.5	3.9						0.19
		1.5	3.5						0.19
		1.5	1.0						0.20
	3	1.5	9.0	81	18	1	1.54	0.42	0.19
		1.5	3.9						0.20
		1.5	2.6						0.20
		1.5	1.0						0.20

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Gravel	1	2.3	9.0	81	18	1	1.51	0.43	0.17
		2.2	4.0						0.18
		2.2	3.5						0.16
		2.2	1.0						0.16
	2	2.3	9.0	81	18	1	1.56	0.41	0.17
		2.3	4.0						0.18
		2.3	3.5						0.17
		2.3	1.0						0.18
	3	2.1	9.0	81	18	1	1.52	0.43	0.17
		2.1	5.0						0.16
		2.1	3.8						0.17
		2.1	1.0						0.17
	1	3.1	9.0	81	18	1	1.52	0.43	0.23
		3.1	5.0						0.21
		3.1	3.8						0.21
		3.1	1.0						0.23
	2	2.9	9.1	81	18	1	1.47	0.45	0.22
		2.9	5.2						0.22
		2.9	4.1						0.22
		2.9	1.0						0.22
	3	3.3	9.1	81	18	1	1.51	0.43	0.23
		3.2	5.0						0.21
		3.2	3.9						0.21
		3.2	1.0						0.22
	1	6.5	8.8	81	18	1	1.39	0.48	0.21
		6.1	8.0						0.19
		6.4	7.0						0.20
		6.5	4.0						0.20
	2	6.8	8.7	81	18	1	1.34	0.50	0.20
		6.6	8.0						0.20
		6.6	7.0						0.20
		6.6	4.0						0.21
	3	6.8	9.4	81	18	1	1.30	0.51	0.19
		6.2	8.0						0.20
		6.4	7.0						0.21
		6.4	4.0						0.20

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Gravel	1	8.5	8.9	81	18	1	1.27	0.52	0.22
	2	8.4	8.9	81	18	1	1.27	0.52	0.23
	3	8.6	9.1	81	18	1	1.27	0.52	0.22
	1	9.0	9.0	81	18	1	1.18	0.55	0.21
	2	9.0	9.1	81	18	1	1.19	0.55	0.21
	3	8.9	9.0	81	18	1	1.25	0.53	0.22
	1	10.0	9.0	81	18	1	1.17	0.56	0.21
	2	10.0	9.2	81	18	1	1.16	0.56	0.21
	3	10.0	9.0	81	18	1	1.18	0.55	0.22

Table 25 - Properties of Subsoils Used in Vegetation Land Treatment Tests

Land Treatment	Test Condition			Subsoil Property					
	Core #	Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Vegetation	1	0.15	8.7	81	18	1	1.66	0.37	0.21
		0.24	4.0						0.22
		0.21	1.5						0.22
		0.20	1.0						0.23
	2	0.17	8.6	81	18	1	1.64	0.38	0.22
		0.24	4.1						0.21
		0.22	1.5						0.23
		0.21	1.0						0.22
	3	0.16	8.6	81	18	1	1.69	0.36	0.23
		0.24	4.0						0.22
		0.21	1.5						0.22
		0.20	1.0						0.22
	1	0.46	8.9	81	18	1	1.63	0.39	0.21
		0.43	3.9						0.21
		0.48	2.0						0.21
		0.46	1.0						0.21
	2	0.39	9.0	81	18	1	1.62	0.39	0.21
		0.37	4.1						0.20
		0.36	1.9						0.21
		0.37	1.0						0.20
	3	0.40	9.2	81	18	1	1.61	0.39	0.20
		0.41	4.0						0.20
		0.38	2.1						0.21
		0.40	1.0						0.21
	1	1.5	9.0	81	18	1	1.60	0.40	0.19
		1.5	4.0						0.21
		1.5	2.6						0.21
		1.5	1.0						0.20
	2	1.5	9.0	81	18	1	1.55	0.42	0.20
		1.5	4.0						0.20
		1.5	2.5						0.21
		1.5	1.0						0.20
	3	1.5	9.0	81	18	1	1.57	0.41	0.20
		1.5	4.0						0.20
		1.5	2.6						0.20
		1.5	1.0						0.20

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Vegetation	1	2.0	9.0	81	18	1	1.54	0.42	0.17
		2.0	4.0						0.18
		1.9	2.5						0.17
		1.9	1.0						0.18
	2	2.1	8.5	81	18	1	1.61	0.39	0.18
		2.0	4.0						0.17
		1.9	2.5						0.17
		2.0	1.1						0.17
	3	2.0	9.0	81	18	1	1.53	0.42	0.17
		2.0	4.1						0.17
		2.0	2.5						0.17
		2.0	1.0						0.17
	1	3.0	9.0	81	18	1	1.43	0.46	0.21
		2.9	6.0						0.22
		2.8	4.0						0.21
		3.0	1.0						0.23
	2	2.7	9.0	81	18	1	1.49	0.44	0.22
		2.7	6.0						0.22
		2.6	4.1						0.21
		2.7	0.9						0.22
	3	3.5	8.9	81	18	1	1.45	0.45	0.22
		3.4	6.0						0.23
		3.3	4.0						0.22
		3.1	1.0						0.22
	1	6.5	8.8	81	18	1	1.40	0.47	0.21
		6.6	7.7						0.20
		6.3	7.1						0.20
		6.3	4.0						0.20
	2	6.4	8.9	81	18	1	1.39	0.48	0.21
		6.5	8.2						0.20
		6.4	7.1						0.19
		6.4	4.0						0.20
	3	6.3	9.4	81	18	1	1.41	0.47	0.21
		6.3	8.3						0.19
		6.2	7.1						0.20
		6.3	4.1						0.21

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Vegetation	1	8.5	8.9	81	18	1	1.29	0.52	0.23
	2	8.5	9.0	81	18	1	1.22	0.54	0.21
	3	8.7	9.0	81	18	1	1.22	0.54	0.23
	1	9.0	9.1	81	18	1	1.26	0.53	0.21
	2	9.1	9.0	81	18	1	1.26	0.53	0.22
	3	8.9	9.0	81	18	1	1.20	0.55	0.21
	1	10.1	9.1	81	18	1	1.19	0.55	0.21
	2	10.1	9.1	81	18	1	1.16	0.56	0.20
	3	10.2	9.0	81	18	1	1.22	0.54	0.21

Table 26 - Properties of Subsoils Used in Porous HMA Land Treatment Tests

Land Treatment	Test Condition			Subsoil Property					
	Core #	Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Porous HMA	1	0.18	8.3	81	18	1	1.65	0.38	0.23
		0.17	3.9						0.21
		0.17	1.5						0.22
		0.17	1.0						0.21
	2	0.25	8.2	81	18	1	1.62	0.39	0.21
		0.21	3.9						0.22
		0.21	1.6						0.22
		0.22	1.0						0.22
	3	0.22	8.3	81	18	1	1.63	0.39	0.22
		0.19	3.9						0.21
		0.19	1.5						0.23
		0.20	1.0						0.21
	1	0.59	9.0	81	18	1	1.56	0.41	0.20
		0.50	4.0						0.22
		0.47	2.5						0.21
		0.44	1.1						0.22
	2	0.49	9.0	81	18	1	1.56	0.41	0.21
		0.41	4.0						0.21
		0.37	2.5						0.20
		0.36	1.0						0.21
	3	0.41	9.1	81	18	1	1.55	0.41	0.22
		0.41	3.9						0.22
		0.40	2.5						0.22
		0.41	1.0						0.22
	1	1.5	8.9	81	18	1	1.55	0.41	0.20
		1.5	4.0						0.19
		1.5	2.5						0.21
		1.5	1.0						0.19
	2	1.6	8.9	81	18	1	1.56	0.41	0.20
		1.5	4.0						0.20
		1.5	2.6						0.19
		1.5	1.1						0.20
	3	1.5	9.0	81	18	1	1.58	0.40	0.19
		1.5	4.0						0.20
		1.5	2.6						0.20
		1.5	1.0						0.21

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Porous HMA	1	2.2	8.9	81	18	1	1.51	0.43	0.17
		2.1	4.0						0.18
		2.1	3.5						0.16
		2.1	1.1						0.16
	2	2.1	9.0	81	18	1	1.56	0.41	0.17
		2.1	4.0						0.18
		2.1	3.5						0.17
		2.0	1.0						0.18
	3	2.0	8.3	81	18	1	1.52	0.43	0.17
		2.0	5.0						0.16
		2.0	4.0						0.17
		2.0	1.0						0.17
	1	2.9	8.3	81	18	1	1.54	0.42	0.23
		3.0	5.0						0.22
		2.7	4.0						0.22
		2.7	1.0						0.21
	2	2.7	8.8	81	18	1	1.50	0.43	0.22
		2.8	4.9						0.21
		2.5	4.0						0.22
		2.8	0.9						0.21
	3	2.6	8.5	81	18	1	1.53	0.42	0.23
		2.9	5.0						0.22
		2.5	4.0						0.22
		2.6	1.0						0.23
	1	6.7	9.3	81	18	1	1.30	0.51	0.19
		6.6	8.1						0.20
		6.6	7.3						0.19
		6.6	4.0						0.20
	2	6.7	9.2	81	18	1	1.36	0.49	0.20
		6.7	8.1						0.20
		6.7	7.5						0.21
		6.7	4.1						0.20
	3	6.7	9.3	81	18	1	1.32	0.50	0.20
		6.6	8.1						0.20
		6.6	7.3						0.20
		6.6	4.1						0.19

Land Treatment	Core #	Test Condition		Subsoil Property					
		Composite Hydraulic Conductivity (in/h)	Rainfall Intensity (in/h)	Soil Composition			Bulk Density (g/cm^3)	Porosity	Field Capacity
				Sand (%)	Silt&Clay (%)	Organic Matter (%)			
Porous HMA	1	8.4	8.9	81	18	1	1.31	0.51	0.23
	2	8.5	9.0	81	18	1	1.28	0.52	0.22
	3	8.4	9.1	81	18	1	1.31	0.51	0.21
	1	9.1	9.1	81	18	1	1.19	0.55	0.21
	2	9.0	9.1	81	18	1	1.19	0.55	0.21
	3	8.9	9.0	81	18	1	1.17	0.56	0.20
	1	10.1	9.1	81	18	1	1.20	0.55	0.21
	2	10.1	9.2	81	18	1	1.15	0.57	0.20
	3	10.0	9.0	81	18	1	1.23	0.54	0.22

APPENDIX F WATER CONTENT MEASUREMENT OF SUBSOILS (KSAT=2.0 IN/H) IN PERMEAMETER

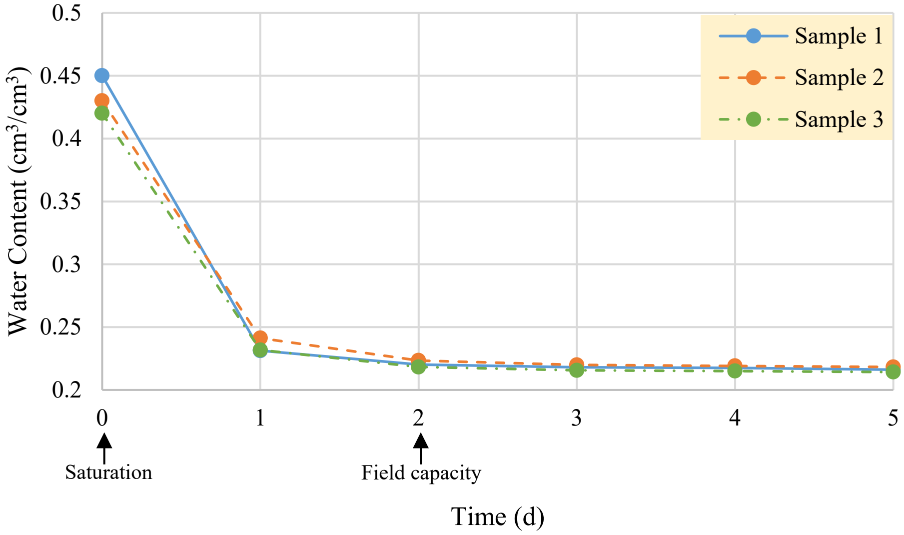


Figure 34. Water Content Measurement of Subsoils (k_{sat} = 2.0 in/h) in Permeameter

APPENDIX G CALIBRATION CURVE OF PRESSURE TRANSDUCER

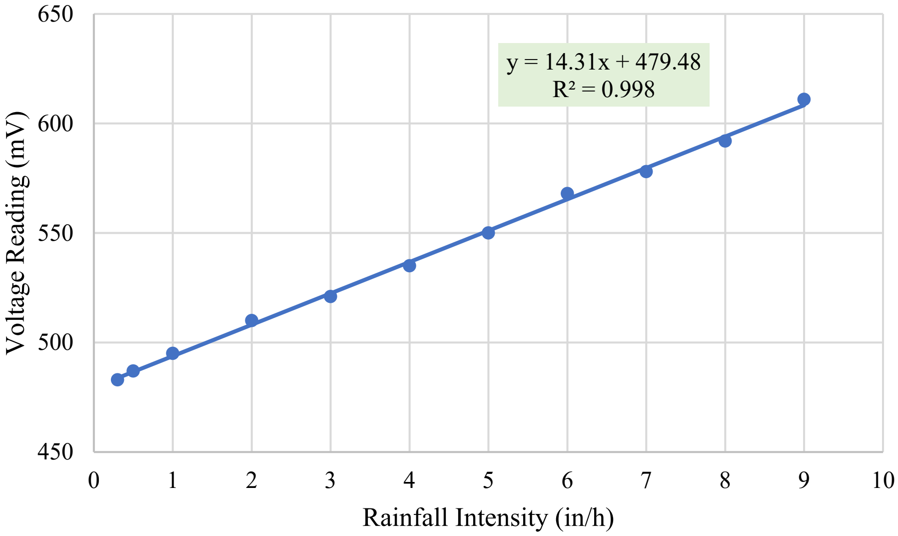
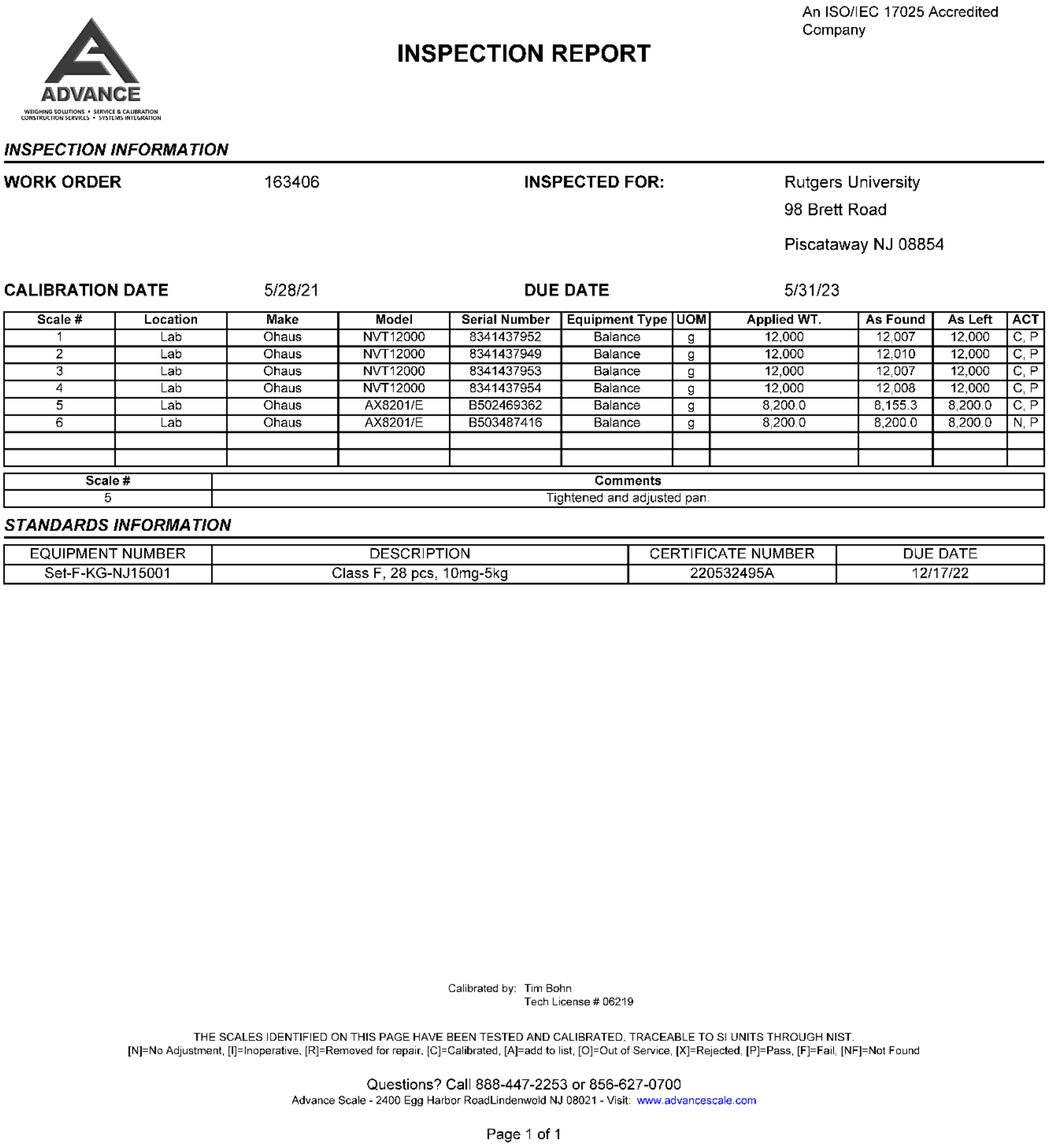


Figure 35. Calibration Curve of Pressure Transducer

APPENDIX H CALIBRATION AND INSPECTION REPORT OF BALANCES USED IN LABORATORY EXPERIMENTS



ADVANCE
WEIGHING SOLUTIONS • SERVICE & CALIBRATION
CONSTRUCTION SERVICES • SYSTEMS INTEGRATION

An ISO/IEC 17025 Accredited Company

INSPECTION REPORT

INSPECTION INFORMATION

WORK ORDER	163406	**INSPECTED FOR:**	Rutgers University 98 Brett Road Piscataway NJ 08854
CALIBRATION DATE	5/28/21	**DUE DATE**	5/31/23

Scale #	Location	Make	Model	Serial Number	Equipment Type	UOM	Applied WT.	As Found	As Left	ACT
1	Lab	Ohaus	NVT12000	8341437952	Balance	g	12,000	12,007	12,000	C, P
2	Lab	Ohaus	NVT12000	8341437949	Balance	g	12,000	12,010	12,000	C, P
3	Lab	Ohaus	NVT12000	8341437953	Balance	g	12,000	12,007	12,000	C, P
4	Lab	Ohaus	NVT12000	8341437954	Balance	g	12,000	12,008	12,000	C, P
5	Lab	Ohaus	AX8201/E	B502469362	Balance	g	8,200.0	8,155.3	8,200.0	C, P
6	Lab	Ohaus	AX8201/E	B503487416	Balance	g	8,200.0	8,200.0	8,200.0	N, P

Scale #	Comments
5	Tightened and adjusted pan.

STANDARDS INFORMATION

EQUIPMENT NUMBER	DESCRIPTION	CERTIFICATE NUMBER	DUE DATE
Set-F-KG-NJ15001	Class F, 28 pcs, 10mg-5kg	220532495A	12/17/22

Calibrated by: Tim Bohn
Tech License # 06219

THE SCALES IDENTIFIED ON THIS PAGE HAVE BEEN TESTED AND CALIBRATED, TRACEABLE TO SI UNITS THROUGH NIST.
[N]=No Adjustment, [I]=Inoperative, [R]=Removed for repair, [C]=Calibrated, [A]=add to list, [O]=Out of Service, [X]=Rejected, [P]=Pass, [F]=Fail, [NF]=Not Found

Questions? Call 888-447-2253 or 856-627-0700
Advance Scale - 2400 Egg Harbor RoadLindenwold NJ 08021 - Visit: www.advancescale.com

Page 1 of 1

Figure 36. Certificate of Calibration of Balances Used in Laboratory Experiments

APPENDIX I ORIGINAL NRCS METHOD

The original NRCS Method to quantify the runoff is presented below. In the current simplified NRCS Method presented in the main body of this report, the initial abstraction is assumed to be linearly related to the potential maximum retention by a factor of 0.2. In the original method, the initial abstraction is independently quantified. In this research project, relationship between the initial abstraction and the rainfall intensity was established from the measured data. The original NRCS Method has better statistical performance and can be used to provide a more accurate runoff prediction. However, it is much more complicated to apply than the current simplified NRCS Method since it will require an input of the rainfall intensity in addition to the rainfall depth of a storm event.

Data Analysis Methods

The method of least squares was applied for data analysis to fit CNs. For each soil column (combination of a subsoil and a land treatment), a measurement-based predicted runoff depth was calculated by an observed rainfall depth and an assumed S value with the original NRCS equation: (6)

$$\mathrm{Q_{pre}} = \frac{(P_{obs} - \mathrm{I_{a-meas}})^2}{P_{obs} + \mathrm{I_a} - S_{fit}} \tag{24}$$

where $\mathrm{Q_{pre}}$ = Predicted runoff depth (in)

$\mathrm{P_{obs}}$ = Observed rainfall depth (in)

$\mathrm{I_{a\text{-}meas}}$ = Measured Initial Abstraction (in)

$\mathrm{S_{fit}}$ = Potential maximum retention after runoff begins (in) to be fitted

Note in the current practices (i.e., TR-55) as shown in the main body of this report, $\mathrm{I_a}$ is pre-set to 0.2S. One S value was assumed to calculate the $\mathrm{Q_{pre}}$ values of all data points within a dataset. The coefficient of determination (R^2) of the dataset was calculated by:

$$\mathrm{R}^2 = \left[\frac{\sum_{i=1}^{n}\left(\mathrm{Q_{obs_i}} - \overline{\mathrm{Q_{obs}}}\right)\left(\mathrm{Q_{pre_i}} - \overline{\mathrm{Q_{pre}}}\right)}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{Q_{obs_i}} - \overline{\mathrm{Q_{obs}}}\right)^2 \sum_{i=1}^{n}\left(\mathrm{Q_{pre_i}} - \overline{\mathrm{Q_{pre}}}\right)^2}}\right]^2 \tag{25}$$

where $\mathrm{Q_{obs}}$ = Observed runoff depth (in)

$\overline{Q_{obs}}$ = Arithmetic mean of observed runoff depths (in)

$\mathrm{Q_{pre}}$ = predicted runoff depth (in);

$\overline{Q_{pre}}$ = arithmetic mean of predicted runoff depths (in)

The solver function in Microsoft Excel was applied to maximize the R^2 of the dataset (i.e., minimizing the sum of residuals of data points from the P-$\mathrm{Q_{pre}}$ curve) by varying the S. The best fit of S was obtained when the maximal R^2 was reached. The best fit of CN was calculated from the best fit S by the established NRCS relation:

$$\mathrm{CN} = \frac{1000}{S_{fit}+10} \tag{26}$$

where CN = Curve number

S_{fit} = Fitted potential maximum retention after runoff begins (in)

All the above-fitted individual CNs of bare soil, gravel, vegetation, and porous HMA were plotted versus composite hydraulic conductivities. A regression analysis (curve fitting) was conducted for each land treatment by using the trendline tool in Microsoft Excel. The linear function was selected as the model for curve fitting because it had the best fit to the data points. The coefficients of determination (R^2) of the CN-composite hydraulic conductivity curve were calculated by the equation below and shall meet the statistical requirements for acceptance (lower limit of 0.60).

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(\mathrm{CN}_{\mathrm{fit}_i}-\overline{\mathrm{CN}_{\mathrm{fit}}}\right)\left(\mathrm{CN}_{\mathrm{pre}_i}-\overline{\mathrm{CN}_{\mathrm{pre}}}\right)}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{CN}_{\mathrm{fit}_i}-\overline{\mathrm{CN}_{\mathrm{fit}}}\right)^2 \sum_{i=1}^{n}\left(\mathrm{CN}_{\mathrm{pre}_i}-\overline{\mathrm{CN}_{\mathrm{pre}}}\right)^2}}\right]^2 \tag{27}$$

where $\mathrm{CN}_{\mathrm{fit}}$ = Fitted individual CN

$\mathrm{CN}_{\mathrm{pre}}$ = CN predicted by the fitted curve

$\overline{\mathrm{CN}_{\mathrm{fit}}}$ = Arithmetic mean of fitted CNs for all the individual soil columns

$\overline{\mathrm{CN}_{\mathrm{pre}}}$ = Arithmetic mean of predicted CNs for all the individual soil columns

Four models (relationships) were established to predict the initial abstraction (I_a) for different land treatments. These models were established based on laboratory measurements of I_a along with mass balance.

Bare Soil

A relationship (figure 37) between initial abstraction (I_a) and rainfall intensity excess over hydraulic conductivity ($i - K_{sat}$) was found based on laboratory measurements. This model was used to predict the initial abstraction (I_a) when applying the original NRCS Method to predict runoff.

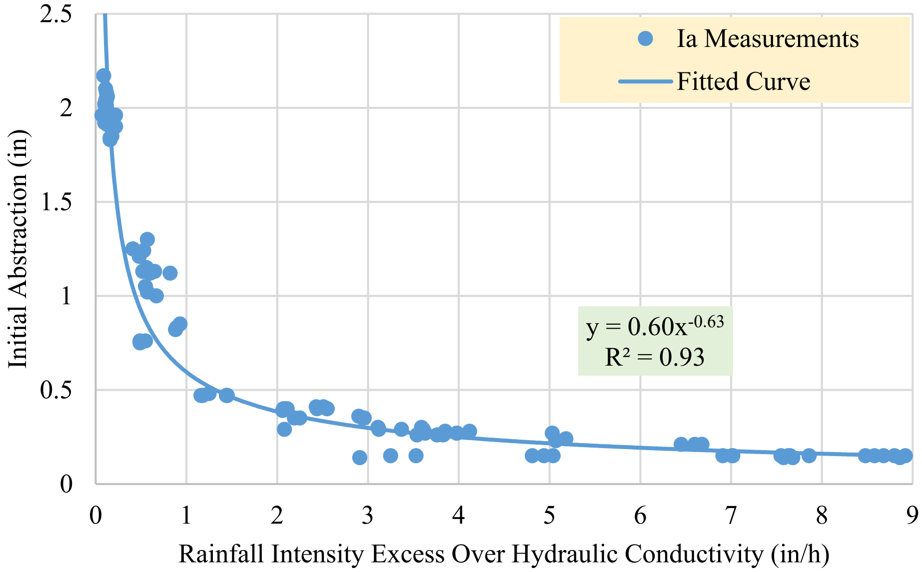


Figure 37. Relationship Between Initial Abstraction and Rainfall Intensity Excess Over Subsoil Hydraulic Conductivity of Bare Soil

Gravel, Vegetation, and Porous HMA

The initial abstractions (I_a) of gravel, vegetation, and porous HMA were modeled in three components: initial abstraction of subsoil (I_o), storage depth of the land treatment (I_s), and depth of infiltration occurs during water ponding in the land treatment layer (I_p). Initial abstraction of subsoil (I_o) was modeled by the relationship between initial abstraction (I_a) and rainfall intensity excess over hydraulic conductivity (i - K_{sat}) found for bare soil. Storage depth of the land treatment (I_s) was calculated by the product of depth and porosity of the land treatment layer. Depth of infiltration occurs during water ponding in the land treatment layer (I_p) was modeled by the product of time and infiltration rate during the ponding. When water started ponding in the land treatment, the subsoil was saturated. As a result, the infiltration rate of the soil column was equal to the hydraulic conductivity of the subsoil. The ponding time was modeled by the storage depth (i.e., depth to be ponded) of the land treatment divided by the rainfall intensity excess over subsoil hydraulic conductivity (i.e., ponding rate). The model is described in detail below.

$$\mathrm{I_a} = \mathrm{I_o} + \mathrm{I_s} + \mathrm{I_p} \tag{28}$$

$$\mathrm{I_s} = \mathrm{D} \times \eta_\mathrm{e} \tag{29}$$

$$\mathrm{I_p} = \mathrm{t_p} \times \mathrm{K_{sat}} \tag{30}$$

$$\mathrm{t_p} = \frac{\mathrm{D}}{\mathrm{i} - \mathrm{K_{sat}}} \tag{31}$$

where I_a = Initial abstraction of gravel, vegetation, or porous HMA (in)

I_o = Initial abstraction of subsoil (in)

I_s = Storage depth of the land treatment (in)

I_p = Depth of infiltration occurs during water ponding in the land treatment layer (in)

D = Depth of land treatment (in)

η_e = Effective porosity of land treatment, calculated by the difference between porosity and field capacity

t_p = time during ponding occurs in the land treatment layer (h)

K_{sat} = hydraulic conductivity of subsoil (in/h)

i = rainfall intensity (in/h)

Runoff predictions were plotted versus runoff observations of all datasets to calculate the Nash–Sutcliffe Efficiency Coefficient (NSE) by:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs_i} - Q_{pre_i})^2}{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q_{obs}})^2} \qquad (32)$$

where Q_{obs} = Observed runoff depth (in)

Q_{pre} = Predicted runoff depth (in)

$\overline{Q_{obs}}$ = Arithmetic mean of observed runoff depths (in)

The NSE shall meet the statistical requirements for acceptance (lower limit of 0.64).

Data Analysis Results

R^2 values of fitted CN for individual soil column of all tested soil hydraulic conductivities and land treatments are listed in table 27. The ranges of R^2 values for bare soil, gravel, vegetation, and porous HMA are 0.79-1.00, 0.80-1.00, 0.73-1.00, and 0.70-1.00, respectively. These values of R^2 are all higher than 0.60 (the lower limit of a satisfactory determination) and are consistently larger than those from using the current simplified NRCS Method (table 9).

Table 27 - R^2 Values of Fitted CN for Individual Soil Column of All Tested Soil Hydraulic Conductivities and Land Treatments

Soil Column Replicate #	Targeted Subsoil Hydraulic Conductivity (in/h)	Bare Soil		Gravel		Vegetation		Porous HMA	
		Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2	Composite Hydraulic Conductivity (in/h)	Individual R^2
1	0.1	0.11	1.00	0.18	1.00	0.20	1.00	0.20	1.00
2			1.00		1.00		1.00		1.00
3			1.00		1.00		1.00		1.00
1	0.5	0.37	0.99	0.49	0.99	0.41	0.99	0.44	0.99
2			0.99		0.99		0.99		1.00
3			0.99		0.99		0.99		0.99
1	1.0	0.87	0.99	1.50	0.90	1.49	0.92	1.51	0.94
2			0.98		0.90		0.91		0.95
3			0.97		0.92		0.92		0.95
1	1.5	1.59	0.91	2.21	0.87	1.98	0.87	2.07	0.83
2			0.92		0.85		0.89		0.84
3			0.89		0.84		0.91		0.85
1	2.0	2.01	0.87	3.05	0.80	2.98	0.85	2.73	0.78
2			0.87		0.82		0.83		0.78
3			0.87		0.92		0.73		0.78
1	4.0	4.09	0.86	6.49	0.96	6.37	0.82	6.65	0.70
2			0.85		0.98		0.90		0.70
3			0.86		0.97		0.90		0.72
1	5.5	5.52	0.84	No runoff		No runoff		No runoff	
2			0.85						
3			0.84						
1	6.0	5.92	0.81						
2			0.79						
3			0.81						
1	8.0	No runoff							
2									
3									
1	10.0								
2									
3									
Range of R^2	/	0.79 – 1.00		0.82 – 1.00		0.73 – 1.00		0.70 – 1.00	

Figure 38, Figure 39, Figure 40, and Figure 41 show the CN of bare soil, gravel, vegetation, and porous HMA, respectively, versus composite hydraulic conductivity. The coefficients of determination ranged from 0.95 to 0.99 and met the statistical requirements for acceptance (lower limit of 0.60).

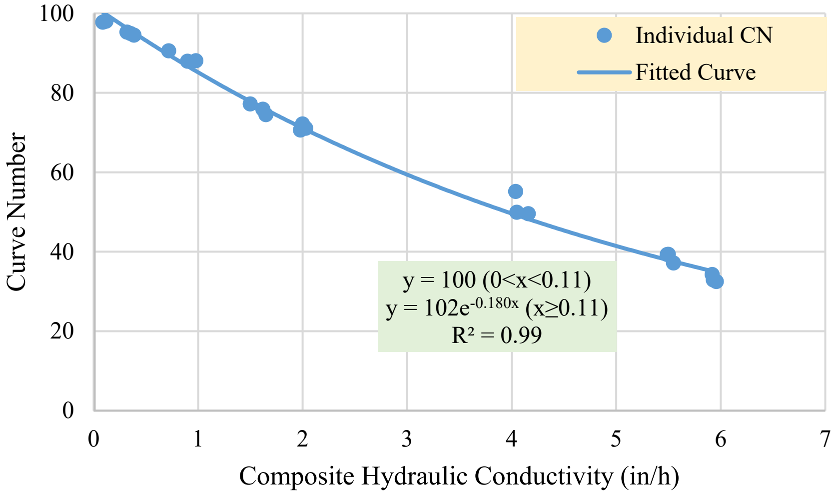


Figure 38. Relationship Between CN and Composite Hydraulic Conductivity of Bare Soil (Original NRCS Method)

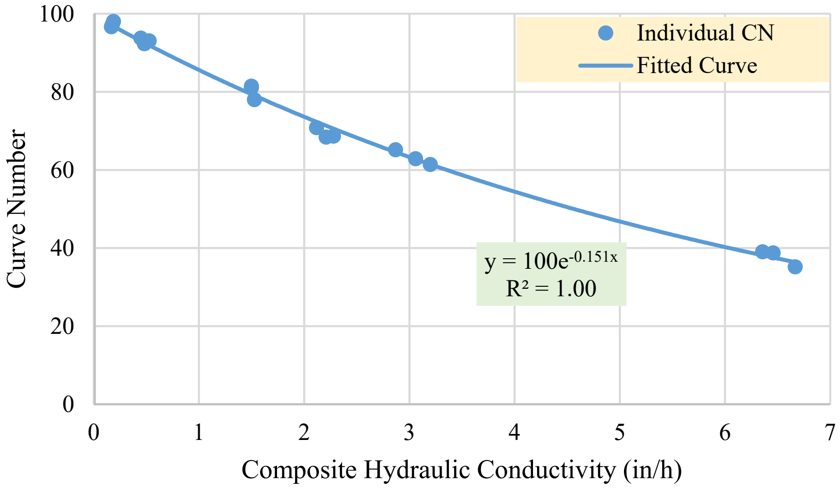


Figure 39. Relationship Between CN and Composite Hydraulic Conductivity of Gravel (Original NRCS Method)

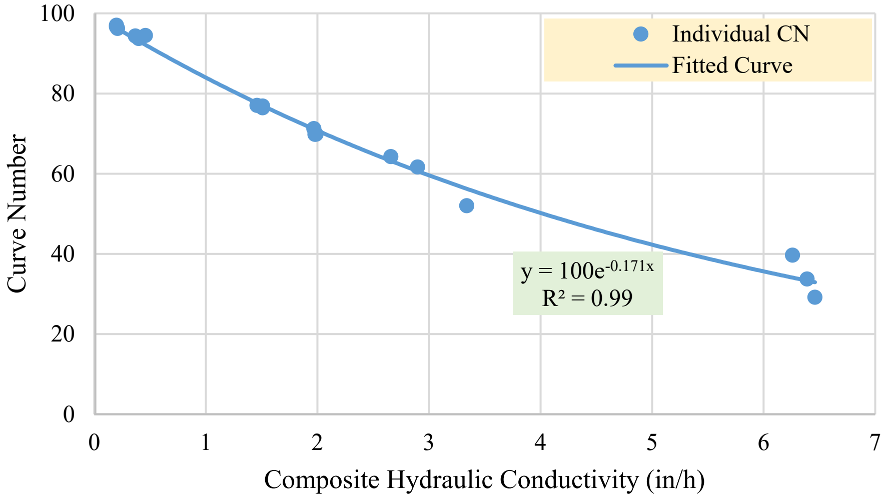


Figure 40. Relationship Between CN and Composite Hydraulic Conductivity of Vegetation (Original NRCS Method)

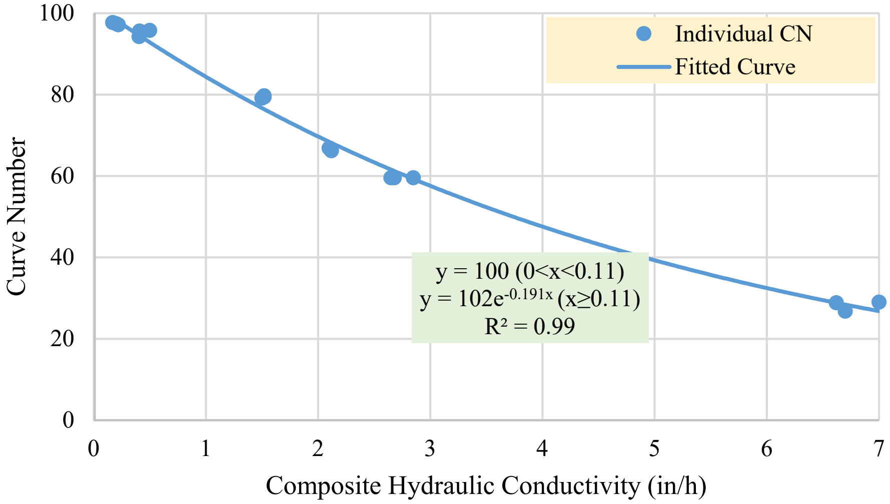


Figure 41. Relationship Between CN and Composite Hydraulic Conductivity of Porous HMA (Original NRCS Method)

Figure 42, Figure 43, Figure 44, and Figure 45 show the NSE values of bare soil, gravel, vegetation, and porous HMA, respectively. All of them met the statistical requirements for acceptance (the lower limit of 0.60 for a satisfactory statistical performance) and considerably improved compared to those for the current simplified NRCS Method and thus the runoff prediction would be more accurate.

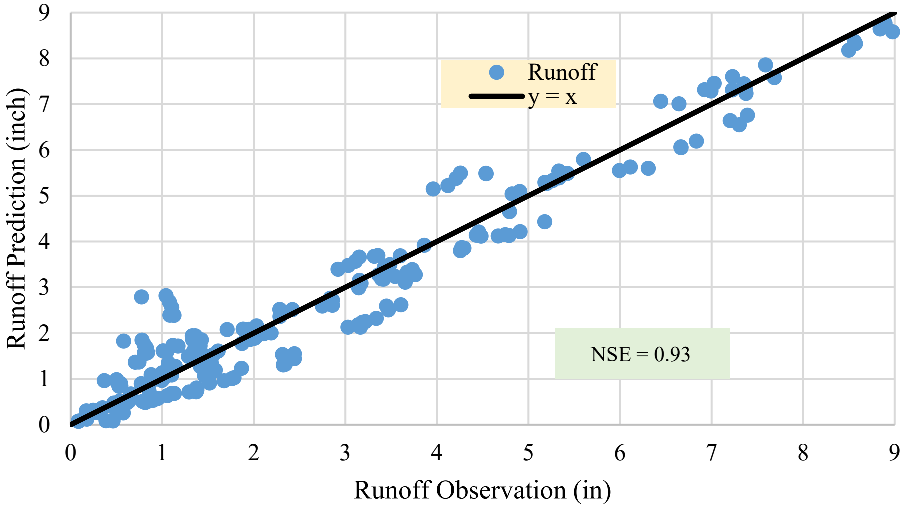


Figure 42. Comparison Between Runoff Prediction and Observation of Bare Soil (Original NRCS Method)

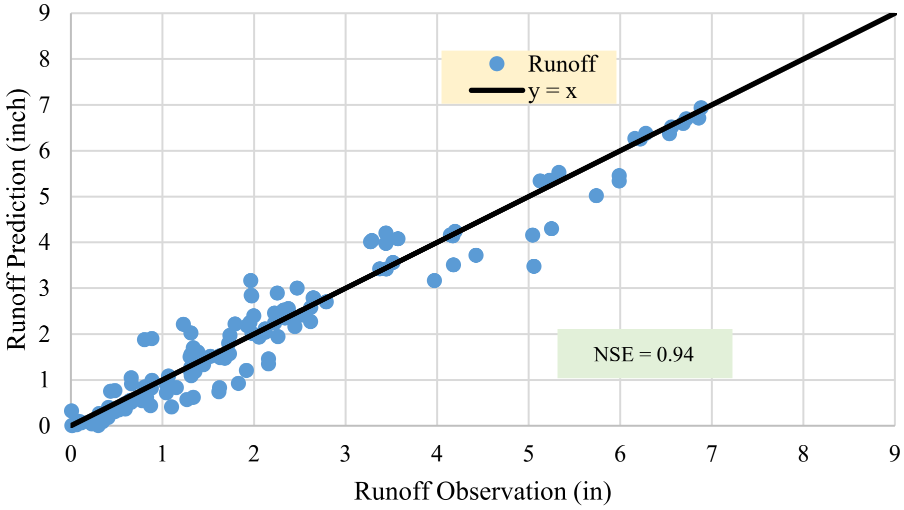


Figure 43. Comparison Between Runoff Prediction and Observation of Gravel (Original NRCS Method)

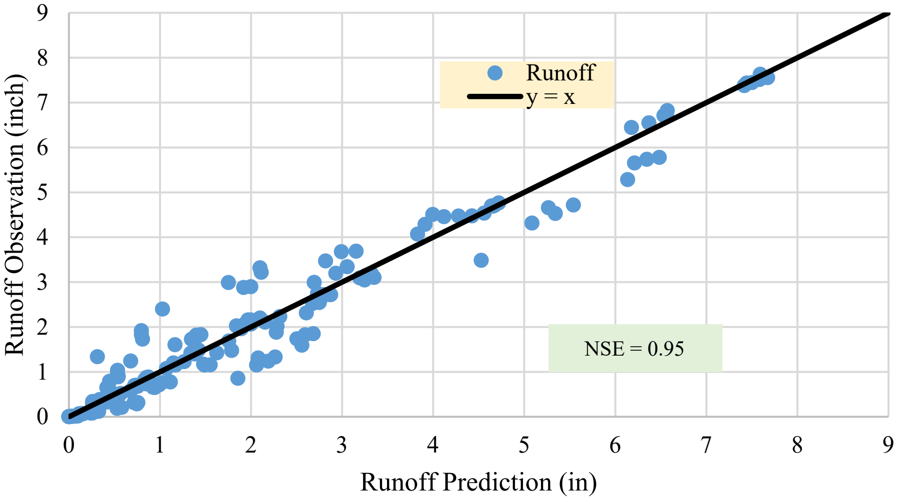


Figure 44. Comparison Between Runoff Prediction and Observation of Vegetation (Original NRCS Method)

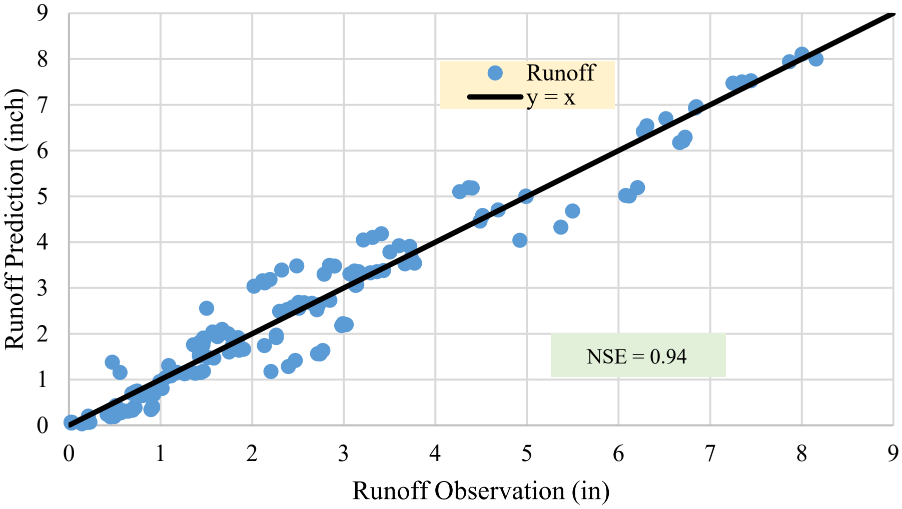


Figure 45. Comparison Between Runoff Prediction and Observation of Porous HMA (Original NRCS Method)

APPENDIX J NRCS METHOD WITH PROPOSED UPDATE OF I_A = 0.05S

The current simplified NRCS Method estimates that the initial abstraction (I_a) has a value of 0.2S. Recently, a new equation has been proposed in draft form in the ASCE-WERI Task Committee guidance. The update has been proposed to reflect that I_a = 0.05S, which will directly impact the runoff result. It is important to note that this guidance is new and has yet to be adopted by the various regulatory agencies such as NJDEP that are responsible for stormwater management regulations. This proposed update of I_a = 0.05S was analyzed in this section to assess changes in CN results and their corresponding statistical performance.

Data Analysis Methods

The method of least squares was applied for data analysis to fit CNs. For each soil column (combination of a subsoil and a land treatment), a measurement-based predicted runoff depth was calculated by an observed rainfall depth and an assumed S value with the original NRCS equation: (6)

$$\mathrm{Q}_{\mathrm{pre}} = \frac{(P_{obs} - \mathrm{I}_{\mathrm{a-meas}})^2}{P_{obs} + \mathrm{I}_{\mathrm{a-meas}} - S_{fit}} \tag{33}$$

where Q_{pre} = Predicted runoff depth (in)

P_{obs} = Observed rainfall depth (in)

$I_{a\text{-}meas}$ = Measured Initial Abstraction (in)

S_{fit} = Potential maximum retention after runoff begins (in) to be fitted

Note in the current practices (i.e., TR-55) as shown in the main body of this report, I_a is pre-set to 0.2S. In this section, the proposed I_a = 0.05S was used. The CN and R^2 values of fitted CNs for individual soil columns of all tested soil hydraulic conductivities and land treatments are listed in table 28. Figure 46, Figure 47, Figure 48, and Figure 49 show the CN of bare soil, gravel, vegetation, and porous HMA, respectively, versus composite hydraulic conductivity. Results showed that CNs fitted by the NRCS Equation with I_a = 0.05S are lower than the ones with I_a = 0.2S for all land treatments and hydraulic conductivities. This is because to fit the same I_a, a lower λ value (from 0.2 to 0.05) requires a larger fitted value of S, and thus a lower CN. Figure 50, Figure 51, Figure 52, and Figure 53 show the individual R^2 values of fitted CN for individual soil column of bare soil, gravel, vegetation, and porous HMA, respectively, versus composite hydraulic conductivity. The NRCS Method with I_a = 0.05S does not have a statistical performance significantly different from that of the current simplified NRCS Method where I_a is set to be 0.2S.

Table 28 - CN and R^2 Values of Fitted CN for Individual Soil Column of All Tested Soil Composite Hydraulic Conductivities ($K_{sat\text{-}comp}$) and Land Treatments

Soil Column Replicate #	Targeted Subsoil Hydraulic Conductivity (in/h)	Bare Soil			Gravel			Vegetation			Porous HMA		
		$K_{sat\text{-}comp}$ (in/h)	CN	R^2	$K_{sat\text{-}comp}$ (in/h)	CN	R^2	$K_{sat\text{-}comp}$ (in/h)	CN	R^2	$K_{sat\text{-}comp}$ (in/h)	CN	R^2
1	0.1	0.12	94	0.98	0.18	74	0.95	0.20	85	0.98	0.17	92	0.99
2		0.09	93	0.98	0.19	75	0.95	0.21	84	0.98	0.22	91	0.99
3		0.11	95	0.98	0.17	74	0.93	0.20	84	0.98	0.20	91	0.99
1	0.5	0.32	90	0.96	0.45	69	0.92	0.37	83	0.97	0.41	89	0.99
2		0.36	90	0.95	0.48	68	0.92	0.40	82	0.98	0.41	90	0.99
3		0.39	89	0.95	0.53	67	0.84	0.46	86	0.97	0.50	89	0.99
1	1.0	0.72	85	0.93	1.53	55	0.84	1.46	62	0.84	1.52	75	0.91
2		0.90	83	0.95	1.50	56	0.79	1.51	62	0.85	1.52	75	0.91
3		0.98	83	0.94	1.50	58	0.86	1.51	62	0.86	1.50	74	0.91
1	1.5	1.50	73	0.82	2.12	44	0.67	1.99	52	0.68	2.12	67	0.79
2		1.62	72	0.82	2.21	43	0.65	1.97	53	0.69	2.12	67	0.79
3		1.65	71	0.77	2.28	43	0.60	1.98	52	0.73	2.10	67	0.80
1	2.0	2.03	65	0.67	3.06	38	0.62	2.66	52	0.77	2.65	62	0.64
2		1.98	65	0.68	2.87	39	0.61	2.90	50	0.75	2.85	65	0.75
3		2.00	65	0.65	3.20	36	0.60	3.34	42	0.62	2.68	64	0.69
1	4.0	4.04	52	0.82	6.36	21	0.80	6.46	23	0.72	7.00	38	0.60
2		4.16	51	0.79	6.67	19	0.81	6.39	25	0.80	6.70	41	0.60
3		4.05	51	0.79	6.46	22	0.84	6.26	28	0.81	6.62	42	0.62
1	5.5	5.50	45	0.81	No runoff			No runoff			No Runoff		
2		5.49	45	0.84									
3		5.55	43	0.81									
1	6.0	5.96	38	0.82									
2		5.93	39	0.81									
3		5.92	40	0.82									
1	8.0	No runoff											
2													
3													
1	10.0												
2													
3													
Range of R^2	/	0.65 - 0.98			0.60 - 0.95			0.62 - 0.98			0.60 - 0.99		

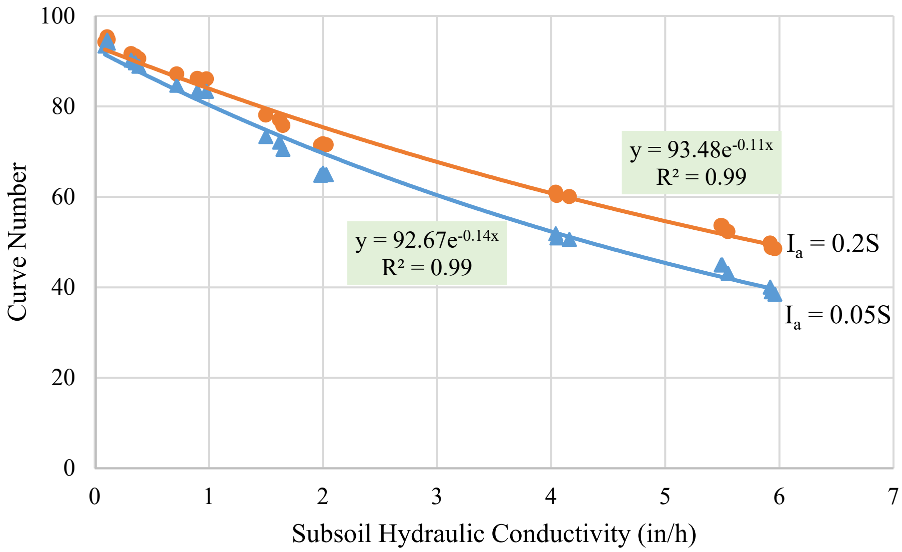


Figure 46. Relationship Between CN and Composite Hydraulic Conductivity of Bare Soil (NRCS Method with I_a = 0.2S and I_a = 0.05S)

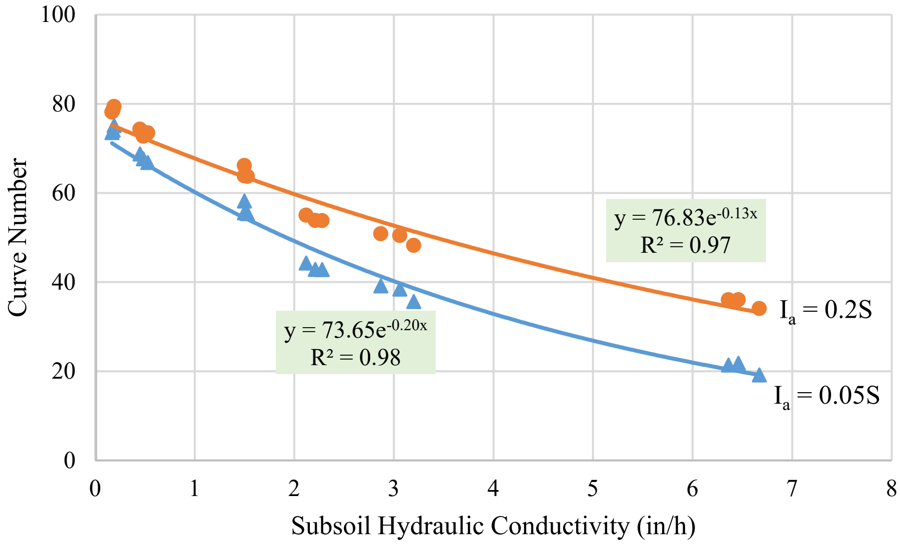


Figure 47. Relationship Between CN and Composite Hydraulic Conductivity of Gravel (NRCS Method with I_a = 0.2S and I_a = 0.05S)

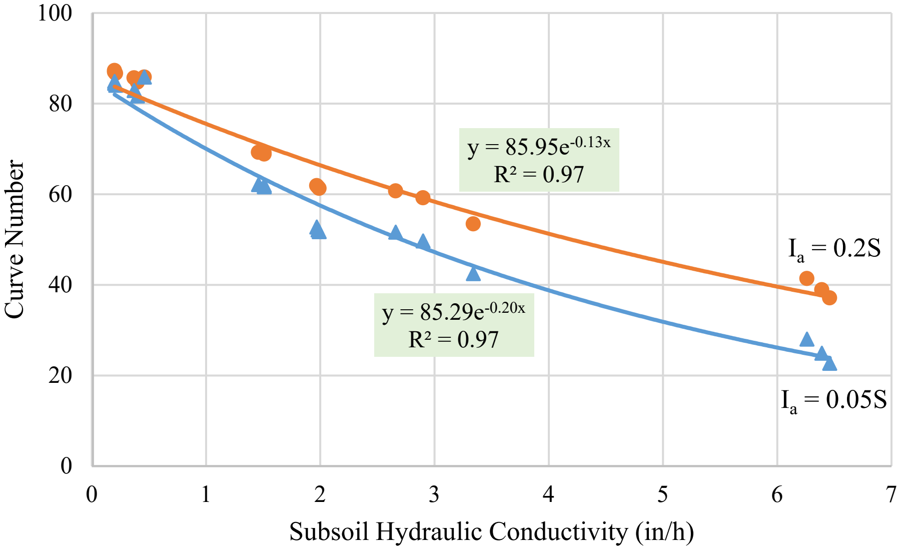


Figure 48. Relationship Between CN and Composite Hydraulic Conductivity of Vegetation (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

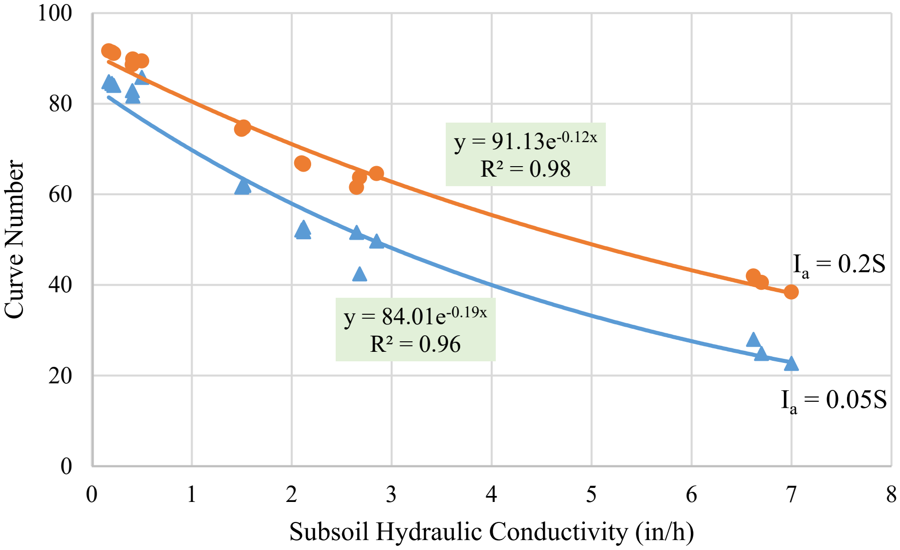


Figure 49. Relationship Between CN and Composite Hydraulic Conductivity of Porous HMA (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

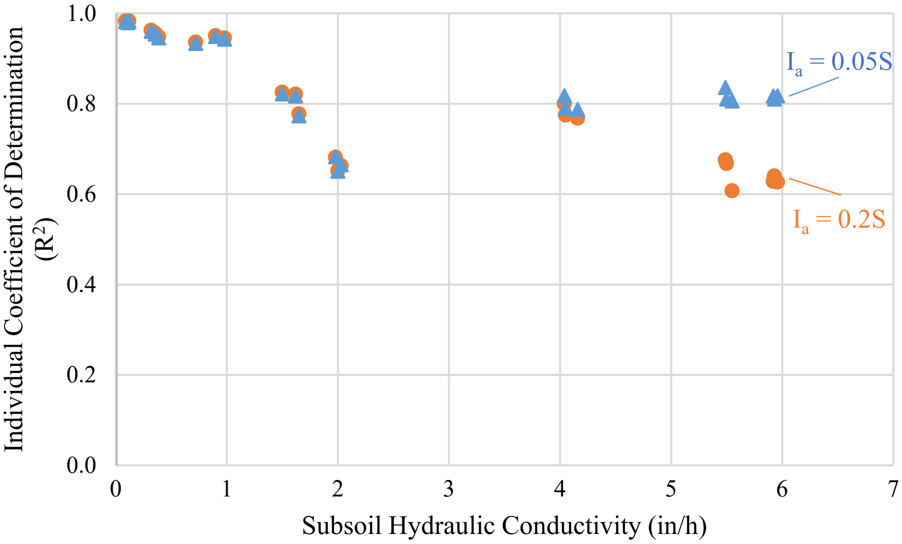


Figure 50. Relationship Between Individual R^2 and Composite Hydraulic Conductivity of Bare Soil (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

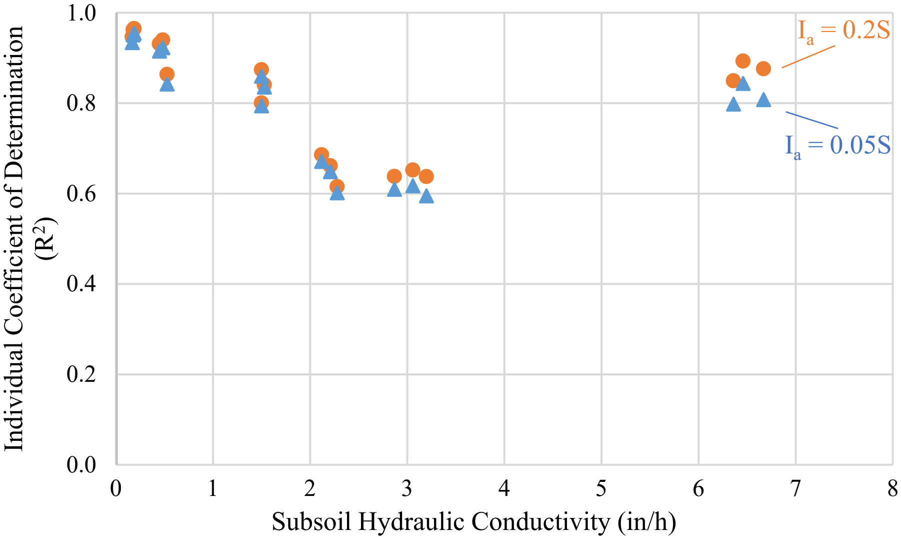


Figure 51. Relationship Between Individual R^2 and Composite Hydraulic Conductivity of Gravel (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

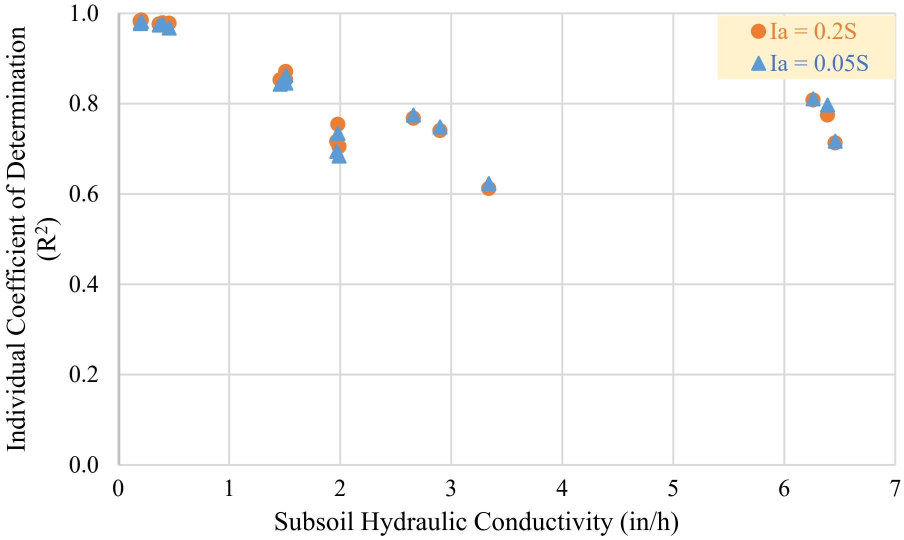


Figure 52. Relationship Between Individual R^2 and Composite Hydraulic Conductivity of Vegetation (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

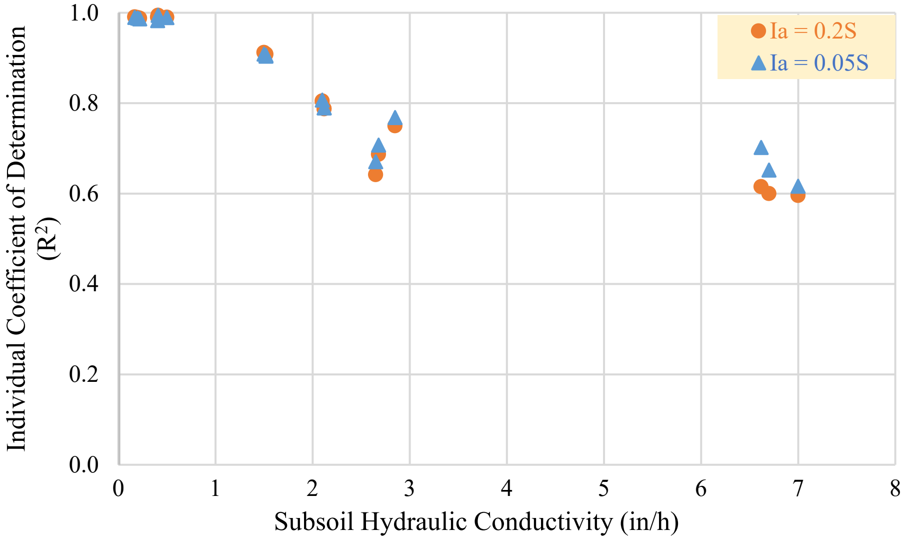


Figure 53. Relationship Between Individual R^2 and Composite Hydraulic Conductivity of Porous HMA (NRCS Method with $I_a = 0.2S$ and $I_a = 0.05S$)

APPENDIX K UNCERTAINTY ANALYSIS (TREATING SAMPLES AS REPLICATES)

The uncertainty analysis of the calculated CN is presented by an example (land treatment of bare soil, subsoil hydraulic conductivity of 1.5 in/h, soil column replicates #1, 2, and 3) in figure 58. The three soil columns are examined simultaneously under the same test conditions in one test and could be treated as replicates rather than as individual samples as done in the main text. Therefore, rainfall depths, runoff depths, and hydraulic conductivities should be averaged among the three soil columns. To achieve this, one data point (at a specific time interval under a specific rainfall intensity) in the dataset (for example, one point in figure 19) was selected from each soil column replicate (a total of three) and then averaged among the three replicates. Following the same procedure, all other points were selected and averaged with corresponding points from the other two replicates. All arithmetic means of lab measurements among three replicates were plotted in one figure (for example, figure 54). The method of least squares was applied to obtain the curve of best fit. As shown in figure 54, the best fit of CN of 77 was obtained through the regression analysis.

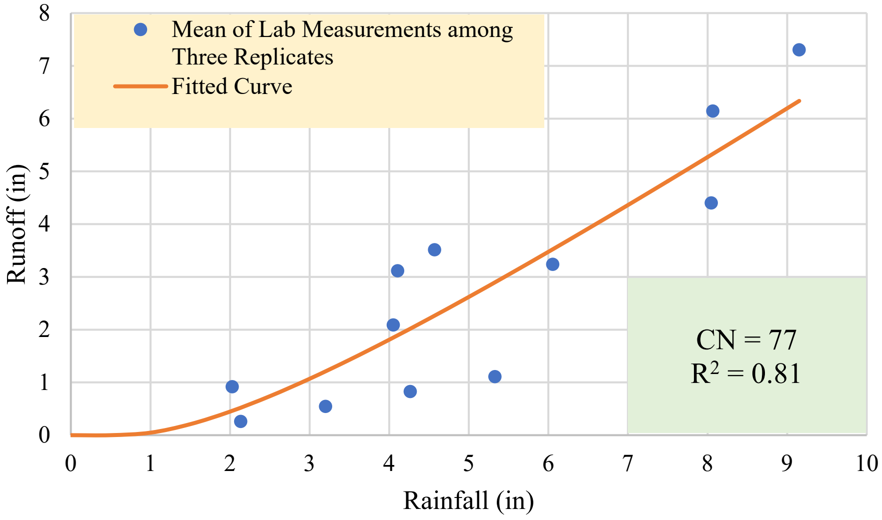


Figure 54. Regression Analysis of Triplicate Samples (land treatment of bare soil, subsoil hydraulic conductivity of 1.59 in/h)

In order to quantify the uncertainty of this fitted CN, the 95 percent confidence interval (CI) of this curve was also calculated and plotted. (34) The 95 percent confidence interval encompassed the true curve of best fit (i.e., true value of CN) with 95 percent confidence. This confidence interval indicated the uncertainties in CN fitting and provided a range of CN with 95 percent confidence level. For example, in the case of figure 55, the CN is fitted to be 77, and the uncertainty is determined to be ±7 with a confidence level of 95 percent (figure 55). All fitted CNs are tabulated in the format of mean ± 95 percent CI in table 29. All but one combination of composite hydraulic conductivity and land treatment have uncertainties smaller than ±10 CNs. It is worth noting that the documentation for recent draft update (not yet adopted) of NEH, Chapter 10 by USDA-NRCS indicated large uncertainties in the estimation of CN from soil groups and land covers/treatments and only half (i.e., 50%) of the CN differences are in the general range of about ±10 CNs while the extremes are much larger. (35).

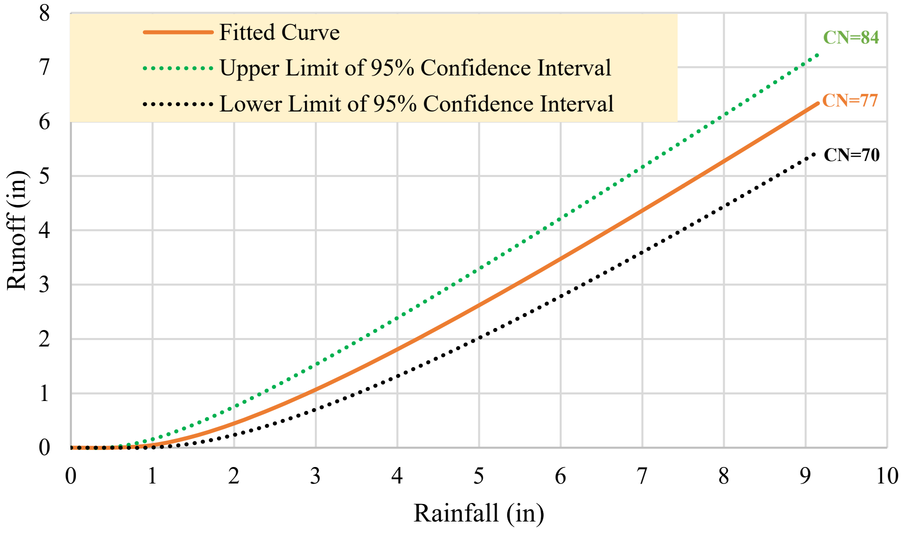


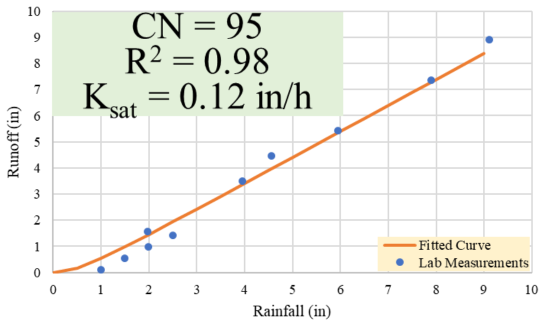
Figure 55. Uncertainty Analysis of Triplicate Samples (land treatment of bare soil, subsoil hydraulic conductivity of 1.59 in/h)

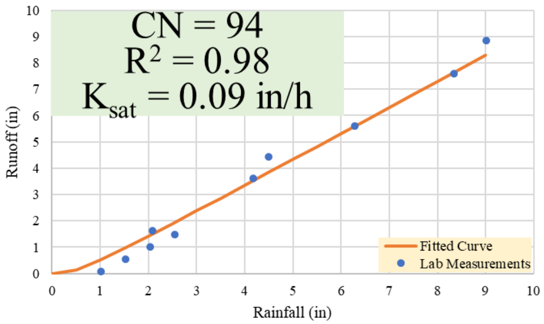
Table 29 - Mean and 95 Percent CI of Fitted CN for Three Replicates of All Mean Soil Composite Hydraulic Conductivities (Mean K_{sat}) and Land Treatments

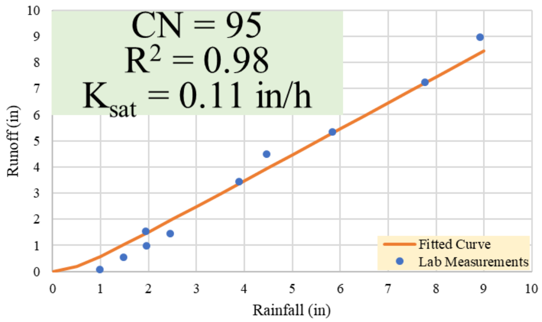
Bare Soil			Gravel			Vegetation			Porous HMA		
Mean K_{sat} (in/h)	Mean CN ± 95% CI	Individual R^2	Mean K_{sat} (in/h)	Mean CN ± 95% CI	Individual R^2	Mean K_{sat} (in/h)	Mean CN ± 95% CI	Individual R^2	Mean K_{sat} (in/h)	Mean CN ± 95% CI	Individual R^2
0.11	95±3	0.98	0.18	79±4	0.96	0.2	87±3	0.98	0.2	91±2	0.99
0.37	91±4	0.96	0.49	74±6	0.91	0.41	85±3	0.98	0.44	89±2	0.99
0.87	86±5	0.94	1.5	65±6	0.84	1.49	69±6	0.86	1.51	75±5	0.91
1.59	77±7	0.81	2.21	54±8	0.65	1.98	62±9	0.72	2.07	67±7	0.79
2.01	72±9	0.67	3.05	50±9	0.64	2.98	58±8	0.71	2.73	63±8	0.69
4.09	60±12	0.78	6.49	35±4	0.87	6.37	39±5	0.77	6.65	40±7	0.60
5.52	53±8	0.65	No runoff			No runoff			No runoff		
5.92	49±8	0.63									

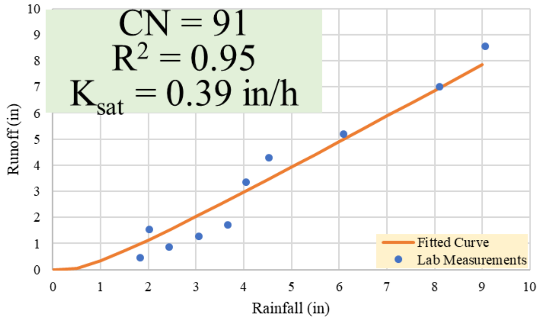
APPENDIX L FITTED CN PLOTS FOR INDIVIDUAL SOIL COLUMN OF ALL TESTED SOIL COMPOSITE HYDRAULIC CONDUCTIVITIES AND LAND TREATMENTS

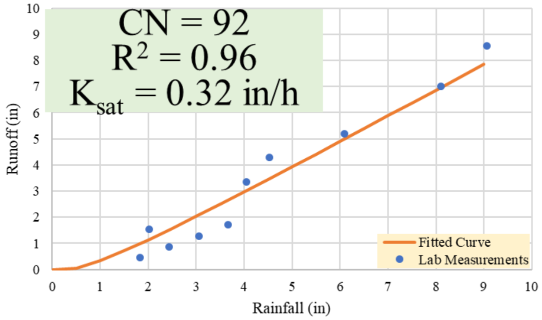
Bare Soil

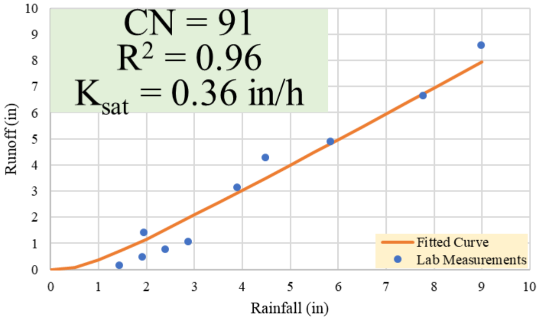


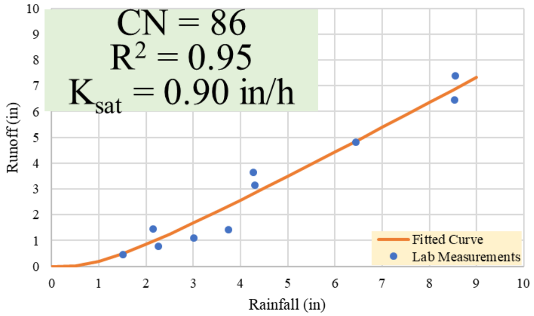


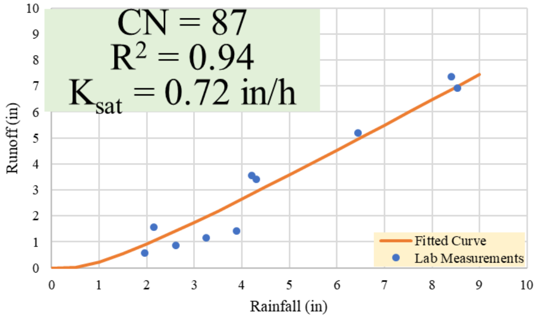


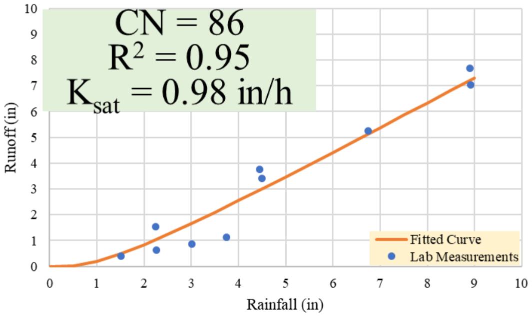


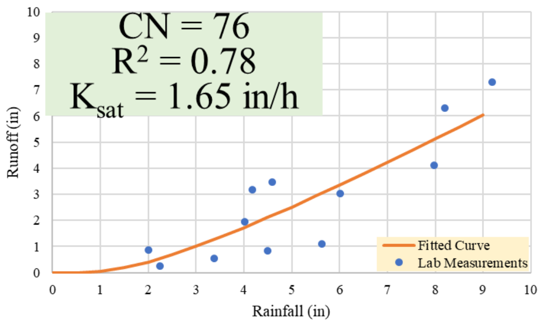




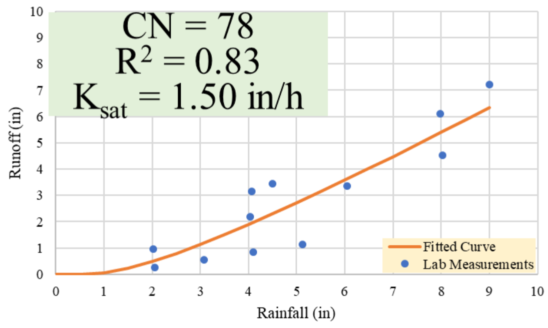




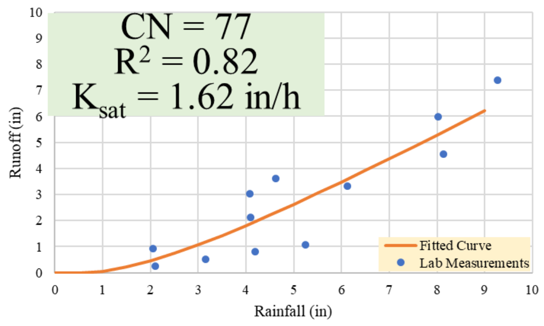




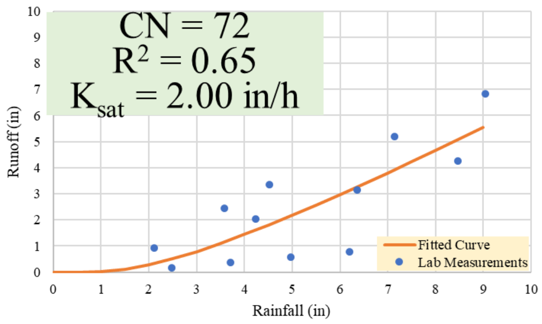
CN = 76
$R^2 = 0.78$
K_{sat} = 1.65 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



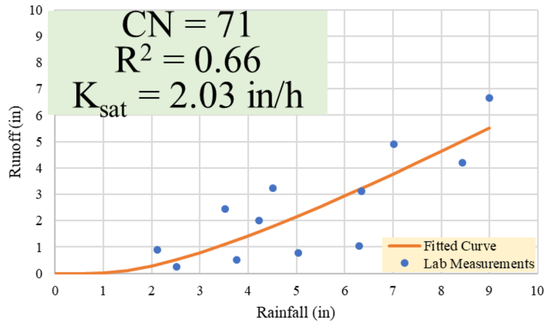
CN = 78
$R^2 = 0.83$
K_{sat} = 1.50 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



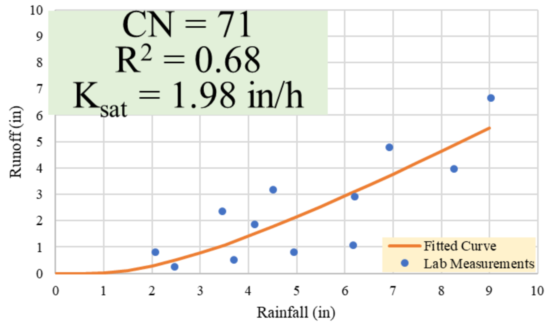
CN = 77
$R^2 = 0.82$
K_{sat} = 1.62 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



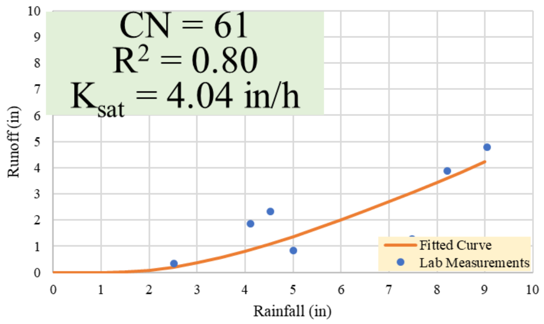
CN = 72
$R^2 = 0.65$
K_{sat} = 2.00 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



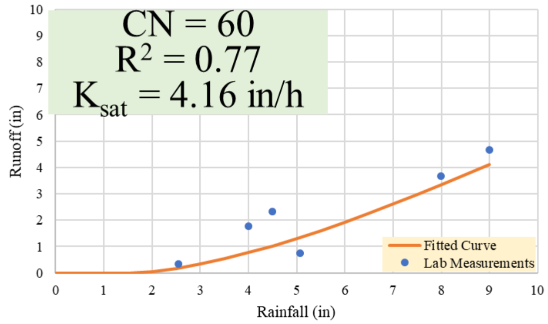
CN = 71
$R^2 = 0.66$
K_{sat} = 2.03 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



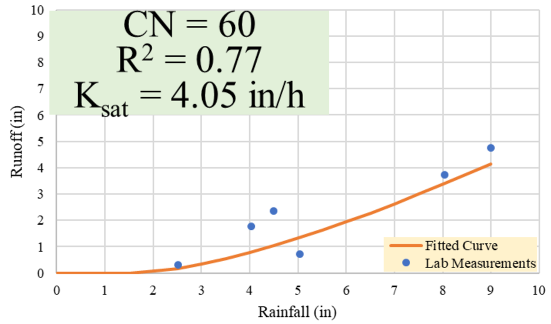
CN = 71
$R^2 = 0.68$
K_{sat} = 1.98 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



CN = 61
$R^2 = 0.80$
K_{sat} = 4.04 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



CN = 60
$R^2 = 0.77$
K_{sat} = 4.16 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10



CN = 60
$R^2 = 0.77$
K_{sat} = 4.05 in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10

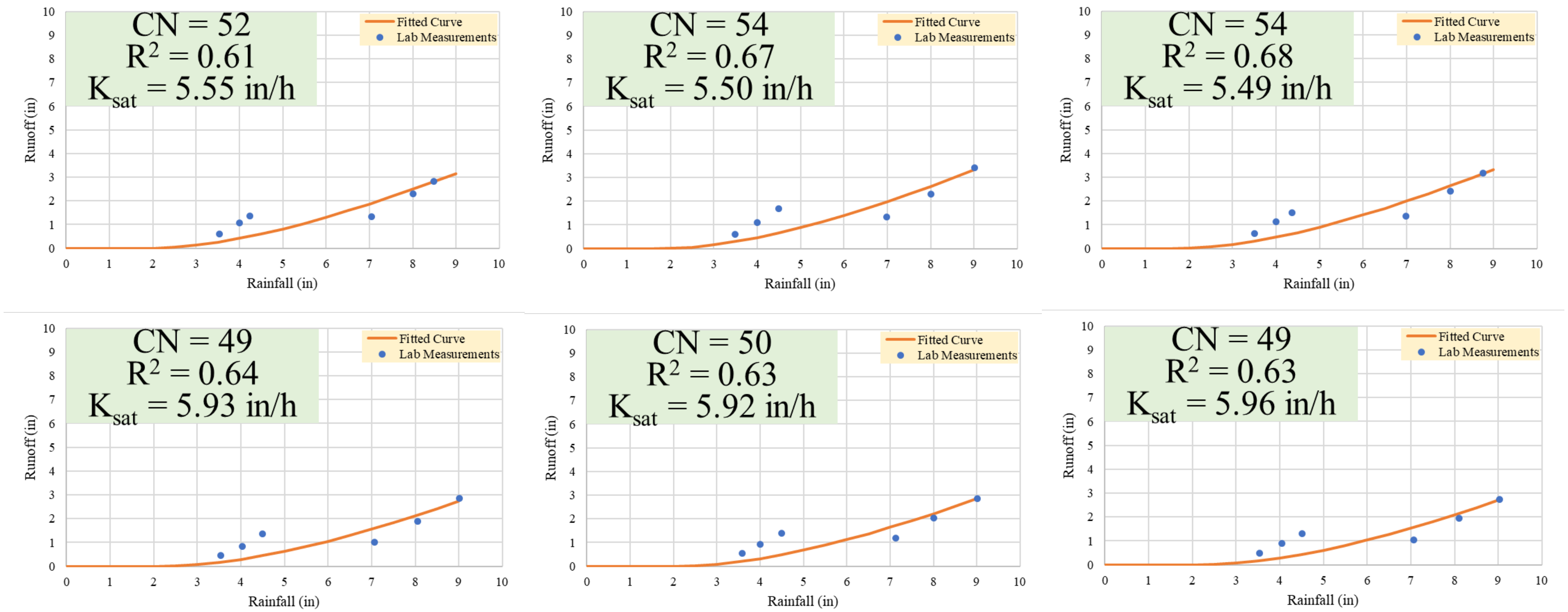
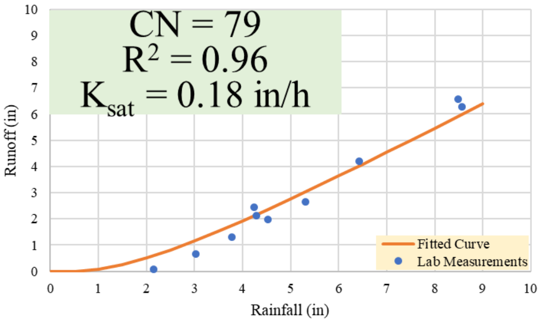
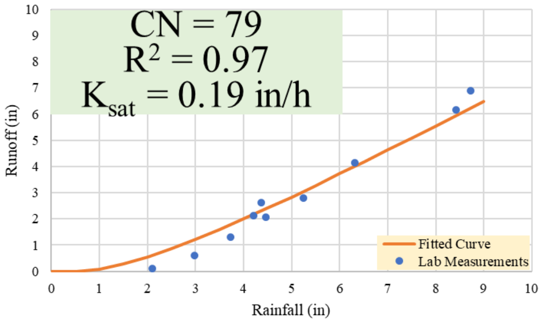
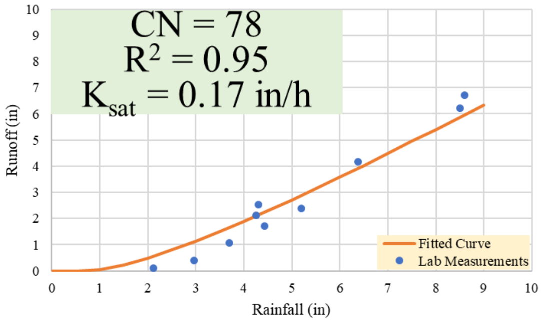


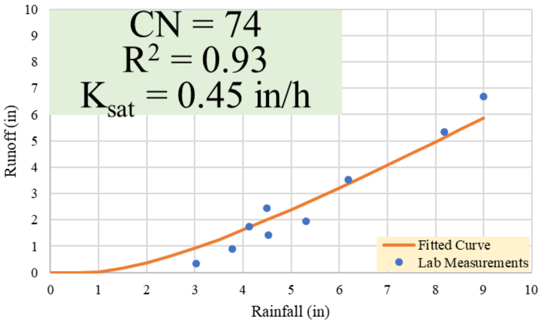
Figure 56. Curve Fitting Plots of Bare Soil (K$_{sat}$ = Composite Hydraulic Conductivity)

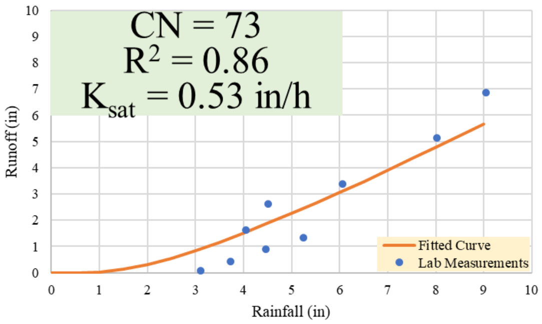
Gravel

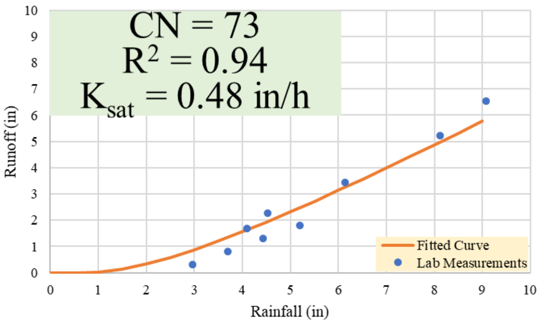

CN = 79
R^2 = 0.96
K_{sat} = 0.18 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements

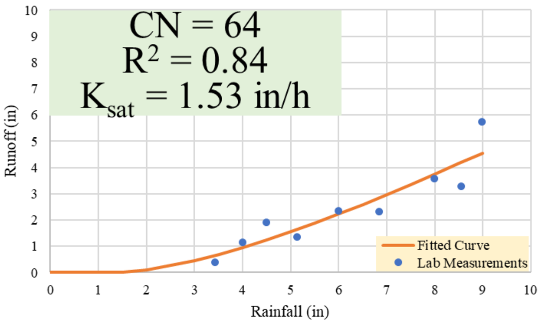

CN = 79
R^2 = 0.97
K_{sat} = 0.19 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements

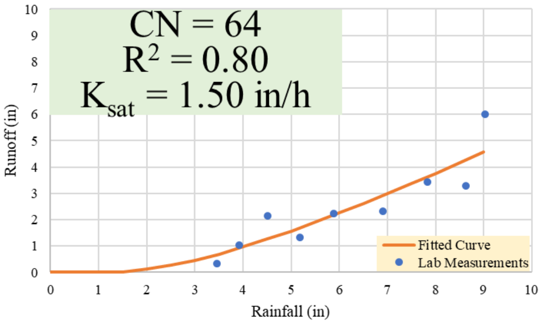

CN = 78
R^2 = 0.95
K_{sat} = 0.17 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements

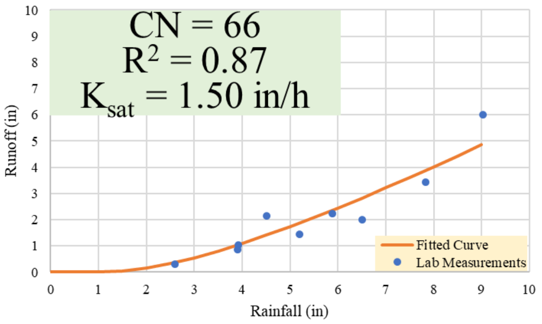

CN = 74
R^2 = 0.93
K_{sat} = 0.45 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements


CN = 73
R^2 = 0.86
K_{sat} = 0.53 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements


CN = 73
R^2 = 0.94
K_{sat} = 0.48 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements


CN = 64
R^2 = 0.84
K_{sat} = 1.53 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements


CN = 64
R^2 = 0.80
K_{sat} = 1.50 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements


CN = 66
R^2 = 0.87
K_{sat} = 1.50 in/h
Runoff (in)
Rainfall (in)
Fitted Curve
Lab Measurements

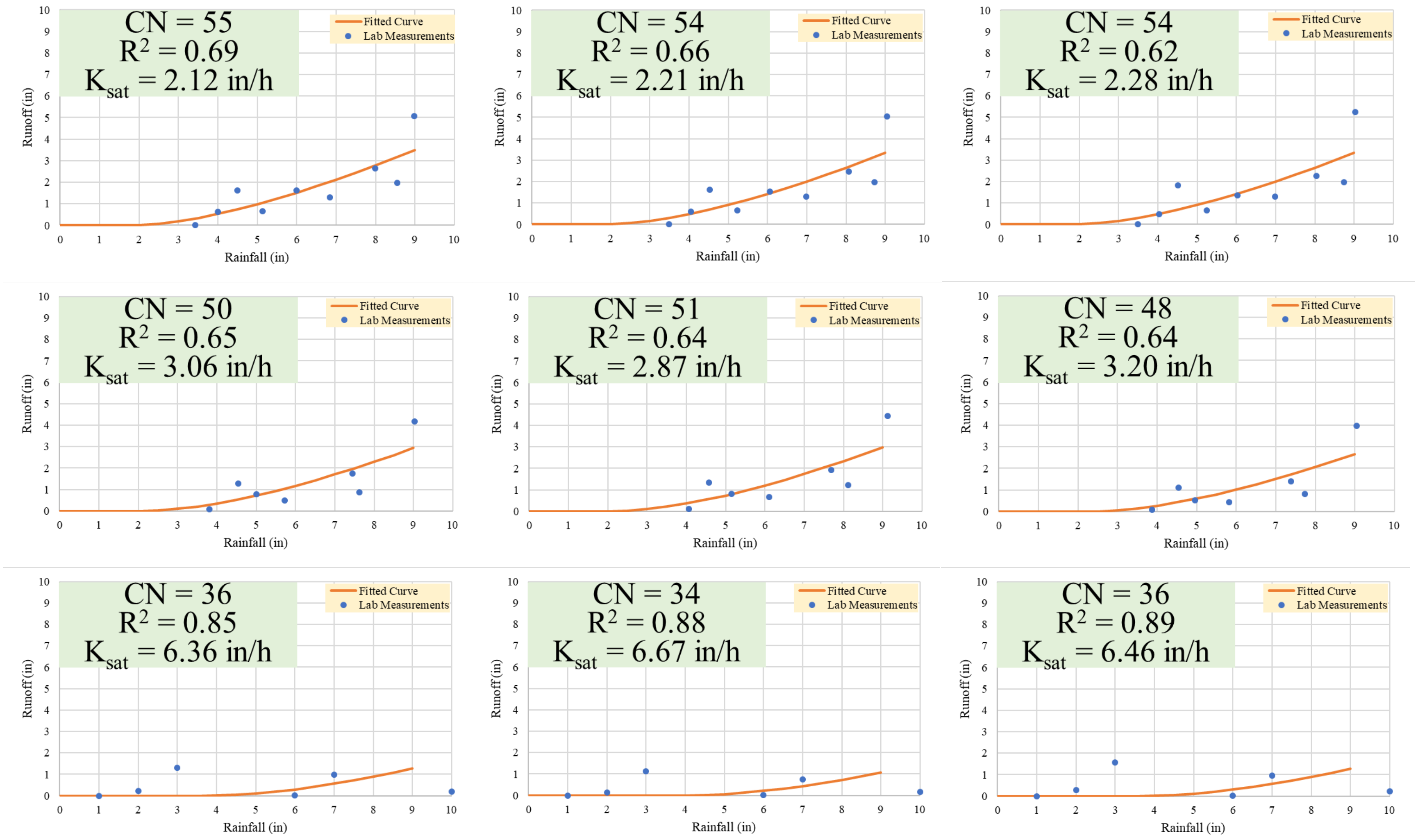
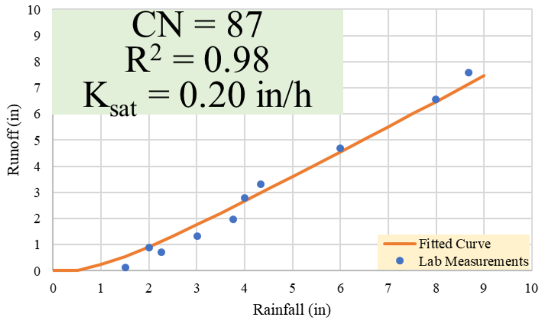
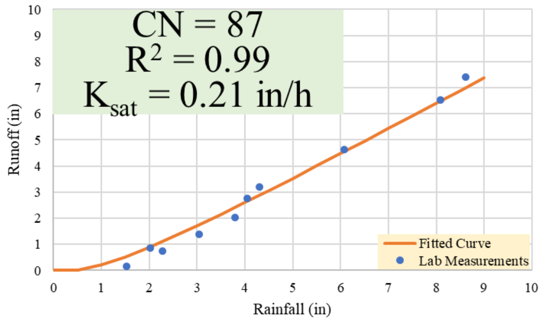
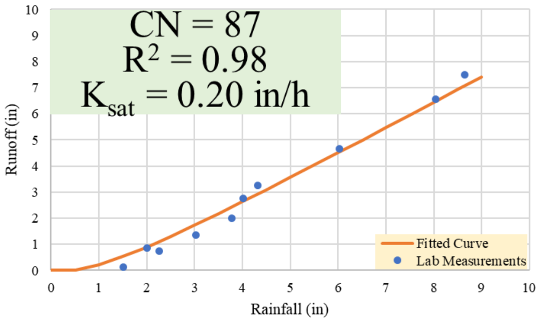


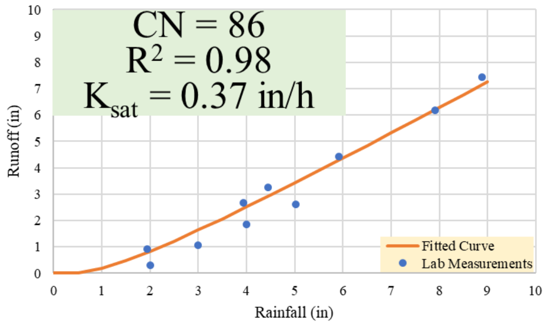
Figure 57. Curve Fitting Plots of Gravel (K_{sat} = Composite Hydraulic Conductivity)

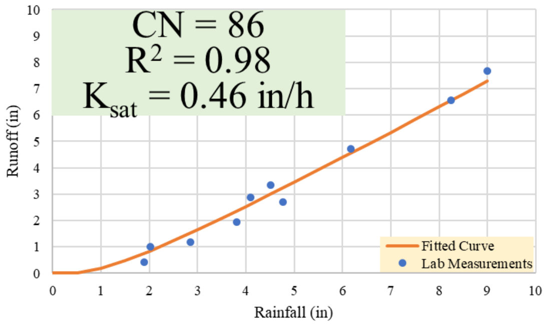
Vegetation

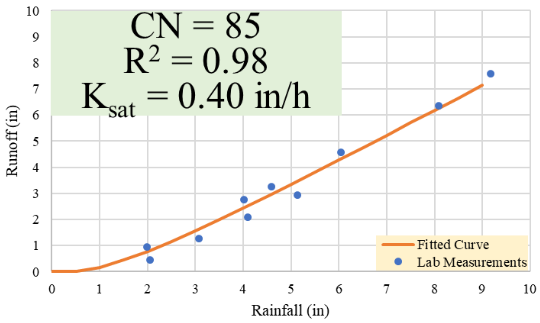

CN = 87
$R^2 = 0.98$
K_{sat} = 0.20 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements

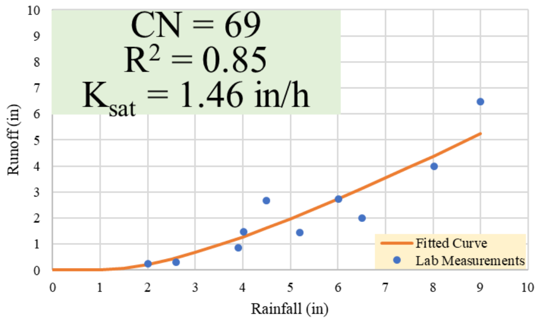

CN = 87
$R^2 = 0.99$
K_{sat} = 0.21 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements

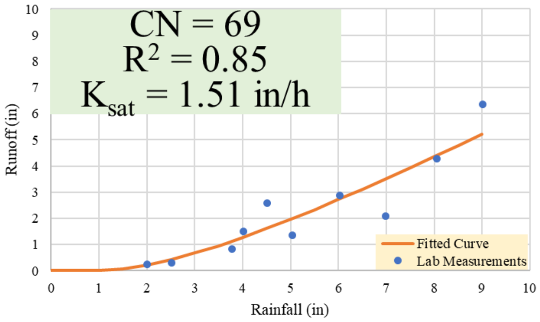

CN = 87
$R^2 = 0.98$
K_{sat} = 0.20 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements

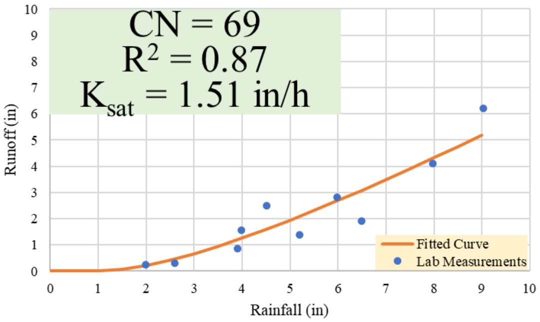

CN = 86
$R^2 = 0.98$
K_{sat} = 0.37 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements


CN = 86
$R^2 = 0.98$
K_{sat} = 0.46 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements


CN = 85
$R^2 = 0.98$
K_{sat} = 0.40 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements


CN = 69
$R^2 = 0.85$
K_{sat} = 1.46 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements


CN = 69
$R^2 = 0.85$
K_{sat} = 1.51 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements


CN = 69
$R^2 = 0.87$
K_{sat} = 1.51 in/h
Runoff (in)
0 1 2 3 4 5 6 7 8 9 10
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10
Fitted Curve
Lab Measurements

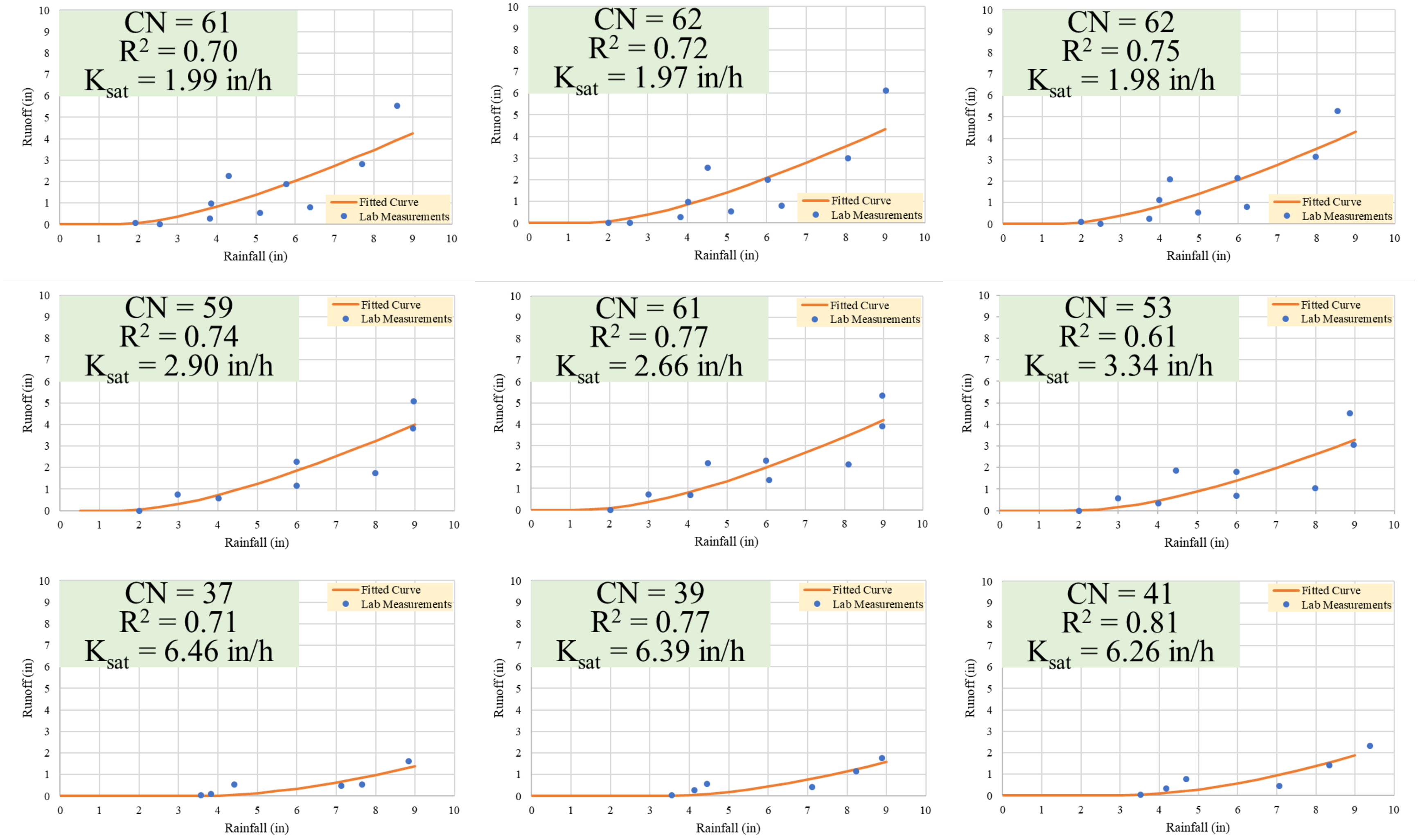
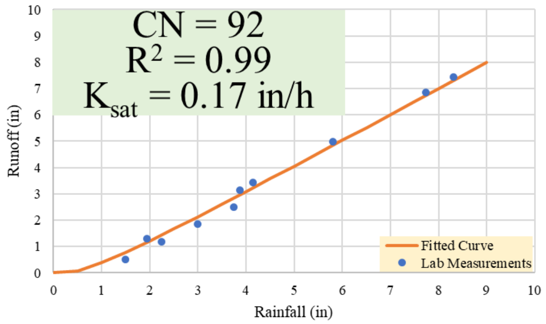
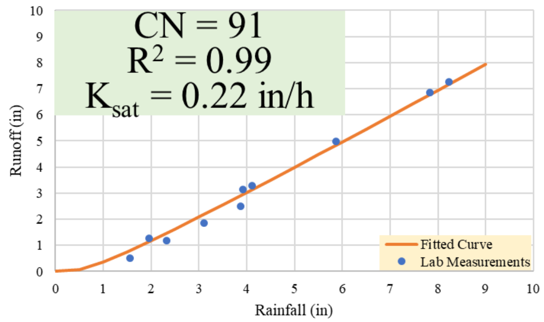
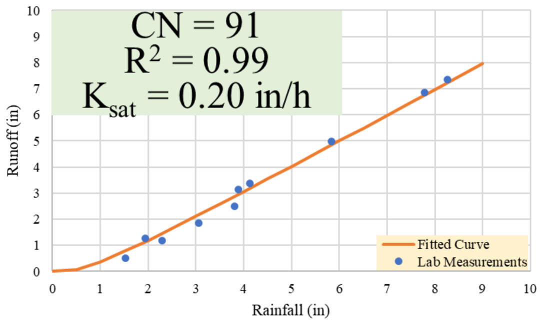


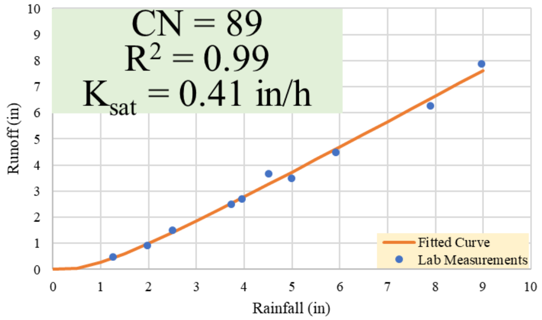
Figure 58. Curve Fitting Plots of Vegetation (K_{sat} = Composite Hydraulic Conductivity)

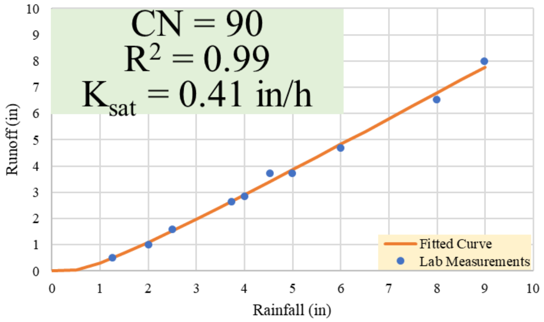
Porous HMA

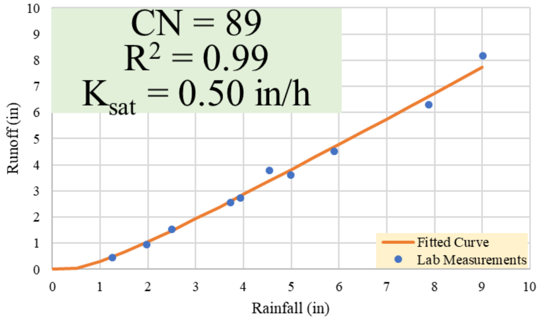

CN = 92
$R^2 = 0.99$
$K_{sat} = 0.17$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10

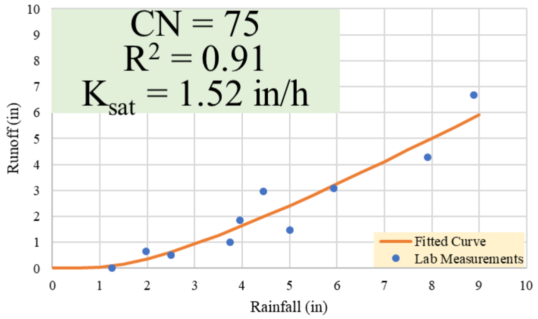

CN = 91
$R^2 = 0.99$
$K_{sat} = 0.22$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10

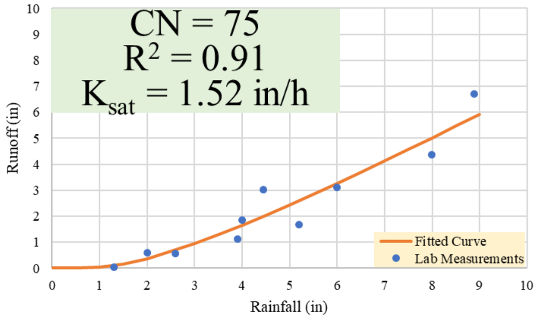

CN = 91
$R^2 = 0.99$
$K_{sat} = 0.20$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10

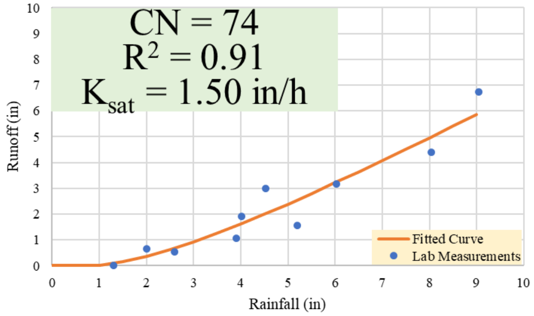

CN = 89
$R^2 = 0.99$
$K_{sat} = 0.41$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10


CN = 90
$R^2 = 0.99$
$K_{sat} = 0.41$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10


CN = 89
$R^2 = 0.99$
$K_{sat} = 0.50$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10


CN = 75
$R^2 = 0.91$
$K_{sat} = 1.52$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10


CN = 75
$R^2 = 0.91$
$K_{sat} = 1.52$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10


CN = 74
$R^2 = 0.91$
$K_{sat} = 1.50$ in/h
Fitted Curve
Lab Measurements
Runoff (in)
Rainfall (in)
0 1 2 3 4 5 6 7 8 9 10

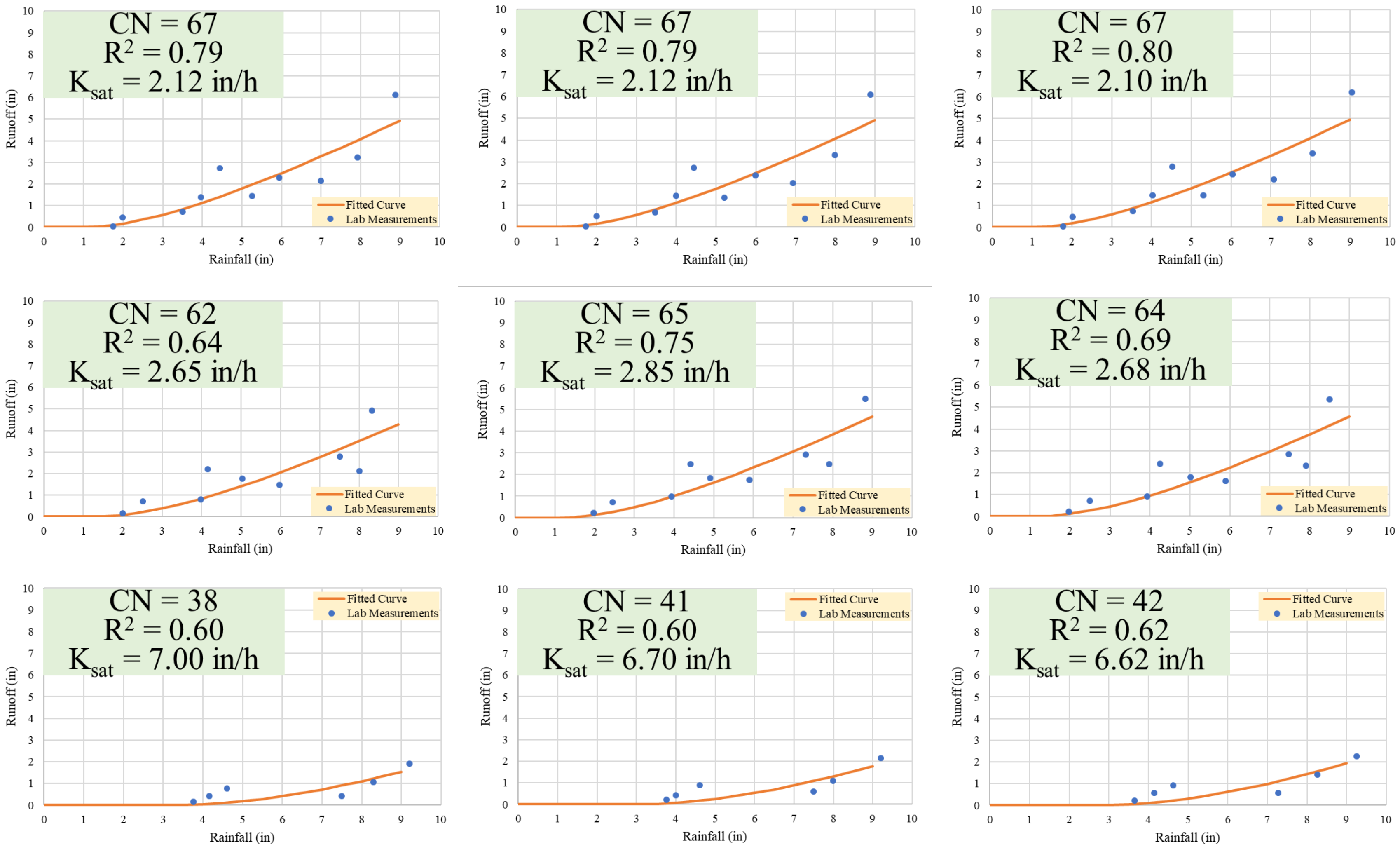
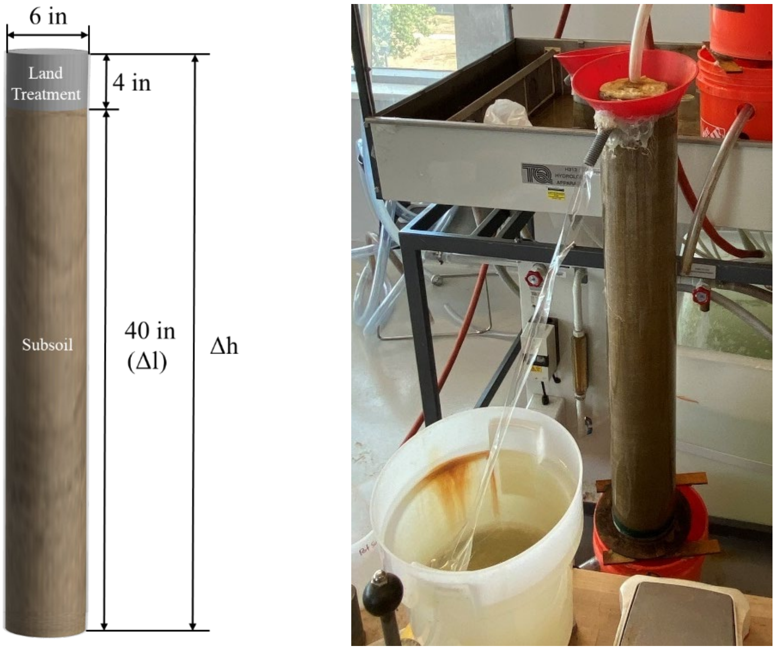


Figure 59. Curve Fitting Plots of Porous HMA (K_{sat} = Composite Hydraulic Conductivity)

APPENDIX M RESULTS OF EXPERIMENTS CONDUCTED IN 44-IN-HIGH SOIL COLUMN

To validate the translation of lab results to field application, the impact of subsoil depth (depth to groundwater table) on CN was examined by additional experiments conducted in a 44-in soil column (figure 60).



(a) (b)

Figure 60. (a) Sketch and (b) Photo of the 44-in-High Soil Column

The diameter of the soil column is 6 in, length is 44 in (40 in of subsoil plus 4 in of land treatment). Following the same sample preparation and testing procedure as the short (i.e., 12 in) soil column, two samples with subsoil hydraulic conductivity of 1.0 in/h and 2.5 in/h were tested under four rainfall intensities for each of the four land treatments. Same data processing and analysis were conducted and fitted CNs are plotted in figure 61, in comparison of CNs obtained from short soil columns.

T-tests were conducted for CNs of each land treatment obtained from experiments conducted in 12-in-high and 44-in-high soil column. (36) This helps to determine if the 44-in-CN is a member of the population of 12-in-CNs. Results show that p-values of all t-tests were all less than 0.05, indicating the 44-in-CN is a member of the population of 12-in-CNs with 95 percent confidence. In other words, the translation of lab results (i.e., with depth to groundwater table equal to 8 in) to field applications (i.e., with depth to groundwater table equal to or deeper than 40 in) is scientifically defensible.

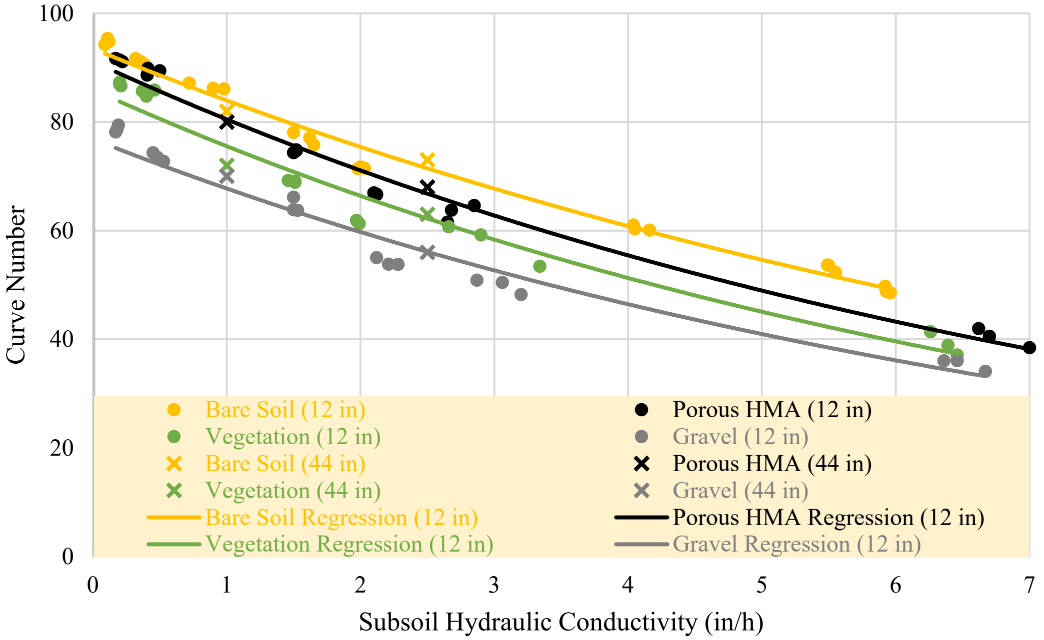


Figure 61. CNs of Experiments Conducted in 12-in-High and 44-in-High Soil Column