5-2017

Comparison of Saturated Hydraulic Conductivity using Geospatial Analysis of Field and SSURGO data for septic tank suitability assessment

Joshua Randall Weaver
Clemson University, rweave3@clemson.edu

COMPARISON OF SATURATED HYDRAULIC CONDUCTIVITY USING GEOSPATIAL ANALYSIS OF FIELD AND SSURGO DATA FOR SEPTIC TANK SUITABILITY ASSESSMENT

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Plant and Environmental Sciences

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by
Joshua Randall Weaver
May 2017

Accepted by:
Dr. Elena A. Mikhailova, Committee Chair
Dr. Christopher J. Post
Dr. Charles V. Privette

ABSTRACT

Saturated hydraulic conductivity (Ksat) is a soil property linked to ecosystem services and it is often used in septic tank suitability determination at various scales. Field and laboratory measurements of Ksat and septic tank suitability are time-consuming and expensive. Soil Survey Geographic Database (SSURGO) data are available for the United States, but limitations of using SSURGO data for Ksat and septic suitability determination are not fully understood. The objectives of this study were to quantify and compare depth to limiting layer, thickness of limiting layer, and Ksat values for a 147-hectare Cornell University Willsboro Research Farm, located in upstate New York based on the following procedures: a) using values reported by SSURGO for each soil map unit (SMU) within the farm and applying that value across each SMU; b) averaging the values of soil cores collected within a specific SMU boundary and applying the averaged value across each SMU; and c) interpolating values across the farm based on the individual soil cores. SSURGO overestimated the depth to the limiting layer and the thickness of the limiting layer when compared to field measured values. Average soil core values representing limiting layer, thickness of limiting layer, and Ksat values were not significantly correlated with SSURGO reported values. Similarly, interpolated soil core values of limiting layer, thickness of limiting layer, and Ksat values were not significantly correlated with SSURGO reported values. Both SSURGO data and field measurements are necessary for proper septic tank suitability determination due to the uncertainties, which often arise from field, laboratory and geospatial variability in data

necessary for such determinations. Application of technological advances may reduce the uncertainty in data collection.

DEDICATION

I would like to dedicate this thesis to my family and friends that helped me get to this point in my academic career. To my wife and kids who allowed me to study when I needed to study, pushed me when I needed to be pushed, and picked me up when I needed to be picked up. To my late grandfather, and uncle, who always told me to get my education and to let nothing stand in the way of doing so. To my mom who always made sure I always had what I needed and told me I could be and do anything in life. To my grandmother who always supported me and gave me constant words of encouragement. To Dr. Steve Cole for mentoring and encouraging me through this journey. To all my professors during my college career and to all my teachers this is dedicated to you for all the help you provided me with and for all the words of encouragement. To Clemson University for allowing me the opportunity to further my education.

ACKNOWLEDGMENTS

I wish to thank my committee members; Dr. Elena Mikhailova, Dr. Christopher Post and Dr. Charles Privette. In addition, I would like to say thank you to my advisor, Dr. Elena Mikhailova, for her unwavering support throughout this journey of writing this thesis and conducting the research for the thesis. Her constant words of encouragement made this an awesome journey and one that will never be forgotten. I also wish to thank Dr. Mark Schlautman, Michael Cope, and Roxanne Stiglitz for helping me tables and maps and other aspects of my thesis. Clemson University provided funding for this study. Technical Contribution No. 6427 of the Clemson University Experiment Station. This material is based upon work supported by NIFA/USDA, under projects: SC-1700452, and SC-1700462.

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CHAPTER ONE

Comparison of Saturated Hydraulic Conductivity using Geospatial Analysis of Field and SSURGO data for septic tank suitability assessment

INTRODUCTION

In-ground septic tank sewage systems are widely used in the United States with approximately one-third of the nations' sewage being disposed utilizing this method (Harman et al., 1996). Septic systems in the United States produce more than 10 billion L of wastewater per day, and this wastewater contains large quantities of pathogens, phosphorus, and nitrate (Gerba et al. 1975; Sawhney and Starr 1977).

The most common type of septic system is a conventional or gravity fed system, which is composed of a septic tank and a drain field (Vepraskas et al., 2009). In properly functioned septic system, all the wastewater must infiltrate into the soil and move through the unsaturated soil before entering a water table (Vepraskas et al., 2009). Properties influencing the suitability for septic tank absorption fields include (Table 1, Soil Survey Staff, 1993): total subsidence (cm), flooding, bedrock depth (m), cemented pan depth (m), free water occurrence (m), saturated hydraulic conductivity (μm/s): minimum (0.6 to 1.5 m), maximum (0.6 to 1 m), slope (%), fragments > 75 mm, downslope movement, ice melt pitting, and permafrost. Field and laboratory measurements of properties related to septic tank suitability are time-consuming and expensive, therefore Soil Survey Geographic Database (SSURGO) data for the United States provides relevant freely available data (Table 2). The SSURGO database contains soil information (displayed by soil map unit, SMU) collected by the National Cooperative Soil Survey based on field and laboratory analyses (Soil Survey Staff, 2016). The map units describe soils with unique properties, and interpretations, including septic suitability (Soil Survey Staff, 2016). The map units, which contain both major and some minor components, are typically named for the major components (Soil Survey Staff, 2016). Septic suitability ratings (“not limited”, “somewhat limited”, “very limited”) include explanation of specific properties, which influence the specific rating. For example, saturated hydraulic conductivity is rated using Ksat class limits (in micrometers per second): “very low” (0.00 to 0.01), “low” (0.01 to 0.1) etc. As it can be noted from Sometime there is a difference in Ksat and septic suitability rating between the sources (e.g. Soil Survey Manual, SSURGO) (Table 2).

Septic suitability is commonly regulated by the State Health Departments, and can vary from state to state. Collick et al. (2006) examined the importance of various properties used in septic suitability analysis and concluded that the Ksat, depth to impermeable layer, and slope are of great importance in the New York City water basin located within the Catskills region. Septic systems performed poorly in undulating landscapes with low Ksat and impermeable layer close to the surface (Collick et al., 2006).

Currently, SSURGO-reported saturated hydraulic conductivity (Ksat) data are often estimated from particle-size analysis (PSA) data from specific locations and then extrapolated across large areas based on soil map units (O’Neal, 1952, Rawls and Brakensiek, 1983, Williamson et al., 2014). The preference for particle-size derived Ksat values can be explained by the low cost and ease of acquisition as well as desire to use a uniform national approach (Williamson et al., 2014). Rare comparisons of SSURGO recorded PSA-derived Ksat values are often different from site-specific field Ksat measurements (Hart et al., 2008). The freely available PSA-derived Ksat data from SSURGO is frequently used for regional and national modelling for the purposes of environmental management, but spatial variability associated with using SSURGO data instead of site-specific data is largely unknown (Hoos and McMahon, 2009). Saturated hydraulic conductivity was identified as a key soil property in provisional and regulating service (Table 3, Adhikari and Hartemink, 2015). For example, it is important in water purification. He at al. (2011) reported that large percentage (52-89%) of land within the Alabama Black Belt region should not have been used for conventional onsite wastewater treatment systems, which are aging posing potential public health risk.

Previous research efforts have focused primarily on estimating Ksat and related soil properties from SSURGO databases, but only rarely making comparisons against actual field measurements within the soil map units. This study is aimed at conducting an assessment of depth to limiting layer, thickness of limiting layer, and Ksat values approach using SSURGO and field measurements at a farm scale.

The objectives of this study were to quantify and compare depth to limiting layer, thickness of limiting layer, and Ksat values for a 147-hectare Cornell University Willsboro Research Farm, located in upstate New York based on the following procedures: a) using values reported by SSURGO for each soil map unit (SMU) within the farm and applying that value across each SMU; b) averaging the values of soil cores collected within a specific SMU boundary and applying the averaged value across each SMU; and c) interpolating values across the farm based on the individual soil cores.

MATERIALS AND METHODS

Study area

The Cornell University Willsboro research farm (Fig. 1) is in Willsboro, NY (44° 22' N, 73° 26' W), northeastern part of New York state (Sogbedji et al., 2000). This 147-hectare farm is situated on the gently rolling lacustrine plain adjacent to Lake Champlain (Mikhailova et al., 1996). The climate in the area is temperate with a 150-day growing season (Mikhailova et al., 1996). Soils (Fig. 2, Table 4, Table 5) are highly variable because of glacial deposits (e.g. glacial till, deltaic or glacial like sands and clays), and include Entisols, Inceptisols, and Alfisols soil orders (Mikhailova et al., 1996). Boundaries of the soil map units were obtained from the SSURGO database at scale of 1:12,000 and mapped in ArcGIS 10.4 (ESRI, 2016) (http://www.nrcs.usda.gov./wps/portal/nrcs/detail/soils/survey/)Study area

Sampling

Fifty-four deep soil cores were collected in the summer of 1995 on a square grid sampling pattern (Fig. 1) with each grid being 137.16 meters by 137.16 meters. Coordinates (NAD27 State Plane Coordinate System's New York East Zone, using Station ESSEX2 and Poke-A-Moonshine L.O.T. and Bench Mark H 395) and elevation values for the 61 grid locations were obtained from a professional land survey team that used an Intelligent Total Station, Set 2C SOKKISHA (Standard deviation: + 3 mm + 2 ppmD) (Mikhailova et al., 1996). Undisturbed soil cores of variable depth (sample depth varied due to the actual possibility of obtaining the sample) were extracted at 54 grid locations using a Giddings hydraulic sampler (Model – GSR-T-S) and plastic tubes with the average diameter of 4.5 cm (Mikhailova et al., 1996).

Laboratory analysis

Plastic tubes with soil samples closed with plastic caps were stored vertically in the refrigerator (at approximately 1°C) until processing and analysis (Mikhailova et al., 1996). For each of the soil cores the following information was recorded: upper and lower boundary of soil horizon, moist and dry soil color (Munsell Color Chart), pH, reaction to weak HCl ("0" = no reaction, "1" = presence of effervescence), and coarse fraction (percent of soil sample that was greater than 2 mm). Soil samples (coarse fraction removed and measured) were air-dried, manually ground and passed through a 2-mm-mesh sieve. Particle-size distribution of the less than 2-mm fraction was determined by the pipette method after pre-treating for carbonates and soluble salts with 1M NaOAc (adjusted to pH 5), and organic matter was removed with 30% H2O2 (Gee and Bauder, 1986). Soil samples were highly variable in soil texture encompassing 8 textural classes in total and having the following distribution by soil order (Fig. 2): Alfisols (across 5 textural classes), Entisols (across 4 textural classes), and Inceptisols (across 3 textural classes).

Determining depth to limiting layer and thickness of limiting layer from SSURGO and field data

Depth to limiting layer and thickness of limiting layer were obtained by interpreting Ksat, color, soil organic matter and presence of coarse fragments from SSURGO data. Depth to limiting layer was determined by identifying the top boundary of a layer with an abrupt reduction in Ksat from reported SSURGO tables. Thickness of limiting layer was obtained by subtracting the lower boundary depth from the top boundary depth of layer(s) based on reported Ksat values from reported SSURGO tables as well as presence of coarse fragments, color and soil organic matter.

Field depth to limiting layer (thickness of limiting layer) was obtained from field soil cores. Depth to limiting layer and thickness of limiting layer were obtained by interpreting Ksat, color, soil organic matter and presence of coarse fragments from field data. Obtained values were averaged for each soil type. Depth to limiting layer was determined by identifying the top boundary of a layer with an abrupt reduction in Ksat from reported field tables. Thickness of limiting layer was obtained by subtracting the lower boundary depth from the top boundary depth of layer(s) based on reported Ksat values from reported field tables as well as presence of coarse fragments, color and soil organic matter.

Obtained values were averaged over soil types. Inverse distance weighting (IDW) was used to interpolate results from the 54 soil cores across the extent of the study area using a 1-m grid cell size in ArcGIS 10.4 (ESRI, 2016). This process created maps that estimated depth to limiting layer (thickness of limiting layer) for each square meter of the field site. The interpolated values (cm) were then averaged within the SSURGO soil boundary to obtain depth to limiting layer (thickness of limiting layer) for each soil map unit (SMU). With each interpolated content map, the average function of zonal statistics in ArcGIS 10.4 was used to compute average depth to limiting layer (thickness of limiting layer) associated with each SSURGO polygon/SMU.

Determining saturated hydraulic conductivity from SSURGO and field data

Saturated hydraulic conductivity (Ksat) was obtained from SSURGO reported midpoint values (reported in units of μm/s) and these values were averaged for each soil type. Estimated values for Ksat were also derived based on the soil texture classes (Table 6; adapted from Rawls et al., 1982 who reported Ksat in units of cm/h) determined from midpoint percentages of sand, silt, and clay reported in SSURGO for the limiting layer. Determination of the saturated hydraulic conductivity of soil containing coarse fragments requires a correction for the volume of coarse (≥ 2mm) fragments (Brakensiek et al., 1986). Both Ksat from SSURGO reported midpoint values (based on coarse fragments (Cf) reported in official soil series descriptions) and field estimated Ksat based on texture (based on field data) using the following equation:

$$\text{Ksat (Cf-corrected)}=((100 - \text{Cf, \% }) / 100) * (\text{Ksat}) \qquad \text{(Eq. 1)}$$

where: Cf, % is the coarse fragment mass percent.

Saturated hydraulic conductivity was also estimated for field data based on the soil texture classes (Rawls et al., 1982) determined from midpoint percentages of sand, silt, and clay (determined from field samples) for the limiting layer. Estimates of Ksat values were corrected for percentage of coarse fragments. Inverse distance weighting

(IDW) was used to interpolate results from the 54 soil cores across the extent of the study area using a 1-m grid cell size in ArcGIS 10.4 (ESRI, 2016). This process created maps that estimated Ksat for each square meter of the field site. The interpolated content values were then averaged within the SSURGO soil boundary to obtain Ksat for each soil map unit (SMU). With each interpolated content map, the average function of zonal statistics in ArcGIS 10.4 was used to compute average Ksat associated with each SSURGO polygon/SMU.

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Calculating area-weighted averages for soil orders

Area-weighted averages of depth to limiting layer, thickness of limiting layer, and Ksat values were calculated using the following formula:

Area-weighted average=(x1*A1 + x2*A2 + x3*A3 + . . .) / (A1 + A2 + A3 + . ..) (Eq. 2)

where: x is an average value (for example depth to limiting layer) for a soil series and A is the area of that soil series within the soil order.

RESULTS AND DISCUSSION

Spatial comparison of depth to limiting layer, thickness of limiting layer, and Ksat at the Willsboro Research Farm

The reported SSURGO depth to limiting layer was consistently deeper than field measured values (SSURGO vs. field measured depth to limiting layer): Alfisols (86 cm vs 31 cm), Entisols (40 cm vs. 32 cm), and Inceptisols (145 cm vs. 28 cm) (Fig. 3, Tables

7, 8, 9). The reported SSURGO thickness of limiting layer was consistently larger than field measured values (SSURGO vs. field measured thickness of limiting layer): Alfisols (79 cm vs 27 cm), Entisols (82 cm vs. 32 cm), and Inceptisols (30 cm vs. 28 cm) (Fig. 4, Tables 7, 8, 9). Correlation plots revealed that there was no discernable pattern when comparing reported SSURGO values for saturated hydraulic conductivity with field estimated values (Fig. 5, 6, Table 10).

Field data from the Willsboro Farm revealed that depth to limiting layer, thickness of limiting layer, and Ksat were highly variable, because these soils were formed in glacial landscapes (e.g., till plains, lake plains, terraces, deltas, and outwash plains). Soil cores were not collected from each SMU present at a field site during field data collection with a regular grid sampling approach. Interpolation of the soil core results to obtain complete coverage resolved this potential shortcoming in sampling (Table 8). Results of this field study in agreement with findings of Collick et al. (2006), which reported low Ksat and impermeable layer close to the surface in the Catskills region. Septic systems performed poorly in this landscapes (Collick et al., 2006).

The difference between SSURGO and field estimated depth to limiting layer, thickness of limiting layer, and Ksat can be explained by the fact that SSURGO values for these properties are frequently measured from a selected pedon from a "type location" and not from the actual study location (Mikhailova et al., 2016). These "type locations" can be located far from study sites and even in different states (Mikhailova et al., 2016). SSURGO SIC values may overestimate the actual content when compared to systematic field measurements (Mikhailova et al., 2016).

CONCLUSIONS

This study analyzed differences in glaciated soil depth to limiting layer, thickness of limiting layer, and saturated hydraulic conductivity in relation to septic suitability assessment at a farm scale using the SSURGO database and detailed field measurements. Based on the results, it can be concluded that detailed site-specific field measurements are more accurate in determining soil depth to limiting layer, thickness of limiting layer and saturated hydraulic conductivity at the soil map unit. SSURGO overestimated the depth to the limiting layer and the thickness of the limiting layer when compared to field measured values. Average soil core values representing limiting layer, thickness of limiting layer, and Ksat values were not significantly correlated with SSURGO reported values. Similarly, interpolated soil core values of limiting layer, thickness of limiting layer, and Ksat values were not significantly correlated with SSURGO reported values. The lack of consistent and significant correlation trends among the different estimation approaches used in the present study highlights the difficulties that must be overcome to generate robust and reliable estimates of depth to limiting layer, thickness of limiting layer, and saturated hydraulic conductivity values in soils dominated by past glacial activity. Detailed site-specific field measurements of depth to limiting layer, thickness of limiting layer, and saturated hydraulic conductivity are needed to accurate assessment of septic suitability in the areas affected by past glaciation.

FUTURE RECOMMENDATIONS

New tools and technology will allow for undisturbed analysis of soil and should be studied to help link the resulting data to determine septic suitability. For example, ground penetrating radar and electromagnetic induction (EC) can be used to determine depth to ground water, depth to limiting layer, as well as drainage patterns (Grunwald and Lamsal, 2016) over a potential field site. This type of analysis could prove more instructive and cost effective when compared to physical soil sampling. Accurate location of the flood plain, through LiDAR mapping (LiDAR, 2017), could prevent the installation of septic systems in areas subject to failure by water inundation and should be included in septic suitability determination. Finally, developing standard methods to survey and archive septic tank locations using accurate Global Positioning Systems (GPS) would greatly improve the ability for state and local agencies to monitor septic systems over time to limit failure caused by lack of maintenance and to keep a clearer overall record of septic systems as population and housing density increase over time. For example, Hu and Zhou (2008) proposed an integrated, GIS-based, on-site wastewater information management system based on three components (a mobile GIS for field data collection; a World Wide Web (WWW) interface for electronic submission of individual on-site wastewater treatment facilities (WWTF) information to a centralized GIS database in a specified agency; and a GIS for the display and management of on-site WWTFs information (including land use, soil types, streams, and topography) for providing environmental protection agencies and public health organizations with a spatial framework for managing on-site WWTFs and assessing the risks related to surface discharges.

APPENDICES

Appendix A

Tables

Table 1. Interpretive soil properties and limitation classes for septic tank soil absorption suitability (Soil Survey Staff, 1993).

Interpretive soil property	Limitation class		
	Slight	Moderate	Severe
Total subsidence (cm)	--	--	> 60
Flooding	None	Rare	Common
Bedrock depth (m)	> 1.8	1-1.8	< 1
Cemented pan depth (m)	> 1.8	1-1.8	< 1
Free water occurrence (m)	> 1.8	1-1.8	< 1
Saturated hydraulic conductivity (µm/s)			
Minimum 0.6 to 1.5 m[a]	10-40	4-10	< 4
Maximum 0.6 to 1 m[a]			> 40
Slope (Pct)	< 8	25-50	> 50
Fragments > 75 mm[b]	< 25	25-50	> 50
Downslope movement			c
Ice melt pitting			c
Permafrost			d

[a] 0.6 to 1.5 m pertains to percolation rate; 0.6 to 1 m pertains to filtration capacity

[b] Weighted average to 1 m.

[c] Rate severe if occurs.

[d] Rate severe if occurs above a variable critical depth.

Table 2. Comparison of terminology used for saturated hydraulic conductivity rating and septic system suitability from various sources.

Source	K_{sat} rating	Soil interpretation for septic suitability
Soil Survey Manual (Soil Survey Division Staff, 1993)	Table 3-7. Saturated hydraulic conductivity classes for Ksat (µm/s): Very low: <0.01 Low: 0.01 to 0.1 Moderately low: 0.1 to 1.0 Moderately high: 1 to 10 High: 10 to 100 Very high: >100	
Soil Survey Manual (Soil Survey Division Staff, 1993)	Table 6-1. Minimum Ksat (0.6-1.5 m – percolation rate) Slight: 10-40 Moderate: 4-10 Severe: <4 Maximum Ksat (0.6-1 m – filtration capacity) Severe: <40	Based on interpretative soil properties (e.g. total subsidence, flooding, bedrock depth etc.) Slight Moderate Severe
SSURGO Web soil survey	Standard K_{sat} class limits (µm/s): Very low: 0.00 to 0.01 Low: 0.01 to 0.1 Moderately low: 0.1 to 1.0 Moderately high: 1 to 10 High: 10 to 100 Very high: 100 to 705	Based on factors affecting use (e.g. Ksat, depth to water table, ponding etc.), for depths of 24-60 inches (64-152 cm): Not limited Somewhat limited Very limited

Table 3. List of ecosystem services provided by hydraulic conductivity (adapted from Adhikari and Hartemink, 2015).

Key soil properties	Provisioning services		Regulating services			
Hydraulic conductivity	Food fuel and fiber	Fresh water/water retention	Climate & gas regulation	Water regulatuion	Erosion & flood control	Water purification
	✓	✓	✓	✓	✓	✓

Table 4. Soil types and septic suitability within Willsboro Farm (Web Soil Survey, Soil Survey Staff, 2017).

Map unit symbol	Septic suitability	Rating reasons (numeric values*)
Alfisols		
BoB	Somewhat limited	Depth to saturated zone (0.80), restricted permeability (0.14)
HgB	Somewhat limited	Seepage (0.90)
KyA	Very limited	Depth to saturated zone (1.00), restricted permeability (1.00)
KyB	Very limited	Depth to saturated zone (1.00), restricted permeability (1.00)
CvA	Very limited	Depth to saturated zone (1.00), restricted permeability (1.00)
CpB	Very limited	Depth to saturated zone (1.00), restricted permeability (1.00), depth to dense material (0.75)
Entisols		
CqB	Very limited	Filtering capacity (1.00), depth to saturated zone (0.80), depth to dense material (0.75)
CuA	Very limited	Depth to saturated zone (1.00), depth to dense material (0.80), restricted permeability (0.31)
DeA	Very limited	Seepage (1.00), filtering capacity (1.00), depth to saturated zone (0.80)
StA	Very limited	Seepage (1.00), depth to saturated zone (1.00), filtering capacity (1.00)
Inseptisols		
AmB	Somewhat limited	Depth to saturated zone (0.80), depth to dense material (0.75)
McB	Very limited	Depth to saturated zone (1.00)
NeB	Not limited	--
NeC	Somewhat limited	Slope (0.20)

* Numerical ratings indicate the severity of individual limitations. The ratings are shown as decimal fractions ranging from 0.01 to 1.00. They indicate gradations between the point at which a soil feature has the greatest negative impact on the use (1.00) and the point at which the soil feature is not a limitation (0.00) (Web Soil Survey, Soil Survey Staff, 2017).

Table 5. An example of soil physical properties for Churchville (CpB) based on SSURGO data.

Map symbol and soil name	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Saturated hydraulic conductivity (micro m/sec)	Saturated hydraulic conductivity classes (Soil Survey Division Staff, 1993)
CpB – Churchville Loam, 2 to 8 percent slopes						
	0-23	0-40-52	28-36-65	7-25-40	1.4-10.00-14.00	Moderately high - High
	23-33	0-17-45	0-28-65	35-55-60	0.01-2.00-4.00	Low - Moderately high
	33-64	0-23-45	0-23-65	35-54-60	0.01-2.00-4.00	Low - Moderately high
	64-89	33-59-85	0-37-50	0-5-17	0.01-1.00-4.00	Low - Moderately high
	89-122	33-63-85	0-28-50	0-9-17	0.01-1.00-4.00	Low - Moderately high
	122-183	33-60-85	0-30-50	0-10-17	0.01-1.00-4.00	Low - Moderately high

Table 6. Hydrologic soil properties classified by soil texture from Rawls et al. (1982).

Texture class	Saturated hydraulic conductivity (Ksat)		Saturated hydraulic conductivity classes (Soil Survey Division Staff, 1993)
	cm/hr	μm/s	
Sand	21.00	58.33	High
Loamy sand	6.11	16.97	High
Sandy loam	2.59	7.19	Moderately high
Loam	1.32	3.66	Moderately high
Silt loam	0.68	1.88	Moderately high
Sandy clay loam	0.43	1.19	Moderately high
Clay loam	0.23	0.63	Moderately low
Silty clay loam	0.15	0.41	Moderately low
Sandy clay	0.12	0.33	Moderately low
Silty clay	0.09	0.25	Moderately low
Clay	0.06	0.16	Moderately low

Table 7. Characteristics of the limiting layer for coarse fraction-corrected saturated hydraulic conductivity (K_{sat}) from SSURGO (2016).

Soil order / Soil series (Map unit symbol)	Total area	Reported depth to limiting layer	Reported thickness of limiting layer	Reported midpoint value for K_{sat} [a]	Estimated value for K_{sat} from soil texture [b]
	m^2	---------------- cm ----------------		-------------- µm/s --------------	
Alfisols (total)	**937923**	**86** [c]	**79**	**1.87**	**2.09**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270606	91	91	4.00	5.76
Churchville loam, 2 to 8 percent slopes (CpB)	36898	122	61	0.75	5.40
Covington clay, 0 to 3 percent slopes (CvA)	49074	91	91	0.10	0.17
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	38	28	10.00	1.83
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480680	86	79 [d]	0.10	0.17
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41985	86	79 [d]	0.10	0.17

Entisols (total)	**378719**	**40**	**82**	**8.08**	**2.88**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64231	66	117	0.50	0.17
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168536	64	119 [e]	0.50	0.17
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	0	25	100.00	16.97
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145621	0	25	20.00	7.19
Inceptisols (total)	**157753**	**145**	**30**	**1.42**	**6.07**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	91	91	0.59	4.68
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	46	15	12.60	3.30
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39027	152	30	0.79	6.26
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107062	152	30	0.79	6.26

[a)] Corrected for percentage coarse fragments present as reported in official soil series descriptions.

[b] Estimates are based on the soil texture classes determined from midpoint percentages of sand, silt and clay reported in SSURGO for the limiting layer identified in [a]. K_{sat} values for these soil texture classes were taken from Rawls et al. (1982) and corrected for percentage coarse fragments as in [a].

[c] Limiting layer values reported for the three soil orders are area-averaged values from the corresponding soil map units.

[d] Limiting layer values reported as depth for the first limiting layer.

[e] Limiting layer values reported as combined depth for the bottom two layers.

Table 8. Characteristics of the limiting layer for coarse fraction-corrected saturated hydraulic conductivity (K_{sat}) from detailed field study (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol)	Total area	Number of Soil Cores	Measured depth to limiting layer	Measured thickness of limiting layer	K_{sat} [a] from texture (averaged)
	m^2		---------------- cm	----------------	μm/s
<u>Alfisols (total)</u>	**937923**	**32**	**31** [b]	**27**	**1.05**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270606	10	31 ± 35 [c]	22 ± 8	2.58 ± 2.08
Churchville loam, 2 to 8 percent slopes (CpB)	36898	n/a [d]	n/a	n/a	n/a
Covington clay, 0 to 3 percent slopes (CvA)	49074	1	48	44	0.17
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	n/a	n/a	n/a	n/a
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480680	19	28 ± 25	27 ± 13	0.35 ± 0.74
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41985	2	55 ± 21	30 ± 16	0.17 ± 0.01
<u>Entisols (total)</u>	**378719**	**18**	**32**	**32**	**9.07**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64231	4	58 ± 17	26 ± 4	5.55 ± 7.85

Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168536	6	27 ± 21	37 ± 25	5.28 ± 7.97
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	1	85	6	7.19
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145621	7	26 ± 23	29 ± 25	15.02 ± 20.33
Inceptisols (total)	**157753**	**4**	**27**	**28**	**3.26**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	n/a	n/a	n/a	n/a
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	n/a	n/a	n/a	n/a
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39027	3	27 ± 19	24 ± 2	1.98 ± 2.55
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107062	1	30	30	3.72

[a] K_{sat} values were estimated from soil texture classes (Rawls et al., 1982) based on measured percentages of sand, silt and clay and then corrected for the presence of coarse fragments. [b] Limiting layer values reported for depth, thickness and K_{sat} for the three soil orders are area-averages from corresponding soil map units (SMUs). Areas of SMUs with no data available were omitted in the calculations.

[c] Means ± standard deviations, unless only one soil core was taken from a specific SMU.

[d] n/a: not applicable. No soil core was taken from the specific SMU.

Table 9. Characteristics of the limiting layer for coarse fraction-corrected saturated hydraulic conductivity (Ksat) from detailed field study by soil type and soil order from interpolated soil core results (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol)	Total area	Number of Soil Cores	Measured depth to limiting layer	Measured thickness of limiting layer	K_{sat} from soil texture [b] (interpolated)
	m2		**---------------------------- cm**	**-----------------------------**	**µm/s**
Alfisols (total)	**937923**	**32**	**30** [c]	**27**	**1.99**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270606	10	52	20	2.70
Churchville loam, 2 to 8 percent slopes (CpB)	36898	n/a	n/a	n/a	1.51
Covington clay, 0 to 3 percent slopes (CvA)	49074	1	26	26	1.81
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	n/a	n/a	n/a	5.93
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480680	19	45	16	1.16
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41985	2	41	41	1.98
Entisols (total)	**378719**	**18**	**41**	**29**	**8.27**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64231	4	48	23	5.46

Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168536	6	32	22	4.39
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	1	22	22	7.15
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145621	7	42	22	14.0
Inceptisols (total)	**157753**	**4**	**30**	**26**	**2.25**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	n/a	n/a	n/a	0.69
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	n/a	n/a	n/a	2.60
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39027	3	30	18	1.26
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107062	1	30	30	2.63

[a)] Corrected for percentage coarse fragments present as reported in official soil series descriptions.

[b)] Estimates are based on the soil texture classes determined from midpoint percentages of sand, silt and clay reported in SSURGO for the limiting layer identified in [a)]. K_{sat} values for these soil texture classes were taken from Rawls et al. (1982) and corrected for percentage coarse fragments as in c[)] Limiting layer values reported for the three soil orders are area-averaged values from the corresponding soil map units.

Table 10. Correlation (r-value, p-value) between SSURGO, and field averaged, and field interpolated soil cores.

SSURGO	Averaged soil cores	Interpolated soil cores
Depth to limiting layer (cm)	-0.345 (0.330)	-0.036 (0.922)
Thickness of limiting layer (cm)	0.047 (0.171)	0.030 (0.933)
Reported Ksat (µm/s)	0.181 (0.617)	0.455 (0.102)

Appendix B

Figures

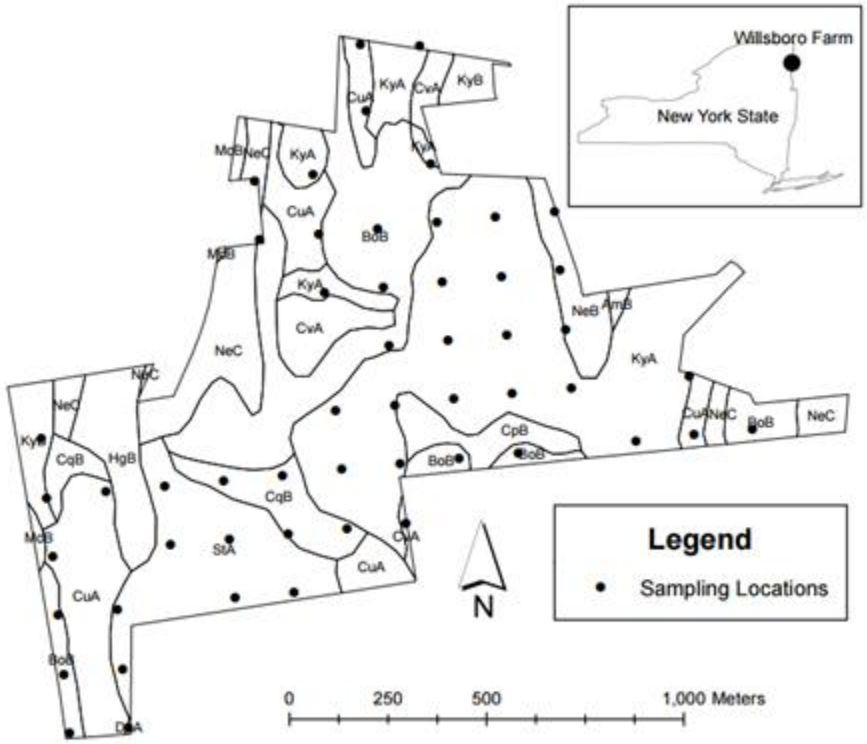


Figure 1. Map of Willsboro Farm, NY.

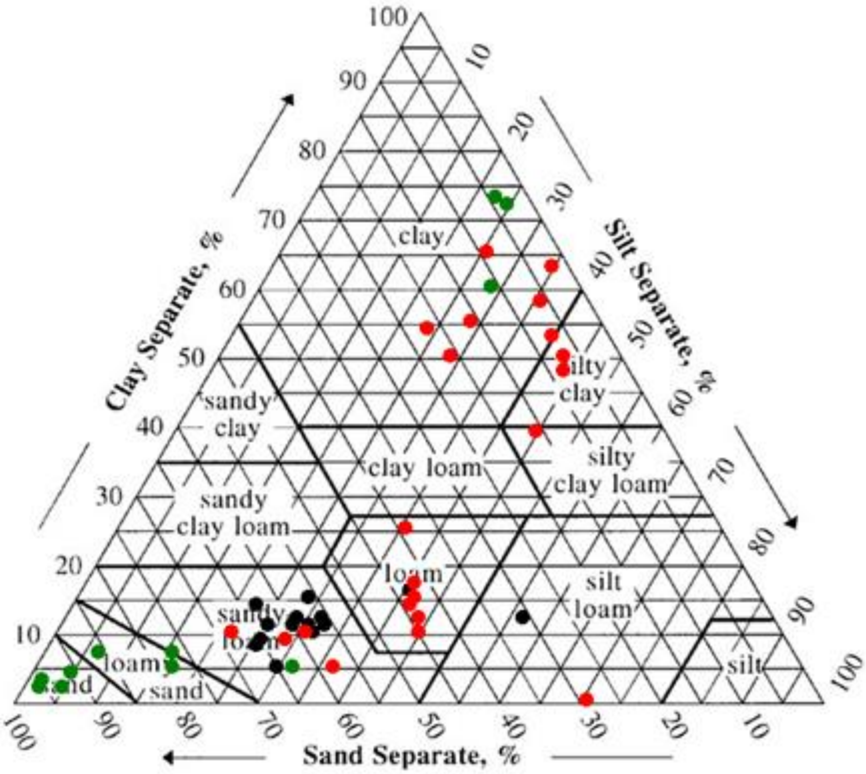


Figure 2. Soil texture of the 14 soil series from SSURGO by soil order: Alfisols (red), Entisols (green), Inceptisols (black)

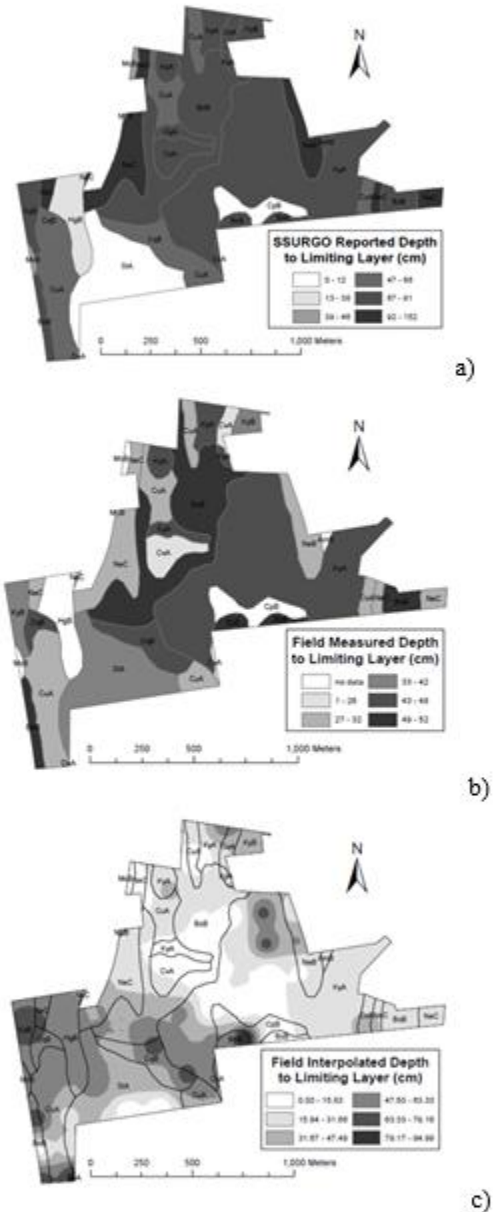


Figure 3. Depth to limiting layer (cm): a) from SSURGO results averaged over SMUs, b) from soil core results averaged over SMUs, and c) interpolated from soil core samples results. In the middle figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map..

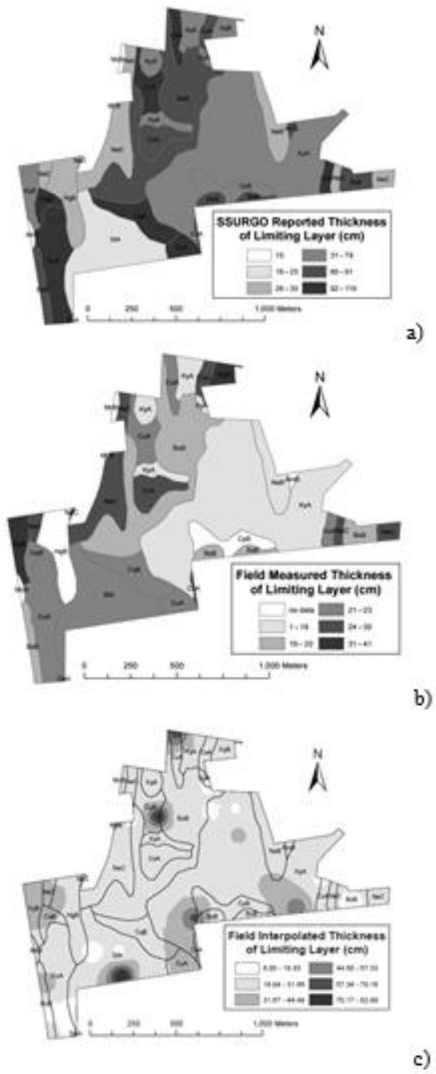
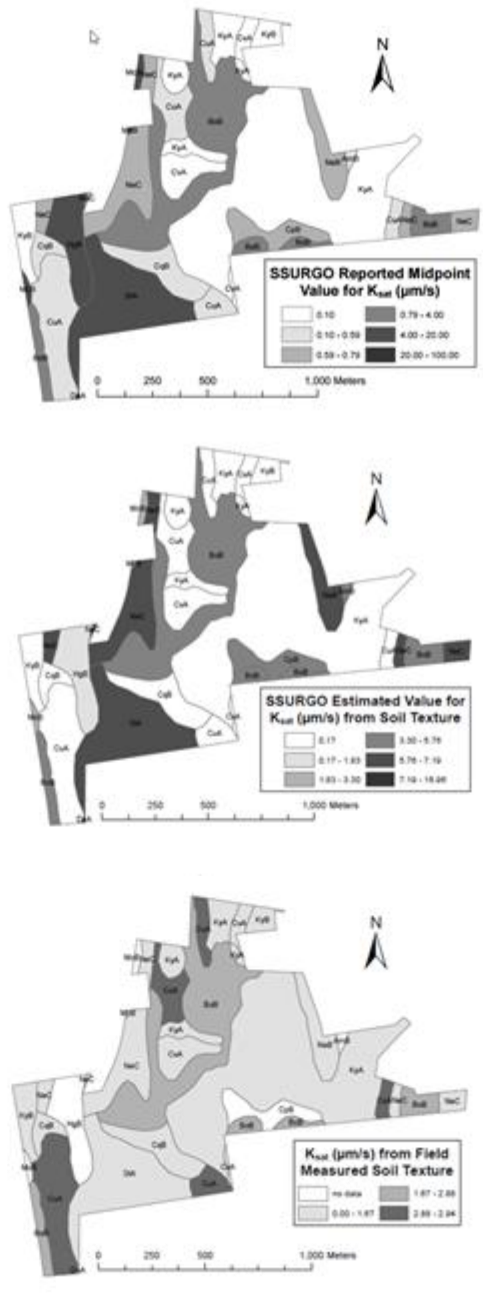


Figure 4. Thickness of limiting layer (cm): a) from SSURGO results averaged over SMUs, b) from soil core results averaged over SMUs, and c) interpolated from soil core samples results. In the middle figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map.



a)

b)

c)

Figure 5. Saturated hydraulic conductivity, Ksat (µm/s): a) from SSURGO results averaged over SMUs, b) from soil core results averaged over SMUs, and c) from soil core samples results averaged over SMUs. In the bottom figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map. Saturated hydraulic conductivity classes for Ksat (µm/s): very high (>100); high (10-100); moderately high (1-10); moderately low (0.1-1); low (0.01-0.1); very low (<0.01) (Soil Survey Division Staff, 1993).

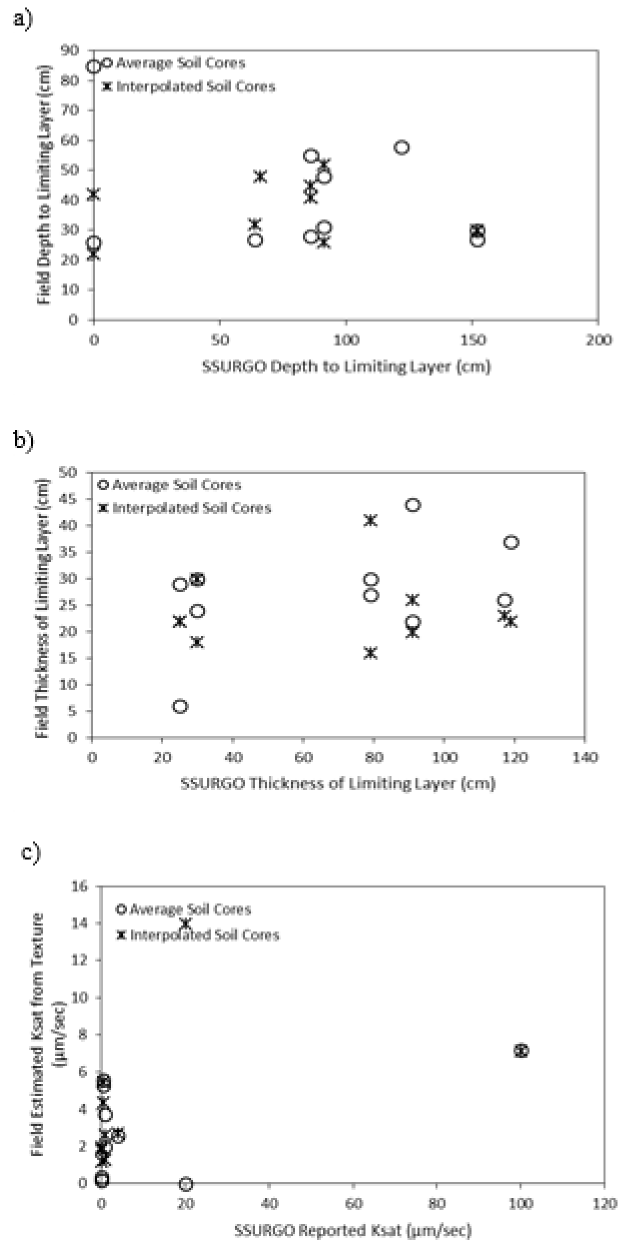


Figure 6. Bivariate correlation plots of: a) depth to limiting layer, b) thickness of limiting layer, and c) field estimated Ksat values from texture versus SSURGO results (reported or estimated) for each SMU.

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