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Short communication

Ground-penetrating radar soil suitability map of the conterminous United States

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Abstract

The performance of ground-penetrating radar (GPR) in soils strongly depends on soil electrical conductivity. Soils having high electrical conductivity rapidly attenuate radar energy, which restricts penetration depths and severely limits the effectiveness of GPR. Factors influencing the electrical conductivity of soils include the amount and type of salts in solution and the clay content. The *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* is a thematic map showing the relative suitability of soils for GPR applications within comparatively large areas of the United States. This map is based on over twenty-five years of field observations made throughout the United States and soil attribute data contained in the State Soil Geographic (STATSGO) database. Attribute data used to determine the suitability of soils include taxonomic criteria, clay content, salinity, sodium absorption ratio, and calcium carbonate content. Based on additional testing, several GPR specific adjustments have been made. This paper describes these revisions and outlines the procedures used to develop the revised map. The revised map limits areas that are rated as being "Unsuited" for GPR to saline and sodic soils, reassesses calcareous and gypsiferous soils, and provides a mineralogy override for soils with low activity clays. This map can be used to assess the relative appropriateness of GPR for soil investigations within comparatively large areas of the conterminous United States.
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Keywords: Electrical conductivity; Ground-penetrating radar; GPR; Soil database; Soil maps; STATSGO

1. Introduction

Increasingly, ground-penetrating radar (GPR) is being used in agronomic, archaeological, engineering, environmental, and soil investigations. Current news articles report the use of GPR in crime scene investigations and the detection of terrorism and military hazards. A common concern of GPR users is whether or not GPR will be able to achieve the desired depth of penetration. GPR is highly suited to most applications in dry sands, where penetration depths can exceed 50 m with low frequency antennas (Smith and Jol, 1995). However, a thin, conductive soil horizon or layer causes high rates of signal attenuation, severely restricting penetration depths and limiting the suitability of GPR for a large number of applications. In saline and sodic soils, where penetration depths are typically less than 25 cm (Daniels, 2004), GPR is an inappropriate tool. In wet clays, where penetration depths are typically less than 1 m (Doolittle et al., 2002), GPR has a very low potential for many applications.

Most GPR users have limited knowledge of soils and are unable to foretell the relative suitability of soils for GPR within project areas. In 2002, the USDA–NRCS developed the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* (Doolittle et al., 2002). Compared with an earlier

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effective ground conductivity map developed by Fine (1954), the USDA–NRCS map is based on a larger sample population and offer more detailed information. This thematic map has helped GPR users assess the relative effectiveness of GPR for a large number of applications within broadly defined areas of the conterminous United States. It was anticipated that modifications would be made to this map as new and additional soil data became available. This paper describes the revisions that have been made and introduces a revised *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States*. The revised map limits areas that are rated as being "Unsuited" for GPR to saline and sodic soils, reassesses calcareous and gypsiferous soils, and provides a mineralogy override for soils with low activity clays. Soils with high potential for GPR remained unchanged.

2. STATSGO database

The State Soil Geographic (STATSGO) database is used to prepare the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States*. The STATSGO database was developed by the USDA–NRCS for broad land use planning that encompass state, multi-state, and regional areas (National Soil Survey Center, 1994). STATSGO data are available for the conterminous United States, Alaska, Hawaii, and Puerto Rico. The STATSGO database consists of digital map data, attribute data, and Federal Geographic Data Committee compliant metadata. The database is linked to soil interpretation records, which contain data on the physical and chemical properties of approximately 18,000 different soils.

Because of the small scale (1:250,000) of STATSGO maps, soil map units and polygons appearing on soil survey maps were combined and generalized to prepare the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States*. This procedure resulted in fewer soil map units and larger soil polygons. The composition of each map unit was coordinated so that the names and relative extent of each soil component would remain the same among survey areas and across political boundaries. In areas where detailed soil maps were not available, existing data were assembled, reviewed, and the most probable classification and extent of soils were determined (National Soil Survey Center, 1994). The STATSGO database contains 9555 unique map units and 78,507 polygons. The minimum polygon size is about 625 ha.

3. Soil factors influencing the penetration depth of GPR

The penetration depth of GPR is determined by antenna frequency and the electrical conductivity of the earthen materials being profiled (Daniels, 2004). Because of rapid rates of signal attenuation, the penetration depth of GPR is greatly reduced in soils that have high electrical conductivity. Clays and salts provide ions and water facilitates the movement of charges transforming electromagnetic energy into electrical currents limiting the propagation of the electromagnetic waves. Electrical conductivity in soils is directly related to the amount, distribution, and phase (liquid, solid, or gas) of the soil water (McNeill, 1980), and the clay and soluble salt contents. Capillary retained water is sufficient to influence electrical conductivity even under dry soil moisture conditions. The lack of adequate data on soil moisture and the high spatial and temporal variations in the degree of soil wetness within soil map units precluded the use of moisture content in the preparation of this map. As a consequence, properties selected to prepare the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* only reflect variations in the clay and soluble salt contents of soils. These properties include percent clay, salinity, sodium absorption ratio, and calcium carbonate and calcium sulfate contents.

Clays have greater surface areas and can hold more water than the silt and sand fractions at moderate and higher water tensions. Because of their high adsorptive capacity for water and exchangeable cations, clays produce high attenuation losses (Daniels, 2004). As a consequence, the penetration depth of GPR is inversely related to clay content. While clayey ($\geq 35\%$ clay) soils are restrictive, most sandy ($< 15\%$ clay) soils are favorable to deep penetration with GPR.

Soils contain various proportions of different clay minerals (e.g., members of kaolin, mica, chlorite, vermiculite, smectite groups). The size, surface area, cation-exchange capacity (CEC), and water holding capacity of clay minerals vary greatly. Variations in electrical conductivity are attributed to differences in CEC associated with different clay minerals (Saarenketo, 1998). Electrical conductivity increases with increasing CEC (Saarenketo, 1998). Soils with clay fractions dominated by high CEC clays (e.g., smectitic and vermiculitic soil mineralogy classes) are more attenuating to GPR signals than are soils with an equivalent percentage of low CEC clays (e.g., kaolinitic, gibbsitic, and halloysitic soil mineralogy classes). Soils classified as kaolinitic, gibbsitic, and halloysitic characteristically have low CEC and low base saturation. As a general rule, for soils with comparable clay and moisture contents, greater depths of penetration can be achieved in highly weathered soils of tropical and subtropical regions that have kandic or oxic horizons than in soils of temperate regions that have argillic horizons. Compared with argillic horizons, kandic and oxic horizons have greater concentrations of low activity clays (Soil Survey Staff, 1999).

Electrical conductivity is directly related to the concentration of dissolved salts in the soil solution, as well as to the type of exchangeable cations and the degree of dissociation of the salts on soil particles (Soil Survey Staff, 1993). The concentration of salts in the soil solution depends upon the degree of water-filled porosity, the soil texture, and the minerals found in soils. In semi-arid and arid regions, soluble salts and exchangeable sodium accumulate in the upper part of some soil profiles. These salts, together with capillary retained water, produce high attenuation losses that restrict the radar's penetration depths (Doolittle and Collins, 1995). Because of their high electrical conductivity, saline (saturated extract electrical conductivity ≥ 4 mmhos cm^{-1}) and sodic (sodium absorption ratio ≥ 13) soils are considered unsuited to GPR.

Calcareous and gypsiferous soils are characterized by layers with secondary accumulations of calcium carbonate and calcium sulfate, respectively. These soils mainly occur in base-rich, alkaline environments in semi-arid and arid regions. High concentrations of calcium carbonate and/or calcium sulfate imply less intense leaching, prevalence of other soluble salts, greater quantities of inherited minerals from parent rock, and accumulations of specific mineral products of weathering (Jackson, 1959). These properties contribute to the higher electrically conductivity of calcareous and gypsiferous soils. Grant and Schultz (1994) observed a reduction in the depth of GPR signal penetration in soils that have high concentrations of calcium carbonate.

4. Determination of the relative suitability index for soil map units

To determine the relative suitability indices used in the preparation of the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States*, each selected soil property was rated and assigned an attribute index value (AIV). Soil horizons are assigned the most limiting AIV for each soil property. These attribute values are summed and the most limiting (maximum) layer indices within depths of either 1.0 (mineral soils) or 1.25 (organic soils) m are selected to represent the component index value (CIV) for each soil. A relative suitability index (SI) is then computed for each soil map unit by summing the percentages of soils with the same CIV and selecting the most dominant CIV.

Soil properties selected to prepare the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* are summarized in Table 1. Attribute index values were assigned to each of the selected soil properties based on over twenty-five years of field observations. Lower AIVs are associated with lower rates of signal attenuation, greater anticipated depths of penetration, and soil properties that are characteristically more suited to GPR. For clay content, AIVs range from 1 to 5. Mineral soil horizons with clay contents less than 10% have a very high potential for most GPR applications and are assigned an AIV of 1. Mineral soil horizons with clay contents greater than 60% have a very low potential for most GPR applications and are assigned an AIV of 5. A mineralogy override has been added for highly weathered soils dominated by low activity clays. Based on taxonomic criteria, a mineralogy override is made to all soils that have kandic or oxic horizons and more than 10% clay. Fabric adjustments and separate indices are used for organic soils. Organic soils with more acidic reactions (dysic; AIV of 1) are typically more nutrient deficient and less limiting to GPR than organic soils with more neutral or alkaline soil reactions (euic; AIV of 2). Distinctions are also made for organic soils with mineral layers that are more than 30 cm thick and occur within depths of 1.25 m (*terric* taxonomic subgroup). Because of their unsuitability to GPR, saline and sodic horizons are assigned an AIV of 6. Based principally on taxonomic criteria, mineral soil horizons with less than 60% clay that are characterized by high gypsum and/or calcium carbonate contents are assigned an added AIV of 1. Very fine textured soil horizons (>60% clay) already have very low potential for GPR and are not assigned this additional AIV.

For each component of a soil map unit, the most limiting condition (highest AIV) for each of the selected properties (clay content, salinity or SAR, and calcium carbonate or calcium sulfate content) at the soil horizon level is selected. These index values are summed to a depth of 1.0 m for mineral soils and 1.25 m for organic soils. The summation of the most limiting conditions represents the CIV, which may range from 1 to 6. A CIV is computed for each soil in the map unit. Table 2 shows the composition (percentage) of different soil components and their CIVs for the Sharpsburg soil map unit of the *Nebraska and Kansas Loess-Drift Hills* land resource area of the Interior Plains (USDA-NRCS, 2006).

The SI of a soil map unit is computed by summing the percentages of soils with the same CIV. Table 3 shows the results of summing the soil component percentages by the CIVs shown for the Sharpsburg soil map unit in Table 2. The dominant CIV is 4 for the Sharpsburg soil map unit shown in Table 3. Soils with this index value make up 90% of the map unit. However, this map unit is also composed of soils that have a more favorable (10%) CIV. The SI for a map unit represents the most dominant attribute properties, but does not identify or weighs the proportion of other soils that have different CIVs and occur within the map unit.

The final product is a lookup table consisting of the map unit identifiers and dominant GPR suitability indices. The SI for a map unit is joined to the map unit identifiers in the digital map

Table 1
Soil criteria used in calculating the GPR component index value

CIV=(A+B+C)	
A. Clay	
A1.1 Mineral soils	
Clay content	Attribute index value
≤10	1
>10 and ≤18	2
>18 and ≤35	3
>35 and ≤60	4
>60	5
A1.2. Mineralogy override for low activity clays	
Taxonomic order	Attribute index value
All Oxisols and those Ultisols that belong to Kandic subgroups or great groups.	% Clay index (A1.1)−1
A2. Fabric override for organic soils	
Soil reaction group and taxonomic subgroup	Attribute index value
Dysic and not Terric subgroup	1
Euic and not Terric subgroup	2
Terric subgroup	% Clay index+1
B. Electrical conductivity (mmho/cm) and sodium absorption ratio	
Salinity and sodicity	Attribute index value
EC ≥ 4 mmhos cm^{-1} or SAR ≥ 13	6
C. Calcium carbonate and calcium sulfate	
Determined from taxonomic classification	Attribute index value
Calcic or Gypsic great group	1
Calcic or Gypsic subgroup	1
Calcareous reaction class	1
Rendolls suborder	1
Histosols order and Marly mineralogy	1
Calcic, Gypsic, Calcareous, Illitic (calcareous), Montmorillonitic (calcareous), or Mixed (calcareous mineralogy)	1
(Determined from representative calcium carbonate percent)>10	1

Table 2
Computed index values for soil components in the Sharpsburg soil map unit

Soil component	Component percent	CIV
Sharpsburg	84	4
Pawnee	6	4
Judson	4	3
Nodaway	4	3
Colo	2	4

for classification and visualization. The dominant GPR suitability indices are displayed as a graduated color map. Graduated color maps have a series of symbols whose colors change according to the values of the particular attribute. The map uses six different shades of color, in a color ramp, to represent the GPR suitability indices. The data are classified into the six soil potential classes and one null data class shown in Table 4.

The inferred suitability of soil polygons shown on *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* is based on observed responses from antennas with center frequencies between 100 and 200 MHz. For mineral soils, the inferred SI is based on unsaturated conditions and the absence of contrasting materials within depths of 1 m. The relative suitability of mineral soils and penetration depths will be less under saturated conditions. Contrasting physical and chemical properties will also affect attenuation rates and penetration depths.

5. Relative suitability of soils for ground-penetrating radar investigations

Areas dominated by mineral soils with less than 18% clay or very deep organic soils have very high and high potentials (SI of 2 or less) for GPR applications. Areas with very high and high potentials afford the greatest possibility for deep, high resolution profiling with GPR. With a 200 MHz antenna, in soils with high potential for GPR, the depth of penetration averages about 5 m. However, because of variations in textural layering, mineralogy, soil water content, and the ionic concentration of the soil water, the depth of penetration can range from 1.0 to greater than 15 m. Many sandy alluvial and aeolian soils contain small amounts of clay, concentrated in lamellae or paleosols, which, depending on the clay mineralogy, can greatly reduce the depth of penetration. In areas with alkaline ground water, the depth of penetration is often restricted to the water table due to high concentrations of dissolved ions.

Areas dominated by mineral soils with 18 to 35% clay or with 35 to 60% clay that are mostly low-activity clay minerals have moderate potential (SI of 3) for GPR. Low activity clays are principally associated with older, more intensely weathered soils formed in materials weathered from highly permeable granitic parent rock on the Piedmont and Coastal Plains of southeastern United States. In soils with moderate potential for GPR, the depth of penetration of a 200 MHz antenna averages about 2.2 m with a range of about 0.5 to 5.0 m. Though penetration depths are restricted, map units with moderate potential are suited to many GPR applications.

Table 3
Soil Component percents summed by CIV for the Sharpsburg soil map unit

Sum component percent	CIV
92	4
8	3

Table 4
GPR potential ratings based on group suitability indices (SI)

GPR suitability index	Potential
≤ 1	Very high
>1 to ≤ 2	High
>2 to ≤ 3	Moderate
>3 to ≤ 4	Low
>4 to ≤ 5	Very low
>5	Unsuited
-99	No data

Areas dominated by mineral soils with more than 35% clays, or calcareous and/or gypsiferous soils with 18 to 35% clay have low potential (SI of 4) for GPR. In soils with low potential for GPR, the depth of penetration of a 200 MHz antenna averages about 0.5 m with a range of about 0.25 to 2.0 m. Areas that are unsuited (SI of 6) to GPR consist of saline and sodic soils. These map units are principally restricted to arid and semi-arid regions and coastal areas of the United States.

Map units with all soil components missing clay content data are excluded in the map classification. These map units are shown as “No Data” on the map. Map units that lack clay content data include miscellaneous areas and some areas mapped at higher levels of soil classification (e.g., Ustorthents, Dystrochrepts). Miscellaneous areas contain little or no soil and support little or no vegetation. Examples include areas of exposed bedrock (e.g., Lava flows, Rock outcrop, Rubble land), recently exposed or deposited materials (e.g., Badlands, Beaches, Rough broken land) and culturally modified materials (e.g., Urban land). These areas shown in gray and are not rated.

6. Discussion

The revised *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* is shown in Fig. 1. Compared with the initial map (Doolittle et al., 2002), areas that are rated as being “Unsuited” to GPR are limited to saline and sodic soils on the revised map. This results from a readjustment of the indices and a reevaluation of the effects of calcareous and gypsiferous soils on GPR. As a consequence, fewer areas are rated as “Unsuited” and more areas are rated as having moderate, low, or very low potentials for GPR. This change is most evident in the soils of the Great Plains. The mineralogy override for soils with low activity clays has resulted in many soils of the Piedmont (especially the Southern Piedmont) being rated as having a moderate rather than a low potential for GPR. Soils with high potential for GPR remained unchanged.

Some artifacts (soil boundaries that follow political rather than soil or physiographic boundaries) continue to be evident on the revised map. These inconsistent features are related to the varying ages, scales, and intensities of soil surveys and to procedural and conceptual changes made in soil mapping and

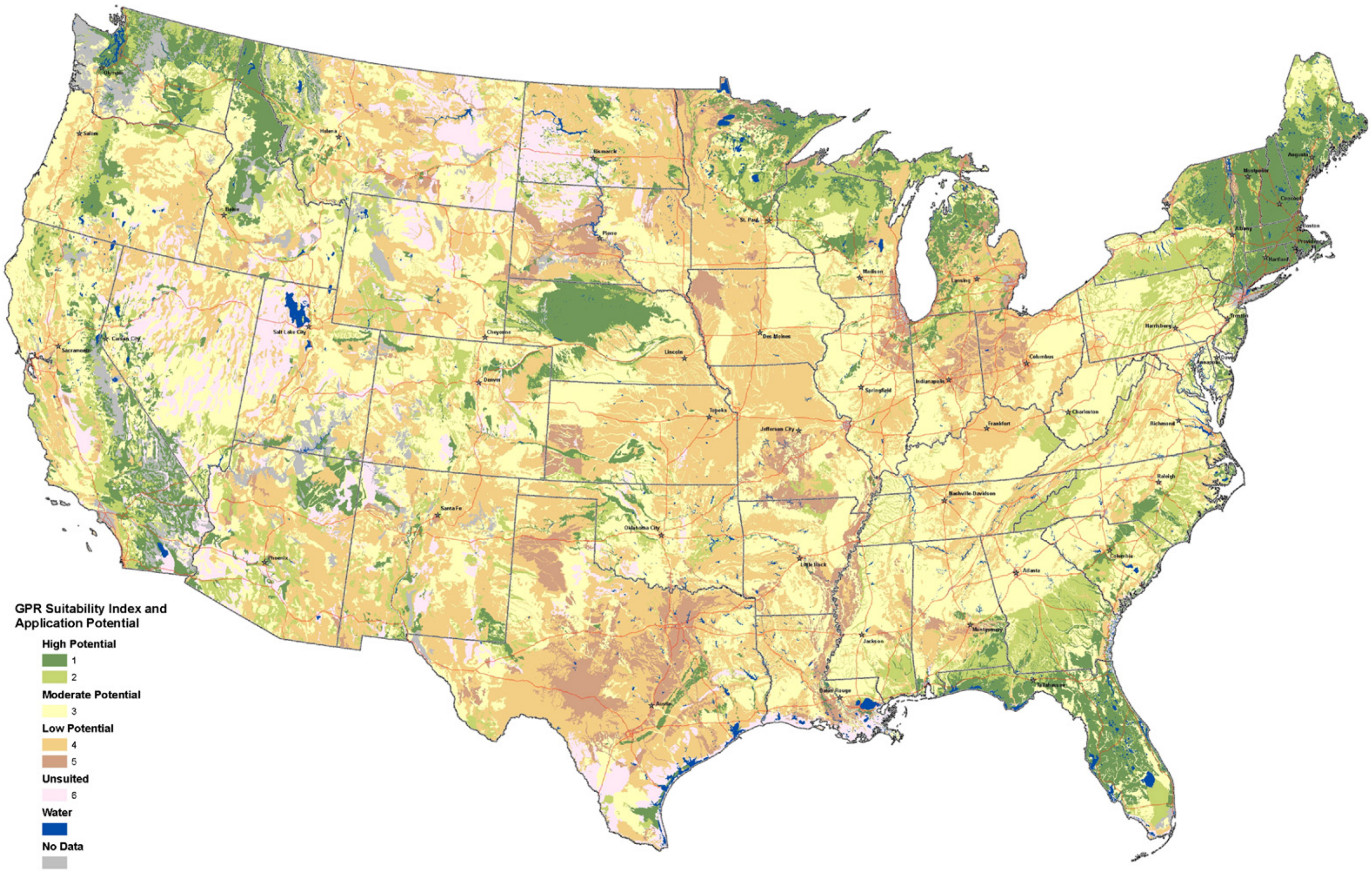

Fig. 1. Ground-penetrating radar soil suitability map of the conterminous United States.

interpretation. As soil surveys are updated and modernized, additional laboratory data obtained, new soils recognized, and map unit concepts improved, the minor artifacts found on this map will be eliminated.

The *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* offers users an indication of the relative suitability of soils for GPR within broadly defined soil and physiographic areas. Within any broadly defined area, the actual performance of GPR will depend on the local soil properties, the type of application, and the characteristics of the subsurface target. This map should not be used to determine the relative suitability of soils within small units of management (e.g., fields, residential areas, communities, and townships or parishes) to GPR. Users would benefit from larger scale maps, which show in greater detail the patterns of soil properties that influence the effectiveness of GPR. Larger scale, more detailed maps have been prepared using the Soil Survey Geographic (SSURGO) database. This database contains the most detailed level of soil mapping and information completed by the USDA–NRCS. The SSURGO data are based on more intensive field work and mapping scales that range from 1:12,000 to 1:63,360. These scales and intensity of soil mapping are more useful for the assessing the general suitability of soils for GPR within smaller areas of the United States. The *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* and State GPR Soil Suitability Maps can be accessed at http://soils.usda.gov/.

References

Daniels, D.J., 2004. Ground Penetrating Radar, 2nd Edition. The Institute of Electrical Engineers, London, United Kingdom.

Doolittle, J.A., Collins, M.E., 1995. Use of soil information to determine application of ground-penetrating radar. Journal of Applied Geophysics 33, 101–108.

Doolittle, J.A., Minzenmayer, F.E., Waltman, S.W., Benham, E.C., 2002. Ground penetrating radar soil suitability map of the conterminous United States. In: Koppenjan, S.K., Hua, L. (Eds.), Ninth International Conference on Ground Penetrating Radar. Proceedings of SPIE, volume 4158, 30 April to 2 May 2002. University of California, Santa Barbara, California, pp. 7–12.

Grant, J.A., Schultz, P.H., 1994. Erosion of ejecta at Meteor Crater: constraints from ground penetrating radar. Proceedings Fifth International Conference on Ground-Penetrating Radar. Waterloo Centre for Groundwater Research and the Canadian Geotechnical Society. June 12–14, 1994, Kitchner, Ontario, Canada, pp. 789–803.

Fine, H., 1954. An effective ground conductivity map for continental United States. Proceedings of the Institute of Radio Engineers 42, 1405–1408.

Jackson, M.L., 1959. Frequency distribution of clay minerals in major great soil groups as related to the factors of soil formation. Clays and Clay Minerals 6, 133–143.

McNeill, J.D., 1980. Electrical conductivity of soils and rock. Technical Note TN-5. Geonics Limited, Mississauga, Ontario.

National Soil Survey Center, 1994. State Soil Geographic Data Base; Data Use Information. US Department of Agriculture- Natural Resources Conservation Service, Miscellaneous Publication No. 1492, Lincoln, Nebraska.

Saarenketo, T., 1998. Electrical properties of water in clay and silty soils. Journal of Applied Geophysics 40, 73–88.

Smith, D.G., Jol, H.M., 1995. Ground-penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments. Journal of Applied Geophysics 33, 93–100.

Soil Survey Staff, 1993. Soil Survey Manual. US Department of Agriculture-Soil Conservation Service, Handbook No. 18, US Government Printing Office, Washington, District of Columbia.

Soil Survey Staff, 1999. Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys 2nd Edition. US Department of Agriculture- Natural Resources Conservation Service, Agriculture Handbook No. 436, US Government Printing Office, Washington, District of Columbia.

USDA-NRCS, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. USDA handbook 296, US Government Printing Office, Washington, District of Columbia.