Hydropedological investigations with ground-penetrating radar (GPR): Estimating water-table depths and local ground-water flow pattern in areas of coarse-textured soils


a USDA-NRCS, 11 Campus Boulevard, Suite 200, Newtown Square, PA 19073, United States
b Ecologistics Limited, 5224 West 350, North, W. Lafayette, IN 47906-9269, United States
c Soil Science Department, Bolley Drive, 233 Walster Hall, P.O. Box 5638, NDSU, Fargo, ND 58105, United States
d USDA-NRCS, P.O. Box 1458, 220 East Rosser Ave., Bismarck, ND 58502-1458, United States
e USDA-NRCS, P.O. Box 974, 207 West Main Street, Rm. 206, Federal Building, Wilkesboro, NC 28697, United States

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Abstract

In coarse-textured soils, ground-penetrating radar (GPR) can provide continuous, high-resolution records that chart the depth to water tables. The use of this information can increase confidence in hydropedological site assessments and reduce the number of wells needed for water-table depth and ground-water flow determinations. Ground-penetrating radar was used to map spatial and temporal variations in water-table depths and ground-water flow patterns within an unconfined aquifer located beneath an eolian landscape in northwestern Indiana. Compared with the data collected at a limited number of wells, the greater number of observations with GPR provided more comprehensive site coverage and mapped more intricate local ground-water flow patterns. Over a 2-year period, GPR revealed systematic temporal and spatial variations in water-table depths and local ground-water flow patterns.

Keywords: Ground-penetrating radar; GPR; Hydropedology; Water table; Ground-water flow

1. Introduction

Recent interests in soil and hydrologic modeling, contaminant fate, and soil quality have amplified the need for information on the depth and movement of ground water beneath landscapes at different spatial and temporal scales (Nielsen et al., 1998; Lin, 2003). The collection of this information is relatively expensive and labor and time intensive. Presently, information on the depth and movement of ground water is collected from a limited number of often widely spaced, piezometers or observation wells. These devices provide information concerning the elevation of the potentiometric surface or the water table at
specific locations. A nest of piezometers is used to estimate ground-water flow direction, flow velocities, and the location of discharge and recharge areas (Freeze and Cherry, 1979; Richardson et al., 1992). However, the number of piezometers is often limited and hydopedologic conditions for the more extensive areas among the piezometers must be inferred. Inferences are often based on assumptions concerning soil and hydrologic conditions that are presumed to exist among the piezometers. In areas of intricate and contrasting soil patterns, undulating topography, and non-homogeneous or anisotropic materials, water-table depths and ground-water flow patterns are more difficult to assess. These areas require a greater number of relatively costly observation wells or piezometers. In these areas, hydrologic data, models, and maps are often oversimplified and are more susceptible to errors (Violette, 1987). Improved tools and methods are needed to supplement the sparse coverage that is often obtained with observation wells and piezometers.

Ground-penetrating radar (GPR) is a noninvasive geophysical tool that is specifically designed to penetrate earthen materials and provided images of the shallow (0 to 30 m) subsurface. Ground-penetrating radar operates by transmitting pulses of radio-frequency electromagnetic energy into the subsurface. These waves of electromagnetic energy propagate through the soil until they impinge upon a layer or object with contrasting dielectric properties. Contrasts in dielectric properties cause a portion of the transmitted electromagnetic energy to be reflected back to an antenna. The amount of energy that is reflected by an interface is dependent upon the contrast in the relative dielectric permittivity ($\varepsilon_r$) of the two layers. Abrupt boundaries that separate contrasting materials reflect more energy than gradual boundaries that separate layers with similar $\varepsilon_r$. The $\varepsilon_r$ of soil materials is principally dependent upon moisture content (Annan et al., 1991) and varies with temperature (phase-dependent), density, and antenna frequency (Daniels, 2004). In coarse-textured soils, large and abrupt contrasts in volumetric water contents exist across the phreatic surface or water table. This contrast produces strong and identifiable reflections on most radar records.

Ground-penetrating radar is a time scaled system. The system measures the time it takes electromagnetic energy to travel from an antenna to an interface (e.g., water table, soil horizon, stratigraphic layer) and back. Typically, GPR produces a time–distance record of the subsurface. The horizontal scale is a distance scale that is based on the speed of antenna advance across the ground surface. The vertical scale represents the two-way travel time of the radar pulse through the subsurface. In order to convert the time scale into a depth scale, the velocity of pulse propagation must be known. The most direct and accurate method to estimate the propagation velocity is to measure the two-way travel time to a reflector of known depth that appears on a radar record. In soils that have low electrical conductivity and energy dissipation, the propagation velocity can be estimated using the following equation (after Daniels, 2004):

$$V = \frac{2D}{T}.$$  \hspace{1cm} (1)

Eq. (1) describes the relationship between the propagation velocity ($V$), depth ($D$), and two-way pulse travel time ($T$) to a subsurface reflector in a low-loss soil. Once computed, the averaged propagation velocity and Eq. (1) can be used to convert the time scale into a depth scale for depth determinations. Time-converted depth scales are reasonably accurate. Smith et al. (1992) compared time-converted interpreted depths to a water table measured at 28 wells. In these wells, water-table depths ranged from 1.74 to 3.15 m. The average difference between measured and interpreted water-table depths was 6 cm with a range of 0 to 23 cm. Bentley and Trenholm (2002) found that, under favorable conditions, GPR could estimate the depths to shallow water tables with an accuracy of about 20 cm.

In soils, a transitional zone, known as the capillary fringe, occurs above the water table. The capillary fringe is partially saturated to saturated with water. As capillary water can only rise in small pores, the thickness of the capillary fringe depends on the number, interconnectivity, and diameters of the soil pores. Finer-textured soil materials have a greater number of smaller capillary pores than do coarser-textured soil materials. As a consequence, the height of capillary rise and the thickness of the capillary fringe are greater in finer-textured soils. As the width of the capillary fringe increases, reflections from the water table have increasingly lower amplitudes, more dispersed characteristics, and are therefore less distinguishable on radar records (Annan et al., 1991). In
coarse-textured soils, the capillary fringe is narrow, and the difference in dielectric properties between the unsaturated and saturated zones is abrupt and contrasting. These characteristics of water tables in coarse-textured soils produce distinguishable reflections on radar records.

Within the capillary fringe, the water content increases with increasing depth from partially saturated in the upper part to saturated in the lower part. Because of this, GPR does not directly measure the water-table depth, but responds to saturated conditions within or near the top of the capillary fringe (Smith et al., 1992; Bentley and Trenholm, 2002). Provided that calibrations are based on measured depths to the water table in wells, this disparity should have little effect on the accuracy of radar interpreted water-table depths (Smith et al., 1992).

In the last decade, improvements in GPR designs and the use of digital output have reduced system sizes and costs, and facilitated surveys. Modern GPR systems are small, lightweight, and portable (see Fig. 1). With an antenna, most GPR systems used for water table and ground water studies require two people to operate. A number of antennas are available, each suited to unique applications, resolution, and profiling depths. Lower frequency (10 to 300 MHz) antennas provide greater penetration depths but poorer resolution of subsurface features than higher (400 to 900 MHz) antennas. Recent developments in processing software have enabled signal enhancement, which has greatly improved target recognition thereby easing interpretations.

For over 30 years, GPR has been used extensively for hydropedological investigations. In areas of coarse-textured soil materials, GPR has been used to chart water-table depths among wells and into nearby areas (Sellmann et al., 1983; Davis et al., 1984; Wright et al., 1984; Shih et al., 1986; Johnson, 1987; Truman et al., 1988; Bohling et al., 1989; Smith et al., 1992; Iivari and Doolittle, 1994; Doolittle et al., 2000). In addition, GPR has been used to provide data for hydrologic models (Violette, 1987; Taylor and Baker, 1988), define recharge and discharge areas (Johnson, 1987; Bohling et al., 1989), predict ground-water flow patterns (Steenhuis et al., 1990; Iivari and Doolittle, 1994; Doolittle et al., 2000; van Overmeeren, 2004), and delineate near-surface hydrologic conditions (Beres and Haeni, 1991; van Overmeeren, 1998). GPR has also been used to study the redirection and concentration of water by soil

Fig. 1. Modern radar systems are rugged, compact, lightweight, and very portable. A 200 MHz antenna is pulled along the surface of a dune as a continuous stream of subsurface information is recorded, stored, and displayed on a portable radar unit that is carried in a shoulder harness by the operator.
horizons and stratigraphic layers into preferential pathways (Vellidis et al., 1990; Kung and Donohue, 1991; Kung and Lu, 1993; Boll et al., 1996; Tomer et al., 1996; Steenhuis et al., 1998; Gish et al., 2002). At intermediate (field or catchment) scales, GPR has been used to map spatiotemporal variations in soil water content (Lesmes et al., 1999; Huisman et al., 2001, 2002, 2003; Hubbard et al., 2002; Grote et al., 2003).

Fig. 2 is a radar record obtained with the 200 MHz antenna across a low (< 2 m) eolian dune in southeastern North Dakota. The dune is in an area that is dominated by calcareous, coarse-textured soils. The ground water is alkaline and conductive. The vertical scale on this and other radar records shown in this paper is a time scale that is expressed in nanoseconds (ns). Time scales are used because of the large difference in propagation velocity across water tables. The velocity of signal propagation ranges from 0.12 to 0.21 m/ns in unsaturated sands (Daniels, 2004). Within the saturated sands below the water table, the higher $E_r$ results in slower propagation velocities of 0.05 to 0.09 m/ns (Daniels, 2004). In Fig. 2, the averaged pulse propagation velocity through the unsaturated sands is about 0.15 m/ns (based on the measured depths to the water table in three wells). Based on this velocity and Eq. (1), the depth to the water table ranges from about 0.9 to 2.8 m on this radar record.

In Fig. 2, the water table provides a continuous, high amplitude reflection that is easily identified and traced across the radar record. Because of oscillations in the reflected radar pulses, the water table, like other interfaces on radar records, appears as a series of two or three bands. These bands limit the ability of GPR to distinguish closely spaced interfaces. For this reason, perched water tables may be difficult to distinguish from underlying, denser and less permeable restricting layers.

Hagrey and Mueller (2000) demonstrated that the amplitudes of reflections increase with increasing pore-water salinity. In soils with conductive ground water (such as evident in Fig. 2), the depth of penetration is restricted to the water table. In coarse-textured materials, depending on the chemistry of the soil solution and the amounts of fines in the soil matrix, signal attenuation and penetration depths will vary. In strongly saline or sodic soils, penetration depths are typically restricted to the surface layers. In calcareous soils, penetration depths are typically less than 2 m. However, under favorable conditions, water tables have been charted with low frequency (<100 MHz) antennas to depths as great as 38 m.

![Fig. 2. A radar record obtained with a 200 MHz antenna on a low eolian dune in North Dakota. The water table provides high amplitude linear reflections. The depth of penetration is limited by the conductivity of the alkaline ground water.](image-url)
Fig. 3 is a radar record that was collected with a 200 MHz antenna on a large dune in eastern North Carolina. Based on an averaged propagation velocity of 0.14 m/ns (through the unsaturated sands), the water table provides a high amplitude reflector that varies in depth from about 3.7 to 12 m on this radar record. The continuous, near-horizontal reflections from the water table contrast in amplitude with the segmented, similarly inclined reflections from strata within the eolian dune. This aids identification. The detection of the water table may have been more difficult and ambiguous had reflections from the strata been continuous and similar in amplitude. Water tables that are either close to the soil surface or obscured by a series of closely spaced horizons or geologic strata are difficult to identify and trace on radar records (van Overmeeren, 1998).

In Fig. 3, not only is the water table distinguishable, but also are the geometry and structure of major stratigraphic layers within the dune. This contrasts with the more restricted penetration depths and dispersed signal characteristics within the high-loss, calcareous dune of North Dakota (see Fig. 2).

The purpose of this investigation was to use GPR to map spatiotemporal variations in water-table depths and ground-water flow within a 32-ha, forested, topographically diverse, eolian landscape in northwestern Indiana. This research was conducted as part of a long-term ground-water study that related soil hydrology to precipitation-evapotranspiration events and to stratigraphic and geomorphic features.

2. Materials and methods

2.1. Study site

The study site is located on a dune–interdune landscape in the northern half of Section 10, T. 31 N., R. 5 W., in east-central Jasper County, Indiana. The site is located within a broad, poorly drained physiographic region known as the Kankakee River Lowlands (Fraser and Bleuer, 1991). During Wisconsinan glaciation, coarse-textured materials were deposited across portions of this region. Thickness of these deposits ranges from about 15 to more than 60 m (Fenelon, 1994). Some of these deposits were later reworked by wind into low (1 to 10 m), southwest to northeast orientated, transverse sand dunes.
Fig. 4 is a shaded relief map of the study site. The site consists of two major dunes separated by lower-lying, nearly level interdunes. Within the study site, relief is about 10 m. No surface water features (i.e. ponds, streams, canals) occur within the site. Soil patterns within the site are intricate. The site contains areas of Morocco loamy sands; Newton loamy fine sands, undrained; Oakville fine sands, 6% to 15% slopes; and Zadog-Maumee loamy sands (Smallwood and Osterholz, 1990). The present taxonomic classifications of these soils are listed in Table 1. These soils consist of about 50% to 90% fine and medium sands, 0 to 25% very fine sands, and less than 10% silts and clays. On dunes, soils are excessively drained. Soils on lower-lying interdune areas are more poorly drained, and have higher clay, organic matter and water contents than soils on dunes. Soils on interdune areas are frequently ponded for brief periods by runoff from surrounding areas, and have water tables that are near or above the surface during the winter and spring (Smallwood and Osterholz, 1990).

An oak-hickory forest has stabilized the dunes and interdune areas (Petty and Jackson, 1966). During late spring and early summer, as leaves emerge, plant roots absorb large quantities of soil water and the water table is rapidly lowered. With the cessation of the growing season in early fall, the water table begins to rise. A water-table aquifer underlies the site.

2.2. Equipment

Fifteen observation wells were installed to measure the elevations of the water table and estimate the direction of ground-water flow. Each well was constructed from schedule 40 polyvinyl CL (PVC) pipe that was 76-mm wide. Transverse slots, 3 by 65 mm chord length, spaced 50-mm apart were cut on opposite sides of each pipe. Each observation well was slotted along the entire length of the riser to the soil surface and covered with geofabric to restrict soil particles from entering the well. At each well site, a hole, 89 mm in diameter, was bored in the soil with a hand auger. The pipe was set into the hole and soil was packed around the pipe. Wells were installed in different soils on both dunes and interdune areas (see Fig. 4). Each well was open to the same water-table aquifer and surveyed to a common datum.

<table>
<thead>
<tr>
<th>Series</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maumee</td>
<td>sandy, mixed, mesic Typic Endoaquolls</td>
</tr>
<tr>
<td>Morocco</td>
<td>mixed, mesic Aquic Udipsamments</td>
</tr>
<tr>
<td>Newton</td>
<td>sandy, mixed, mesic Typic Humaquepts</td>
</tr>
<tr>
<td>Oakville</td>
<td>mixed, mesic Typic Udipsamments</td>
</tr>
<tr>
<td>Zadog</td>
<td>fine-loamy over sandy or sandy-skeletal, parasesquic, mixed, mesic Typic Endoaquolls</td>
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The radar unit was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc. Daniels (2004) discusses the use and operation of GPR. The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-volt DC battery powered the system. This unit is backpack portable and requires two people to operate. A 200 MHz antenna was used in this study.

2.3. Field methods

Radar traverse lines were established on three, north–south and two, east–west access trails. The length of each north–south trail was about 420 m. The length of each of the east–west trails was about 810 m. Two additional interior lines were established through the woods. The lengths of these lines were about 630 and 690 m. Along each of these seven lines, to capture major breaks in topography, reference flags were inserted in the ground at irregular intervals. The average spacing on level interdune areas was 30 m. This procedure provided 147 reference points. Two additional radar traverse lines were laid out connecting the 15 wells. The coordinates and elevation of each reference point and well were obtained using GPS and standard surveying methods. The locations of these 162 points are shown in Fig. 4.

Eight GPR surveys were completed at intervals of 3 to 4 months over a 2-year period. Each survey required 1 day of fieldwork. Pulling the 200 MHz antenna along each of the nine lines completed a radar survey. As the antenna passed each well or reference point, a vertical mark was impressed on the radar record. At each marked point on the radar record, the water table reflection was identified and the two-way travel time to this reflector was measured.

Although GPR provides a continuous image of the subsurface, interpretations were restricted to the 162 marked and geo-referenced well or reference points. At the time of each radar survey, water levels in the 15 wells were measured and used to determine the propagation velocities of the radar signal and to scale the radar records. Because of the spatiotemporal variability in propagation velocities and the known complexity of soil and landform patterns, a predictive equation based on water-table depths and two-way travel times was developed for each GPR survey. The measured depth and the two-way pulse travel time to the water table at the 15 wells were compared. For each survey, a least square line was fitted to the GPR data and used to predict the depth to water table at each of the 162 well or reference points. For the eight radar surveys, using predictive equations, the average difference between measured and predicted depths to the water table at the 15 wells was 16 cm with a maximum difference of 69 cm. One-half of the predicted water-table depths were within ± 14 cm of the measured values.

For each survey, the elevation of the water table was determined at each reference point by subtracting the interpreted depth to the water table from the measured elevation of the ground surface.

3. Results and discussion

3.1. Interpretation of radar records

Fig. 5 is a portion of a radar record from a traverse that crossed a dune in the extreme northwestern portion of the study site (see Fig. 4). In Fig. 5, using an averaged velocity of propagation of 0.145 m/ns ($E_r$ was 4.2), the depth to the water table ranges from about 1.9 to 7.0 m. Not only is the water table clearly distinguishable beneath this portion of the dune, but also the geometry and structure of slip faces or bedding planes within the dune are evident in this radar record. Abrupt and contrasting differences in density, grain size, and moisture contents produce high amplitude reflections (Schenk et al., 1993; Harari, 1996). In general, reflections from the interior of eolian dunes are produced principally by changes in moisture contents (Schenk et al., 1993; Bano et al., 1999; Bristow et al., 2000).

Dunes consist mostly of reworked eolian sands. In the right-hand portion of Fig. 5, a series of inclined reflections dip from left to right and suggest lateral migration and foreslope accretion (Bristow et al., 2000). These reflections are believed to represent slip faces on the dune’s lee slope. These inclined reflectors are truncated by modern erosion and deposition facies near the surface. The water table lies directly above the contact that separates coarse-textured, reworked eolian from sand plain deposits. Reflections from strata within the sand plain appear horizontal and contrast with the more inclined strata of the dune.

3.2. Water-table surface maps

Figs. 6 and 7 contain two-dimensional representations of the three-dimensional water-table surface for the surveys that were completed in the spring and fall.

1 Manufacturer’s names are provided for specific information; use does not constitute endorsement.
of 1997 and 1998. In each plot, the elevation of the water table is shown. In each figure, the two larger plots show the elevations of the water table as determined by both well measurements and radar interpretations across the entire 32-ha site. The two smaller plots in each figure are based on measurements made at the 15 wells alone. In each of the larger plots, a rectangular boundary is used to enclose the area represented in the smaller plots. In each plot, the isoline interval is 50 cm. These lines are equipotential lines as they represent the water table surface and connect points of equal hydraulic head. In unconfined aquifers, water flows from areas of high to areas of low-hydraulic head. In Figs. 6 and 7, vectors indicate the conceptual flow paths of ground water. Water-table surface maps represent the potentiometric surface for an unconfined aquifer (Fetter, 2001).

Ground-penetrating radar significantly increased the number of observations and provided greater and more comprehensive coverage of the site. Compared with the water-table surface maps prepared from well measurements alone (smaller plots in Figs. 6 and 7), water-table surface maps prepared from GPR and well data show more intricate local ground-water flow patterns. The plots in Figs. 6 and 7 confirm the spatiotemporal variations in water-table depths. Areas of higher-hydraulic head underlie the dunes. Areas of lower-hydraulic head underlie the interdunes. These areas contract and expand with changes in the seasons. Across most of the site, the water-table surface has a shallow gradient with fairly widely spaced equipotential lines.

The local flow patterns shown in Figs. 6 and 7, while influenced by surface topography, do not always mirror the topography. Areas of higher-hydraulic head do approximate the ridgeline of the higher dune. However, there is a noticeable lateral displacement of areas with higher-hydraulic head from the two major dunes into the interdune area. The longer, northwest to southeast trending well line crosses two dunes and an interdune area. Based on GPR interpretations, this line of wells appears to have been unknowingly located on a local drainage divide, which is best expressed in the fall plots (when the water table surface is at its lowest elevation). Along this line, a ridge of higher-hydraulic head extends outwards from the two opposing dune into the interdune area. This groundwater divide splits the direction of local ground-water flow into two discharge areas. This groundwater divide was not clearly imaged on the water-table surface maps created by the sparse well data set alone.

During summer and early fall, evapotranspiration losses by the forest plant community results in the depletion of soil water and the rapid drawdown of the water table (Jenkinson et al., 2002). During this period of the year, with the exception of the interior of the largest dunes, the water table is being lowered and attains its lowest elevation beneath most portions of

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Fig. 5. The water table and internal stratigraphic features of a dune and underlying outwash deposits are evident in this radar record that was obtained with a 200 MHz antenna across a dune in the Jasper County Site.
Fig. 6. Comparison of water-table depths and ground-water flow patterns beneath the Jasper County Site for two surveys and for two sample populations: larger plots simulate well and GPR data ($n = 162$); smaller plots simulate well data alone ($N = 15$). Directions of ground-water flow are indicated with arrows. Surveys were completed in the spring (upper plots) of 1997 and the fall (lower plots) of 1997.
Fig. 7. Comparison of water-table depths and ground-water flow patterns beneath the Jasper County Site for two surveys and for two sample populations: larger plots simulate well and GPR data ($n = 162$); smaller plots simulate well data alone ($N = 15$). Directions of ground-water flow are indicated with arrows. Surveys were completed in the spring of 1998 (upper plots) and the fall (lower plots) of 1998.
this landscape. Beneath a portion of the largest dunes (see “A” in Figs. 6 and 7), the water table did not respond to the seasonal evapotranspiration losses, but rose and remain at relatively high elevations causing a noticeable mound, which persisted for almost 1 year.

By the fall of each year, the water table is drawn down to lower elevations by evapotranspiration losses. In September 1997, the average elevation of the water table was 213.4 m with a range of 211.8 to 218.6 m. One-half of the reference points had elevation of the water table between 212.8 and 213.7 m. In October 1998, the average elevation of the water table was 213.1 m with a range of 210.0 to 216.0 m. One-half of the reference points had elevation of the water table between 212.7 and 213.4 m. In the fall, with plant dormancy, transpiration ceases and the water table rises. In the winter, in some portions of the interdune areas, the water table breaches the surface and temporary ponds develop from snowmelt and storm runoff. By spring, the water table is at its highest elevation. In May 1997, the average elevation of the water table was 214.4 m with a range of 212.9 to 217.0 m. One-half of the reference points had elevation of the water table between 213.8 and 214.8 m. Compared with 1997, 1998 was a slightly wetter year. In May 1998, the average elevation of the water table was 214.7 m with a range of 212.7 to 219.8 m. One-half of the reference points had elevation of the water table between 214.3 and 214.9 m.

In general, the dunes act as recharge areas; the interdune areas act as discharge areas. During the summer of 1997, a depression (lower hydraulic head) in the water table surface formed beneath a portion of largest dune (see “B” in Figs. 6 and 7). This depression underlies a slight swale located on the dune’s side slope. This depression in the water table surface persisted for almost a year (through the early summer of 1998). During this interval, in this portion of the dune, water flowed from interdune areas towards the dune’s interior despite the higher topographic elevation of the dune’s surface.

4. Summary

Ground-penetrating radar increased the number of observations and provided more comprehensive coverage of water-table depths within the Jasper County site. The greater number of observations formed more intricate water table and local ground-water flow patterns. Over a 2-year period, GPR surveys revealed systematic spatiotemporal variations in water-table depths and local ground-water flow patterns. Radar interpretations of water-table depths were reasonably accurate. For the eight radar surveys, using predictive equations, the average difference between measured and predicted depths to the water table at the 15 wells was 16 cm with a maximum difference of 69 cm.

In areas of coarse-textured soil, GPR can supplement and reduce the number of wells or piezometers needed for water table and ground-water flow studies. Water-table surface maps constructed from GPR data are useful in establishing spatial and temporal relationships at field scales. Maps created from GPR and surface topographical surveys may be used to estimate water-table surfaces, flow directions, and hydraulic gradients, which in turn may help to improve, adjust, and verify hydropedological models. Ground-penetrating radar surveys can be used to guide the location of wells.

References


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