Groundwater

Methods Note/

A Rapid Method for Analyzing Well Log Records in Preparation for Water Resource Mapping

by Kurt O. Thomsen[1]

Abstract

The needs of subregional and local entities for water resource management are immediate, and required information is not forthcoming in a timely and relatively inexpensive manner. The following method allows one to use all available well record data to produce baseline hydrogeologic unit maps using geographic information system querying and mapping techniques. Subjective borehole and geophysical strata descriptions are converted to objective equivalent numerical values by establishing the average hydraulic conductivity of the combined soils making up the stratum of interest. These hydraulic conductivity values are then used to assign each stratum to a hydrogeologic unit based on typical ranges of hydraulic conductivity for aquifers, aquitards and aquicludes. The resulting data are queried and mapped to provide a preliminary description of a shallow aquifer system composed of unconsolidated materials. This method can be used to provide information to make initial estimates of the configuration of the shallow aquifer system and to plan for groundwater sustainability. Two examples of maps for an area in northeastern Illinois that were prepared using the resulting database are presented.

Introduction

All available well log descriptions are used to define a given shallow aquifer system and build a representative stratigraphic model. To accomplish this, stratigraphic records must be transferred to an electronic database if they are not already available in that format. Most of a project's objectives will be met by analysis of the resulting database conversion. Innovative mapping techniques and statistics make use of the resulting data to create a stratigraphic model. The following describes the sequential tasks required to create the database to use this approach.

Method

The shallow aquifer system is made up of unconsolidated soil materials. Descriptions of these materials rely heavily on the relative portions of clastic materials that make up the mixture called soil. The common names of the clastic materials that make up soil are listed in Table 1 along with their respective particle sizes.

The soil composition is the major factor that contributes to the soil hydraulic conductivity. The possible combinations of particles making up a soil are infinite; consequently, soils can only be described in the broadest sense. In most cases, the combination of particles is estimated in the field when the samples are retrieved from a borehole during drilling operations. Larger size gravel, cobbles, stones, and boulders, if present, are noted but cannot be sampled. Sometimes the samples are taken back to a laboratory and are redescribed by a person other than the one who collected the sample. On rare occasions or for engineering studies, samples are submitted for a particle/grain-size analysis. In this analysis the proportions of the various size particles are actually measured rather than estimated as done in the field.

Table 2 is an expanded soil texture table commonly used by drillers and soil engineers to describe the composition of soil recovered from borehole samples for the purpose of creating a borehole or well log of the hole being drilled (Wilun & Starzcwski 1972). This table has been expanded to include most of the terms encountered in well log soil descriptions. The information listed in the

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Table 1
USDA Soil Particle Sizes

	USDA Particle Size Range	
Particles	**Millimeters (mm)**	**Inches (in)**
Clay	<0.002	<0.0008
Silt	0.002 to 0.05	0.00008 to 0.002
Sand	0.05 to 2	0.002 to 0.08
Gravel	2 to 76	0.08 to 3
Cobbles	76 to 250	3 to 10
Stones	250 to 600	10 to 24
Boulders	>600	>24

Table 2
Terms Used to Describe Borehole Materials

Use of Terms	Terms	Content (%)	Weighting Factor
Conjunctions	and, comma, slash, hyphen	60	6
Nouns	clay, silt, sand, gravel cobbles, boulders	60	6
Adjectives	clayey, silty, sandy, gravelly, stoney, cobbley, bouldery	40	4
Prepositions	in, with	30	3
	few	20	2
Adverbs	considerable, frequent, much, numerous	30	3
	a bit, contain, containing, little, scattered, slightly, small amount, some	20	2
	isolated, occasional, trace	10	1

right column (Weighting Factor) is usually not included in a soil texture table. This information will be used later when describing soils in terms of hydraulic conductivity is discussed.

To overcome the difficulty of dealing with cumbersome soil descriptions, this method uses an approach that reduces soil descriptions to the basic soil particles contained in the description and the language that relates the particles together and converts this description to an equivalent estimated average hydraulic conductivity value. Converting the soil description to hydraulic conductivity values facilitates their use in mapping.

Average hydraulic conductivity values are used to represent the soil description of each stratum listed in a given well log. In turn, average hydraulic conductivity is also used to assign hydrogeologic units to the strata.

The basic building blocks of shallow aquifer systems are mixtures of the materials listed in Table 1. Since hydraulic conductivity is a measurable numerical characteristic of soil material, it is reasonable to define the stratigraphy of a shallow aquifer system using this

Table 3
Average Hydraulic

Conductivity of Soil Materials	
Soil Material	**Average Log_{10} K (cm/s)**
Clay	−7.5
Silt	−5.0
Sand	−2.5
Gravel	1.0
Stones	2.0
Cobbles	3.0
Boulders	3.0

Table 4
Modifiers and Relative Changes in Hydraulic

Conductivity Values			
Modifier	**Change in Log_{10} K Value**	**Modifier**	**Change in Log_{10} K Value**
Cemented	−2	Medium-very coarse	+2
Coarse	+2	Packed	−1
Cohesive	−1	Soft	−1
Dense	−1	Small	0
Fine	−0.5	Stiff	−1
Fine-coarse	+1	Very coarse	+3
Fine-medium	+0.5	Very dense	−1.5
Fine-very coarse	+1.5	Very fine	−1
Firm	−1	Very fine-coarse	+1
Gummy	−1	Very fine-fine	−0.5
Hard	−1	Very fine-medium	0
Large	+1	Very fine-very coarse	+2
Loose	+1	Very soft	−1.5
Medium	+1	Very stiff	−1.5
Well sorted	+0.5	Well graded	−0.5
Poorly sorted	−0.5	Poorly graded	+0.5

characteristic of the stratigraphic units. Table 3 lists the average hydraulic conductivity values for the basic soil types most present in shallow aquifer systems (Morris & Johnson 1967; Bear 1972; Domenico & Schwartz 1990; Sanders 1998 and USDA 2017).

Table 4 is a list of modifiers that are commonly found in soil descriptions that affect the hydraulic conductivity value assigned to a soil description. Also listed are relative hydraulic conductivity values attributed to these modifiers (Sedimentaryores.Net 2017).

The following equation is used to estimate the hydraulic conductivity of a soil component listed in a well log.

$$K_s = ((K_1 w_1 + K_2 w_2 + K_3 w_3 + K_4 w_4 + K_5 w_5)\, W) + M$$

Table 5
Examples of Calculation of Estimated Hydraulic Conductivity Values

Materials	Number of Terms	K_1	K_2	K_3	K_4	K_5	C_1	C_2	C_3	C_4	C_5	P	M	K_s
Sand	1	−2.50					6					0.167		−2.50
Fine-medium sand some cobbles	2	−2.50	−2.50				6	2				0.125	0.5	−0.63
Clay and sand some gravel	3	−7.50	−2.50	1.00			6	6	2			0.071		−4.14
Silty dense clay some coarse sand trace gravel	4	−5.00	−7.50	−2.50	1.00		4	6	2	1		0.077	1.0	−4.31
Silty clay and gravely silt with sand	5	−5.00	−7.50	1.00	−5.00	−2.50	4	6	4	6	3	0.043		−4.35

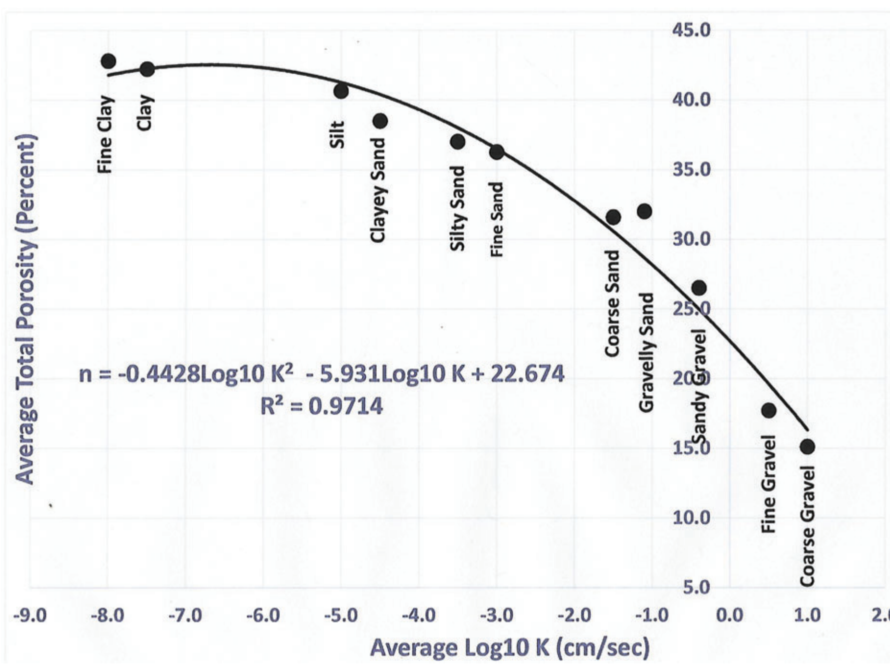

Figure 1. Average total porosity as a function of average hydraulic conductivity.

where K_s, $\log_{10}$ average hydraulic conductivity of stratum; $K_{(1\text{-}5)}$, $\log_{10}$ average hydraulic conductivity of soil component from Table 3; $w_{(1\text{-}5)}$, soil component weighting factor from Table 2; W, soil component weighting distribution factor ($1/(w_1 + w_2 + w_3 + w_4 + w$ and $_5)$; M, sum of soil component modifiers from Table 4).

The main part of a soil description is the soil material (Table 1), usually used as a noun or adjective. When used as a noun by itself the soil material will be the major component of the soil description making up about 60% of the soil. If the soil material is used as an adjective, it makes up about 40% of the soil volume. If more than one noun or soil material is used in the descriptions, then the terms are weighted using the weighting factors listed in Table 2.

The combined weight of each component of the soil description must equal 100%. The weighting factors are added together, the reciprocal is determined, and this value becomes the distribution factor. Table 5 has several examples of soil descriptions and the resulting estimated hydraulic conductivity values calculated using the above relationship.

Figures 1 and 2 show the relationship of total porosity and effective porosity respectively as a function of the estimated hydraulic conductivity values calculated in the manner shown above (Terzaghi et al. 1996; Sanders 1998; Das 2008; Zreda 2015). Porosity values are also included in the resulting database. Total porosities might be used to estimate pore water volumes of excavated soils while effective porosities would be used to estimate groundwater velocities.

Once the well log database has been revised and populated with the hydraulic conductivity and porosity estimates, each soil description in the database will have a representative hydraulic conductivity and porosity values. The representative hydraulic conductivity values are then

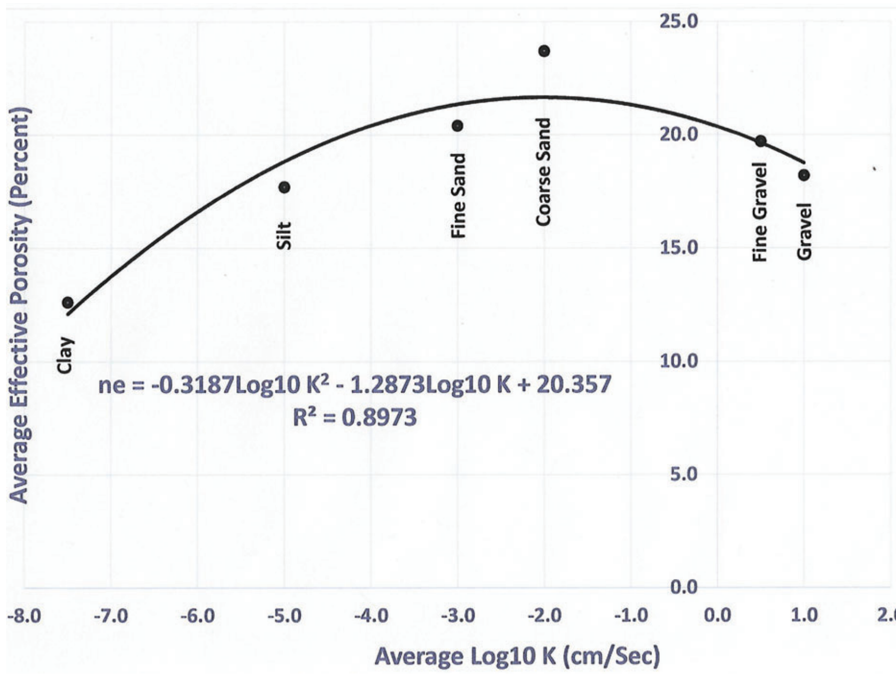

Figure 2. Average effective porosity as a function of average hydraulic conductivity.

Table 6
Definitions of Unconsolidated Hydrogeologic Unit Materials

Hydrogeologic Unit Materials	Average Log_{10} K (cm/s)
Aquifer	≥ -2.50
Aquitard	< -2.50 and > -7.00
Aquiclude	≤ -7.00

Table 7
Examples of Populated Database Entries

Material	K_s	n	n_e	Unit
Fine-medium sand some cobbles	−0.63	26.2	21.0	Aquifer
Clay and sand some gravel	−4.14	39.6	20.2	Aquitard
Silty dense clay some coarse sand trace gravel	−4.31	40.0	20.4	Aquitard
Silty clay and gravely silt with sand	−4.35	40.1	19.9	Aquitard

used to identify classes of materials that would make up the basic hydrogeologic units, i.e., aquifers, aquitards, and aquicludes.

Table 6 lists the average range of hydraulic conductivity for each of the three hydrogeologic unit materials (Zreda 2015). Using the information in Table 6, each stratum description in the database is assigned a hydrogeologic unit. At this point, a representative average hydraulic conductivity and one of three hydrogeologic unit materials define every description in the database as shown in Table 7 for the soil descriptions listed in Table 5.

The numerical hydraulic conductivity values are used to map the distribution of estimated hydraulic conductivity. Once the distribution of estimated hydraulic conductivity is established, the ranges of estimated hydraulic conductivity presented in Table 6 are applied to define the distribution in terms of hydrogeologic units.

Mapping Examples

Use of the resulting database is greatly simplified and facilitates rapid preliminary mapping of the hydrogeology of sub-regional areas for planners to make initial assessments of water resource needs The above procedure was used by the Barrington Area Council of Governments (BACOG) to define the preliminary hydrogeologic characteristics of a 625 mile^2 area centered on Barrington Illinois located northwest of Chicago (Figure 3). Barrington area residents are reliant on the shallow aquifer system for their water. Electronic well log records were obtained from the Illinois State Water Survey (ISWS). The ISWS data package consisted of 24,182 well logs. Geographic information system (GIS) techniques were used to query the well logs and set up a database where the well log descriptions were converted to estimated hydraulic conductivity and porosity equivalent values using the above described procedure. The ISWS well logs consisted of 106,296 lines of data resulting in 14,454 unique soil descriptions and approximately 750 descriptions that could be called standard. Once the database was prepared, the distribution of average hydraulic conductivities of 5-ft layers extending

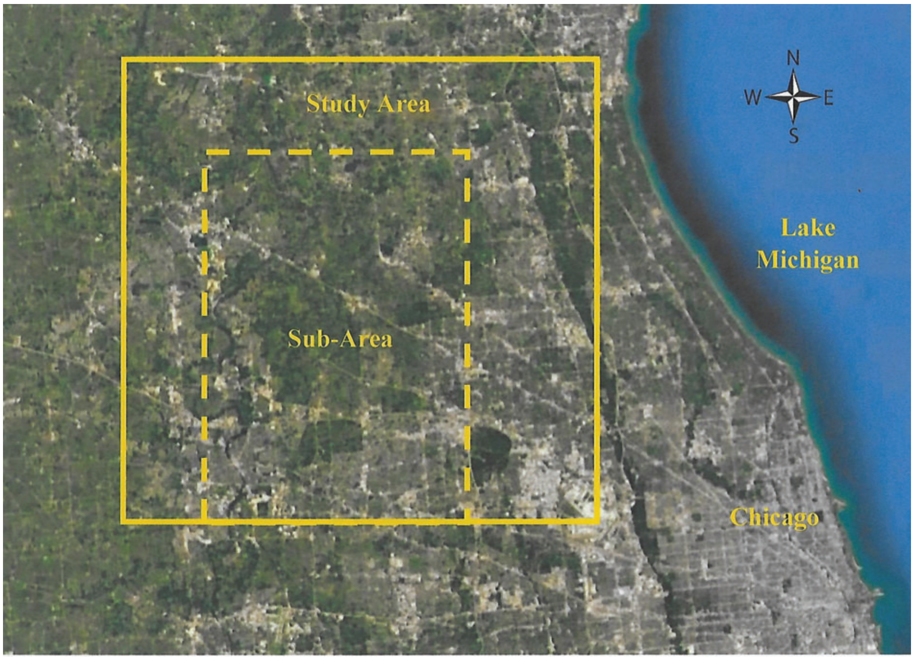

Figure 3. Study area location.

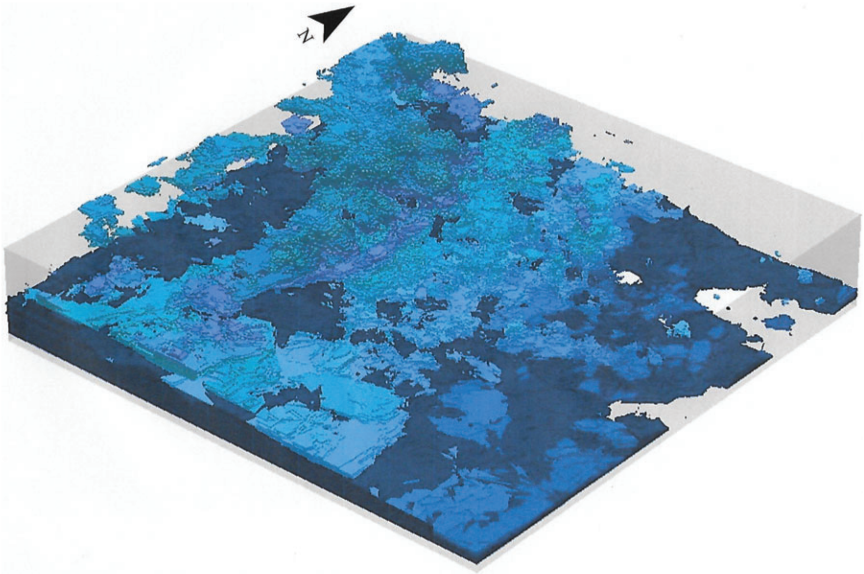

Figure 4. Areal and vertical distribution of aquifer materials in the study area.

from the surface to the bedrock was established using kriging methods. In this manner, the areal and vertical extent of the distribution of aquifer materials within the study area was developed as shown in Figure 4 (Thomsen et al. 2006a). A variety of blues were used in Figure 4 to provide a three-dimensional effect. The dark blue in the figure is the aquifer material overlying the bedrock surface. A variety of maps were prepared using the data. Of immediate use to local planners was a recharge area map. A 280 mile^2 sub-area of the study area was used to estimate the distribution of recharge characteristics (Thomsen et al. 2006b). The database was queried to estimate the average hydraulic conductivity of the strata encountered between the surface and the uppermost aquifer at each location. These data were used to estimate the relative time for infiltrating water to travel to the uppermost aquifer at each well location within the sub-area. Figure 5 is the resulting recharge map showing the distribution of recharge characteristics from the most sensitive to very poor recharge areas. This map is currently being used to establish wellhead protection areas.

Conclusion

The method described above allows one to use all available well log record data to produce baseline

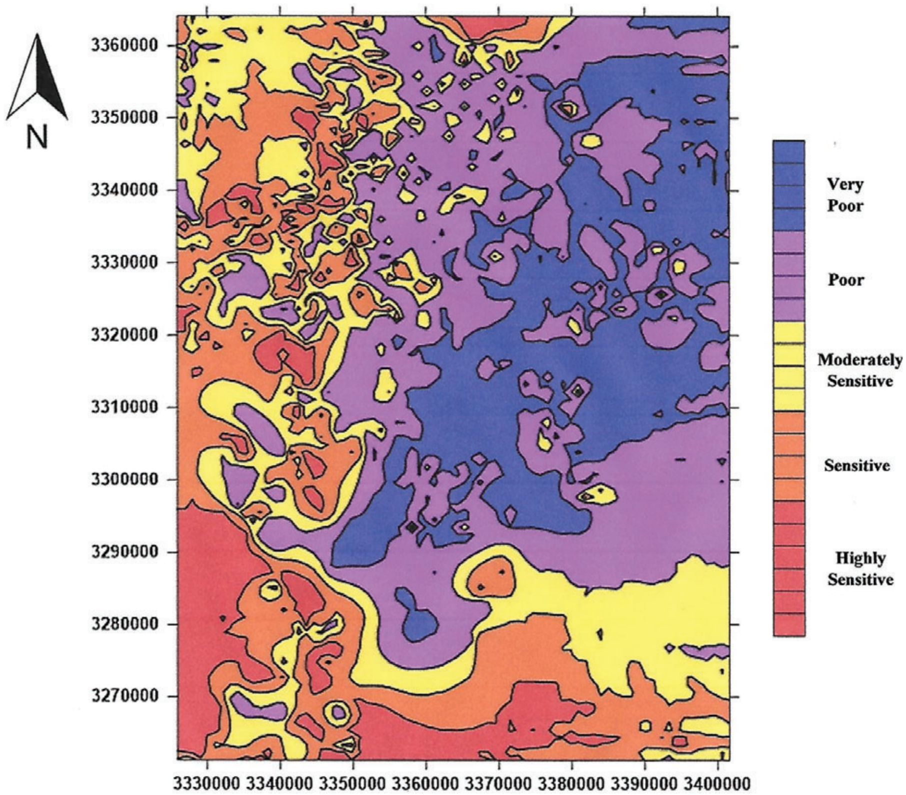

Figure 5. Subarea recharge characteristics.

hydrogeologic unit maps using GIS querying and mapping techniques. The use of the method is straightforward, relatively fast and inexpensive.

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Author's Note

The author(s) does not have any conflicts of interest.

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