Planning for Sustainability - Mapping the Shallow Groundwater Resource

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Abstract

Over the past decade the public has become more and more concerned with water resources. As a proactive measure, the Barrington Area Council of Governments (BACOG), an association of villages and townships in far northwest suburban Chicago, is currently working on a project to establish water resource baseline conditions in their immediate and surrounding area. Under the direction of BACOG and a professional advisor, a committee of volunteers is conducting much of the work of this water resource initiative using data readily available for little or no cost.

To establish water resource baseline conditions using limited resources, BACOG developed a method to produce baseline hydrogeologic unit maps from readily available borehole log data using GIS querying techniques. Borehole strata descriptions were converted to numerical values by establishing the average hydraulic conductivity of the combined soils making up the stratum of interest. These hydraulic conductivity values were then used to assign each stratum to a hydrogeologic unit based on typical ranges of hydraulic conductivity for aquifers, aquitards and aquicludes. In this manner, the well log data were queried to describe the shallow aquifer system. This approach was used to estimate the health of the shallow aquifer system to plan for sustainability using a water budget model. Estimates were made for the components of the water budget that included: storage, septic loading, inflows including through flow and seepage, discharge, consumption, and outflows including through flow and seepage.

All available stratigraphic data are used to define a given shallow aquifer system and build a representative stratigraphic model. To accomplish this, well log 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 model. Innovative mapping techniques are used. These techniques are based on replacing subjective strata descriptions with equivalent average hydraulic conductivity values and the use of statistics to create the model. The following describes the sequential tasks required using this approach.

<u>Task 1: Prepare an Electronic Well Log Database</u>

An electronic database is prepared containing all available stratigraphic data for the chosen site. The database is prepared in Microsoft® Excel or Access. Having an electronic database makes the stratigraphic information easily accessible using GIS querying techniques. Additionally, it is required that the stratigraphic information be made available to facilitate the mapping tasks. Figure 1 is an example of a portion of a database prepared for the Barrington Area council of Governments (BACOG).

<u>Task 2: Configure Database for Hydrogeologic Unit Mapping</u>

Once the electronic database has been completed it needs to be simplified by converting the subjective strata descriptions to objective numerical equivalents. This is accomplished by completing the following subtasks.

Task 2a: Identify Unique Identifiers

The first step in configuring the database is to eliminate all duplicate descriptions. This results in a list of descriptions that are unique to the database, i.e., unique identifiers. The BACOG project database contained information from almost 25,000 well records translating to about 102,000 lines of data having over 14,000 unique identifiers.

Task 2b: Cleanup Database

Basic strata descriptions list particles of sizes ranging from clay to boulders and include words that provide a measure of proportion between the particles listed. Adjectives such as those describing color, moisture content, density, etc. are removed as part of the cleanup process.

Task 2c: Create Standard Identifiers

Once the database is cleaned, the remaining identifiers are queried to remove duplicates. The remaining identifiers are the standard identifiers that will be used to populate the database. The BACOG database had over 750 standard identifiers.

Task 2d: Calculate Hydraulic Conductivity Values and Hydrogeologic Units

The standard identifier descriptions are based only on the materials that are considered important for analysis using hydraulic conductivity, resulting in a manageable number for use in further analysis.

For example, there are several terms for clay, which include kaolin, bentonite, and talc. The descriptions can also include green clay, blue clay, and brown clay. All of these materials have approximately the same average hydraulic conductivity values, and once they are identified, the analyst records them in the database so that they are all one classification instead of seven separate classifications. Every time this is done, it further reduces the number of times complicated querying procedures need to be evoked as the number of unique identifiers is condensed.

Once the analyst becomes familiar with the terms in the database, confirms with the geologist what terms should be used and what terms should be lumped together as one (i.e. green clay will be changed to clay), then the resulting terms will be populated with corresponding average hydraulic conductivity values.

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

The basic building blocks of unconsolidated aquifer systems are mixtures of clay, silt, sand, gravel, cobbles and boulders. Since hydraulic conductivity is a measurable numerical characteristic of soil material, it is used to define the stratigraphy of the unconsolidated aquifer system using this characteristic of the stratigraphic units. This numerical characteristic makes hydraulic conductivity ideal for analysis using computer analytical techniques. Table 1 lists the average hydraulic conductivity values for the basic soil types present in most unconsolidated aquifer systems.

In the database, average hydraulic conductivity will be determined for each stratum in a given well log. The average hydraulic conductivity will then be used to establish the hydrogeologic unit in which the stratum will be placed. This will be discussed below.

Soil Material	**Average $\log_{10}$ K (cm/sec)**
Clay	-7.5
Silt	-5.0
Sand	-3.0
Gravel	1.0
Stones	2.0
Cobbles	3.0
Boulders	3.0

Table 1 Average Hydraulic Conductivity (K) of Soil Materials

Table 2 is a table of terms that are used to proportion the specific soil materials. These terms are the basic key words that will be used to convert soil descriptions to representative average hydraulic conductivity values.

Use of Terms	**Terms**	**Content**	**Proportion Factor**
Nouns	clay, silt, sand, gravel cobbles & boulders	60%	6
Conjunctions	and, comma, slash & hyphen	60%	6
Adjectives	clayey, silty, sandy, gravelly, cobbley, & bouldery	40%	4
Prepositions	in & with	30%	3
	few	20%	2
Adverbs	considerable, frequent & much	30%	3

	a bit, contain, containing, little, scattered, slightly, small amount, & some	20%	2
	isolated, occasional, & trace	10%	1

Table 2 Key Terms Used for Soil Description Conversions

Converting soil descriptions of the standard identifiers to representative hydraulic conductivity values will follow principles similar to sentence diagramming. The main part of a description is the soil type, usually used as a noun or adjective. When used as a noun by itself the soil will be the major component of the soil making up about 60 percent of the soil. If the soil is used as an adjective it makes up about 40 percent of the soil volume. Use of a conjunction such as “and,” a comma, or a hyphen with nouns gives the nouns equal weight. Two nouns not separated by a comma or an “and” become an adjective and a noun respectively, such as “clay gravel.” “Clay gravel is equivalent to clayey gravel. If the soil is used with any of the prepositions or adverbs listed in Table 2, the contribution to the soil volume will be equal to the percents listed in the table.

If more than one noun is used in the descriptions then the terms are weighted using the proportion factors listed in Table 2. Figure 2 contains a number of example soil descriptions having one to five soil types and shows how the proportion factors are used. For example, line 6 in Figure 1 is clayey gravel.” Gravel is the noun and clayey is an adjective and their proportion factors are 6 and 4 respectively. The proportions for each component of the entire term must equal a 100 percent. The proportion factors are added together, the proportion coefficient is determined and this value (0.100) is multiplied by the proportion factor for clay (4) and then by the clay average hydraulic conductivity value (-7.50). The resulting value (-3.00) is added to the product of the reciprocal value (0.100), the proportion factor for gravel (6) and the average hydraulic conductivity value (1.00) as follows:

Description: clayey gravel

Proportioning Factors: $4 + 6 = 10$

Proportioning Coefficients: $1/10 = 0.10$

Equation: $K_s = (0.100)(4)(-7.50) + (0.100)(6)(1.00) = -2.40$

As noted, sometimes a soil description contains two nouns not separated by “and” or a comma in which case the first noun becomes an adjective. Line 12 (Figure 1) is an example of such a case. The description is “sand some gravel clay” in which gravel describes clay. This description is made more difficult because the “gravel clay” has a proportion factor of 2 because the adverb “some” modifies “gravel clay.” Normally “gravel clay” would proportion as 4 + 6. This is still the case but the term becomes a sub calculation of the whole. Once the hydraulic conductivity is determined, this value is used in the main calculation as shown below.

Description: sand some gravel clay

Proportioning Factors: $6 + 2 = 8$
$4 + 6 = 10$

Reciprocal Coefficients: $1/8 = 0.125$
$1/10 = 0.0$

Equation: $K_s = (0.125)(6)(-3.00) + (0.125)(2)[(0.01)(4)(1.00) + (0.01)(6)(-7.50)] = -2.45$

Once the well log database is populated with the hydraulic conductivity estimates, each soil description in the database will have a representative hydraulic conductivity value. These representative hydraulic conductivity values are then used to identify classes of materials that would make up the basic hydrogeologic units, aquifers, aquitards, and aquicludes. Table 3 lists the average range of hydraulic conductivity for each of the three hydrogeologic unit materials. In addition, average porosity and effective porosity are included for use in future tasks.

Hydrogeologic Unit Materials	**Average Log_{10} K (cm/sec)**	**Porosity (Percent)**	**Effective Porosity (Percent)**
Aquifer	≥ -3.00	25	18
Aquitard	< -3.00 and > -5.00	35	11
Aquiclude	≤ -5.00	50	2.5

Table 3 Definitions of Unconsolidated Hydrogeologic Unit Materials as a Function of Average Hydraulic Conductivity, Porosity and Effective Porosity Values

Using the information in Table 3, 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. The numerical hydraulic conductivity values are used to map the distribution of hydraulic conductivity. Once the distribution of hydraulic conductivity is established, the ranges of hydraulic conductivity presented in Table 3 will be used to define the distribution in terms of hydrogeologic unit materials.

The resulting database will be greatly simplified and will facilitate rapid preliminary mapping of the hydrogeology of sub-regional areas for planners to make initial assessments of water resource needs.

Once the strata standard descriptions, hydraulic conductivity values, and hydrogeologic unit classification have been added to the database, the database will be ready for the preparation of the stratigraphic model

Task 3: Prepare a Stratigraphic Model

A stratigraphic model was prepared of the unconsolidated aquifer system for the 600 square mile study area for the BACOG project. Figures from this project are used to illustrate the modeling procedure.

The stratigraphic model is essentially a stack-map sequence of the study area made up of maps showing the areal distribution of major aquifer material units at regular intervals extending from the land surface to the lower limits of the data or the bedrock surface whichever is applicable. Use of a five-foot interval for the BACOG project provided an excellent demonstration of the vertical relationship of the major aquifer material units. Figure 3 is an example of one of the horizontal five-foot layers of the study area at an elevation of 700 feet above mean sea level (AMSL).

The numerical hydraulic conductivity values are used to map the distribution of hydraulic conductivity for each layer. Once the distribution of hydraulic conductivity is established, the ranges of hydraulic conductivity presented in Table 3 are used to define the distribution in terms of hydrogeologic unit materials.

To generate each of the model's layers, GIS techniques are used to query the database to determine the average hydraulic conductivity of the material encountered at the desired elevation of every usable well log in the database. Once the average hydraulic conductivities are obtained, along with location information, the procedure described above is used to develop the map.

Generally, the regional bedrock surface in the BACOG area slopes to the east. This slope is also reflected in the general trend of the regional land surface. Review of Figure 3 shows that, at an elevation of 700 feet AMSL, the bedrock is exposed (dark blue) in the western portion of the study area while the land surface is shown in the Des Plaines River valley in the eastern portion of the study area. The Fox River to the west and the Des Plaines River to the east are shown as light blue ribbons. Aquifer materials are depicted in medium blue and are extensive in the western portion of the study area where they come in contact with the bedrock. The light tan areas represent deposits of aquiclude materials and the darker tan areas are aquitard materials. In most cases, the aquitard materials seem to act as a transition zone between the aquiclude and aquifer materials and act as a harbinger of upcoming locations of aquifer materials as one moves downward through the model layers.

Using the stratigraphic model, cross-sections of the study area boundaries shown in Figure 4 can be generated. Cross-sections are created from the edges of the individual layers. If the cross-sections are expanded the space between the layers can be detected. Figure 5 is an example of an expanded stratigraphic model showing the layers. Because of the short distance between layers, there does not appear to be any radical differences between layers. Everything appears to flow together and is consistent. The model also appears to be consistent as one moves downward through the stratigraphic column and indicates that the drift aquifer material is interconnected throughout the study area. There are probably isolated units of aquifer materials or perched units present, but these units are not evident as one navigates downward through the model. Figure 6 shows the relationship between aquifers. This figure represents the stratigraphic model block diagram (Figure 7) with all materials except aquifer materials removed

Task 4: Assist M&E to Adapt Stratigraphic Model to Ground Water Flow Model

KOTECI will work with M&E to adapt the stratigraphic model to the groundwater flow model. The objective is to ensure that the groundwater flow model represents the stratigraphic model as closely as possible and practical.

Task 5: Water Budget Characteristics

Once the stratigraphic model is completed, the distribution of the aquifer material is documented. Using the model, water budget characteristics are established to estimate the amount of water available and the effect of current water use practices on the stored water using the following relationship:

$$\Delta S = Gw_i + R + S_i + S_l - Gw_o - D - S_o - C$$

where:

S = Storage
Gw_i = Groundwater Inflow
R = Recharge
S_i = Seepage Inflow
S_l = Septic Loading
Gw_o = Groundwater Outflow
D = Discharge
S_o = Seepage Outflow
C = Consumption

Task 5a Estimate Storage

Using the layers of the stratigraphic model, the surface areas of each hydrogeologic unit are determined and multiplied by the 5-foot interval between layers to yield volumes of materials. These values a summed for each layer contained in the model. The porosity and specific yield values listed in Table 3 are applied and the total volume of water and the portion that can be extracted are estimated.

Task 5b: Estimate Annual Inflow and Outflow

A three-dimensional box or other shape having areal extent as well as depth represents the stratigraphic model of the study area. Inflow and outflow of groundwater flows through the walls of the box. The sides of the box are cross-sections of the study area boundary showing the distribution of aquifer, aquitard, and aquiclude materials. The interval maps generated as part of stack mapping are used to create cross-sections of each study area boundary. Saturated aquifer materials are identified and the cross-sectional areas of these units are determined. Finally, the potentiometric surface for the aquifer system is used to determine the direction of groundwater flow and the gradient at the border of the box. The groundwater gradient is used with the hydraulic conductivity and effective porosity of the aquifer materials to calculate groundwater velocity. Combining velocity with area information yields the flow into and out of the system through the border. The flow values will be converted to an appropriate annual volume

Task 5c: Estimate Annual Recharge and Discharge

Stream-flow records of a river(s) within or near the study area can be used to estimate annual recharge and discharge values using one of several available models from the U.S. Geologic Survey.

Task 5d: Estimate Vertical Seepage

Vertical groundwater movement occurs into and out of shallow groundwater system and the underlying bedrock. The potentiometric map grid values of the bedrock are subtracted from the grid values of the shallow aquifer system potentiometric map to identify areas of inflow and outflow. Based on the types of material and their characteristics, vertical velocities are determined and multiplied by areas to estimate flow in and out of the shallow aquifer system.

Task 5e: Estimate Annual Consumption

Annual water consumption is estimated using available records. If necessary, consumption estimates will be derived from census data and average percapita consumption rates.

Task 5f: Estimate Annual Septic Loading

Annual septic loading is also estimated using available records. If necessary, loading estimates will be derived from census data and average percapita loading rates to septic fields.

When the above tasks are completed, a planner has the answers to the following questions:

Where is the water?
How much is there?
Are we using too much?

An effective groundwater management program is directly related to how well these questions can be answered.