STATIGRAPHIC MAPPING FOR ESTABLISHING A GROUNDWATER RESOURCE BASELINE

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Abstract

Over the past decade the public has become more and more aware of problems with water resources. This paper describes data querying and subsequent mapping techniques used to establish baseline conditions for groundwater resources. Well log data were queried using geographical information systems (GIS) to define the shallow aquifer system. The bedrock surface and overlying basal aquifer were defined. Aquicludes, aquitards and lesser aquifers overlying the basal aquifer were defined and their inter-relationships were established. A water budget was established to determine the amount of water in storage and identify the inflows and the outflows of water in the study area. A determination was made to establish if the area's water storage capacity is in a net water loss, balanced, or net water gain mode. This information will be used to plan future water needs for growth.

Background

The BACOG geographic area is located approximately 40 miles northwest of downtown Chicago in northeastern Illinois. BACOG is a regional planning organization comprised of seven member municipalities:

- Barrington
- Barrington Hills
- Deer Park
- Lake Barrington
- North Barrington
- South Barrington
- Tower Lakes

Politically, BACOG's jurisdiction covers portions of four counties:

- Cook
- Kane
- Lake
- McHenry

It also includes multiple townships and the seven villages, all of which have independent governing bodies. The area is a unique regional community with a central business district and village atmosphere surrounded by semi-rural countryside residential areas and extensive acreage in wetlands, forest preserves, parks, agriculture, and horse farms. As a regional planning organization, BACOG's primary functions are to promote the regional comprehensive land use plan and protect environmental resources, for the greater good and preservation of the community.

Over 30 years ago, community and municipal leaders joined together to develop the first regional comprehensive plan for BACOG. The plan was based on the relationship of land uses to natural resources, and the resources available to support development were to limit development. This plan has been implemented substantially, but there is still much development to occur within BACOG until complete build-out. The concept of development being limited to naturally sustainable levels has been steadfastly maintained since 1970 through the BACOG comprehensive plan, the municipal comprehensive plans, and other planning policies.

Groundwater is the lifeblood of the BACOG area. Residents are dependent primarily on the shallow aquifer, and within that, primarily the shallower layers of the shallow aquifer, for all water needs. Only the central “hub” village of Barrington, Tower Lakes, and small sections of the other communities offer public water or sewer, again with the water supply coming primarily from the shallow aquifers. The countryside communities require well and septic systems that utilize the shallow aquifer and large lot zoning (one or more acres) that are necessary for proper functioning of those systems. With very few exceptions, public water is not offered or planned for the area, and only those areas currently served contain the infrastructure required for public utilities. Publicly provided water is metered, but most other water consumption is not measured or estimated. Any threat to the quantity or quality of water in the aquifers would threaten the community structure, the public health, safety and welfare, and the ability of families and businesses to survive.

As more development occurs throughout and surrounding the BACOG area and the BACOG municipalities experience increasing pressures for higher density development and higher intensity uses, development sometimes attempts to break zoning and planning by threatening lawsuits and land disconnection in order to negotiate higher densities and secure water and sewers from other towns. BACOG towns find it more and more difficult to fend off development that could negatively affect the wetlands, natural areas, and aquifers of the area.

High density and commercial/industrial development in villages and areas adjacent to BACOG also could affect water resources locally. Peaker power plants, users of extremely high amounts of water, have attempted to locate in nearby communities. Water resources do not respect political boundaries, and the water that is available today to residents and to sustain sensitive natural areas could be compromised by intense development in surrounding communities or by mining and other industrial uses nearby.

Concerns about groundwater supply and quality have been prominent for some time because of the dependence of BACOG’s more than 35,000 residents on groundwater. There is virtually no possibility of obtaining water from Lake Michigan. Other northeastern Illinois communities are using the maximum allocation, governed by a Supreme Court ruling and international treaty. Regardless, the cost of providing infrastructure from so far away would be very high, and the cost of providing new infrastructure to serve homes in the countryside communities would be exorbitant. Available allocation and infrastructure costs would also be impediments to obtaining water from the Fox River, where there also are restrictions on diversion of water. As water quality and quantity in the deep aquifer have declined over past decades, fewer deep wells have been developed, and in fact, numerous municipalities have abandoned their deep wells. Areas within and adjacent to BACOG have been identified by the Northeastern Illinois Planning Commission's (NIPC's) water management plan (NIPC, 2001) as having the potential for water shortages in the future. Developing trends towards higher usage of the shallow aquifer, the vulnerability of the shallow aquifer to contamination, and constraints on alternative water supplies have resulted in concern for the sustainability of groundwater in the BACOG area.

Recognizing these concerns, in early January 2001 BACOG proposed to the member villages a study of groundwater resources. The Executive Board agreed and authorized the formation of a committee to begin a study. The Committee is entirely staffed by volunteers and includes advisory members from the Illinois State Water Survey, the Lake County Health Department, and a private environmental consulting firm. In addition to representatives from all the BACOG villages and a number of county boards and townships, members also include representatives of conservation and community organizations. Under the direction of the BACOG Executive Director, the Water Resources Committee conducted its first meeting in April 2001, providing educational materials and presentations for its members for the first few months. The Committee began identification of local groundwater issues, data collection, research, and structuring of the project later that year. Since then work has continued through regular meetings of the committee and its five subcommittees. Project progress has been reported on a regular basis (Peters, Agnoletti, and Thomsen, 2003; and Agnoletti and Thomsen, 2003).

Since the footprint of the communities that comprise the BACOG area is irregular, a boundary was drawn around the extent of the seven communities to establish the BACOG area for the purposes of this study. The extent of the BACOG area for the water project is approximately 175 square miles (Figure 1). A six-mile wide buffer was established around the BACOG area to identify the entire BACOG study area. This buffer zone was included to insure that the system characteristics at the border of the BACOG area can be established. The complete BACOG study area contains about 600 square miles.

Figure 1 BACOG Study Area

The groundwater system in this study area includes the unconsolidated sand and gravel water-bearing units (aquifers) located in the glacial drift (material deposited by glaciers) as well as the uppermost bedrock immediately underlying the glacial drift. The bedrock unit is a Silurian dolomite/limestone and is located at 150 to 350 feet below the ground surface. One to five aquifers may be present at any given location within this study area (Meyer, 1998). These units may be interconnected or they may be separated by impermeable (aquicludes) or semi-permeable units (aquitards) of glacial till (fine materials deposited by glaciers). Therefore, these units may exhibit unconfined, semi-confined or confined hydraulic conditions.

Water Balance

A water balance approach is being used to characterize the groundwater system in the study area. The water balance approach develops a conceptual model of the study area indicating that the change in groundwater storage is equal to the sum of the groundwater inflows minus the sum of the groundwater outflows. Inflows to the groundwater system include the groundwater that flows across the site boundary into the study area, groundwater recharge, and upward seepage from the underlying bedrock. Outflows include the groundwater that flows across the site boundary out of the study area, the groundwater that is withdrawn for consumption, seepage to the underlying bedrock, and groundwater discharging to the surface system (Figure 2).

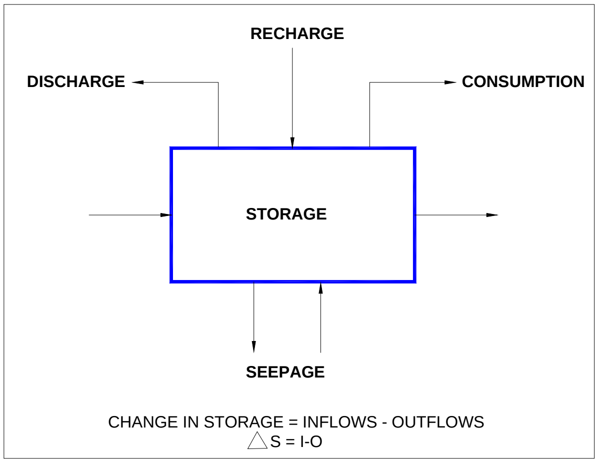


FIGURE 2: CONCEPTUAL MODEL OF THE GROUNDWATER SYSTEM

Stratigraphic Mapping

Because of the vertical and areal variation in the distribution of the materials that make up the shallow aquifer system, defining the stratigraphy of the system is very difficult. Traditionally, known stratigraphic units are defined by relating unit characteristics to similar characteristics of materials encountered when drilling reference boreholes. Reference borehole information is related to nearby wells using well logs from the Illinois State Geological Survey (ISGS) database (ISGS, 2001). Interpretation of the stratigraphy of an area is based on the use of descriptors and is very subjective. This type of analysis is not very compatible with analysis using computer techniques.

Since the interest of this study lies in the location and flow characteristics of water, geological formation descriptions, while of interest, are not required to define the shallow aquifer system. A numerical technique that is objective and compatible with computer analytical techniques was developed to determine the intermediate stratigraphy of the sub-area. As it turned out, the same technique could be used for establishing the entire sub-area stratigraphy between the bedrock surface and the ground surface including the basal aquifer.

The materials composing the stratigraphic units in the sub-area are clay, sand, gravel and cobbles as mentioned before. Silt has not been included because when a geologist describes borehole soil samples, the difference between clay and silt cannot be discerned with the naked eye. The term “boulders” is commonly used in well log descriptions. Boulders are large rocks that would stop drilling operations. Since the well logs do not include notes saying that the boulders were drilled through, or that the borehole was relocated, it was assumed that the boulders were small enough to be pushed aside by continued drilling making the rocks small enough to be cobbles rather than boulders. Therefore, whenever the term “boulders” was encountered in a well log, “cobbles” was substituted.

When stratigraphic units are composed of materials of varying particle sizes (clay, sand, gravel, and cobbles), void spaces exist between particles. Collectively, the volume of void spaces of a stratigraphic unit is its porosity. Porosity is important because the void spaces are where the water is found. The smaller the particle size of the material composing a unit (such as a clay unit) the higher the porosity. On the other hand, the same characteristic of a clay unit gives it a low permeability. Permeability is the property of a soil that allows it to transmit water. A saturated clay unit holds a lot of water but water has difficulty flowing through it because of friction and the electrostatic forces associated with the soil particles. Closely related to permeability is hydraulic conductivity. Hydraulic conductivity is a measure of the ability of water to flow through a soil unit.

Since hydraulic conductivity is a measurable numerical characteristic of soil material, it was decided to define the stratigraphy of the shallow 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 soil types present in the shallow aquifer system (Sanders, 1998).

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

Table 1 Average Hydraulic Conductivity (K) of Soil Materials

A technique called stack-unit mapping (ISGS, 1995 and Stumpf, Hansel, and Barnhardt, 2004) was used to define the stratigraphy of the shallow aquifer system. Using this technique, the sub-area was divided into 20-foot vertical sections that extended from below bedrock and through the surface. For instance, the 680 to 700-foot layer or stack is a 20-foot layer extending over the entire sub-area at a level from 680 to 700 feet above mean sea level (AMSL). Twenty-foot layers above and below this layer are stacked together to depict the stratigraphy of the sub-area.

The distribution of the hydraulic conductivity of the soils within the layers is the characteristic that is used to define the stratigraphy. Within each layer, an average vertical hydraulic conductivity is determined for each well location. The average hydraulic conductivities are then contour mapped, creating a map showing the average distribution of soil hydraulic conductivities for the layer. This distribution represents the characteristics of the 20-foot layer. These layers are stacked together to yield the soil distribution of hydraulic conductivity of the entire sub-area.

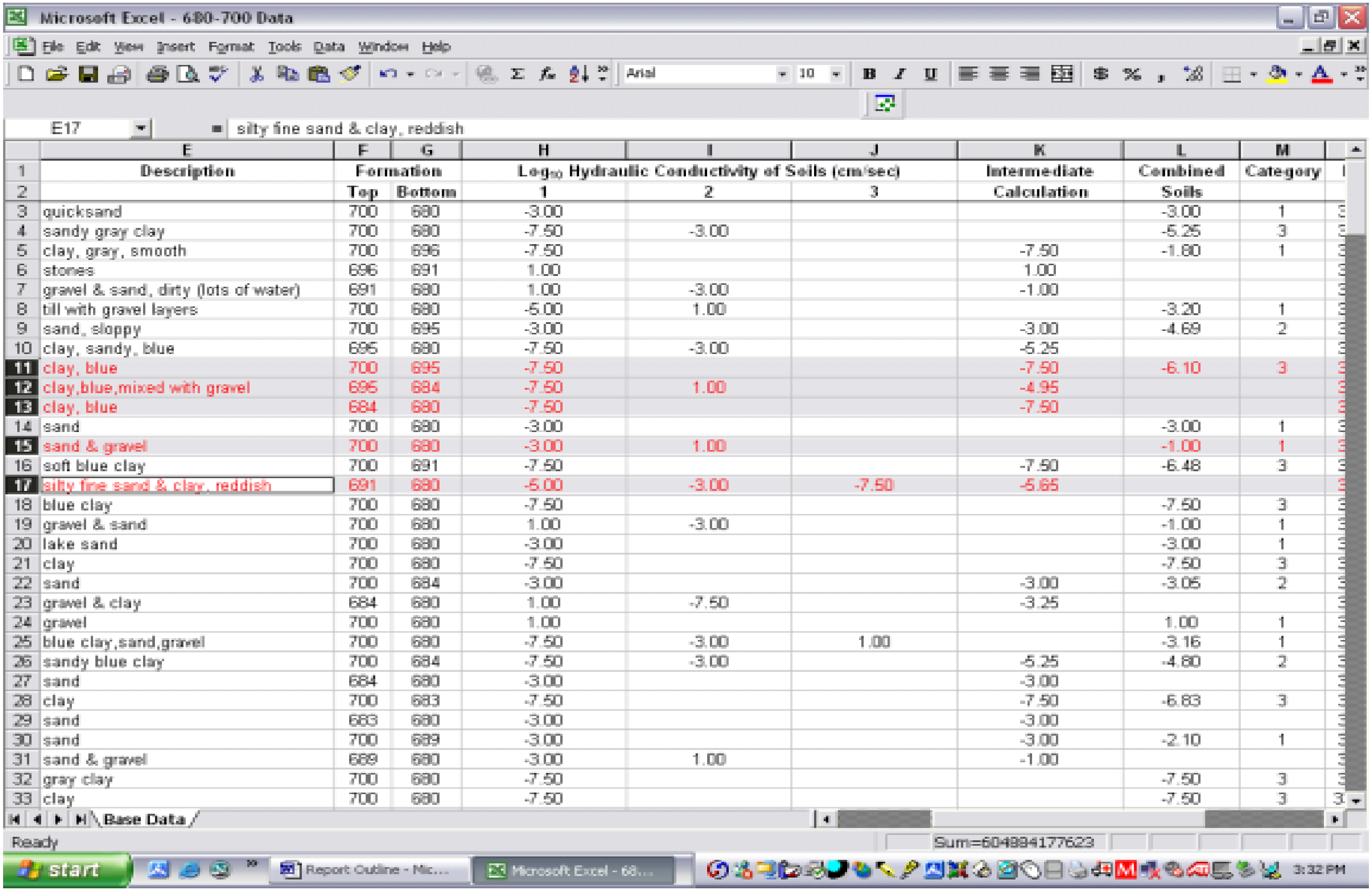
Using the 680 to 700-foot layer as an example, the first task was to query all the wells in the sub-area bedrock wells database to identify and isolate the 680 to 700-foot layer for each well. The first step was to convert the top depth and bottom depth of each strata or formation to its elevation AMSL. The first query was set up to find all strata with a top elevation of greater than 680 feet and with a bottom elevation of less than 700 feet. As a result of this query, most strata selected did not have a top elevation of 700 feet and a bottom elevation of 680. For example, a more typical occurrence was 714 feet for a top elevation and 651 feet for a bottom elevation, for example. This meant that the soil material between elevations 714 and 651 feet was the same. Therefore, the next step was to change the elevations to 700 and 680 feet respectively.

Occasionally the query identified multiple strata occurring within a 20-foot interval, such as 709 to 694 feet for a top unit, followed by a unit from 694 to 687 feet, and a third unit 687 to 671 feet. In this case the 709 feet was changed to 700 feet and the 671 feet was changed to 680 feet resulting in a 20-foot layer having three sub-layers. Figure 3 is a portion of the spreadsheet used to determine the distribution of the soil hydraulic conductivity for the 680 to 700-foot stack. Column E contains the description of the formation as recorded in the well log for each location. Columns F and G record the top and bottom elevations for each formation. In most cases these are 700 and 680 feet respectively. Elevations other than these indicate wells that have sub-strata in the 20-foot interval from 680 to 700 feet.

The next query addressed the composition of the soils in each layer or sub-layer. As can be seen by reviewing Column G in Figure 3, most of the strata are made up of varying amounts of clay, sand, and gravel. Column G was queried using the terms clay, sand, and gravel individually or in combination to determine strata composition. The first term encountered in a description was placed in Column H, the second in Column I, and the third in Column J. Cobbles were rarely found; if found, they would be placed in Column K and information in subsequent columns would be shifted to the right.

After Columns H, I, and J were completed, the soil terms in each column were replaced with their respective average hydraulic conductivity value taken from Table 1. These values are shown in Figure 3.

Average hydraulic conductivity values were calculated for strata having more than one soil in its composition and/or strata having sub-strata. Final strata hydraulic conductivity values are listed in Column L (Figure 3). For strata having only one soil type, the average hydraulic conductivity value was moved directly from Column H to Column L. All other strata required manipulation of the data to arrive at the average hydraulic conductivity for the strata.



E17 silty fine sand & clay, reddish

	E	F	G	H	I	J	K	L	M
1	**Description**	**Formation**		**Log$_{10}$ Hydraulic Conductivity of Soils (cm/sec)**			**Intermediate**	**Combined**	**Category**
2		**Top**	**Bottom**	**1**	**2**	**3**	**Calculation**	**Soils**	
3	quicksand	700	680	-3.00				-3.00	1
4	sandy gray clay	700	680	-7.50	-3.00			-5.25	3
5	clay, gray, smooth	700	696	-7.50			-7.50	-1.80	1
6	stones	696	691	1.00			1.00		
7	gravel & sand, dirty (lots of water)	691	680	1.00	-3.00		-1.00		
8	till with gravel layers	700	680	-5.00	1.00			-3.20	1
9	sand, sloppy	700	695	-3.00			-3.00	-4.69	2
10	clay, sandy, blue	695	680	-7.50	-3.00		-5.25		
11	clay, blue	700	695	-7.50			-7.50	-6.10	3
12	clay,blue,mixed with gravel	695	684	-7.50	1.00		-4.95		
13	clay, blue	684	680	-7.50			-7.50		
14	sand	700	680	-3.00				-3.00	1
15	sand & gravel	700	680	-3.00	1.00			-1.00	1
16	soft blue clay	700	691	-7.50			-7.50	-6.48	3
17	silty fine sand & clay, reddish	691	680	-5.00	-3.00	-7.50	-5.65		
18	blue clay	700	680	-7.50				-7.50	3
19	gravel & sand	700	680	1.00	-3.00			-1.00	1
20	lake sand	700	680	-3.00				-3.00	1
21	clay	700	680	-7.50				-7.50	3
22	sand	700	684	-3.00			-3.00	-3.05	2
23	gravel & clay	684	680	1.00	-7.50		-3.25		
24	gravel	700	680	1.00				1.00	1
25	blue clay,sand,gravel	700	680	-7.50	-3.00	1.00		-3.16	1
26	sandy blue clay	700	684	-7.50	-3.00		-5.25	-4.80	2
27	sand	684	680	-3.00			-3.00		
28	clay	700	683	-7.50			-7.50	-6.83	3
29	sand	683	680	-3.00			-3.00		
30	sand	700	689	-3.00			-3.00	-2.10	1
31	sand & gravel	689	680	-3.00	1.00		-1.00		
32	gray clay	700	680	-7.50				-7.50	3
33	clay	700	680	-7.50				-7.50	3

Figure 3 Example of Stack-Unit Map Calculations

Description	**Interpretation**
“equal” (“and” or x, y)	0.5x + 0.5y
3 “equal” components	0.3x + 0.3y + 0.3z
Adjective (such as, “sandy”)	0.4x + 0.6y
“with”	0.3x + 0.7y
“some”	0.2x + 0.8y
“trace”	0.1x + 0.9y
- where x, y, z are average Ks of included soils	

Table 2 Interpretations of Strata Descriptions Used to Calculate Average Ks

Table 2 is a summary of the interpretations of strata and sub-strata descriptions used to determine the average hydraulic conductivity of the strata or sub-strata in question. For instance, line 15 (Figure 3) describes the stratum as “sand & gravel.” Using the information from Tables 1 and 2, the calculation of the average hydraulic conductivity of the stratum would be:

$K = 0.5(-3.00) + 0.5(1.00) = -1.00$

This value was placed in Column L because it describes the entire stratum. The average hydraulic conductivity of the stratum would be –1.00 cm/sec.

Line 17 describes a sub-stratum composed of three types of soil. The description is, “silty fine sand & clay, reddish.” The sub-stratum hydraulic conductivity would be calculated by:

$K = 0.2(-5.00) + 0.3(-3.00) + 0.5(-7.50) = -5.65$

In this example, there are three types of soil, but only two parts: silty sand and clay. Therefore, the stratum contains 50 percent silty sand (a 40/60 percent combination) and 50 percent clay.

Another example is line 12 that describes the stratum as “clay, blue, mixed with gravel.” The average hydraulic conductivity for this stratum would be:

$K = 0.7(-7.50) + 0.3(1.00) = -4.95$

This value was placed in Column K because it is the average hydraulic conductivity of a sub-stratum and is an intermediate calculation. A review of lines 11 through 13 indicates that the 20-foot stratum contains sub-strata having average hydraulic conductivities of -7.50, -4.95, and –7.50 respectively. The sub-strata average hydraulic conductivities are proportioned over the 20-foot layer as follows:

$$K = (((700–695)/20)*-7.50) + (((695–684)/20*-4.95)) + (((684–680)/20*-7.50)) = -6.10$$

The combined average hydraulic conductivities of the sub-strata yield an average hydraulic conductivity of the 680 to 700-foot layer of –6.10 cm/sec at the given location.

The values in Column L, combined with their respective well locations were used to create a contour map showing the distribution of the average soil hydraulic conductivity in the 680 to 700-foot layer across the sub-area (Figure 4). This distribution was modified to represent the hdrogeologic units (aquifer, aquitard, and aquiclude) using the information in Table 3 and is presented in Figure 5.

Hydrogeologic Units	Log_{10} K (cm/sec)
Aquifer	Greater than –3.0
Aquitard	-5.0 to –3.0
Aquiclude	Less than –5.0

Table 3 Definition of Hydrologic Units Based on Average Hydraulic Conductivity

At this time, not all of the layers in the sub-area have been defined. Figure 6 is an example of stack-unit mapping using three layers that have been completed.

The stratigraphic mapping technique detailed above are used in the determination of the magnitude of the water balance components recharge and groundwater through flow (Agnoletti, Thomsen, and Peters, 2004).

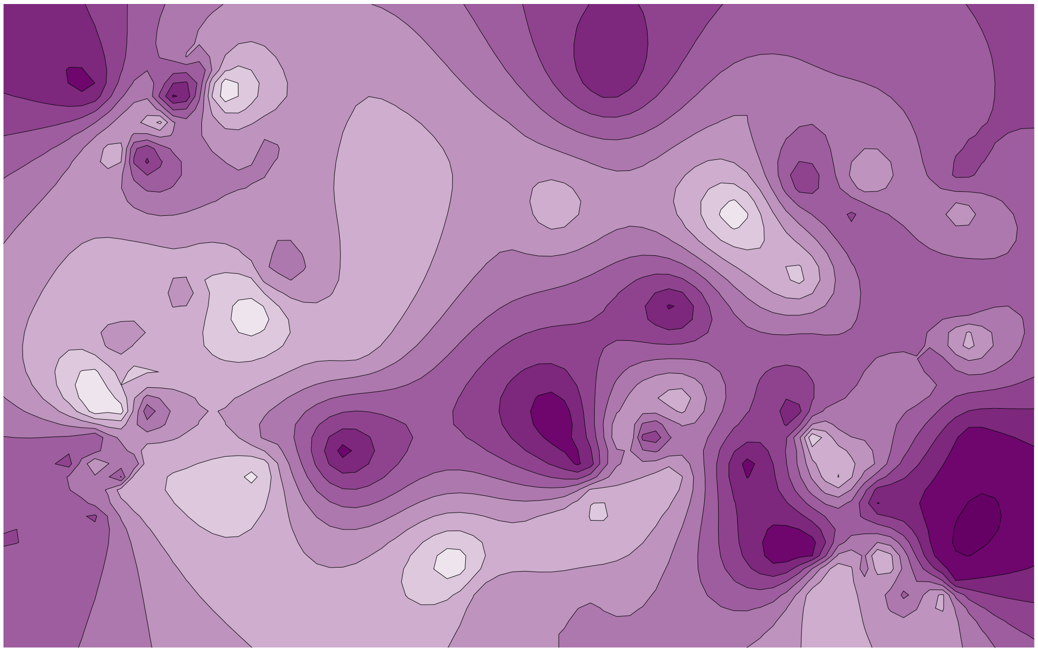


Figure 4 Distribution of Average Hydraulic Conductivity in the 680 to 700-Foot Layer
(Dark to Light Shading = Increase in K)

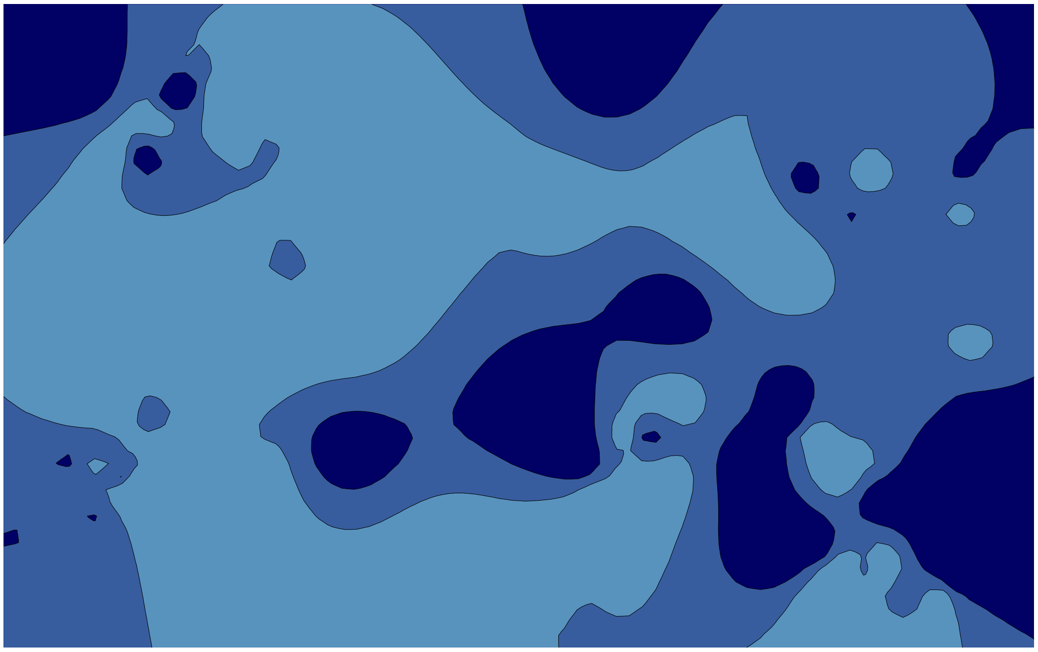


Figure 5 Hydrogeologic Units Based on Distribution of Average Hydraulic Conductivity
(Light = Aquifer Medium = Aquitard Dark = Aquiclude)

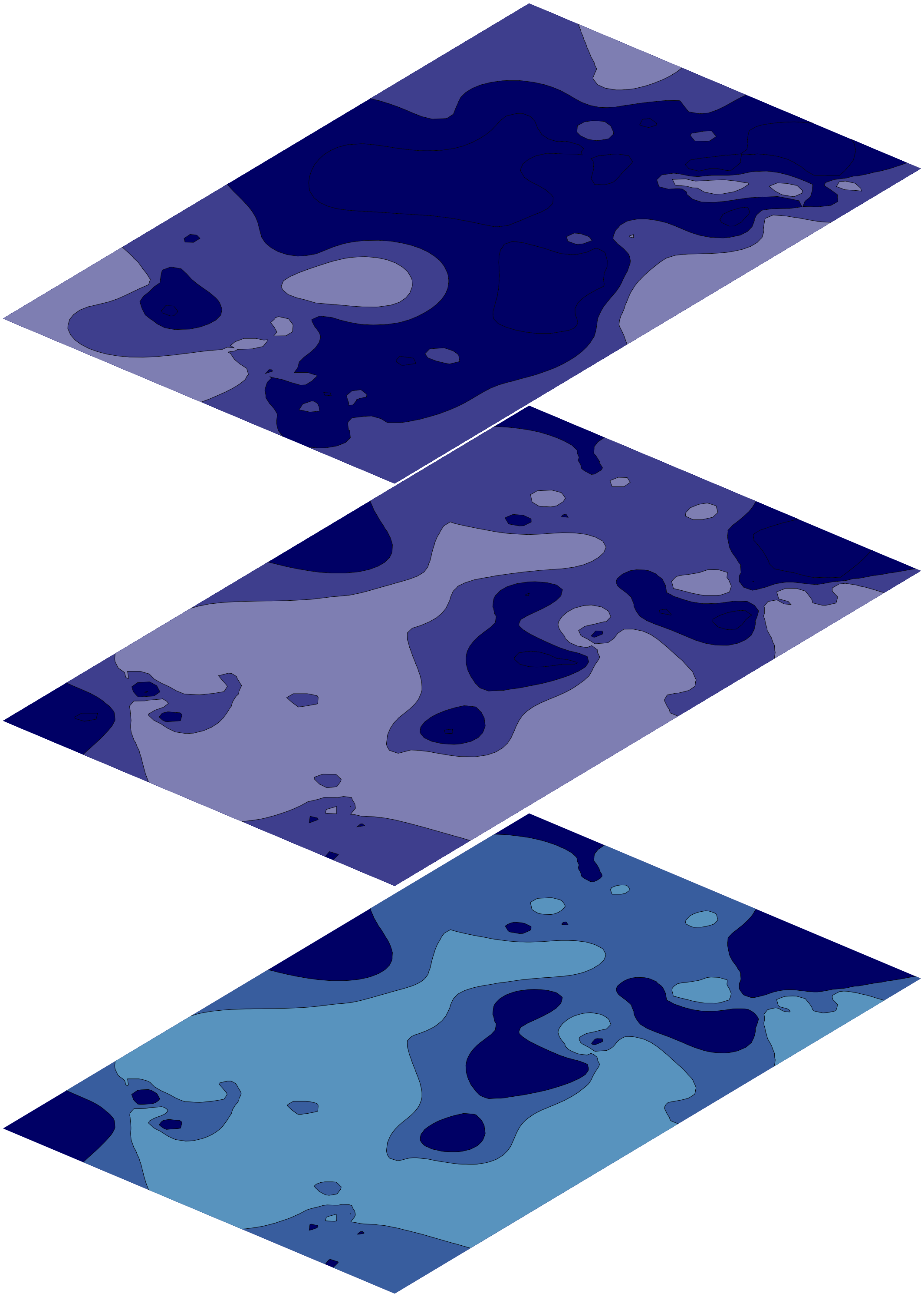


Figure 6 Partial Sub-Area Stack Unit Map
(From Top: 740 to 720 Feet; 720 to 700 Feet; 700 to 680 Feet

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