Evaluating Ground Water Supplies in Fractured Metamorphic Rock of the Blue Ridge Province in Northern Virginia

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More than 1000 controlled aquifer tests have been performed in the fractured metamorphic rock of the Blue Ridge Province in Loudoun County, Virginia to support groundwater supply development studies since 1987. Key findings of ongoing evaluation of relationships between well drilling results, drawdown patterns, fracture fabric mapping, lineament analysis, surface geophysical survey imaging, topography, and geologic mapping will be presented. Case studies will be used to illustrate success and failure using surface geophysical and lineament analysis methods to site high-yield wells.

Introduction

Loudoun County, which is located in northern Virginia approximately 30 miles west of Washington D.C., has been one of the fastest growing counties in the United States since the 1980s. In the western portion of the County, the primary source of water for municipal, commercial, and individual domestic water supplies is groundwater pumped from thousands of wells drilled into fractured metamorphic rock of the Blue Ridge Geologic Province.

A geologic map of Loudoun County is provided in Figure 1, and was recently revised by Southworth et al. (2006). The north-northeast trending Bull Run Fault separates the Blue Ridge Province to the west from the Culpeper Basin of the Piedmont Province to the east. The Blue Ridge Province is underlain by Mesoproterozoic to Early Cambrian rocks, which are part of the Blue Ridge anticlinorium, a large allochthonous fold apparently formed during the Alleghenian orogeny. The anticlinorium is cored by weakly to strongly foliated high-grade Mesoproterozoic granitic and nongranitic gneisses, which were deformed and metamorphosed during the Grenville orogeny. Nine granitic gneiss (metagranite) types, which compose more than 90 percent of the basement rock volumetrically, and three nongranitic basement units were mapped by Southworth et al. (2006). A cover sequence of Late Proterozoic to Early Cambrian metasedimentary and metavolcanic rocks unconformably overlies the basement gneisses along ridges where it has not been eroded. The metavolcanic rocks (primarily Catoctin Formation metabasalt) were fed by a northeast-trending swarm of tabular late Proterozoic metadiabase dikes that intruded the basement rocks during continental drifting. The cover rocks were later deformed and metamorphosed to greenschist facies during the Alleghenian orogeny.

Concern about the adequacy of available groundwater quantity and quality to meet the needs of the growing County led to the implementation of hydrogeologic testing requirements in 1987, development of an extensive wells database, and creation of an integrated water monitoring program. The current hydrogeologic testing requirements at residential subdivision sites underlain by the Blue Ridge rocks include drilling test wells on 50% of proposed lots, conducting controlled 8-hour aquifer tests with observation wells at each test well, performing detailed water quality analyses on groundwater samples from each

450 to 464

test well, and related data analysis and reporting. For proposed community water-supply systems, requirements include fracture fabric mapping (if outcrops are present), lineament analysis, performance of a surface geophysical survey to site wells, conduct of a minimum 72-hour aquifer test with observation wells, and related data analysis and reporting.

Findings regarding groundwater availability derived from examination of the Wells database, monitoring program results, high-yield well groundwater exploration studies, and investigations of aquifer anisotropy are presented herein.

Wells Database

The Loudoun County Departments of Public Health and Building and Development have created an extensive database of location, construction, and yield information for approximately 19,000 water wells in the County, including approximately 11,500 wells in the Blue Ridge Geologic Province (Figure 2) and 1,800 hydrogeologic study test wells in the Blue Ridge Province (Figure 3).

Statistical analyses were performed on the wells database as updated through August 2007 to evaluate differences in well yield characteristics as a function of host rock type, proximity to lineaments, proximity to streams, proximity to faults, and other factors. Wells data were attributed to specific bedrock units, and well distances to lineaments, streams, and faults were calculated using GIS methods. Yield data included in the County database are primarily based on 'air-lift' well discharge measurements made by drillers during well construction and are of variable accuracy. Prior analyses of water well characteristics in Loudoun County based on a smaller population of wells were made by Sutphin et al. (2000 and 2001).

A summary of water yield and depth data for 9302 water-supply wells located in the Blue Ridge of Loudoun County (with reported both yield and depth data) is provided in Table 1. Box and whiskers plots of reported well yields for different geologic units are presented in Figure 4. These plots illustrate the quartile distributions of yield for each unit and also show high-yield outliers and mean yield values. Well yield distribution curves for bedrock units in the study area are shown in Figures 5 and 6.

Overall, the well data show that yield distributions in the metagranites are similar and tend to be higher than yields in wells completed to the nongranitic Mesoproterozoic rocks and the Catoctin metabasalt, and much higher than rocks drilled into the Harpers Formation phyllite and metasiltstone. Approximately 5 to 10% of the wells are reported to yield less than one gallon per minute (gpm), which is the minimum acceptable yield for domestic wells based on Loudoun County standards. Less than 5% of the wells have very high yields (>50 gpm) desirable for community water-supply use. Given the cost of well drilling, this emphasizes the need to apply reasonable methods to increase the probability of drilling high-yield wells for community water-supply development.

Mean and median well depths in the Blue Ridge of Loudoun County have increased from approximately 300 to 500 feet between 1980 and 2007 (Figure 7). Well drillers generally continue drilling to greater depths until a satisfactory yield is achieved at a particular location. Thus, as shown in Figure 8, there is a negative (weak) correlation between well yield and well depth. Factors that have led to increasing well depth include: (1) increased willingness to pay for deeper wells with higher yields and more storage capacity, (2) improved deep drilling capability, and (3) recognition that acceptable domestic yields can be encountered at great depth (Figure 9). Another factor is that many deep wells were drilled as part of hydrogeologic studies conducted between 2002 and 2006 to avoid time delays associated with obtaining permits for replacement wells.

Monitoring Program

Loudoun County, in conjunction with the U. S. Geological Survey and the Virginia Department of Environment Quality, initiated an integrated Water Resource Monitoring Program (WRMP) in October 2002. A goal of the WRMP is to provide a scientific basis for making land use decisions that affect water resources. Currently, stream levels and flows are being monitored at ten stations, ground water levels are being recorded in 11 wells, and precipitation is recorded at a few stations (Figure 10). Ultimately, the County plans to establish a network of 20 to 30 monitoring wells.

Groundwater levels have been monitored in one well located in the Catoctin Formation on Short Hill Mountain since the 1960s (Figure 11) and in six other bedrock wells in the Blue Ridge Province. Review of these data show that: (1) hydraulic heads in bedrock fluctuate less than ten feet per year, (2) heads generally rise due to recharge in late Fall to early Spring and during heavy precipitation events at other times, and, (3) there is no evidence of a long-term hydraulic head trend at the monitored locations.

Streamflow has been monitored at stations on Goose Creek (Figure 12) and Catoctin Creek (Figure 13) since 1930 and 1971, respectively. Streamflow appears well-correlated with precipitation rate. It is difficult to discern any effect of groundwater pumping on streamflow rates at the gauged stations.

Streamflow data and watershed information have been used to estimate recharge rates in the Blue Ridge province (e.g., Rutledge and Mesko, 1996; Nelms et al., 1995). Calculations of recharge rate based on the streamflow recession curve displacement method using the U.S. Geological Survey RORA program (Rutledge, 1993, 1998, and 2003) were made for the periods between 1973 and 2006 for the Catoctin Creek watershed (Figure 14) and between 2002 and 2006 for seven smaller watershed areas in the Blue Ridge Province of Loudoun County (Figure 15). Estimated recharge rates are typically between 10 and 13 inches per year, but range from less than 5 inches per year to more than 20 inches per year during extended periods of drought and extreme precipitation, respectively. For the purpose of water budget and nitrates mixing calculations, Loudoun County stipulates the use of recharge rates of 10 and 6 inches per year, respectively, to represent normal and drought years. These rates greatly exceed net groundwater pumping rates associated with rural residential subdivisions where wastewater is dispersed via onsite septic drainfield systems on lots that exceed three acres each.

High-Yield Well Siting

Crystalline metamorphic bedrock in the Blue Ridge has essentially no primary porosity. Its capacity to store and transmit groundwater is highly dependent on the density and interconnectivity of secondary void spaces (primarily open fractures) present in the rock.

Fracture trace analysis (Parizek and Lattman, 1964), which is referred to herein without respect to linear feature length as lineament analysis, and surface geophysical surveys have been used to site high-yielding wells in fractured metamorphic rock with varied success at many sites in Loudoun County.

Review of prior studies on the relationship of well yields in crystalline metamorphic rock to lineaments and topographic setting reveal mixed findings. Yin and Brook (1992) performed a statistical analysis of well yields in crystalline bedrock of the Georgia Piedmont and Blue Ridge. They found that well yields in valleys and draws were generally higher than on hills, but also reported that their "findings suggest that locations for high-yield wells should be determined by fracture trace mapping rather than the 'lay of the land'." Studying well yields in metamorphic rocks on Georgetown Island, Maine, Mabee (1999) concluded that both topographic setting and proximity to lineaments influence well productivity. Luhrs (1993) and others have presented case studies showing highly successful results using lineament analysis to site wells in crystalline rock.

Studies showing that high well yields are not apparently correlated with proximity to lineaments were reported by Henriksen (2006) and Mabee et al. (2002). Henriksen (2006) studied the yields of 697 wells in metamorphic rock in Sunnfjord, Norway and found that wells near lineaments (<170 feet away) had lower yields than wells at greater distance, and that wells in valley bottoms had higher yields than wells in other topographic settings. Mabee et al. (2002) compared lineaments to groundwater inflow zones that were mapped in a 6 mile section of a 16-ft diameter tunnel constructed to an average depth of 230 feet in metamorphic rock in eastern Massachusetts. They found that: 15 of 35 coincident lineaments that crossed the tunnel correlated with mapped inflow zones, but that 20 lineaments did not correlate with inflow zones; 6 of the 19 mapped inflow zones did not correlate with any mapped lineament; 'fracture-supported' lineaments (those which parallel nearby surface fracture sets) do not necessarily improve the ability of lineaments to discriminate flow zones in bedrock; and it is difficult to distinguish lineaments that will be successful in predicting underlying water-bearing zones.

Lineament analysis has been performed in Loudoun County using a variety of imagery platforms, including black and white aerial photographs, color and color infrared aerial photographs, shaded-relief digital elevation maps (DEMs), and topographic contour maps. Using GIS methods, well distances to lineaments mapped based on a shaded-relief DEM and 5-ft topographic contours in western Loudoun County were calculated to examine the relationship between well yield and topographic lineaments. Well yield distribution curves for wells located less than 100 feet, 100 to 300 feet, and greater than 300 feet from a lineament shown in Figure 16 suggest that lineament analysis is helpful for siting high yield wells. Well yield distribution curves plotted based on lineament strike for wells located within 300 feet of a lineament show no obvious correlation of higher yields and lineament orientation (Figure 17). Similarly, no clear relationship is evident between well yield and distance from a geologic fault (Figure 18). Finally, as expected, well yield distribution curves for wells located close to a floodplain (Figure 19) reveal a pattern similar to that shown in Figure 17 and suggest that siting high yield wells can benefit from both lineament analysis and 'lay-of-the-land' methods. However, it is apparent that most wells sited near lineaments and/or floodplains in the Blue Ridge of Loudoun County will have low to moderate yields (<20 gpm).

An extensive comparative study was performed to examine the efficacy of several geophysical investigation methods to characterize fractured bedrock aquifers and identify major water-bearing fracture zones in New Hampshire by the U.S. Geological Survey (Degnan et al., 2001). Surface methods examined included seismic refraction, ground-penetrating radar, magnetics, very low frequency (VLF) electromagnetics (EM), inductive EM terrain conductivity, two-dimensional direct-current (dc) resistivity, and azimuthal-square array dc resistivity. Of these methods, analysis of the 2-D resistivity surveys provided the most quantitative information on fracture-zone location and dip direction (Degnan et al., 2001).

Experience in Loudoun County is consistent with the findings of Degnan et al. (2001). Electrical resistivity profile imaging using automatic electrode switching systems has been used with success to select drilling locations for community water-supply wells in fractured metamorphic rock at many sites in western Loudoun County. Typically 2-D resistivity profile imaging is performed using an automated electrode switching system (e.g., AGI's Sting/Swift system) and a dipole-dipole array with 6 to 10 meter electrode spacings. Data are processed using the RES2DINV program (Loke, 1997). High-yield bedrock fracture zones are inferred by low resistance anomalies (<400 ohm meters).

An example of varied success achieved using lineament analysis and electrical resistivity surveying is shown in Figure 20 and 21. Wells 2 and P were sited near a lineament intersection and on a single prominent lineament, respectively. Very high yields were obtained in both wells. Wells A and K, however, which were also located near the intersection of two prominent lineaments, had very low yields. Well L was drilled on a low resistance anomaly and encountered high-yield fractures at depth. Curiously, the resistivity profile suggests tight rock at the location of Well R, which also proved to be a high-yield well. Experience indicates that lineament analysis and electrical resistivity survey work are cost-effective (but not always successful) methods for siting high-yield wells in the fractured metamorphic rocks of the Blue Ridge Province.

Investigation of Anisotropy

It has been hypothesized (e.g., Drew et al., 2004) that the most dominant and pervasive fracture fabric features, which control ground water flow in the Blue Ridge of Loudoun County include (1) the pervasive northeast-striking, moderately to steeply dipping (generally to the southeast) metadiabase dikes that intrude the older metagranites, and (2) subparallel northeast-trending Paleozoic cleavage (schistosity). Northwest-trending foliation in the Mesoproterozoic basement rock, which was overprinted by dike intrusion and Paleozoic cleavage, is also observed in much of western Loudoun County. A block diagram showing idealized geologic structures in the Blue Ridge is shown in Figure 22.

Drew et al. (2004) prepared two-dimensional variogram maps using the Variowin software (Pannatier, 1996) to process well yields and infer geologic structure anisotropy in four areas within the Blue Ridge of Loudoun County. Prior to Variowin analysis, a field geologist predicted structural trends (by creating block diagrams) affecting ground water flow and well yields in several areas of the Blue Ridge, and prepared rose diagrams of photolineament fracture traces to support each prediction. Two-dimensional variogram maps were then computed and compared to the geologist's predictions. In general, predictions made by the geologist were consistent with the variogram analysis of the water well yield data. The results suggested anisotropic trends of bedrock structure to the north-northeast and north-northwest in four areas studied, with differences between areas.

Thousands of additional wells have been added to the version of the County wells database used by Drew et al. (2004). For example, the numbers of wells available for statistical analysis increased from 165 to 308 wells and from 247 wells to 536 wells in Areas 1 and 2 of their study, respectively. Using the expanded wells database, we prepared two-dimensional variogram maps using Variowin of the four areas examined by Drew et al. (2004). Our results were only partially consistent with the findings of the earlier study. In Area 1 (Figure 23), we found a predominant north-northeast yield trend compared to the more easterly north-northeast trend discerned in the prior study. In Area 2, we found no discernible anisotropic trend, whereas Drew et al. (2004) identified weak northeast and northwest trends. In Area 3, we discerned very faint north-northeast and northwest trends which compared to the well-defined north-northeast trend identified in the prior study. As noted by Drew et al. (2004), variography results can suggest the underlying geologic structure in areas with many water wells but little rock outcrop.

In order to examine aquifer anisotropy in a more direct manner, automated water-level recording devices were deployed in numerous observation wells during aquifer tests conducted at seven sites in the Blue Ridge of Loudoun County, and time-drawdown data acquired during 22 aquifer tests where drawdown was observed at three or more observations wells were analyzed using the Papadopulous (1965) equation for nonsteady ground water flow in an infinite anisotropic confined aquifer as implemented in the TENSOR2D (Maslia and Randolph, 1987) and AQTESOLV (beta version, Duffield, 2007) computer programs. As shown in Figures 24 and 25, although the parameter estimates from TENSOR2D and AQTESOLV are somewhat close, the solution using AQTESOLV provides a much better fit of observed and simulated drawdown at each well. Thus, results shown for the analyses of 15 tests where the data reasonably fit an anisotropic solution are presented based on the AQTESOLV analysis in Figure 26 and Table 3.

Results of the anisotropic aquifer analyses indicate that different tensor orientations are observed in different areas of 100 to 250 acre study sites and that observed anisotropy is not always consistent with mapped geologic structural features. Interpreted tensor orientations vary between N70E and N79W. Nine of the 15 orientations are between N5E and N38W.

Conclusion

Extensive hydrogeologic investigation in the Blue Ridge of northern Virginia confirms that the fractured metamorphic bedrock is very complex. Adequate ground water supply is generally available to support rural residential use. High-yield well development for community and commercial water supplies, however, presents greater challenges related to siting and potential drawdown impacts. Bedrock fracture complexity emphasizes the need for extensive monitoring to determine the impacts of high-rate pumping. Given the extensive hydrologic data compiled for Loudoun County, understanding of the hydrogeologic system would benefit from detailed quantitative and conceptual analyses using a numerical model.

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Robert Cohen is a hydrogeologist with GeoTrans, Inc. in Sterling VA where he has worked since graduating from Penn State with a MS in 1982. Charles Faust is President of GeoTrans, Inc. Since leaving the USGS to co-found GeoTrans with James Mercer, Charlie has been involved in a variety of groundwater modeling, contamination, remediation, and water-supply projects. Dave Skipp has been a hydrogeologist with GeoTrans since 1988. He has more than 22 years of experience in hydrogeology, numerical modeling of groundwater flow and transport, site investigation, groundwater system management, aquifer test evaluation, saltwater intrusion analysis, jazz bass, and groundwater supply development.

Table 1. Geologic map units and water well yield and depth statistics for the Blue Ridge Province of Loudoun County, VA.

Map Unit	*Rock Unit*	*Area (mi^2)*	*# Wells*	*Mean Yield (gpm)*	*Median Yield (gpm)*	*Yield Range (gpm)*	*Mean Depth (feet)*	*Median Depth (feet)*	*Depth Range (feet)*	*Mean Yield per foot (gpm)*
Cover rocks										
Lower Cambrian:										
Ct	Tomstown dolomite	0.2	6	3.2	1.8	0.5 to 9	667	650	360 to 900	4.8E-03
Ccp	Carbonaceous phyllite	0.2	26	20.9	7.5	0 to 150	415	400	77 to 1200	5.0E-02
Ca	Antietam quartzite	0.6	31	17.0	8.0	0 to 80	387	400	150 to 700	4.4E-02
Ch	Harpers Fm phyllite and metasiltstone	6.1	217	7.9	4.0	0 to 50	537	500	80 to 1300	1.5E-02
Cw	Weverton Fm quartzite	11.7	77	14.8	7.5	0 to 250	437	400	75 to 1000	3.4E-02
Cl	Loudoun phyllite	1.2	4	13.8	14.5	1 to 25	435	400	240 to 700	3.2E-02
Late Proterozoic:										
Zc	Catoctin Fm metabasalt	73.7	1798	14.7	8.0	0 to 500	444	420	85 to 1200	3.3E-02
Zcr	Catoctin Fm metatuff	0.3	13	13.8	12.0	0 to 50	391	380	125 to 800	3.5E-02
Zcp	Catoctin Fm quartz muscovite phyllite	2.9	40	28.7	15.0	1 to 200	372	340	85 to 850	7.7E-02
Zcm	Catoctin Fm marble	0.8	6	20.1	17.5	0.5 to 50	335	280	160 to 600	6.0E-02
Zsp	Swift Run Fm marble, slate, and phyllite	3.5	138	20.4	10.0	0 to 151	358	300	75 to 865	5.7E-02
Zss	Swift Run Fm metagraywacke	3.2	101	21.7	10.0	0 to 246	358	300	75 to 925	6.1E-02
Zfa	Fauquier Fm meta-arkose	2.5	20	13.4	6.0	0 to 75	463	500	180 to 905	2.9E-02
Zfs	Fauquier Fm metamudstone	0.8	9	16.9	12.0	0 to 50	332	305	125 to 500	5.1E-02
Basement rocks										
Late Proterozoic:										
Zmd	Metadiabase dikes	19.3	602	16.4	8.5	0 to 553	422	400	85 to 1320	3.9E-02
Zrd	Metarhyolite dikes	0.5	24	17.1	7.0	0 to 100	357	360	100 to 600	4.8E-02
Zrr	Robertson River Suite granite	1.4	2	18.5	6.5	12 to 25	133	133	120 to 145	1.4E-01
Middle Proterozoic:										
Yg	Leucocratic metagranite	14.9	621	14.0	8.0	0 to 216	413	400	80 to 1100	3.4E-02
Ygt	Garnetiferous metagranite	40.3	1620	17.0	10.0	0 to 650	398	360	80 to 1200	4.3E-02
Ybg	Biotite granite gneiss	4.7	199	15.0	6.0	0 to 200	470	450	120 to 1300	3.2E-02
Ymb	Biotitic Marshall metagranite	56.4	1951	18.3	10.0	0 to 432	414	385	80 to 1300	4.4E-02
Ymc	Coarse-grained Marshall metagranite	8.0	320	21.2	12.0	0 to 160	374	340	105 to 1000	5.7E-02
Yml	Pink leucocratic gneiss	10.6	297	20.3	12.0	0 to 150	397	340	100 to 1080	5.1E-02
Yhm	Hornblende monzogranite gneiss	16.9	503	16.3	10.0	0 to 230	390	340	80 to 1320	4.2E-02
Ylg	Layered granite gneiss	19.2	258	18.3	10.5	0 to 200	403	360	100 to 920	4.6E-02
Ypg	Porphyroblastic granite gneiss	10.4	197	13.0	8.0	0 to 110	458	400	100 to 1040	2.8E-02
Yc	Charnockite	1.8	67	13.9	8.0	0 to 102	482	403	140 to 1000	2.9E-02
Yn	Metanorite	2.4	74	12.2	5.3	0 to 130	457	415	100 to 1180	2.7E-02
Yp	Paragneiss	2.7	81	13.4	8.0	0 to 100	430	400	100 to 900	3.1E-02
Total		318.6	9302	16.5	10.0	0 to 650	418	400	75 to 1320	4.0E-02

Table 2. Incremental time mean and median yield and depth statistics for 9903 wells drilled in the Blue Ridge geologic province of Loudoun County, Virginia (465 wells per increment, except for 467 in last increment).

Drilling Increment	Time Range		Duration (days)	Mean Yield (gpm)	Median Yield (gpm)	Mean Well Depth (feet)	Median Well Depth (feet)	Mean Yield per Foot (gpm)	Median Yield per Foot (gpm)
1	8/10/1963	1/26/1982	6744	14.17	9.9	265	225	0.053	0.044
2	1/26/1982	6/3/1986	1589	13.95	8.0	318	305	0.044	0.026
3	6/3/1986	2/19/1988	626	15.62	10.0	365	325	0.043	0.031
4	2/19/1988	6/1/1989	468	20.46	8.0	374	345	0.055	0.023
5	6/1/1989	10/25/1990	511	15.68	8.0	401	390	0.039	0.021
6	10/26/1990	6/1/1993	949	16.26	8.0	388	360	0.042	0.022
7	6/1/1993	6/1/1995	730	15.53	8.0	400	370	0.039	0.022
8	6/1/1995	7/10/1997	770	17.64	10.0	388	360	0.045	0.028
9	7/11/1997	10/27/1998	473	16.33	10.0	413	400	0.040	0.025
10	10/28/1998	10/29/1999	366	17.00	8.0	415	400	0.041	0.020
11	10/29/1999	8/3/2000	279	16.58	10.0	406	380	0.041	0.026
12	8/4/2000	2/5/2001	185	15.89	10.0	414	400	0.038	0.025
13	2/6/2001	9/11/2001	217	16.80	8.0	457	420	0.037	0.019
14	9/11/2001	8/2/2002	325	16.11	8.0	478	500	0.034	0.016
15	8/3/2002	10/29/2003	452	16.93	10.0	493	480	0.034	0.021
16	11/3/2003	9/10/2004	312	21.47	12.0	460	420	0.047	0.029
17	9/13/2004	6/20/2005	280	17.08	10.0	493	460	0.035	0.022
18	6/21/2005	1/16/2006	209	16.55	8.0	458	420	0.036	0.019
19	1/16/2006	4/18/2006	92	14.30	10.0	457	400	0.031	0.025
20	4/18/2006	6/20/2007	428	16.37	8.0	518	500	0.032	0.016

Table 3. Preliminary Summary of Anisotropic Aquifer Test Analyses in Loudoun County Using the Papadopulous (1965) method in TENSOR2D and AQTESOLV.

					Tensor2D Results								Aqtesolv Results								
Site	PW	Test Date	Pump Rate (gpm)	Hrs	#OW	# OWs Used	Angle	Tmax	Tmin	ratio	S	OWs omitted	#OW	#Used	Angle	Tmax	Tmin	ratio	S	OWs omitted	Fit*
HF	HF2	7/16/01	293.0	50	5	4	66	8.83E+02	1.87E+02	4.7	4.22E-05	OK-5	5	4	42.62	5.01E+02	2.65E+02	1.9	5.64E-05	OK-5	G
RM	RM3	3/20/06	57.4	96	7	7	106	2.36E+03	4.82E+02	4.9	1.42E-04	none	7	7	171.70	7.30E+03	2.41E+01	302.5	1.28E-05	none	P
HH	HUN5	2/7/05	45.0	24	7	6	153	4.74E+03	1.14E+02	41.6	1.62E-03	Wilt	7	5	168.30	8.35E+02	1.51E+00	551.3	5.33E-05	Wilt, 2B	F
HH	HUN5	2/7/05	45.0	24									7	3	165.60	1.84E+02	9.42E+00	19.5	1.02E-04		F
AF	AF5	4/13/06	2.5	8	3	3	91	1.28E+02	3.24E+00	39.0	2.43E-05	none									
AF	AF9	4/17/06	2.5	8	4	4	129	2.06E+02	8.31E+01	2.5	2.33E-05	none									
AF	AF11	4/14/06	6.0	8	5	5	79	5.91E+02	7.17E+01	8.2	4.72E-05	none	5	5	85.69	1.87E+03	2.73E+01	68.6	1.80E-05	none	P
AF	AF11	4/14/06	6.0	8									5	3	138.80	7.52E+02	3.43E+00	219.2	3.17E-06	15, 21	P
AF	AF19	4/7/06	6.0	8	3	3	131	3.96E+02	1.56E+02	2.5	3.98E-05	none	3	3	168.80	1.65E+02	6.73E+01	2.4	3.47E-05	none	G
AF	AF29	4/13/06	15.0	8	4	4	NC	NC	NC	NC	NC	NC	4	4	126.00	2.48E+02	7.76E+01	3.2	3.71E-05	visual	G
AF	AF31	4/19/06	2.5	8	6	6	92	1.60E+02	4.50E+01	3.6	1.96E-05	none	6	6	94.06	1.35E+02	6.08E+01	2.2	4.01E-05	none	F
JH	JH10	3/7/07	9.0	8	3	3	77	1.58E+02	1.46E+01	10.8	5.34E-05	none	3	3	115.40	1.38E+02	9.12E+00	15.1	6.59E-05	none	F
JH	JH24a	2/8/07	3.0	8	4	3	124	9.67E+01	2.32E+01	4.2	8.00E-05	JH25	4	3	117.70	9.54E+01	2.69E+01	3.5	9.17E-05	JH25	G
JH	JH24b	2/8/07	3.0	8	4	3	137	3.56E+02	8.43E+00	42.2	2.59E-05	JH22	4	4	127.80	2.21E+02	1.05E+01	21.0	4.16E-05	none	G
JH	JH25	2/15/07	1.5	8	4	3	40	1.01E+02	2.85E+01	3.5	6.87E-05	JH24	4	3	53.46	1.17E+02	3.70E+01	3.2	5.32E-05	JH24	G
JH	JH25	2/15/07	1.5	8	4	4	NC	NC	NC	NC	NC	none	4	4	55.51	5.29E+01	3.75E+01	1.4	6.00E-05	none	G
GF	GF10	11/3/05	4.0	8	4	3	107	9.13E+01	8.73E-01	104.5	2.08E-05	GF11	4	3	97.94	3.07E+02	1.44E+00	213.0	1.81E-05	GF11	F
GF	GF10	11/3/05	4.0	8	4	4	NC	NC	NC	NC	NC	none	4	4	100.30	1.13E+02	2.02E+00	55.9	3.10E-05	none	F
GF	GF69	11/10/05	13.0	8	4	3	41	8.93E+02	6.05E+01	14.8	1.42E-04	GF59	4	3	34.56	9.68E+02	1.89E+01	51.2	1.06E-04	GF59	G
GF	GF69	11/10/05	13.0	8	4	4	NC	NC	NC	NC	NC	none	4	4	37.76	4.61E+02	2.63E+01	17.5	1.60E-04	none	G
BF	BF14	11/15/05	6.0	8	3	3	1	2.27E+02	5.07E+01	4.5	4.27E-05	none	3	3	20.40	1.58E+02	6.87E+01	2.3	3.92E-05	none	G
L	L7	2/27/06	5.5	8	4	4	106	1.09E+03	2.28E+01	47.6	7.69E-05	none	4	4	84.86	9.67E+01	3.70E+00	26.2	3.16E-05	none	F
L	L9	3/13/06	7.0	8	7	7	36	7.95E+01	5.82E+01	1.4	8.49E-05	none	7	7	125.90	4.95E+01	3.05E+01	1.6	3.42E-05	none	F
L	L9	3/13/06	7.0	8	7	5	125	6.03E+01	3.76E+01	1.6	3.63E-05	13, 19	7	5	102.50	4.98E+01	1.24E+01	4.0	3.51E-05	13, 19	F
L	L21	3/8/06	8.0	8	8	8	85	3.21E+02	4.83E+01	6.6	6.50E-05	none	8	8	178.40	9.27E+01	9.27E+01	1.0	4.65E-05	none	P
L	L23	3/7/06	5.0	8	8	8	90	6.28E+02	4.49E+01	14.0	9.57E-05	none	8	8	104.80	1.75E+03	2.43E+00	720.5	1.54E-05	none	G
L	L29	3/3/06	10.0	8	4	4	108	4.03E+02	6.28E+01	6.4	1.39E-04	none	4	4	97.66	3.86E+02	3.41E+01	11.3	1.37E-04	none	F
L	L37	3/20/06	15.0	8	4	4	124	3.59E+02	1.06E+02	3.4	2.07E-04	none	4	4	118.10	2.81E+02	1.16E+02	2.4	2.18E-04	none	F

*Fit is based on initial visual assessment of match between time-drawdown data derived using Tensor2D and Aqtesolve best-fit matching routines.

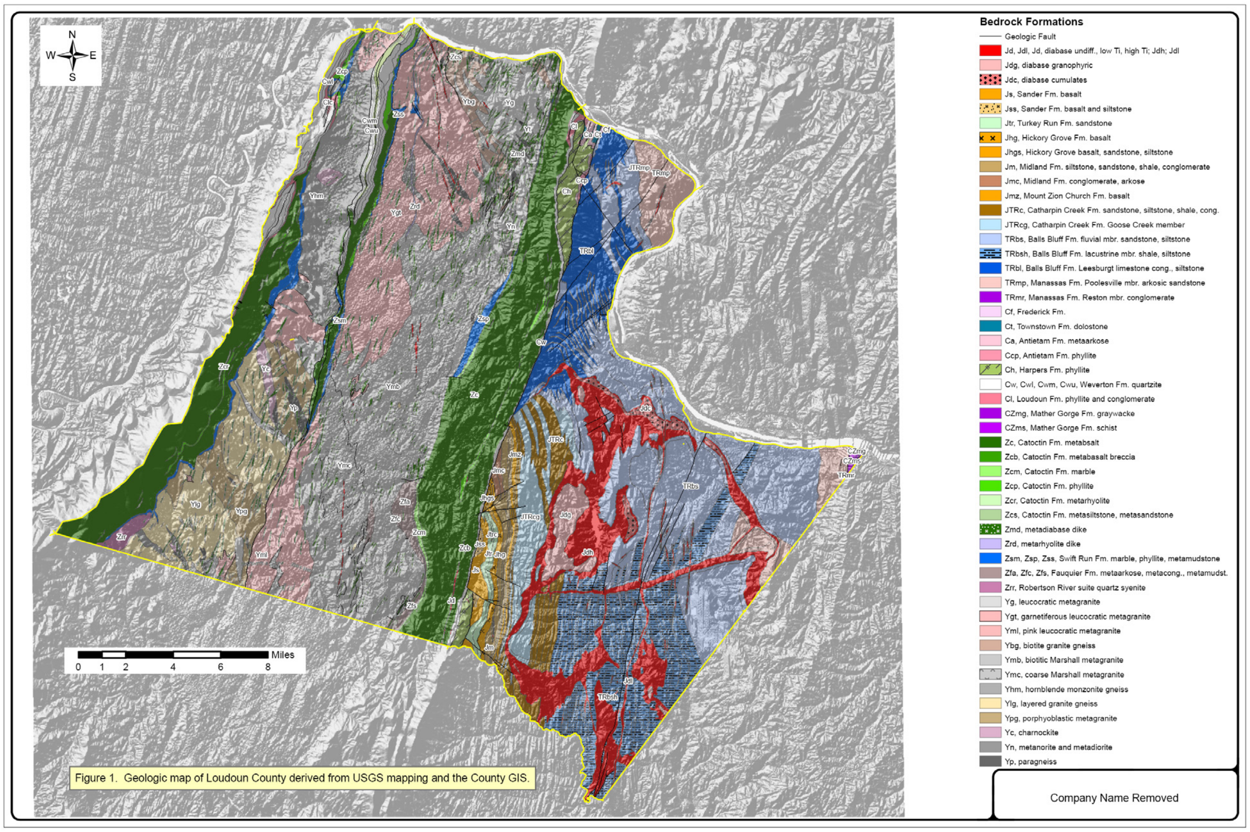


Figure 1. Geologic map of Loudoun County derived from USGS mapping and the County GIS.

Figure 1

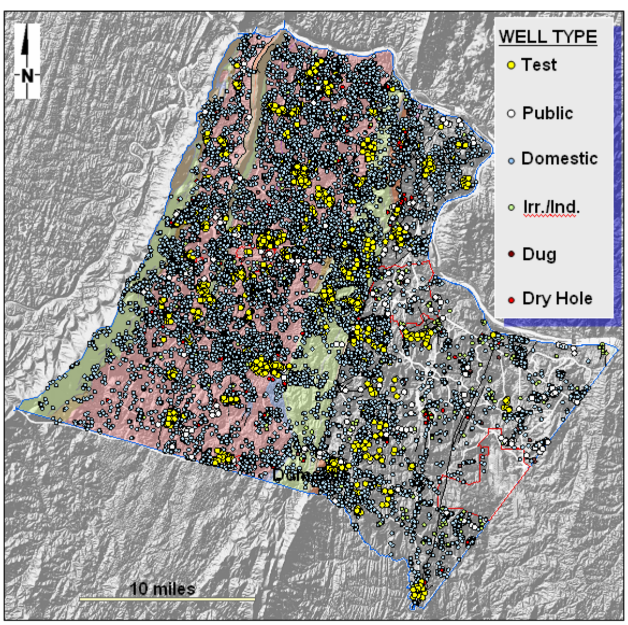


Figure 2. Locations of ~19,000 wells in Loudoun County circa 2007, including ~ 11,500 wells in the Blue Ridge Province.

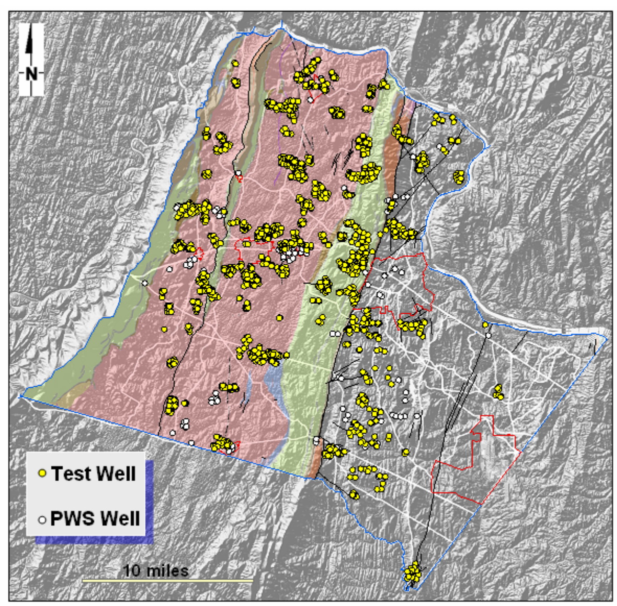
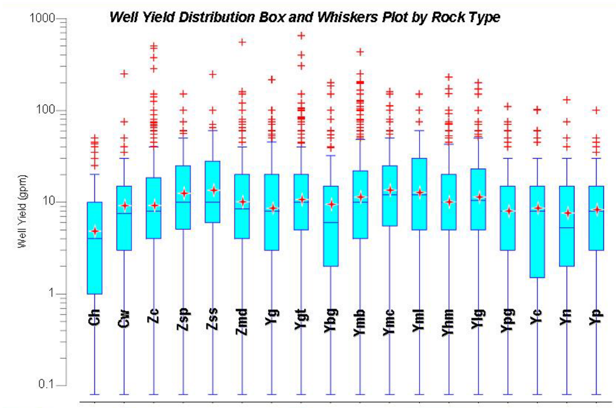


Figure 3. Hydrogeologic study test wells and public water supply wells in Loudoun County circa 2006, including ~1,800 test wells drilled in the Blue Ridge Province.



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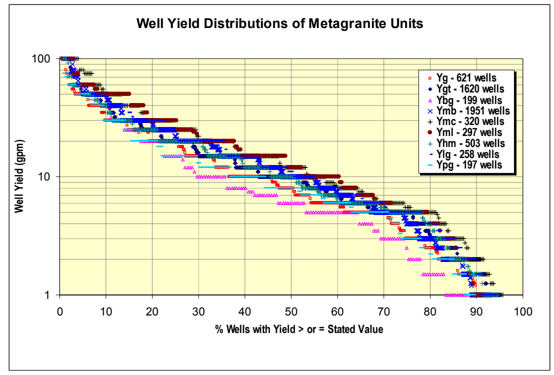

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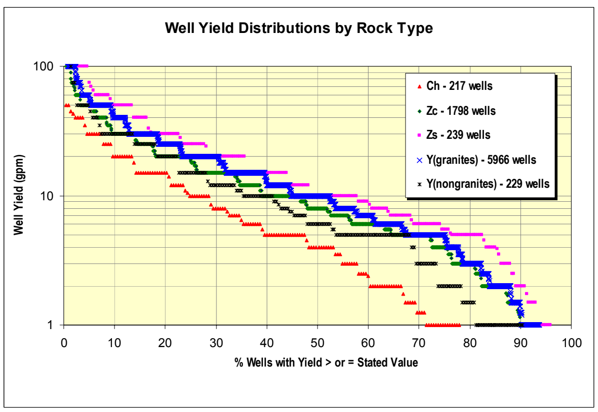

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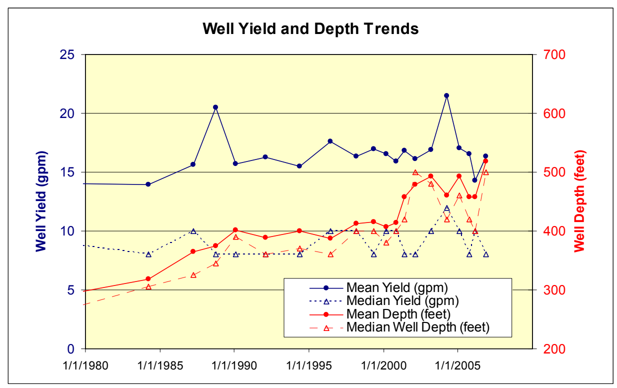

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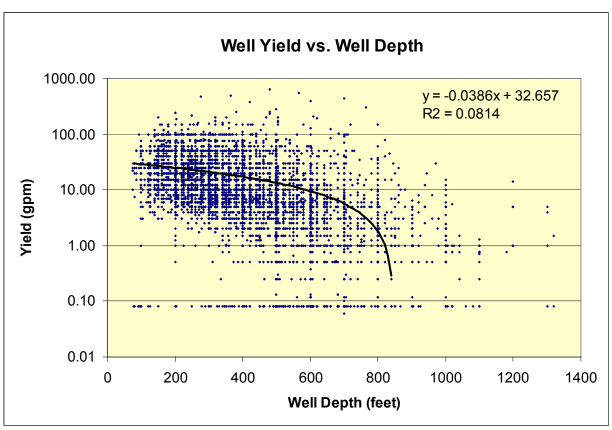

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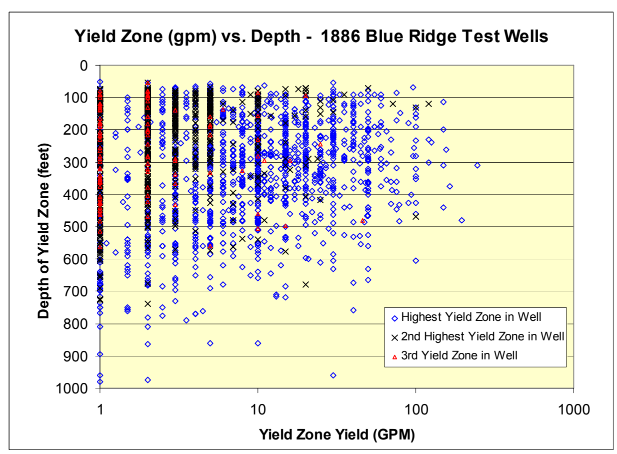

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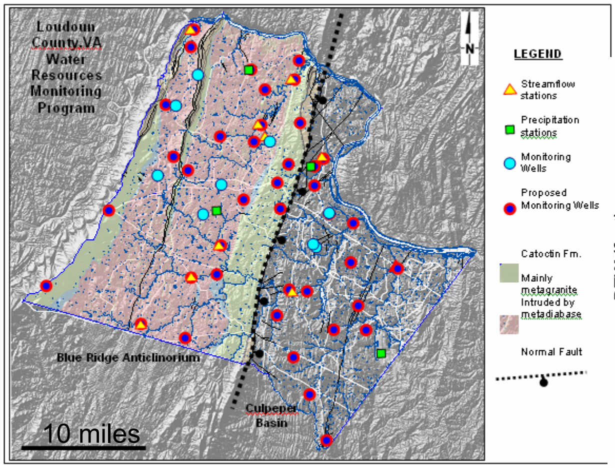

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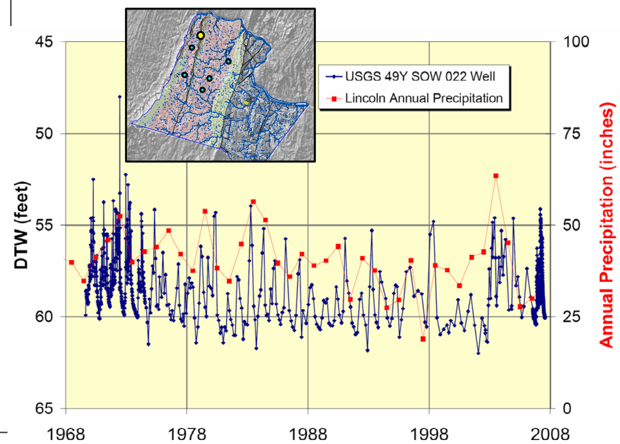

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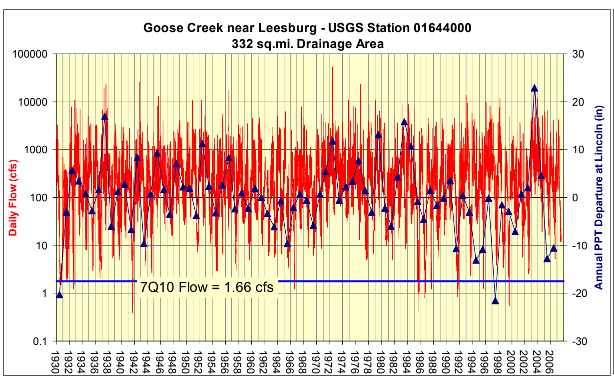

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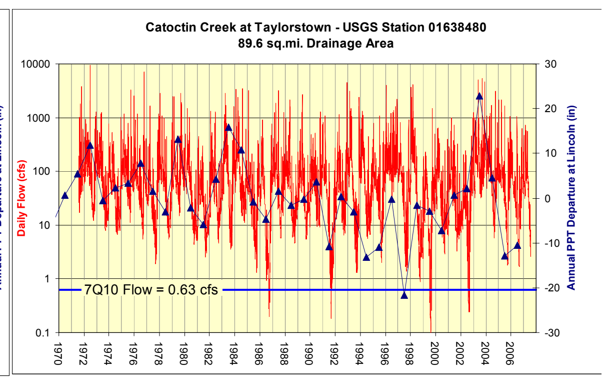

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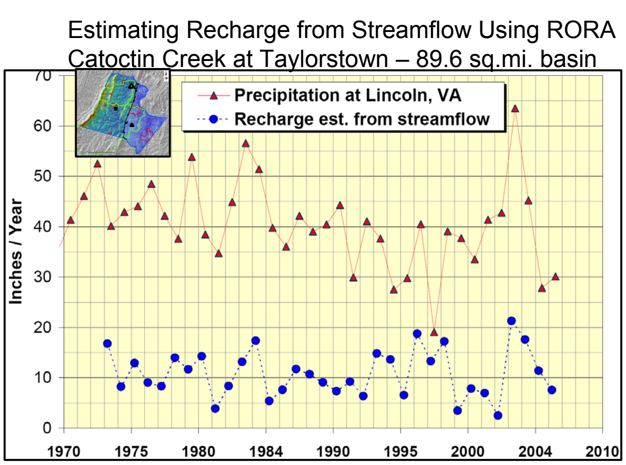

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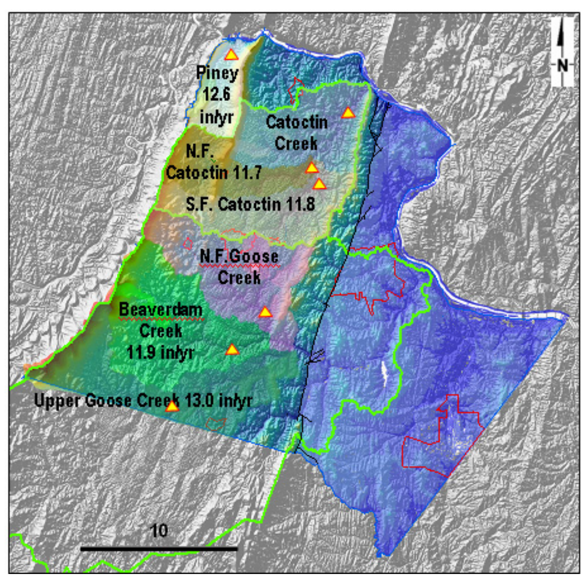

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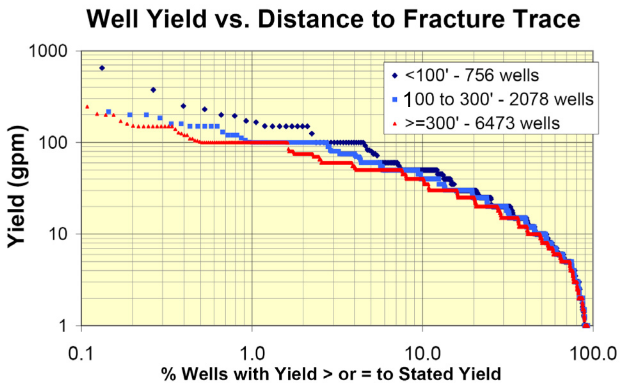

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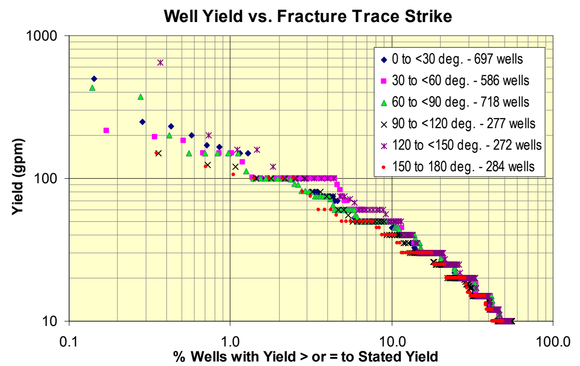

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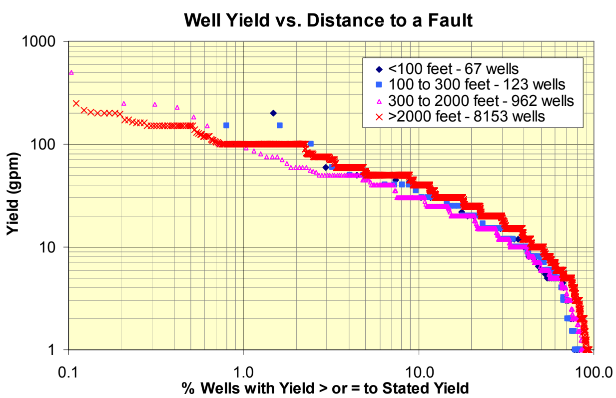

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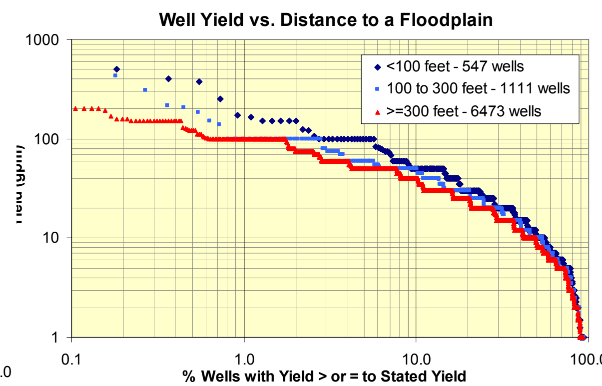

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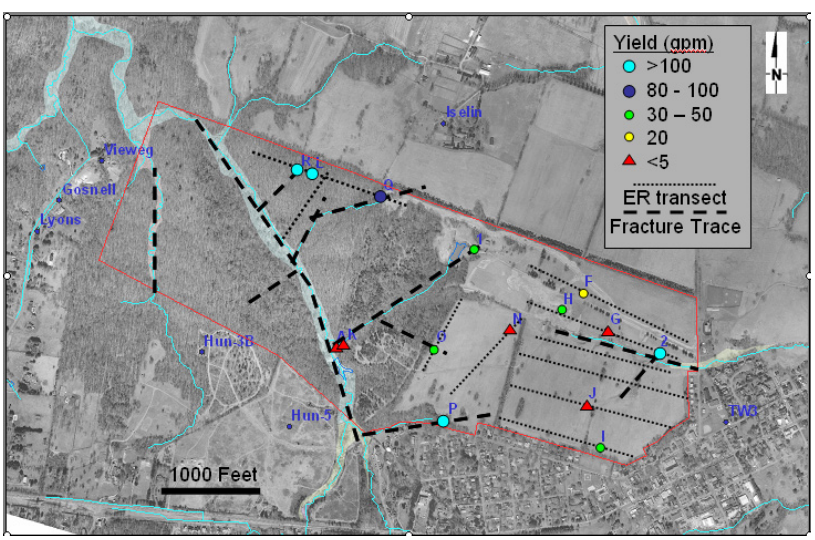
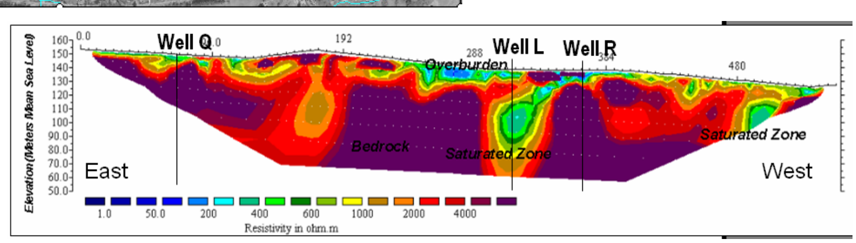
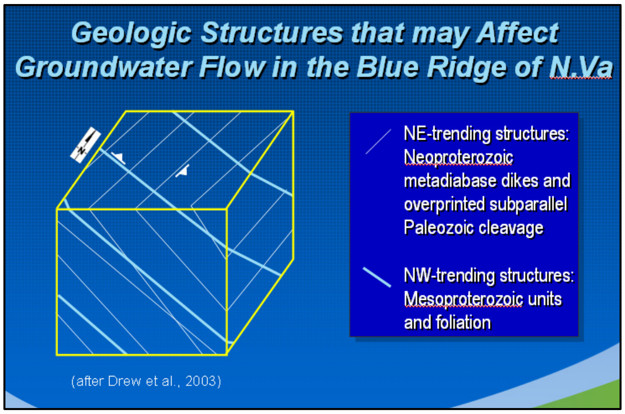


Figure20.

Figure21.





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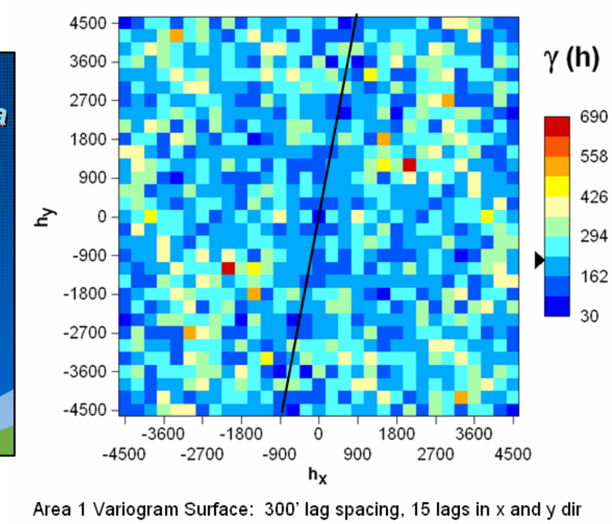

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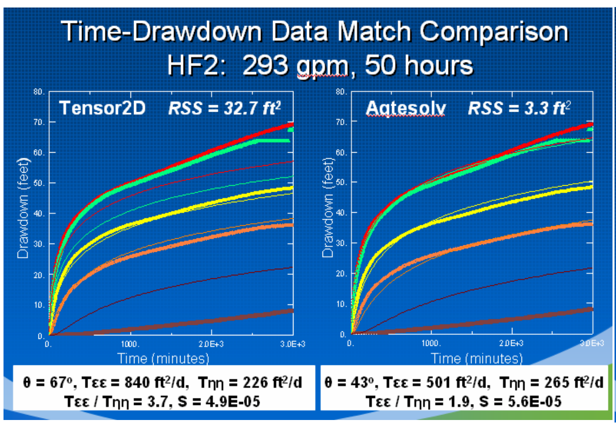

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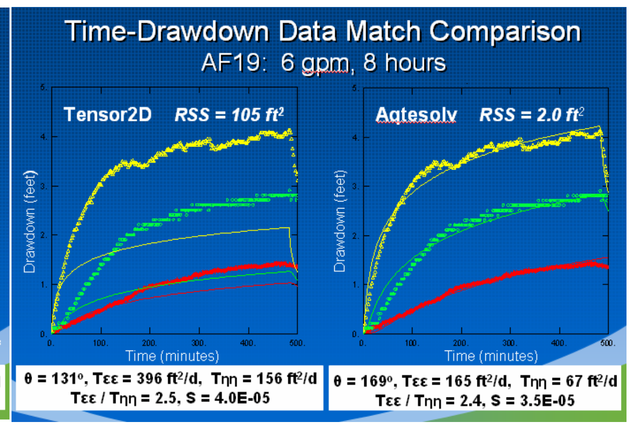

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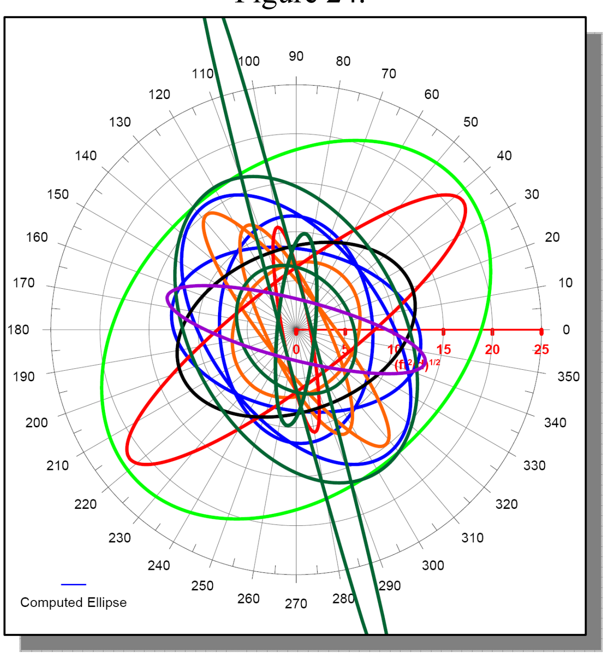

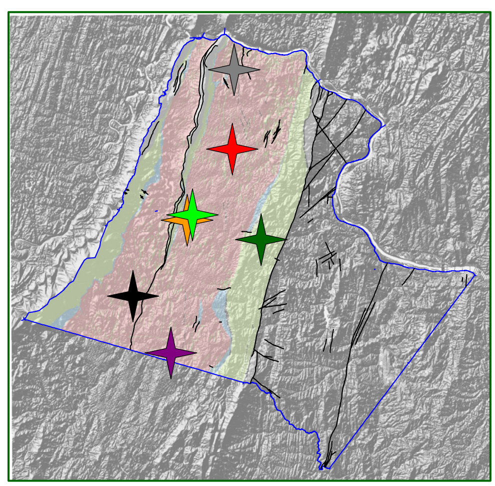

Figure 26. Composite of anisotropic transmissivity tensor [(ft²/d)^0.5] results for 15 aquifer tests at 7 sites.