Maryland Department of the Environment

Water and Science Administration

Water Supply Program

Gregory Busch, Manager

# INTERFERENCE IMPACTS CAUSED BY GROUNDWATER WITHDRAWALS FROM PUBLIC SUPPLY WELLS IN THE CRYSTALLINE ROCK AQUIFERS OF CENTRAL MARYLAND

by

Patrick A. Hammond

**2022**

# CONTENTS

## ILLUSTRATIONS

**Figure**

**Table**

## CONVERSION FACTORS AND SYMBOLS

| Multiply | by | to obtain |
|---|---|---|
| *Length* | | |
| inch (in) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| *Area* | | |
| square foot ($ft^2$) | 0.0929 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.59 | square kilometer ($km^2$) |
| *Volume* | | |
| gallon (gal) | 3.785 | liter (l) |
| *Discharge Rate* | | |
| gallon per minute (gpm) | 3.785 | liter per minute (l/min) |
| *Production Rate* | | |
| gallon per day (gpd) | $3.785 \times 10^{-3}$ | cubic meter per day ($m^3/d$) |
| *Transmissivity* | | |
| gallon per day per foot (gal/d-ft) | 0.0124 | square meter per day ($m^2/d$) |

Annual average use gallons per day = gallons per day average (gpd avg)
Use during the month of maximum use =-gallons per day maximum (gpd max)

Use of notation: As close as possible, the original scientific or mathematical notations of any papers discussed have been retained, in case a reader wishes to review those studies.

# HYDROLOGICAL IMPACTS CAUSED BY GROUNDWATER WITHDRAWALS FROM PUBLIC SUPPLY WELLS IN THE CRYSTALLINE ROCK AQUIFERS OF CENTRAL MARYLAND

by
Patrick A. Hammond

## KEY RESULTS

The few published investigations of potential impacts of withdrawals in fractured rock aquifers are related to nearly horizontal, bedding plane, controlled groundwater flow or an exceptionally high yielding well field in a semi-confined limestone aquifer. As such, there are no comparable aquifers in the crystalline rock areas of Maryland. The few crystalline rock aquifer impacts that have occurred in Maryland were due to withdrawals from Myersville (four domestic wells with declining yields) and Middletown public supply wells (one domestic well and a lawn irrigation well with declining yields, and two other domestic wells with high turbidity levels). Impacts (three domestic wells with declining yields) also occurred during aquifer testing at the Waterside community of a proposed public supply well that was never placed in service. An investigation of reports of declining yields or increased turbidity in domestic wells at the Maplecrest community indicated that those problems were not related to withdrawals from the nearby Westminster Votech well. A ¼ fracture length (¼ L) model was developed from data collected during aquifer testing and monitoring at the Myersville Water Treatment Plant (WTP) well site. This simple analytical technique assumes an effective well radius (equal to ¼ fracture length), instead of the actual well radius, to calculate drawdowns in pumping wells. The heterogeneity of an aquifer is estimated by assigning higher storage and transmissivity values to the weathered zone relative to the bedrock portion of an aquifer to calculate drawdowns in shallow domestic wells. The modelling results, in conjunction with fracture trace analyses and geophysical investigations, identified conjugate vertical fracture systems at the Myersville and Waterside sites, and single vertical fractures at the Middletown well 17 and A.C. Jets sites and the Westminster Votech/Maplecrest site. The modelling simulations indicate that transmissivity values derived from the aquifer tests were reliable, but that the storage constants were underestimated by at least an ½ order of magnitude, probably due to lags in drawdowns in observation wells. The ¼ L method produces improved results over the common radial flow models, but the expected error with its application is about 25% or greater.

# Introduction

The State of Maryland is in the Mid-Atlantic region of the eastern United States and has a wide range of geology and aquifer types. The aquifers vary from high yielding (wells commonly producing more than 500 gpm), confined and unconfined, unconsolidated sandstone layers on the eastern shore and southern Maryland to relatively, low yielding aquifers (wells generally producing less than 100 gpm) in the fractured rock areas of the Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau provinces of central and western Maryland. The state includes much of the major Washington-Baltimore metropolitan complex, where about 5 million people live. Most of the metropolitan area is served by surface water from the Potomac River and the Baltimore City reservoir system. Some of the fastest growing suburban areas, however, are in the Piedmont and Blue Ridge areas, and are supplied by wells in fractured rock aquifers.

There have been about 100 known private wells of nearly 200,000 in the State, impacted by groundwater withdrawals in the fractured rock aquifers of Maryland, and all those water supplies have been effectively replaced. There have been more than 400 water use permits issued to large users in the fractured rock aquifers of the State or those withdrawing more than an annual average of 10,000 gpd. Only a few permittees have caused unreasonable impacts, of which more than 90% can be attributed to withdrawals by Poolesville and Taneytown municipal wells, and dewatering of the Mettiki Coalmine, all in consolidated sedimentary rock formations, and dewatering of limestone quarries in the State. The impacts associated with these withdrawals have been successfully mitigated, primarily because they occurred in formations where it is relatively easy to drill and complete replacement wells. The remaining few impacts were due to withdrawals from Myersville and Middletown public supply wells.

# Location of Study Area

The locations of the sites discussed in this report are shown in Figure 1. The study area is in central Maryland, and includes Carroll and Frederick Counties, a portion of which is part of the Baltimore-Washington Metropolitan region.

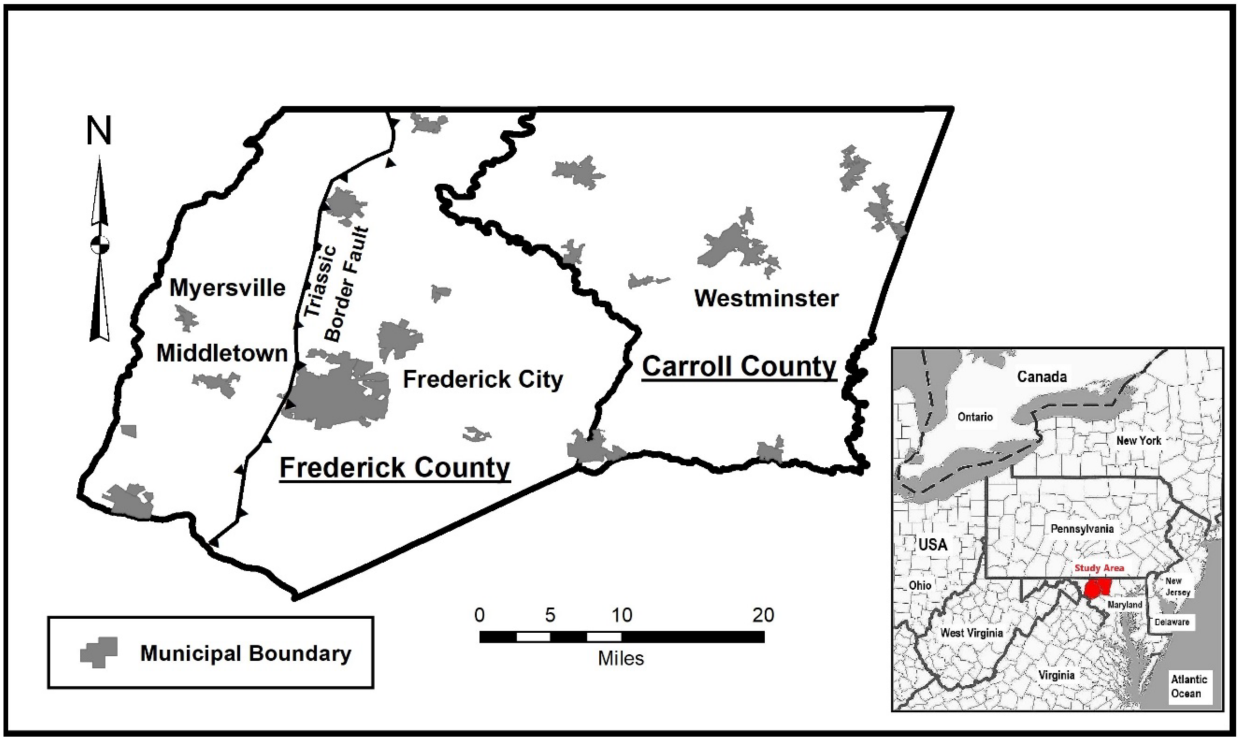

**Figure 1.** Location map of study area.

## The History of Water Appropriation or Use Regulations in Maryland

The Water Appropriations Act of 1933 created regulatory authority over the appropriation of surface and ground waters for any use (with significant exemptions, especially for subdivisions, municipal and agricultural users). The Well Drillers Law was passed in 1945 and addressed the issue of licensing well drillers. It also required permits before and completion reports after drilling of any water well, providing a wealth of data on the ground waters of the State. The permitting system for well drillers and water appropriations was one of the earliest such programs in the nation. The 1933 law was largely ignored until about 1957, when the "Regulated Riparian" system for surface water adopted. At that time, the "American Rule" or Reasonable Use Doctrine governed groundwater use, which states that a landowner has the right only to a reasonable and beneficial use of the waters upon his land. The reasonable use theory does not prevent the proper, non-wasteful consumption of such waters for use on the land to be developed, allowing the underground waters of neighboring properties to be interfered with or diverted. In 1988, the water use regulations were modified based on the Restatement (second) of Torts, Section 858, which requires replacement impacted water supplies, with some restrictions. They also require consideration of the aggregate and cumulative changes of new and future appropriations, and their contributions to future degradation of the State's waters, which are used to protect the hydrologic balance of the State's water resources.

# Background Discussion-Previous Studies

Relatively few investigations have been published concerning impacts caused by pumping wells in fractured rock aquifers. Vecchioli (1967) reported a drawdown of 4.1 feet at 1550 feet from a well pumped at 500 gpm for 48 hours, in the consolidated sedimentary rock Brunswick Shale of New Jersey. He also included anecdotal information that pumping of various wells had caused significant drawdowns or adverse impacts up to a mile in the same type of aquifer. Kohurt et al. (1983) reported significant drawdowns (10 feet at 4900 ft and 16 feet at 3300 ft) along line sinks, while pumping two, high-capacity wells at 200-250 gpm, in a granodiorite aquifer located in British Columbia. They indicated that deglaciation of the area led to isostatic rebound resulting in the development of additional bedrock fractures, especially sheet type ones that were flat lying. The troughs of depression that occurred during testing did not parallel any major areal fracture directions but developed along trends that coincided with the intersections with and bisected the angles between two major joint sets, that may have been connected to sheet type fractures at depth. Stewart and Langevin (1999) collected data related to pumping from the Floridan aquifer by the Cross Bar Ranch well field, which indicated that a drawdown of 10 feet occurred at five miles from the well field while it was pumped over a 12-year period, beginning at 10 Mgd and ending at 25 Mgd.

The Vermont Rural Water Association (Hanson, 2009) conducted a study of the interference to observation wells caused by withdrawals of Public Community Water Systems (PCWS). A PCWS was defined as having at least at least 10 connections serving at least 25 people for at least 60 days in one year, the majority of which were in fractured crystalline rock aquifers. Of 547 PCWS, 203 had source/evaluation reports and observation monitoring well data. Of those, 18 PCWS caused interference problems (cannot meet projected demand) in 68 cases, involving 53 observation wells and cumulative impacts by multiple PCWS sources to 15 observation wells. The Vermont Water Supply Division instituted the following Water Supply Rule – groundwater Monitoring, based on the pumping rate of the PCWS and maximum radial monitoring distance: 5-19.9 gpm – 1000 ft; 20-49.9 gpm – 2000 ft; 50-99.9 gpm – 2500 ft; and 100+ gpm – 3000 ft. 52 maps show locations of PCWS and observation wells, but there are no details of time-drawdown data from aquifer interference tests presented. No information on how the Water Supply Rule was developed could be found.

In Maryland, there are no aquifers comparable to the Floridan or the British Columbia granodiorite aquifers. The Brunswick Shale of New Jersey is like the Gettysburg Shale in Maryland; however, there are no verified impacts due to withdrawals from the Gettysburg Shale in Maryland. It is noted that the data in the three published studies were taken from only three pumping wells and the Cross Bar Ranch well field. In Maryland, the State agency has collected long-term test and/or monitoring data taken as part of several dozen projects. The result is that there are substantially more data in Maryland that can be used to determine what distances from pumping wells are adequate for preparing water supply inventories related to fractured rock aquifer tests and determining what are the significant factors related to impacts on water supplies caused by groundwater withdrawals.

# Methods of Investigation

An extensive review of all significant case studies in Maryland was completed where impacts are known to have occurred and testing produced significant drawdowns in nearby wells. The review included analyses of aquifer tests that were performed, and methods used to predict impacts, presentation of long-term monitoring data, comparisons of actual to predicted drawdowns, and methods used to mitigate the impacts.

Relatively simple analytical techniques were used to predict the impacts of well interference. An effective well radius (equal to ¼ fracture length), instead of the actual well radius, was used to calculate drawdowns in pumping wells. The heterogeneity of an aquifer was estimated by assigning higher storage and transmissivity values to the weathered zone relative to the bedrock portion of an aquifer. While this improves the estimates of drawdowns relative to the commonly used Theis (1935) and Cooper-Jacob (1946) methods, there still can be substantial errors (on the order of 25% or greater) involved when using this technique.

These methods were developed in lieu of complex groundwater flow models, since reliable numerical analyses often require more data than is commonly available at most sites, and they are usually very costly and time-consuming. There are, however, several studies where numerical analyses were used to define groundwater flow in fractured rock aquifers, van Tonder et al. (2001a), Rushton & Chen (1976) and Tiedeman & Hsieh (2001). None of these studies presented long-term test or monitoring data to confirm the reliability of the flow models. Over the past 25+/- years the Maryland Department of Natural Resources-Water Resources Administration (MDNR-WRA) and the Maryland Department of the Environment (MDE) have collected long-term test or monitoring data from several dozen projects, mostly in Poolesville, Taneytown, Myersville, and Middletown, that will be used to verify the accuracy of the predictions of impacts using the present MDE methods and techniques.

MDE now requires that an inventory be completed to identify nearby water supplies and those which should be monitored during aquifer tests. The radial distances from a proposed production well to which inventories are to be completed are based on case studies conducted by the State over the past 25 years. Those distances are: 1500 feet, crystalline rocks; 2000 feet, carbonate rocks; and 3000 feet, consolidated sedimentary rocks. The have been no impacts in crystalline rock aquifers outside of 1200 feet, although significant drawdowns (up to 26 ft) have been observed at distances up to 1760 feet during aquifer tests. There have been no impacts in carbonate rock formations (not including those any associated with quarry activity), although a drawdown of three feet was observed at 3000 feet during one test. Impacts have occurred at distances more than 5000 feet from a pumping well in consolidated sedimentary rocks.

## Acknowledgements

This study fulfills one of the objectives of a cooperative regional study, (USGS Publication SIR 2012-5160) of the fractured rock areas of Maryland, Fleming et al. (2012). that involved MDE, the Maryland Geological Survey (MGS), the U.S. Geological Survey (USGS) and the Monitoring and Non-Tidal Assessment (MANTA) division of MDNR.

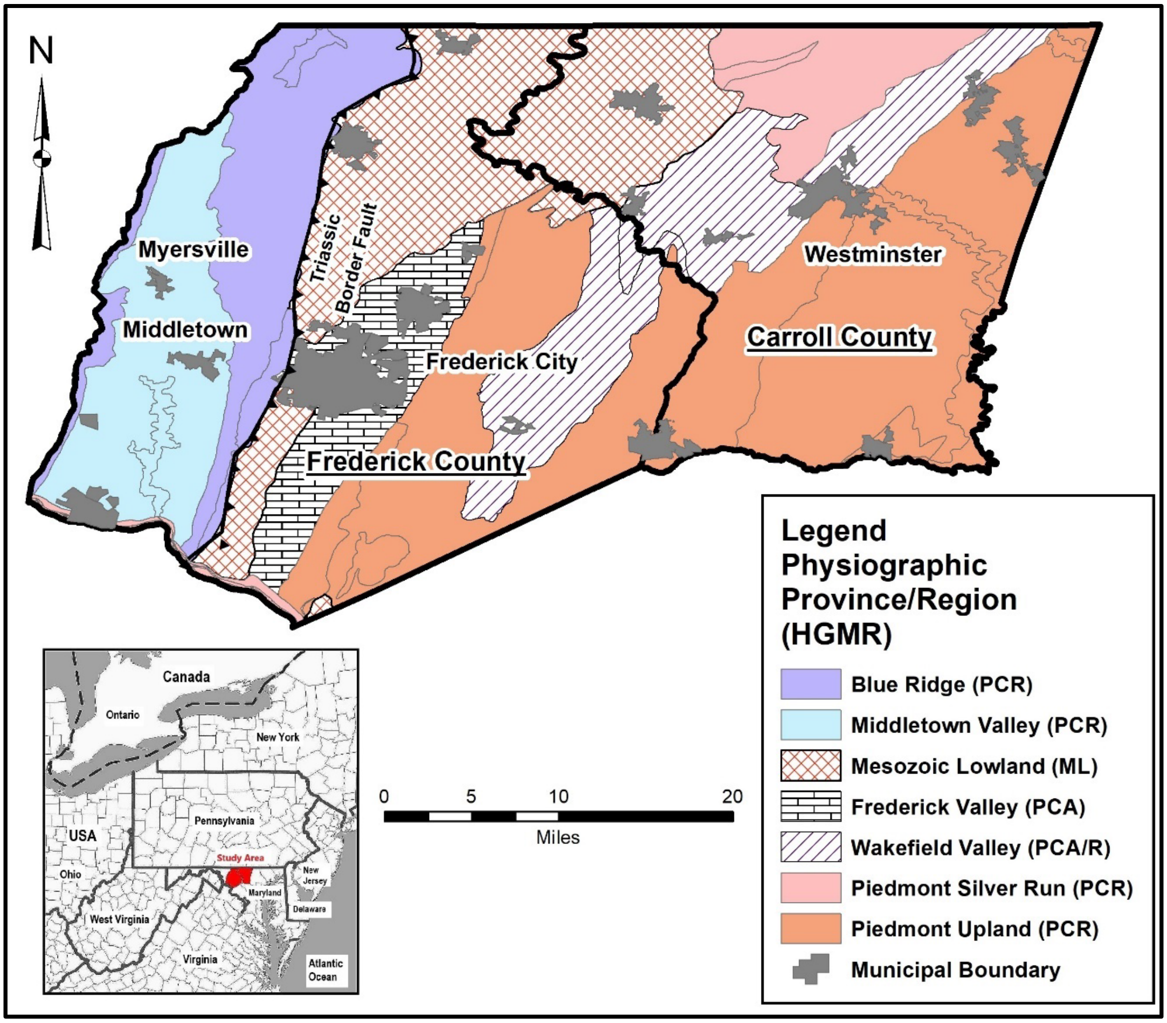

**Figure 2.** Physiographic and hydrogeomorphic (HGMR) regions of the study area. The HGMRs are the Blue Ridge (BR), Mesozoic Lowland (ML), Piedmont Carbonate (PCA) and Piedmont Crystalline (PCR) regions.

## General Hydrogeology and Geology of Central Maryland

The study area is in central Maryland and consists of parts of the major Blue Ridge and Piedmont physiographic provinces. The Piedmont province in this area has been further subdivided into the Western Piedmont and Mesozoic Lowland provinces. Bachman, Lindsey, Brakebill and Powers (1998) combined physiographic provinces with generalized lithology to define eleven hydrogeomorphic regions (HGMRs) for the Chesapeake Bay watershed. Figure 2 shows the four HGMRs that are within the study area; the Piedmont Crystalline (PCR), the Piedmont Carbonate (PCA), the Mesozoic Lowland (ML), and the Blue Ridge (BR) regions. The rock types generally consist of carbonates and consolidated sedimentary rocks in the central lowland areas (Frederick and Wakefield valleys, and the Gettysburg and Culpeper basins), and metamorphosed volcanic, volcaniclastic, and epiclastic rocks in the eastern portion of the study area and the Blue Ridge Mountains to the west. All discussions of geologic formations are based on the Geologic Map of Maryland (Cleaves et al.,1968), with some minor changes, William Junkin (personal communication, 2019).

The Piedmont Crystalline HGMR (PCR) occurs in the eastern portion of the study area and the Middletown Valley to the west. It is primarily underlain by Precambrian and Cambrian metamorphic and igneous rocks, including, in some areas, metacarbonates and metaquartzites. Two prominent formations underlie most of the eastern area. The Marburg Schist is a bluish gray to silvery-green, fine-grained schist that underlies parts of Carroll, Frederick, and Montgomery counties. The Ijamsville Formation consists of blue, green, or purple phyllite, and phyllitic slate and interbedded metasiltstone and metagraywacke rock units. It underlies an area of approximately 100 square miles (260 square kilometers) in Frederick and Carroll counties. Intermingled with the Ijamsville Formation are other metavolcanic and carbonate rocks, located primarily in the Wakefield Valley. Westminster is in the eastern PCR region. The Middletown Valley is flanked by South Mountain to the west and Catoctin Mountain to the east. It is underlain by Precambrian granitic gneisses and metavolcanic rocks, intruded by metadiabase dikes. Myersville and Middletown are in the Middletown Valley.

The Piedmont Carbonate HGMR (PCA) is located within the Monocacy River Basin in the central part of Frederick County. The rocks underlying the Frederick Valley form a syncline, bounded on the west by the high-angle reverse Triassic Border Fault and in the east by the Piedmont Upland. Most of the floor of the Frederick Valley is underlain by the Frederick Limestone, which is a thin-bedded, dark colored clayey limestone and weathers to slab-like medium-colored layers. The Grove Limestone overlies the Frederick Limestone in a narrow strip in the central part of the Frederick Valley and is a massive pure limestone, with a fine-grained dolomite in the lower part and a basal highly quartzose limestone. The Waterside Community near Frederick City is in the Frederick Valley. The Tomstown Dolomite and Frederick Limestone are exposed in a narrow belt along the foothills of Catoctin Mountain and adjacent to the Triassic border fault.

The Mesozoic Lowland (ML) HGMR is present in central and northeastern Frederick County, northwestern Carroll County, and western Montgomery County. This HGMR is characterized by its underlying geology of Triassic sedimentary rocks and Jurassic intrusions. The Triassic rocks north of the City of Frederick are part of the Newark-Gettysburg basin, which extends from the New York City area to Frederick. The Triassic rocks south of Frederick are part of the Culpepper basin, which extends from Frederick to near Charlottesville, Va. The Triassic rocks in the study area are comprised primarily of the Gettysburg Formation and the underlying New Oxford Formation (Cleaves et al. 1968; Nutter,1975; Otton, 1981; and Duigon and Dine, 1987). In the Culpepper basin, the correlative unit to the New Oxford Formation is the Poolesville Member of the Manassas Formation (Brezinski, 2004).

The Gettysburg Formation generally consists of a soft, reddish-brown shale containing interbedded siltstones, sandstones, and quartz and limestone conglomerates. It is exposed in the western part of the ML portion of the study area, in the vicinity of the towns of Emmitsburg and Thurmont.

The New Oxford Formation consists of an interbedded sequence of sandstones, siltstones, shales, and conglomerates. The sandstone beds are lenticular, are not regionally extensive, and appear to be more competent and have denser fracture networks than the shale units. The residuum in Triassic-rock aquifers can be thin and may not extend below the zone of saturation. The mean porosity of Triassic sandstones and conglomerates is 6 percent (Otton, 1981), and in some places, may be even higher, due to secondary solution of calcite cementing materials.

The Blue Ridge HGMR (BR) is in the western part of Frederick County and is bounded on the east by the Triassic Border Fault. The rocks of the Blue Ridge HGMR are principally Late Precambrian metavolcanic rocks that make up the Catoctin Formation and include metabasalt, metarhyolite, and greenstone schist rocks. There are, also, minor quartzite and phyllite, units in the HGMR. Small areas on the up-thrown side of the Triassic Border Fault are underlain by the Tomstown Dolomite and Frederick Limestone, but those units are part of the Piedmont Carbonate HGMR (PCA).

# Crystalline Rock Aquifer Case Studies

## Myersville Water Treatment Plant (WTP) Well

At the WTP site two aquifer pumping tests were conducted in 1987 and 1989, at 35 gal/min and 15 gal/min for 54 hours and 30 hours, respectively. The first test had to be secured early, when a drawdown of 195 ft caused the nearby Weirer domestic well to go dry, Figure 3. That was close to the 240 ft of drawdown in the WTP well at the end of the test. Drawdowns in the nearby Easterday and Mangiafico (after 240 min) domestic wells were 77 ft and 7 ft, respectively. The Easterday well was the only one in which the weathered zone was saturated prior to and remained so during the test. This would indicate that the limited drawdown in that well was due to a high T in its immediate vicinity. Due to the excessive drawdowns, the three residential homes were hooked up to the Myersville public water system. The second test was secured when water levels reached apparent equilibrium during the last 10 hours of the test. No water levels were measured in the house wells during the second test. Figure 4 is a time-drawdown graph of the two tests.

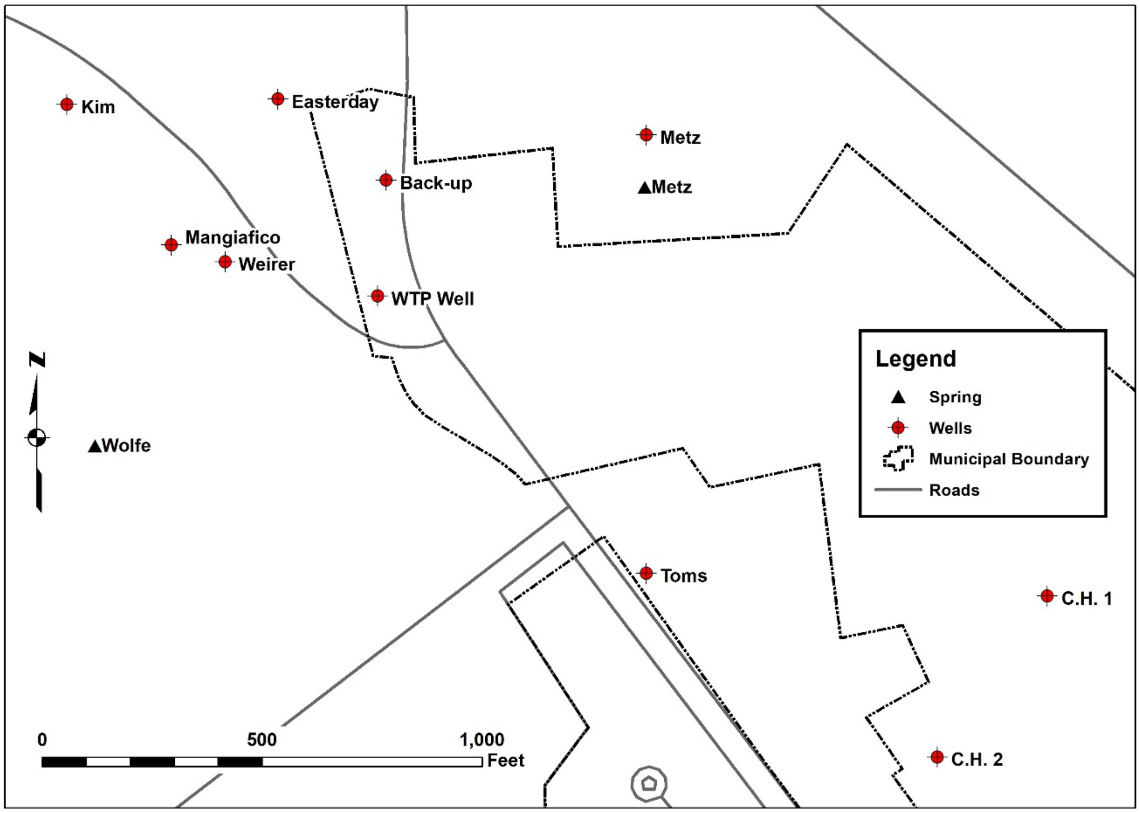

**Figure 3.** Location Map. Myersville Water Treatment Plant site.

In 1993 the Town was issued a temporary increase in its water use permit, with a provision that additional aquifer testing be conducted. Before the testing could be performed, the MDNR-WRA received a complaint that another domestic (Kim) well had gone dry. The MDNR-WRA collected recovery data from the production well, the four domestic wells and the nearby Canada Hill test wells for about five weeks during the fall of 1993. Myersville had been pumping the Town Well at an average of about 12.5 gal/min for the previous two years, which was increased to 18 gal/min during the last two months of the period. A well driller's measured water level in the Kim well indicated that the drawdown in that well was about 110 feet due to pumping of the WTP well.

After the WTP well was shutdown, from the relative recovery of the water levels in each well and the drawdown noted in the Kim well (110 feet), it is estimated the drawdown in the production and back-up wells probably exceeded 150 feet; in the Weirer well it was about 150 feet; and in the Mangiafico well it was about 130 feet. Water levels in the nearby Canada Hill test wells (CH. 1 and CH. 2, 1700 ft southeast of the WTP well) were about 2-3 feet, indicating that the impacts were due to withdrawals from the WTP well, not an on-going, moderate drought.

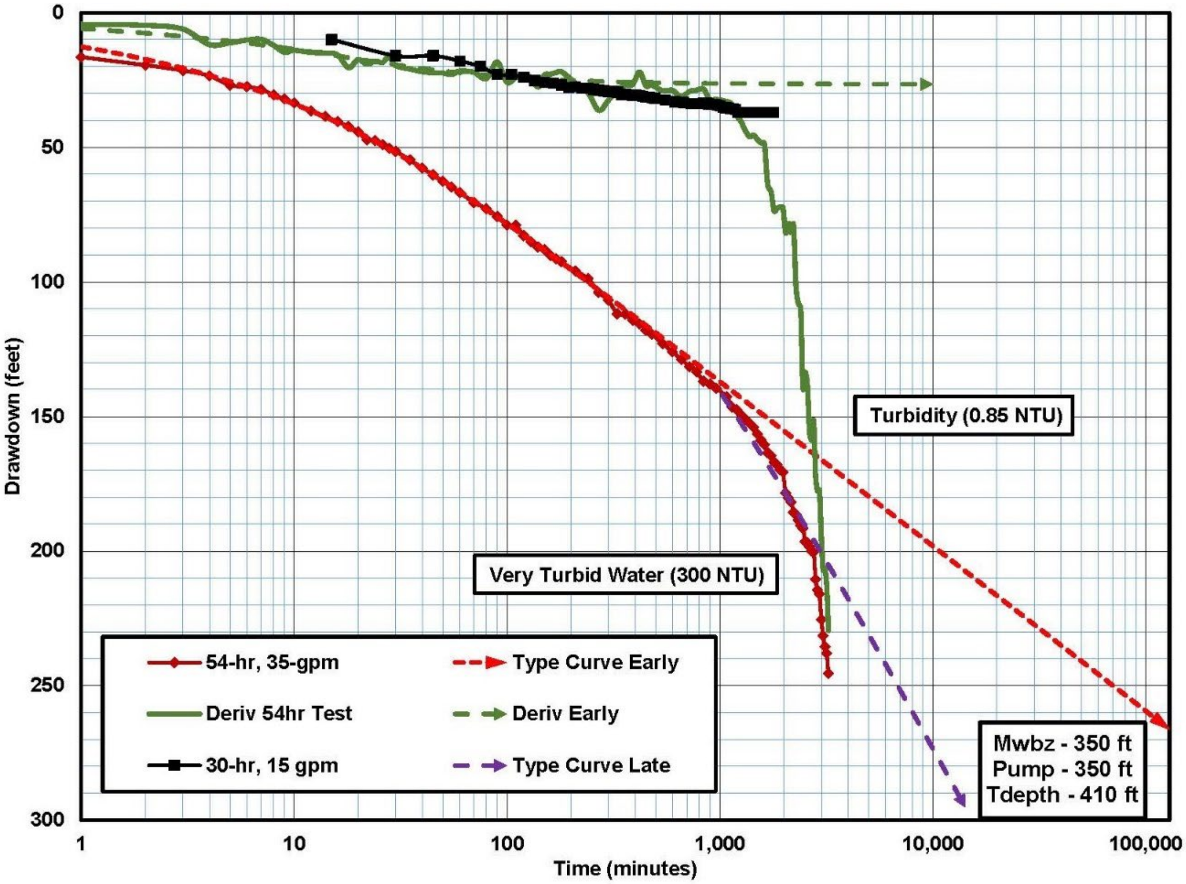

**Figure 4.** Myersville water treatment plant (WTP) well – Semi-log plot of drawdowns from 54-hr, 35 gpm and 30-hr, 15 gpm aquifer tests, Gringarten-Witherspoon SVF solution.

The long-term pumping rate prior to the five-week recovery period was near the 15 gal/min pumping rate used during the 30-hour pumping test; consequently, the recovery data probably approximated the drawdown that would have occurred in the pumping and observation wells during a long-term aquifer test at that pumping rate. This indicated that the earlier 15 gal/min pumping test probably should have been run for at least one week, to obtain the late time drawdown data needed to determine the impacts of pumping the WTP well at that rate.

The aquifer test data were analyzed using the AQTESOLV automated curve fitting program, Hydrosolve, Inc. (2007), with instructions by Duffield (2007), and methods of investigation developed by Hammond and Field (2014). The Gringarten SVF model, Gringarten and Witherspoon (1972), best fit the drawdown data in the interval 20-300 minutes, when a clear break in the data occurs at 140 feet of drawdown. The extrapolated 90-day drawdown is 265 ft for an estimated yield of 18 gal/min.

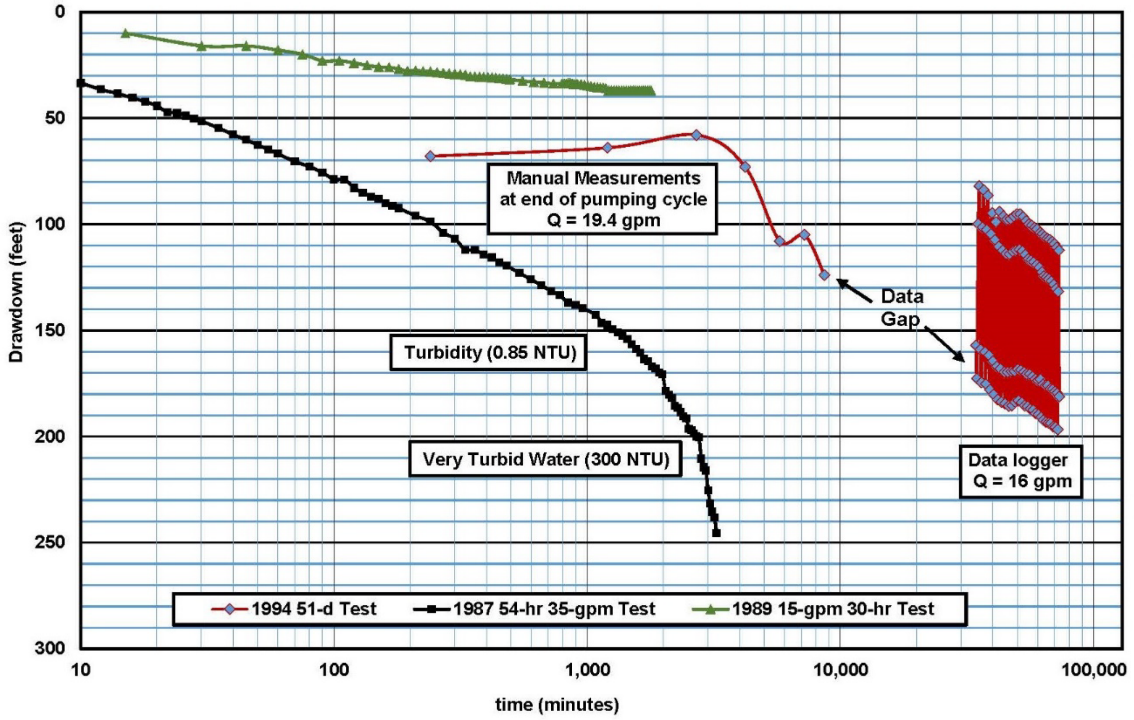

**Figure 5.** Myersville water treatment plant (WTP) well – Semi-log plot of a composite of drawdowns from the 51-d, 54-hr and 30-hr aquifer tests.

Due to the potential impacts to the Kim well and the relatively low estimated yield, a long-term test of the WTP well was conducted for 51 days in Jul-Aug 1994. Figure 5 compares the results of the long-term test to the earlier shorter ones. Like the 30-hr test, the initial the water level was a relatively stable drawdown of about 60 feet for the first 3-4 days at about 19 gal/min. After that point, and like the 54-hr test, the water level declined steadily to a drawdown at the end of the test of 191 feet, at 16 gal/min. This indicates that the reliable yield is likely less 16 gal/min since the test was not conducted under severe drought conditions.

During the 54-hr, 35-gpm test of the WTP well, the drawdown in that Weirer house well was nearly the same as that of the pumping well, providing evidence that both wells were hydraulically well-connected by a prominent, discrete fracture. The nearly identical drawdowns in the Easterday and Mangiafico wells, but the significant distance between them, suggested that they might be located equidistant from, but on opposite sides of, a second fracture running between those two wells. Subsequent geophysical surveys and long-term testing demonstrated that, while that interpretation was essentially correct, the fracture system was more complex than previously thought.

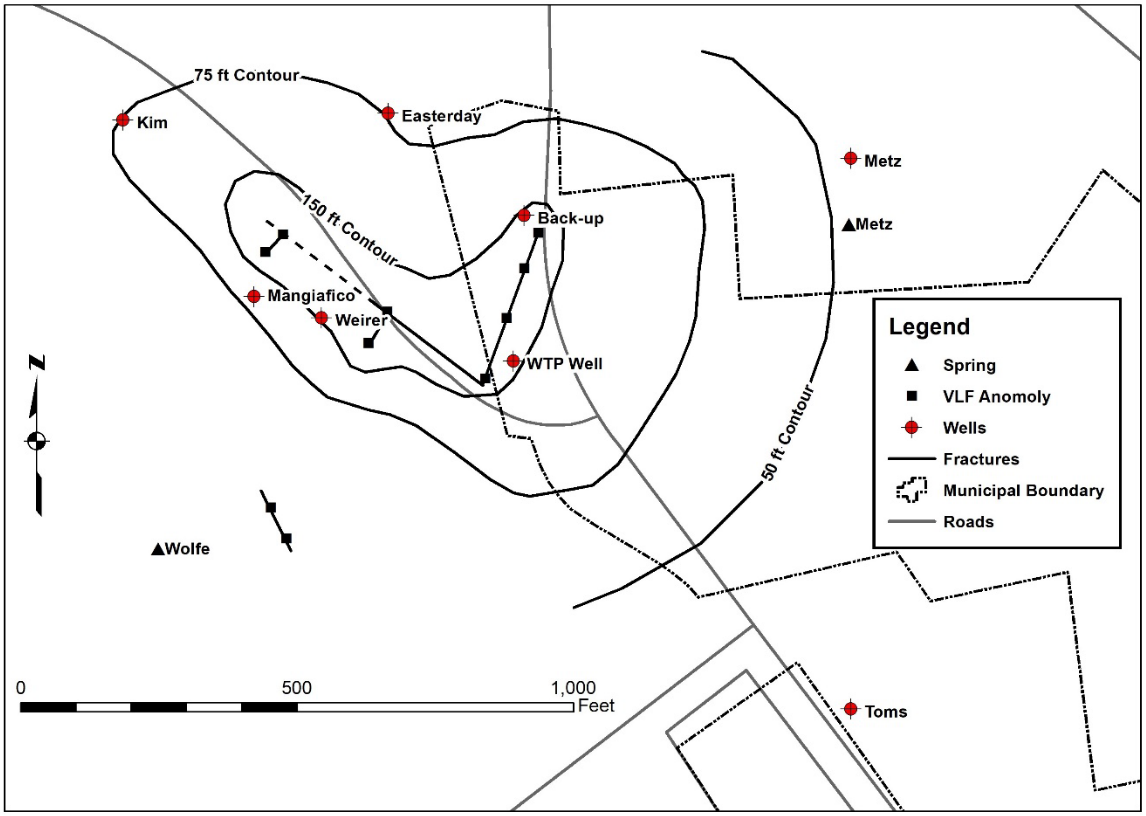

**Figure 6.** Map of drawdowns from the 51-d, 19-16 gpm test of the Water Treatment Plant well.

Figure 6 is a map that shows the results of a VLF geophysical survey and the drawdowns at the end of the 51-day aquifer test conducted by the State between June and August of 1994. The VLF traces and drawdowns (155 feet) indicate that there is a prominent northeast trending fracture (280 feet long) connecting the WTP well and its back-up well. The drawdown (150 feet) in the Weirer well and the VLF traces suggest that there is a second compound northwest trending fracture (280 feet long) connecting the WTP and Weirer wells. The estimated minimum total length of the primary fracture system is then 560 feet; however, since they are nearly perpendicular to each other, a vector analysis was conducted that produced an effective fracture length of 385 feet. The drawdowns (75-79 feet) in the Mangiafico, Kim and Easterday wells indicate that those wells are off fracture; but were still substantially affected by pumping of the WTP well. In those cases, it is expected that micro-fractures provided the means for groundwater to flow from the house wells to the extended-well fracture system. Those data also indicate that the VFL anomalies near the Mangiafico well, and between the Weirer well and the Wolfe spring are isolated from the primary fracture system. Finally, both springs went dry within one week of the start of the 51-d test.

The results of the 54-hr and 51-d tests were used to develop the ¼ fracture length model used by the State, in lieu of costly numerical simulations, to estimate impacts to water supplies caused by groundwater withdrawals in the fractured rock aquifers of Maryland. In a petroleum industry paper, Prats (1961) indicated that for fractures with an infinite capacity, the effective well radius is equal to ¼ of the fracture length. A similar relationship had been noted in the Myersville WTP test data, in that effective well radii of 100 to 200 feet may have produced the drawdown observed in the pumping well. From these observations, the ¼ fracture length (1/4 L) model was developed.

Using a derived T value (which is more accurate than S or storage coefficient), the S and effective well radii values are adjusted by iterative methods, until a match of the drawdown observed in the pumping well during a test is achieved. Those T and S values are then substituted into the Theis (1935) equation to see if a match with the observation well data can be obtained. If there is no geophysical evidence of the fracture dimensions, then this usually requires moving the fracture until all the drawdowns of the pumping and observation wells can be reasonably well matched.

It is noted that the distance used in the calculations is not the distance to the pumping well, but the distance to the fracture plus ¼ L. The reason for this is shown by the position of OW3 in Figure 7. That observation well is inside of ¼ L effective radius, producing a drawdown in the observation well greater than that in the pumping well, which is not physically possible.

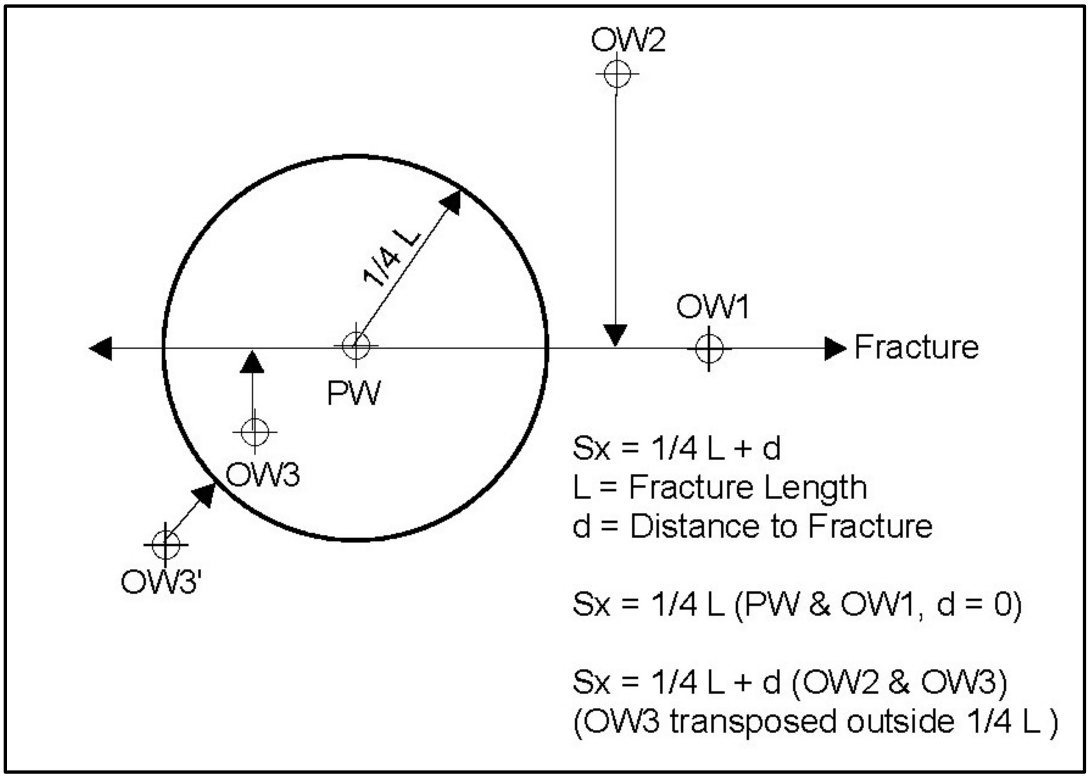

**Figure 7.** ¼ fracture length (1/4 L) model.

**Table 1.** Results of AQTESOLV analyses of the WTP well 54-hr, 35-gpm test.

| Test-Obs Well | T | S | r | s | t | Model | DERIV | RSS | Criterion | Var | S.D. | Mean | Lf |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | gpd/ft | | ft | ft | min | | | ft$^2$ | | ft$^2$ | ft | ft | ft |
| WTP Well (Single Well Test) | 288 | N/A | N/A | 108 | 20-300 | SVF-F | Linear/IARF | 9.9 | ETOL | 0.41 | 0.644 | 0.002 | N/A |
| | 253 | N/A | N/A | 140 | 20-1000 | SVF-F | Linear/IARF | 28 | RTOL | 0.73 | 0.853 | 0.028 | N/A |
| | 123 | N/A | N/A | 108 | 20-300 | Barker | Linear/IARF | 9.8 | ETOL | 0.39 | 0.625 | 0.002 | N/A |
| | 49 | N/A | N/A | 140 | 20-1000 | Barker | Linear/IARF | 30 | ETOL | 0.74 | 0.86 | -0.036 | N/A |
| | 68 | N/A | N/A | 186 | 1140-2220 | SVF-F | Linear | 99 | RTOL | 6.57 | 2.56 | 0.013 | N/A |
| | 40 | N/A | N/A | 186 | 1140-2220 | Barker | Linear | 97 | ETOL | 5.70 | 2.39 | 0.008 | N/A |
| Weier Well (Multi-Well Test) | 143 | 8.5E-06 | 225 | 55 | 20-300 | SVF-F | Linear/IARF | 13.7 | RTOL | 0.57 | 0.76 | 0.006 | N/A |
| | 142 | 8.5E-06 | 225 | 111 | 20-1000 | SVF-F | Linear/IARF | 75 | ETOL | 1.97 | 1.40 | 0.043 | N/A |
| | 326 | 2E-06 | 355 | 55 | 20-300 | Barker | Linear/IARF | 14 | ETOL | 0.58 | 0.76 | 0.004 | N/A |
| | 354 | 2E-06 | 355 | 111 | 20-1000 | Barker | Linear/IARF | 218 | RTOL | 5.6 | 2.36 | 1.38 | N/A |
| | 62 | 5E-05 | 225 | 160 | 1140-2220 | SVF-F | Linear | 41 | ETOL | 2.72 | 1.65 | 0.0005 | N/A |
| | 67 | 1E-05 | 355 | 160 | 1140-2220 | Barker | Linear | 42 | ETOL | 2.47 | 1.57 | 0.002 | N/A |
| Composite Plot WTP,Weirer & Mangiafico Wells - Inverse Maximum Displacement Weighting Method | 119 | 1E-04 | 355/485 | 55/25 | 20-300 | Barker | Linear/IARF | 2.05 | RTOL | 0.0370 | 0.190 | 0.12 | N/A |
| | 164 | 4E-05 | 355/485 | 111/41 | 20-1000 | Barker | Linear/IARF | 0.052 | BTOL | 0.0020 | 0.045 | 0.013 | N/A |
| | 163 | 4E-05 | 225/342 | 55/25 | 20-300 | SVF-F | Linear/IARF | 0.95 | ETOL | 0.017 | 0.13 | 0.074 | 293 |
| | 135 | 1E-04 | 225/342 | 111/41 | 20-1000 | SVF-F | Linear/IARF | 2.0 | BTOL | 0.024 | 0.15 | 0.085 | 300 |
| Mangiafico Well (Multi-Well Test) | 205 | 5E-05 | 342 | 70 | 0-2880 | SVF-F | Erratic | 61 | BTOL | 15 | 3.89 | -0.415 | N/A |
| | 108 | 2E-05 | 485 | 70 | 0-2880 | Barker | Erratic | 45 | ETOL | 9 | 2.99 | -0.316 | N/A |

Table 1 provides the results of the analyses of the drawdown data collected from the WTP, Weirer and Mangiafico wells during the 1987, 35-gpm, 54-hour test. On figure 4, by visual inspection, there were three segments on the drawdown curves. The first one occurred between 20 and 300 minutes after the start of pumping, which produced the best results. Data from the period 20-1000 minutes also produced good visual and statistical fits to the data. The derivatives indicate that there was an initial linear flow response followed by an IARF period, which would be typical of a flow regime produced by a single vertical fracture. The second segment lasted from 1140 to 2220 minutes in both wells. The late time derivative and drawdown curves indicate that linear flow was probably present during that portion of the test, which is typical of a limited aquifer. Near the end of the test, there were rapid drawdowns in each well and a sharp increase of turbidity in the pumping well. That third segment was not the result of the aquifer responding to pumping; but was probably due to a partially clogged pump intake filter. This caused rapid drawdowns in the pumping well, the extended fracture and nearby Weirer well, but not the more distant domestic wells.

Included in Table 1 are results made using the solutions that provided the best visual and numerical/statistical fits to each set of data. Analyses were initially made by the single-well method for the WTP drawdown data and by the multi-well method for the Weirer and Mangiafico observation well data, and a final analysis of the data from all three wells on a composite plot.

For the single-well analysis of the early-time segment between 20 and 300 minutes in the WTP well, the best fit to the drawdown data was achieved using the Gringarten-Ramey (1974) solution for a single vertical facture with a finite conductivity (SVF-F), producing a T value of 288 gpd/ft. Conversely, the Barker (1988) General Radial Flow (GRF) solution also provided good fits the data; but produced a T value that was much lower (123 gpd/ft). For the multi-well analysis of the Weirer well data, both the GRF and SVF-F solutions provided good visual and statistical numerical fits, producing T values of 143 and 326 gpd/ft and S values of 8.5E-5 and 2E-5, respectively. For the multi-well analysis of the Mangiafico well data, both the GRF and SVF-F solutions provided good visual and statistical numerical fits, producing T values of 205 and 108 gpd/ft and S values of 4E-5 and 1E-4, respectively. The derivatives depicted linear/IARF responses, which, combined with the geophysical evidence, indicate that the SVF-F model best describes the flow regime observed during the test.

For the single-well analysis, good fits to the late-time data (1140-2220 minutes) from the WTP well were achieved using both the SVF-F or GRF models, producing T values of 68 and 40 gpd/ft, respectively. For the multi-well analysis of the Weirer well data, the GRF and SVF-F solutions produced T values of 62 and 67 gpd/ft, and S values of 5E-5 and 1E-5, respectively. The late time linear derivative response is typical of a limited aquifer; consequently, the calculated hydraulic constants may not be truly presentative of the flow regime; however, such an aquifer would be expected to have low T and S values like those that were calculated

A composite plot can be used when matching the drawdown data from both pumping and observation wells. The drawdown data is usually weighted by using the magnitude of the inverse of the maximum displacement of the observations in each well. The purpose of this weighting method is to account for significant differences in drawdown that can occur during aquifer tests, by assigning weights proportional to the drawdowns measured in individual wells. Table 1 includes the results of the WTP 54-hour test for the WTP, Weirer and Mangiafico wells when using these methods. For the early-time data, the hydraulic constants (163 gpd/ft and 4E-5) were like those from the Weirer multi-well analysis (143 gpd/ft and 9E-6) for the SVF-F model. The T value (119 gpd/ft) calculated using the GRF model was about 1/2 that of the multi-well analysis for the Weirer well. For the late-time data using the SVF-F model, there was no good visual fit to the data, except for the Mangiafico data, indicating that the inverse maximum displacement method produced biased results in this case. The residual statistics also indicated that the composite method produced much less error that the single- or multi-well techniques; however, the same result occurred when the inverse maximum displacement method was applied to the single-well data; although, in that case, the same weights were applied to each data point. There was no obvious difference in the visual fits to the data, suggesting that the low values of the residuals for the composite plot were a function of the weighting method chosen rather than any improvement of fits to the physical models

Although there were only eight measurements in the Mangiafico data, those data were analyzed and produced results like the early-time SVF-F solutions for the WTP and Weirer wells, or a T of 205 gpd/ft and S of 5E-5. The data from the Easterday well were not analyzed because there were only nine data points and they were too erratic, which was probably due to household use at the Easterday residence. The shape of the drawdown curve, however, was somewhat like those of the WTP and Weirer wells, prior to dewatering of the shallow, higher permeability zones, as well as that for the Mangiafico well.

**Table 2.** Time-distance-drawdown calculations 0.21d (300 min) using ¼ L model.

| T | S | Q | t | x | d | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | Well | ft | |
| | | | | | | | | |
| 160 | 2E-05 | 35 | 0.21 | 82 | 0 | WTP | 108 | |
| 160 | 2E-05 | 35 | 0.21 | 177 | 95 | Weirer | 55 | |
| 160 | 2E-05 | 35 | 0.21 | 324 | 242 | Mangiafico | 25 | |
| 160 | 2E-05 | 35 | 0.21 | 432 | 350 | Easterday | 16 | |
| 160 | 2E-05 | 35 | 0.21 | 500 | | | | |
| 160 | 2E-05 | 35 | 0.21 | 700 | | | | |
| 160 | 2E-05 | 35 | 0.21 | 850 | | | | |
| 160 | 2E-05 | 35 | 0.21 | 1000 | | | | |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | |
| | | | | | | | | Error |
| $S_{82}$ = | 57.8 | 1.87 | = | 108 | | WTP | 108 | 0% |
| $S_{225}$ = | 57.8 | 1.21 | = | 70 | | Weirer | 55 | 21% |
| $S_{342}$ = | 57.8 | 0.68 | = | 39 | | Mangiafico | 25 | 36% |
| $S_{450}$ = | 57.8 | 0.43 | = | 25 | | Easterday | 16 | 36% |
| $S_{500}$ = | 57.8 | 0.30 | = | 18 | | | Average | 23% |
| $S_{700}$ = | 57.8 | 0.01 | = | 1 | | | 1/4 L | 82 ft |
| $S_{850}$ = | 57.8 | -0.16 | = | -9 | | | | |
| $S_{1000}$ = | 57.8 | -0.30 | = | -17 | | | | |

Hydraulic constants derived from the 54-hour test were used to simulate the drawdowns observed at two points during that test and the results are given in Table 2. Through an iterative process, a T value of 160 gpd/ft and S values of 2E-5 were able to provide a good match to the drawdowns observed in the WTP and Weirer wells at 0.21d (300 min) after the start of the test. An estimated L of 328 ft was calculated, which is like that calculated using the Gringarten-Ramey SVF-F solution (300 ft) and the L (400 ft) determined by vector analysis. The simulated drawdowns in the Mangiafico and Easterday wells were significantly more than the observed levels. This may have been due to the lag in response to pumping that lasted for several hours in both wells, a common effect that has been observed in many pumping tests in the low-permeability, fractured rock aquifers of Maryland.

The late-time drawdown was then modeled for a pumping period of 1.6 days (2300 min), Tables 3a and 3b. Beyond that time, there were rapid drawdowns in the WTP and Weirer wells, possibly due to clogging of the pumping well intake. Based on an average of the Weirer well and WTP T values (65 gpd/ft) and the Weirer S value of 5E-5, there were good matches to the Weirer observation well data (-10%, 18% and -21%), and an overall absolute error of 12%, including the WTP well. In addition, the estimated L of 704 feet is greater than the geophysical evidence would support. Holding the T value constant, the S value was adjusted (3E-5, 4E-5, and 6E-5) until reasonably good fits to the drawdowns in all wells were achieved, producing Ls of 912 ft, 788 ft and 644 ft, and overall errors of 17%, 12% and 15%, respectively. An L of 644 ft corresponds more closely to the 560-foot L derived from the geophysical evidence.

**Table 3a.** Time-distance-drawdown calculations 1.6d (2300 min) using ¼ L model.

| T | S | Q | t | x | d | Drawdowns | | x |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | | | ft |
| | | | | | | Well | ft | ft |
| 65 | 5E-05 | 35 | 1.6 | 82 | | | | |
| 65 | 5E-05 | 35 | 1.6 | 176 | 0 | WTP | 185 | 176 |
| 65 | 5E-05 | 35 | 1.6 | 271 | 95 | Weirer | 160 | 301 |
| 65 | 5E-05 | 35 | 1.6 | 418 | 242 | Mangiafico | 65 | 418 |
| 65 | 5E-05 | 35 | 1.6 | 526 | 350 | Easterday | 55 | 526 |
| 65 | 5E-05 | 35 | 1.6 | 700 | | | | |
| 65 | 5E-05 | 35 | 1.6 | 850 | | | | |
| 65 | 5E-05 | 35 | 1.6 | 1000 | | | | |

| | | | | |
|---|---|---|---|---|
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s |
| | | | | |
| $S_{82}$ = | 142.2 | 1.97 | = | 280 |
| $S_{176}$ = | 142.2 | 1.30 | = | 185 |
| $S_{301}$ = | 142.2 | 0.93 | = | 132 |
| $S_{418}$ = | 142.2 | 0.55 | = | 79 |
| $S_{526}$ = | 142.2 | 0.35 | = | 50 |
| $S_{700}$ = | 142.2 | 0.10 | = | 15 |
| $S_{850}$ = | 142.2 | -0.06 | = | -9 |
| $S_{1000}$ = | 142.2 | -0.20 | = | -29 |

| | | error |
|---|---|---|
| WTP | 185 | 0% |
| Weirer | 160 | -21% |
| Mangiafico | 65 | 18% |
| Easterday | 55 | -10% |
| | Avg | 12% |
| 1/4 L | 176 ft | |

| T | S | Q | t | x | d | Drawdowns | | x |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | | | ft |
| | | | | | | Well | ft | ft |
| 65 | 6E-05 | 35 | 1.6 | 82 | | | | |
| 65 | 6E-05 | 35 | 1.6 | 161 | 0 | WTP | 185 | 161 |
| 65 | 6E-05 | 35 | 1.6 | 256 | 95 | Weirer | 160 | 256 |
| 65 | 6E-05 | 35 | 1.6 | 403 | 242 | Mangiafico | 65 | 403 |
| 65 | 6E-05 | 35 | 1.6 | 511 | 350 | Easterday | 55 | 511 |
| 65 | 6E-05 | 35 | 1.6 | 700 | | | | |
| 65 | 6E-05 | 35 | 1.6 | 850 | | | | |
| 65 | 6E-05 | 35 | 1.6 | 1000 | | | | |

| | | | | |
|---|---|---|---|---|
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | | |
| | | | | |
| $S_{100}$ = | 142.2 | 1.89 | = | 268 |
| $S_{161}$ = | 142.2 | 1.30 | = | 185 |
| $S_{286}$ = | 142.2 | 0.90 | = | 128 |
| $S_{403}$ = | 142.2 | 0.51 | = | 72 |
| $S_{511}$ = | 142.2 | 0.30 | = | 43 |
| $S_{700}$ = | 142.2 | 0.03 | = | 4 |
| $S_{850}$ = | 142.2 | -0.14 | = | -20 |
| $S_{1000}$ = | 142.2 | -0.28 | = | -40 |

| | | error |
|---|---|---|
| WTP | 185 | 0% |
| Weirer | 160 | -25% |
| Mangiafico | 65 | 10% |
| Easterday | 55 | 25% |
| | Avg | 15% |
| 1/4 L | 161 ft | |

**Table 3b.** Time-distance-drawdown calculations 1.6d (2300 min) using ¼ L model.

| T | S | Q | t | x | d | | | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | Drawdowns | | x |
| | | | | | | Well | ft | ft |
| 65 | 4E-05 | 35 | 1.6 | 82 | | | | |
| 65 | 4E-05 | 35 | 1.6 | 197 | 0 | WTP | 185 | 197 |
| 65 | 4E-05 | 35 | 1.6 | 292 | 95 | Weirer | 160 | 292 |
| 65 | 4E-05 | 35 | 1.6 | 439 | 242 | Mangiafico | 65 | 439 |
| 65 | 4E-05 | 35 | 1.6 | 547 | 350 | Easterday | 55 | 547 |
| 65 | 4E-05 | 35 | 1.6 | 700 | | | | |
| 65 | 4E-05 | 35 | 1.6 | 850 | | | | |
| 65 | 4E-05 | 35 | 1.6 | 1000 | | | | |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | |
| | | | | | | | | |
| $S_{82}$ = | 142.2 | 2.06 | = | 293 | | | | error |
| $S_{197}$ = | 142.2 | 1.30 | = | 185 | | WTP | 185 | 0% |
| $S_{322}$ = | 142.2 | 0.96 | = | 137 | | Weirer | 160 | -17% |
| $S_{439}$ = | 142.2 | 0.61 | = | 86 | | Mangiafico | 65 | 24% |
| $S_{547}$ = | 142.2 | 0.42 | = | 59 | | Easterday | 55 | 7% |
| $S_{700}$ = | 142.2 | 0.20 | = | 29 | | | Avg | 12% |
| $S_{850}$ = | 142.2 | 0.03 | = | 5 | | 1/4 L | 197 ft | |
| $S_{1000}$ = | 142.2 | -0.11 | = | -15 | | | | |

| T | S | Q | t | x | d | | | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | Drawdowns | | x |
| | | | | | | Well | ft | ft |
| 65 | 3E-05 | 35 | 1.6 | 82 | | | | |
| 65 | 3E-05 | 35 | 1.6 | 228 | 0 | WTP | 185 | 228 |
| 65 | 3E-05 | 35 | 1.6 | 323 | 95 | Weirer | 160 | 323 |
| 65 | 3E-05 | 35 | 1.6 | 470 | 242 | Mangiafico | 65 | 470 |
| 65 | 3E-05 | 35 | 1.6 | 578 | 350 | Easterday | 55 | 578 |
| 65 | 3E-05 | 35 | 1.6 | 700 | | | | |
| 65 | 3E-05 | 35 | 1.6 | 850 | | | | |
| 65 | 3E-05 | 35 | 1.6 | 1000 | | | | |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | | | | | | |
| | | | | | | | | |
| $S_{82}$ = | 142.2 | 2.19 | = | 311 | | | | error |
| $S_{176}$ = | 142.2 | 1.30 | = | 185 | | WTP | 185 | 0% |
| $S_{301}$ = | 142.2 | 1.00 | = | 142 | | Weirer | 160 | -13% |
| $S_{418}$ = | 142.2 | 0.67 | = | 96 | | Mangiafico | 65 | 32% |
| $S_{526}$ = | 142.2 | 0.49 | = | 70 | | Easterday | 55 | 21% |
| $S_{700}$ = | 142.2 | 0.33 | = | 46 | | | Avg | 17% |
| $S_{850}$ = | 142.2 | 0.16 | = | 22 | | 1/4 L | 228 ft | |
| $S_{1000}$ = | 142.2 | 0.02 | = | 2 | | | | |

**Table 4a**. Time-distance-drawdown calculations 51d test using ¼ L model.

| T | S | Q | t | x | D | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | Well | ft | |
| | | | | | | | | |
| 65 | 5E-05 | 16 | 51 | 82 | 0 | WTP/Backup | 155 | |
| 65 | 5E-05 | 16 | 51 | 161 | | | | |
| 65 | 5E-05 | 16 | 51 | 176 | | | | |
| 65 | 5E-05 | 16 | 51 | 197 | | | | |
| 65 | 5E-05 | 16 | 51 | 177 | 95 | Weirer | 150 | |
| 65 | 5E-05 | 16 | 51 | 256 | | | | |
| 65 | 5E-05 | 16 | 51 | 271 | | | | |
| 65 | 5E-05 | 16 | 51 | 292 | | | | |
| 65 | 5E-05 | 16 | 51 | 324 | 242 | Mangiafico | 79 | |
| 65 | 5E-05 | 16 | 51 | 403 | | | | |
| 65 | 5E-05 | 16 | 51 | 418 | | | | |
| 65 | 5E-05 | 16 | 51 | 439 | | | | |
| 65 | 5E-05 | 16 | 51 | 432 | 350 | Easterday | 75 | |
| 65 | 5E-05 | 16 | 51 | 511 | | | | |
| 65 | 5E-05 | 16 | 51 | 526 | | | | |
| 65 | 5E-05 | 16 | 51 | 547 | | | | |
| 65 | 5E-05 | 16 | 51 | 672 | 590 | Kim | 76 | |
| 65 | 5E-05 | 16 | 51 | 751 | | | | |
| 65 | 5E-05 | 16 | 51 | 766 | | | | |
| 65 | 5E-05 | 16 | 51 | 787 | | | | |
| 65 | 5E-05 | 16 | 51 | 1782 | 1700 | Canada Hill | 0 | |
| 65 | 5E-05 | 16 | 51 | 1861 | | | | |
| 65 | 5E-05 | 16 | 51 | 1876 | | | | |
| 65 | 5E-05 | 16 | 51 | 1897 | | | | |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | |
| | | | | | | | | Error |
| $S_{82}$ = | 65.0 | 3.47 | = | 226 | | WTP/Backup | 155 | 28% |
| $S_{161}$ = | 65.0 | 2.88 | = | 187 | | | 155 | 18% |
| $S_{176}$ = | 65.0 | 2.81 | = | 182 | | | 155 | 15% |
| $S_{197}$ = | 65.0 | 2.71 | = | 176 | | | 155 | 12% |
| $S_{177}$ = | 65.0 | 2.80 | = | 182 | | Weirer | 150 | 18% |
| $S_{256}$ = | 65.0 | 2.48 | = | 161 | | | 150 | 7% |
| $S_{271}$ = | 65.0 | 2.43 | = | 158 | | | 150 | 5% |
| $S_{292}$ = | 65.0 | 2.37 | = | 154 | | | 150 | -3% |
| $S_{324}$ = | 65.0 | 2.28 | = | 148 | | Mangiafico | 79 | 47% |
| $S_{403}$ = | 65.0 | 2.09 | = | 136 | | | | 42% |
| $S_{418}$ = | 65.0 | 2.06 | = | 134 | | | | 41% |
| $S_{439}$ = | 65.0 | 2.01 | = | 131 | | | | 40% |
| $S_{432}$ = | 65.0 | 2.03 | = | 132 | | Easterday | 75 | 43% |
| $S_{511}$ = | 65.0 | 1.88 | = | 122 | | | | 39% |
| $S_{526}$ = | 65.0 | 1.86 | = | 121 | | | | 38% |
| $S_{547}$ = | 65.0 | 1.82 | = | 118 | | | | 36% |
| $S_{672}$ = | 65.0 | 1.64 | = | 107 | | Kim | 76 | 29% |
| $S_{751}$ = | 65.0 | 1.55 | = | 101 | | | | 25% |
| $S_{766}$ = | 65.0 | 1.53 | = | 99 | | | | 23% |
| $S_{787}$ = | 65.0 | 1.51 | = | 98 | | | | 22% |
| | | | | | | 1/4L = 82 ft | Avg | 33% |
| | | | | | | 1/4L = 161 ft | | 26% |
| | | | | | | 1/4L = 176 ft | | 24% |
| | | | | | | 1/4L = 197 ft | | 23% |
| $S_{1782}$ = | 65.0 | 0.80 | = | 52 | | Canada Hill | 0 | N/A |
| $S_{1861}$ = | 65.0 | 0.76 | = | 49 | | | | |
| $S_{1876}$ = | 65.0 | 0.76 | = | 49 | | | | |
| $S_{1897}$ = | 65.0 | 0.74 | = | 48 | | | | |

The hydraulic factors derived from the simulations using the late-time data (T = 65 gpd/ft, S = 5E-5 and ¼ L = 82, 161, 176 and 197 ft) were then used to estimate the drawdowns that would have occurred at the end of the 51-d test. The results are shown in Table 4a, indicating that the individual errors in estimating the drawdowns varied from -3% to 47%, with absolute overall averages of 23% to 33%. The drawdown, however, in the Canada Hill well was 48 to 52 ft compared to the measured value of 0 ft. The unreasonable calculated drawdown in the Canada Hill wells is important because it indicated that the no-flow boundary condition at that point was violated, and the model is not reliable when using the constants for that simulation. Şen (1992) indicated that while fracture length is not directly related to transmissivity, it can affect the storage constant by as much as an order of magnitude. By an iterative method, a S of 3E-4 provided reasonably good fits to the drawdown data, Table 4b. The best overall fit to the data was achieved by assuming a L equal to 464 ft, producing an overall absolute error of 14%. The L value is reasonable since it is between the measured combined L of 560 ft and the L of 385 ft derived from vector analysis.

There are several observations that can be taken from the results of the testing and analysis of data from the WTP well tests. The aquifer functions as two layers of differing hydraulic characteristics. One explanation is that an upper 100-150 ft layer has a higher T value and probably exists under effective confined conditions. The deeper layer has a lower T value and, due to aquifer dewatering, is semi-confined. A second possibility is that there is a lateral variation in hydraulic properties, in that there is a high T in the vicinity (about 100 ft) of the fracture and a low T off the fracture trend. Several factors support the second hypothesis. The driller's log indicates that in the WTP well there is only 20 ft of overburden and below that depth is the un-weathered, crystalline Catoctin Metabasalt (Green Mountain Rock), while the reported static water level was 25 ft. In addition, the Kim, Mangiafico, and Weirer and WTP back-up wells' static water levels were all below the depth of the overburden. One exception was the Easterday well; however, the drawdowns measured in that well during the 54-hr test were unreliable and the weathered zone was dewatered during the 51-d test. It then appears that any weathered zone is thin and may have been unsaturated. Other supporting evidence was gained during testing of the nearby Canada Hill wells. A T of 161 gpd/ft was derived from testing of Canada Hill well 1 (FR-88-3098), located at the intersection of two fracture traces, while a T of 68 gpd/ft was derived from the testing of Canada Hill well 2 (FR-88-3400), located off the fracture traces. Those results were nearly the same as the early- and late-time T values calculated from the 54-hr test of the WTP well.

Finally, it is noted that the calculated S constant from the long-term operational test was about ½ order of magnitude more than that from the initial aquifer test. As indicated by Şen (1994) this may be "Due to elastic lag in confined aquifers and especially capillary fringe lag in unconfined aquifers" and/or the effect of a discrete fracture on groundwater flow.

The best calculated L of 464 ft is more than the L derived from the SVF-F solution (300 ft) or the L derived by vector analysis (385 ft); but less than the composite L of 560 ft obtained from the geophysical survey. In this case, L is about 50% greater than the SVF-F solution, suggesting than under typical test conditions, there will be a substantial error in derived L values. Under most field conditions, there will not be detailed geophysical surveys conducted. In those cases, it is expected that the errors in estimating drawdowns in potentially impacted wells could be greater than 25% and may exceed 50%.

**Table 4b.** Time-distance-drawdown calculations 51d test using ¼ L model.

| T | S | Q | t | x | D | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | ft | Well | ft | |
| | | | | | | | | |
| 65 | 3.0E-04 | 16 | 51 | 82 | 0 | WTP/Backup | 155 | |
| 65 | 3.0E-04 | 16 | 51 | 116 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 161 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 176 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 197 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 177 | 95 | Weirer | 150 | |
| 65 | 3.0E-04 | 16 | 51 | 211 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 256 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 271 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 292 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 324 | 242 | Mangiafico | 79 | |
| 65 | 3.0E-04 | 16 | 51 | 358 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 403 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 418 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 439 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 432 | 350 | Easterday | 75 | |
| 65 | 3.0E-04 | 16 | 51 | 466 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 511 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 526 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 547 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 672 | 590 | Kim | 76 | |
| 65 | 3.0E-04 | 16 | 51 | 706 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 751 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 766 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 787 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 1782 | 1700 | Canada Hill | 0 | |
| 65 | 3.0E-04 | 16 | 51 | 1816 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 1861 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 1876 | | | | |
| 65 | 3.0E-04 | 16 | 51 | 1897 | | | | |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | | = | s | | | |
| | | | | | | | | Error |
| $S_{82}$ = | 65.0 | 2.69 | = | 175 | | WTP/Backup | 155 | 11% |
| $S_{116}$ = | 65.0 | 2.39 | = | 155 | | | | 0% |
| $S_{161}$ = | 65.0 | 2.11 | = | 137 | | | | -13% |
| $S_{176}$ = | 65.0 | 2.03 | = | 132 | | | | -17% |
| $S_{197}$ = | 65.0 | 1.93 | = | 126 | | | | -23% |
| $S_{207}$ = | 65.0 | 2.02 | = | 132 | | Weirer | 150 | -14% |
| $S_{241}$ = | 65.0 | 1.87 | = | 122 | | | | -23% |
| $S_{286}$ = | 65.0 | 1.70 | = | 111 | | | | -35% |
| $S_{301}$ = | 65.0 | 1.65 | = | 108 | | | | -39% |
| $S_{322}$ = | 65.0 | 1.59 | = | 103 | | | | -46% |
| $S_{324}$ = | 65.0 | 1.50 | = | 97 | | Mangiafico | 79 | 19% |
| $S_{358}$ = | 65.0 | 1.41 | = | 92 | | | | 14% |
| $S_{403}$ = | 65.0 | 1.31 | = | 85 | | | | 7% |
| $S_{418}$ = | 65.0 | 1.28 | = | 83 | | | | 5% |
| $S_{439}$ = | 65.0 | 1.24 | = | 80 | | | | 1% |
| $S_{432}$ = | 65.0 | 1.25 | = | 81 | | Easterday | 75 | 7% |
| $S_{4662}$ = | 65.0 | 1.18 | = | 77 | | | | 3% |
| $S_{511}$ = | 65.0 | 1.10 | = | 72 | | | | -4% |
| $S_{526}$ = | 65.0 | 1.08 | = | 70 | | | | -7% |
| $S_{547}$ = | 65.0 | 1.04 | = | 68 | | | | -10% |
| $S_{727}$ = | 65.0 | 0.87 | = | 56 | | Kim | 76 | -36% |
| $S_{761}$ = | 65.0 | 0.82 | = | 53 | | | | -43% |
| $S_{806}$ = | 65.0 | 0.77 | = | 50 | | | | -52% |
| $S_{821}$ = | 65.0 | 0.75 | = | 49 | | | | -55% |
| $S_{842}$ = | 65.0 | 0.73 | = | 47 | | | | -62% |
| $S_{1837}$ = | 65.0 | 0.02 | = | 1 | | Canada Hill | 0 | 0% |
| $S_{1861}$ = | 65.0 | 0.00 | = | 0 | | | | |
| $S_{1916}$ = | 65.0 | -0.02 | = | -1 | | | | |
| $S_{1931}$ = | 65.0 | -0.03 | = | -2 | | | | |
| $S_{1930}$ = | 65.0 | -0.04 | = | -2 | | | | |
| | | | | | | 1/4L = 82 ft | Avg | 15% |
| | | | | | | 1/4L = 116 ft | Avg | 14% |
| | | | | | | 1/4L = 161 ft | Avg | 19% |
| | | | | | | 1/4L = 176 ft | Avg | 23% |
| | | | | | | 1/4L = 197 ft | Avg | 24% |

# Middletown

## Municipal Well 17

Middletown's well 17 was completed in the crystalline rock Catoctin Metabasalt. An initial, 96-hour, 41-gpm aquifer test was conducted on that well, while monitoring the Town's well 14 and three nearby domestic wells. As a condition of the associated water use permit, a follow-on, 60-day, 30-gpm test was performed, while monitoring wells 14 and 17, and six domestic wells within 1300 feet of well 17, Figure 8.

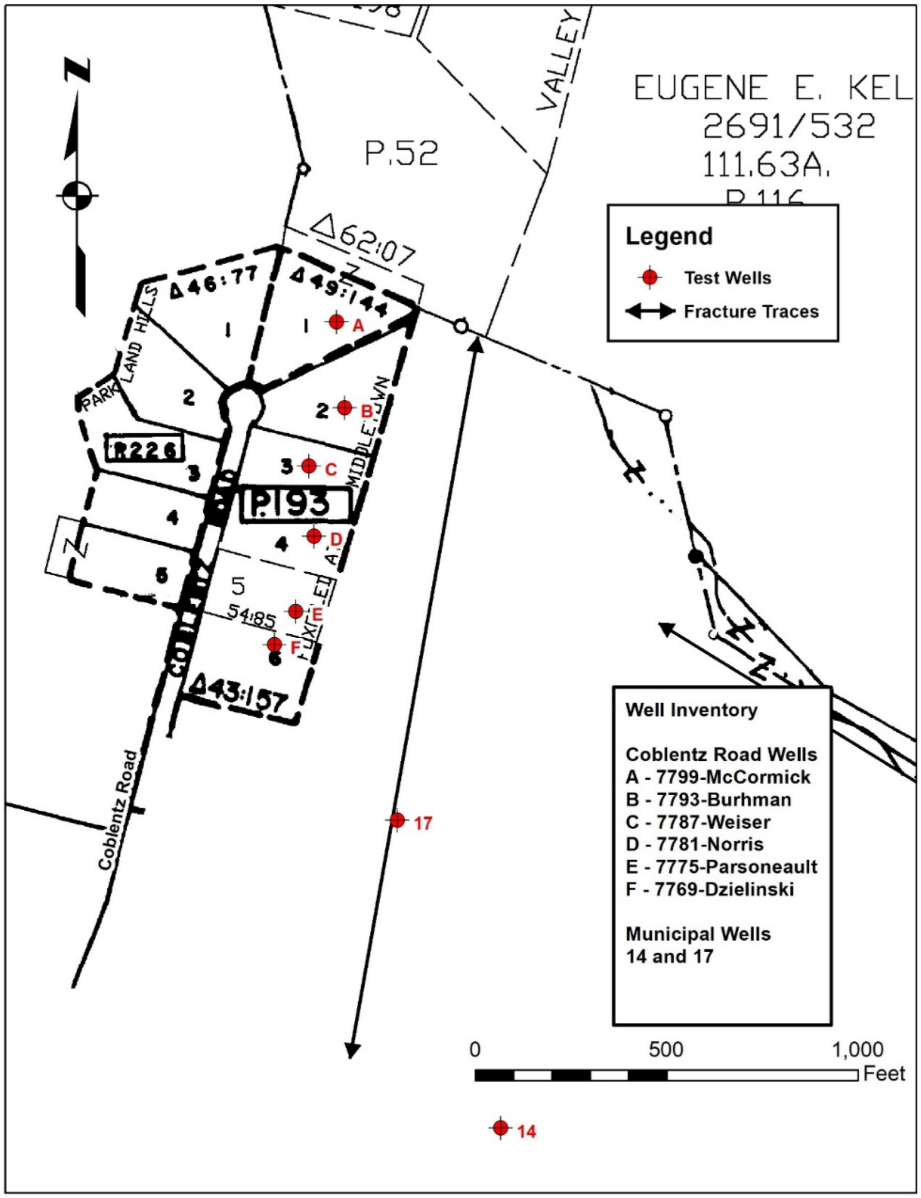

**Figure 8.** Location map. Middletown well 17 aquifer tests.

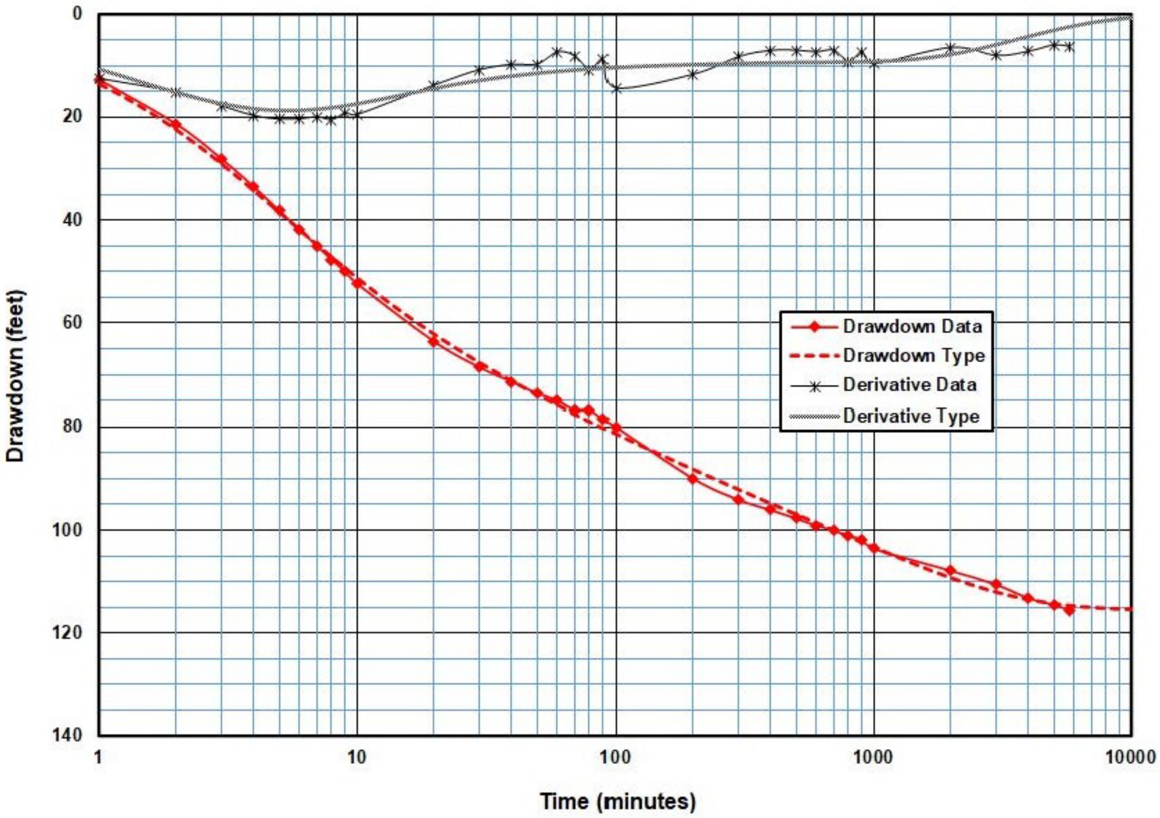

**Figure 9.** Middletown well 17. Semi-log plot of drawdown and derivative data from a 6-h, 41 gpm aquifer test. Moench Type III type solution.

The only useful data during the 96-hour test were taken from well 17 and the Norris domestic well. The water levels data in the Dzielinski and Parsoneault domestic wells were significantly affected by household use, so hydraulic constants could not be derived from those data. The drawdowns in those two wells at the end of the test were about 2-3 feet, which were substantially less than the 17 feet in the Norris well, although they were much closer to the pumping well. This suggested that a discrete fracture, or combination of fractures, might be affecting groundwater flow and that the fracture was much closer to the Norris well than the other two domestic wells. The data from Well 14 was unusable since it was shut down just prior to the test and its water level continued to recover throughout the pumping period.

The best fit to the Well 17 data was achieved using the Moench Type 3 leaky aquifer model, Moench (1984), Figure 9, producing a T value of 262 gpd/ft. For the Norris well data, the best overall solution was made using the SVF-F model, Figure 10, from which a T of 1243 gpd/ft and an S of 1E-4 were derived.

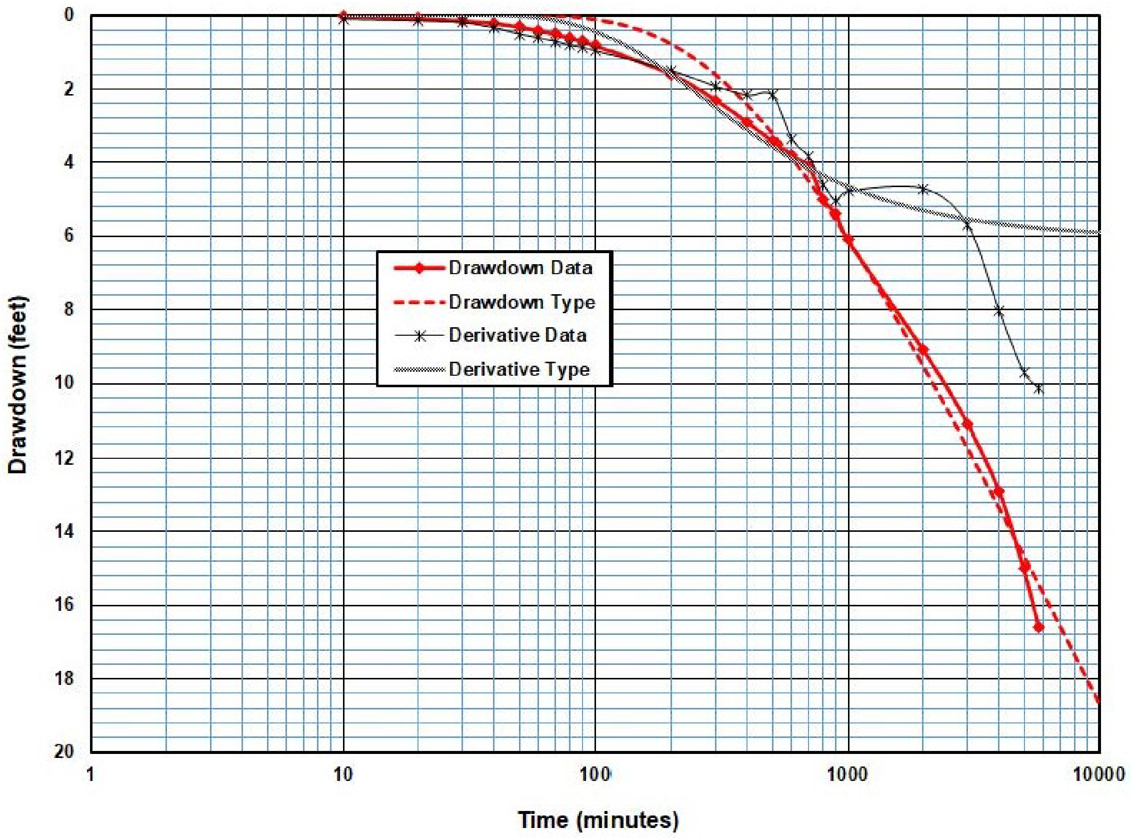

**Figure 10.** Norris domestic well. Semi-log plot of drawdown and derivative data from a 96-h, 41 gpm aquifer test of Middletown well 17. Gringarten-Witherspoon SVF-F solution.

The complete results of the analyses of the drawdown data measured in well 17 and the Norris well are given in Table 5. Using the calculated T values and adjusting the S values, matches to the observed drawdowns at the end of the 96-hour test in well 17 and the Norris well, with an estimated length for the primary fracture was 200 feet, derived using the ¼ fracture length model; however, the drawdowns in the Dzielinski and Parsoneault wells were substantially over-estimated (by 367%), Table 6.

Better water level data were obtained during the follow-on, 30-gpm, 60-day test. Well 14 and the Norris well remained unused throughout that test, Figure 11. Of special note is that the drawdowns in the most distance house wells (1200-1300 ft from the pumping well: Buhrman and McCormick) were much greater than the nearest house wells (570-620 ft from the pumping well: Dzielinski and Parsoneault), which indicated that a prominent discrete fracture was controlling groundwater flow in the vicinity of the test wells.

**Table 5.** Results of AQTESOLV analyses of the Middletown well 17 96-h and 60-d tests.

| Test-Obs Well | T | S | r | Bedrock | Swl | b | Final W/L | s | t | Model | DERIV | RSS | Var | S.D. | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | gpd/ft | | ft | ft | ft | ft | ft | ft | min | | | ft$^2$ | ft$^2$ | ft | ft |
| **WELL 17; 96-hr, 41-gpm TEST** | | | | | | | | | | | | | | | |
| Well 17 | 262 | - | 0 | | | | | 116 | 0-5760 | Moench3 | Leaky | 34 | 1.16 | 1.08 | -0.061 |
| | | | | | | | | | | | | | | | |
| Norris Well; 7781 Coblentz | 1466 | 0.0001 | 770 | | | | | 6 | 0-1000 | Moench3 | Leaky | 1.03 | 0.06 | 0.025 | 0.068 |
| | 1243 | 9.6E-05 | 770 | | | | | 17 | 1000-5760 | SVF-F | Linear | 1.7 | 0.85 | 0.92 | 0.015 |
| **WELL 17; 60-day, 30-gpm TEST** | | | | | | | | | | | | | | | |
| Well 17 | 714 | - | 0 | 5 | 44 | -39 | 114 | 70 | 30-4000 | Moench3 | Leaky | 8.4 | 0.07 | 0.27 | -0.0005 |
| | 69 | - | 0 | 5 | 44 | -39 | 201 | 157 | 30K-86.4K | SVF | SVF | 827 | 0.33 | 0.58 | -0.0097 |
| | | | | | | | | | | | | | | | |
| Well 14 | 1359 | 3E-05 | 850 | 54 | 21 | 33 | 29 | 8 | 0-2000 | Moench3 | Leaky | 0.28 | 0.007 | 0.08 | 0.005 |
| | 157 | 3E-04 | 850 | 54 | 21 | 33 | 80 | 59 | 20K-86.4K | SVF | Linear | 8.6 | 0.57 | 0.76 | 0.014 |
| | | | | | | | | | | | | | | | |
| Norris Well; 7781 Coblentz | 1312 | 8E-05 | 770 | 72 | 40 | 32 | | 4 | 0-1000 | Moench3 | leaky | 0.47 | 0.008 | 0.09 | 0.0004 |
| | 188 | 1E-04 | 770 | 72 | 40 | 32 | 99 | 59 | 20K-86.4K | Cooper-Jacob | - | 4589 | 1.22 | 1.1 | -2E-06 |
| | 165 | 3E-04 | 770 | 72 | 40 | 32 | 99 | 59 | 2K-86.4K | SVF | Linear | 6542 | 1.33 | 1.15 | 0.39 |
| | | | | | | | | | | | | | | | |
| Dzielinski Well; 7769 Coblentz | 439 | 1E-03 | 570 | 70 | 41 | 29 | 63 | 22 | 20K-86.4K | Cooper-Jacob Straight Line Fit | - | 3E+04 | 7.8 | 2.8 | 2E-08 |
| Parsoneault Well; 7775 Coblentz | 330 | 1E-03 | 620 | 80 | 47 | 33 | 73 | 26 | | | - | 4E+04 | 7.9 | 2.8 | 6E-09 |
| Weiser Well; 7787 Coblentz | 191 | 2E-04 | 940 | 64 | 54 | 10 | 108 | 54 | | | - | 866 | 0.20 | 0.44 | 1E-08 |
| Burhman Well; 7793 Coblentz | 125 | 1E-04 | 1100 | 34 | 70 | -36 | 148 | 78 | | | - | 5504 | 1.25 | 1.12 | 2E-09 |
| McCormick Well; 7799 Coblentz | 140 | 8E-05 | 1300 | 71 | 95 | -24 | 167 | 72 | | | - | 9643 | 2.18 | 1.48 | -6E-08 |
| | | | | | | | | | | | | | | | |
| Weiser Well; 7787 Coblentz | 1649 | 8E-05 | 940 | 64 | 54 | 10 | 59 | 5 | 0-2000 | SVF | linear | 25 | 0.19 | 0.44 | 0.05 |
| Burhman Well; 7793 Coblentz | 1232 | 1E-04 | 1100 | 34 | 70 | -36 | 74 | 4 | | | linear | 4.6 | 0.04 | 0.19 | 0.03 |
| McCormick Well; 7799 Coblentz | 1504 | 1E-05 | 1300 | 71 | 95 | -24 | 103 | 8 | | | linear | 61 | 0.47 | 0.69 | -0.002 |
| | | | | | | | | | | | | | | | |
| Dzielinski Well; 7769 Coblentz | 555 | 5E-04 | 570 | 70 | 41 | 29 | 63 | 22 | 0-86.4K | SVF | erratic | 5.E+04 | 8.0 | 2.8 | 0.08 |
| Parsoneault Well; 7775 Coblentz | 536 | 1E-03 | 620 | 80 | 47 | 33 | 73 | 26 | | | erractic | 4.E+04 | 7.1 | 2.7 | 0.10 |
| Weiser Well; 7787 Coblentz | 221 | 7E-05 | 940 | 64 | 54 | 10 | 108 | 54 | | | linear | 4.E+03 | 0.8 | 0.9 | 0.10 |
| Burhman Well; 7793 Coblentz | 127 | 1E-04 | 1100 | 34 | 70 | -36 | 148 | 78 | | | linear | 1.E+04 | 2.1 | 1.4 | 0.11 |
| McCormick Well; 7799 Coblentz | 138 | 9E-05 | 1300 | 71 | 95 | -24 | 167 | 72 | | | linear | 2.E+04 | 4.0 | 2.0 | 0.20 |
| | | | | | | | | | | | | | | | |
| Dzielinski Well; 7769 Coblentz | 560 | 1E-03 | 570 | 70 | 41 | 29 | 63 | 22 | 10k-86.4K | SVF | erratic | 4.E+04 | 7.9 | 2.8 | 0.001 |
| Parsoneault Well; 7775 Coblentz | 536 | 1E-03 | 620 | 80 | 47 | 33 | 73 | 26 | | | erractic | 4.E+04 | 7.2 | 2.7 | 0.009 |
| Weiser Well; 7787 Coblentz | 221 | 2E-04 | 940 | 64 | 54 | 10 | 108 | 54 | | | linear | 1.E+03 | 0.3 | 0.52 | -0.006 |
| Burhman Well; 7793 Coblentz | 117 | 1E-04 | 1100 | 34 | 70 | -36 | 148 | 78 | | | linear | 6.E+03 | 1.3 | 1.12 | 0.015 |
| McCormick Well; 7799 Coblentz | 138 | 1E-03 | 1300 | 71 | 95 | -24 | 167 | 72 | | | linear | 1.E+04 | 2.1 | 1.5 | -0.002 |

**Table 6.** Time-distance-drawdown calculations 4d test well 17 using ¼ L model.

| T | S | 2.0E-05 | t | x | x = 1/4L+d | Drawdowns | | r | d |
|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | Well | ft | ft | ft |
| | | | | | | | | | |
| 262 | 1.0E-05 | 41 | 4 | 230 | L=920ft | Well 17 | 116 | 0.3 | 0 |
| 1243 | 1.0E-04 | 41 | 4 | 330 | 1/4L=230ft | Norris | 17 | 770 | 100 |
| 1243 | 1.0E-04 | 41 | 4 | 630 | | Dzielinski | 3 | 570 | 400 |
| 1243 | 1.0E-04 | 41 | 4 | 580 | | Parsoneault | 3 | 620 | 350 |
| | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | |
| | | | | | error | | | | |
| $S_{230}$ = | 41.3 | 2.77 | = | 115 | 1% | Well 17 | 116 | | |
| $S_{330}$ = | 8.7 | 2.14 | = | 19 | -12% | Norris | 17 | 770 | 100 |
| $S_{630}$ = | 8.7 | 1.57 | = | 14 | -367% | Dzielinski | 3 | 570 | 400 |
| $S_{580}$ = | 8.7 | 1.65 | = | 14 | -367% | Parsoneault | 3 | 620 | 350 |

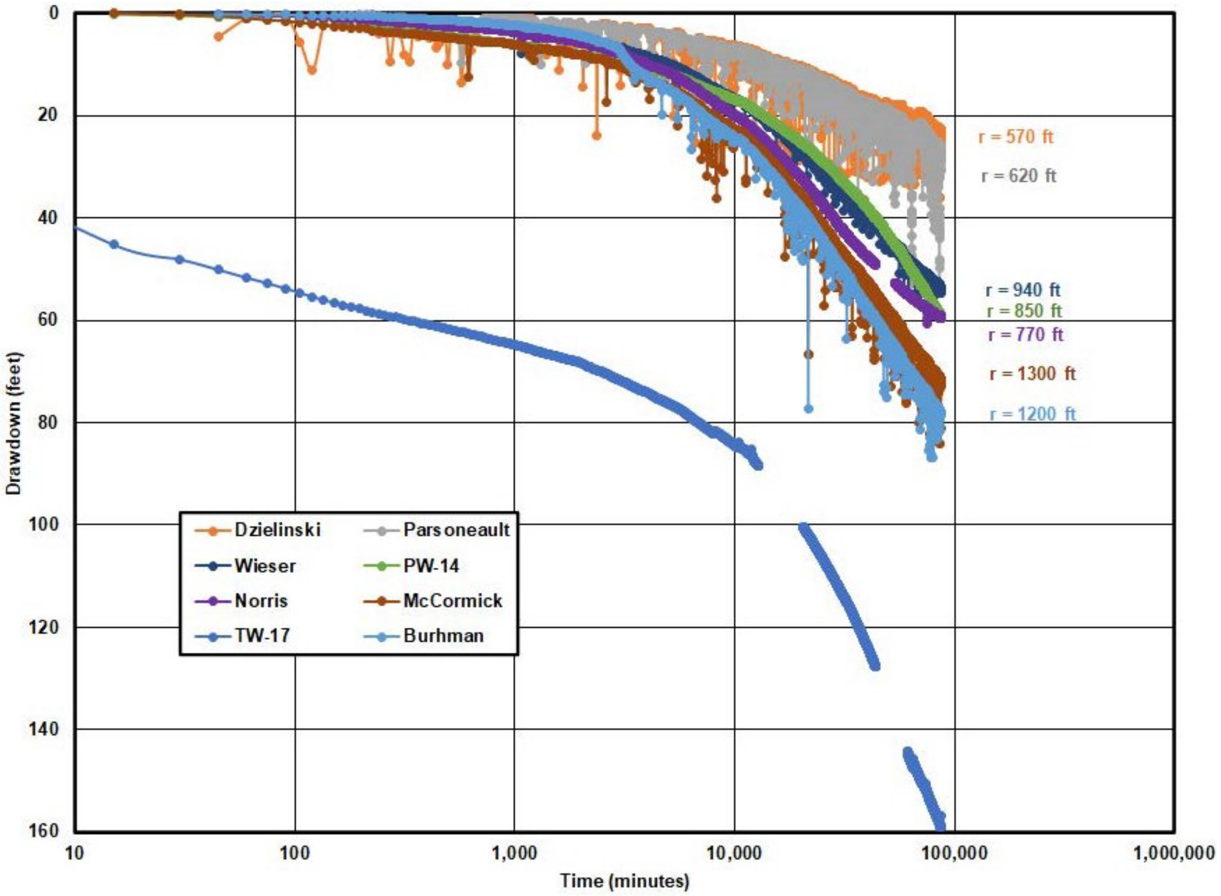

**Figure 11.** Middletown well 17. Semi-log plot of drawdown and derivative data for pumping well TW-17 and observation wells from a 60-d, 30 gpm aquifer test.

The aquifer constants derived from the 60-day test are shown in Table 5. Due to the erratic data collected in several of the house wells, the Cooper-Jacob straight-line method was initially used to calculate aquifer constants from the late-time data for the period of 20,000 to 86,400 minutes. There were two segments in the drawdown curves derived for each well. The early-time (0 to 1000-4000 minutes) T values were 714, 1359, and 1312 gpd/ft for well 17, well 14 and the Norris well, respectively. The S values were 3E-5 for well 14 and 8E-5 for the Norris well. From the late-time (2,000-30,000 to 86,400 minutes) data, T values were 67, 157 and 165 gpd/ft for well 17, well 14 and the Norris well, respectively. The S values were 3E-4 for well 14 and 3E-4 for the Norris well. The late time decline in the T values and increase in the S values was most likely related to dewatering of the weathered portion of the aquifer. The late-time T and S values in the five remaining domestic wells are like those for well 14 and the Norris well, except for the Dzielinski and Parsoneault wells, which had higher T (344 and 360 gpd/ft) and S values (1E-3 each). This could provide an explanation for the smaller drawdowns observed in those wells relative to the Norris well and the inability to match estimated to observed drawdown when using the basic ¼ fracture length model, which assumes an isotropic aquifer.

**Table 7.** Time-distance-drawdown calculations 60d test well 17 using ¼ L model.

| T | S | Q | t | x | x = 1/4L+d | Drawdowns | | r | d |
|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | Well | ft | ft | ft |
| | | | | | | | | | |
| 262 | 1.0E-05 | 30 | 60 | 230 | L=920ft | Well 17 | 159 | 0.3 | 0 |
| 1243 | 1.0E-04 | 30 | 60 | 1080 | 1/4L=230ft | Well 14 | 58 | 850 | 850 |
| 1243 | 1.0E-04 | 30 | 60 | 560 | | Norris | 60 | 770 | 330 |
| 1243 | 1.0E-04 | 30 | 60 | 610 | | Dzielinski | 23 | 570 | 380 |
| 1243 | 1.0E-04 | 30 | 60 | 570 | | Parsoneault | 27 | 620 | 340 |
| 1243 | 1.0E-04 | 30 | 60 | 605 | | Weiser | 54 | 940 | 375 |
| 1243 | 1.0E-04 | 30 | 60 | 560 | | Burhman | 79 | 1100 | 330 |
| 1243 | 1.0E-04 | 30 | 60 | 710 | | McCormick | 71 | 1300 | 480 |
| | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | |
| | | | | | error | | | | |
| $S_{230}$ = | 30.2 | 3.95 | = | 119 | 33% | Well 17 | 159 | | |
| $S_{900}$ = | 6.4 | 2.28 | = | 15 | 287% | Well 14 | 58 | 850 | 425 |
| $S_{815}$ = | 6.4 | 2.85 | = | 18 | 233% | Norris | 60 | 770 | 340 |
| $S_{875}$ = | 6.4 | 2.78 | = | 18 | 28% | Dzielinski | 23 | 570 | 400 |
| $S_{825}$ = | 6.4 | 2.84 | = | 18 | 50% | Parsoneault | 27 | 620 | 350 |
| $S_{875}$ = | 6.4 | 2.79 | = | 18 | 200% | Weiser | 54 | 940 | 400 |
| $S_{805}$ = | 6.4 | 2.85 | = | 18 | 339% | Burhman | 79 | 1100 | 330 |
| $S_{855}$ = | 6.4 | 2.65 | = | 17 | 318% | McCormick | 71 | 1300 | 380 |

Table 7 provides the results of a simulation when applying the T and S values derived from the 96-h test to the drawdowns observed at the end of the 60-d test. That simulation produced exceptionally large errors between 28% and 339%. Better matches to the 60-d drawdowns were achieved by using the late-time T (69 gpd/ft) derived for well 17 and an average of 200 gpd/ft was used for the remaining wells. After adjusting the S values by iteration, good matches to the drawdown data were made for all wells (absolute average error of 24%), except for the Dzielinski and Parsoneault wells, the drawdowns which were overestimated by -57% and -52%, respectively, Table 8.

**Table 8.** Time-distance-drawdown calculations 60d test well 17 using adjusted ¼ L model.

| T | S | Q | t | x | x = 1/4L+d | Drawdowns | | r | d |
|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | Well | ft | ft | ft |
| | | | | | | | | | |
| 69 | 2.0E-04 | 30 | 60 | 475 | L=1900ft | Well 17 | 159 | 0.3 | 0 |
| 200 | 2.0E-04 | 30 | 60 | 900 | 1/4L = 475ft | Well 14 | 58 | 850 | 425 |
| 200 | 2.0E-04 | 30 | 60 | 815 | | Norris | 60 | 770 | 340 |
| 200 | 2.0E-04 | 30 | 60 | 875 | | Dzielinski | 23 | 570 | 400 |
| 200 | 2.0E-04 | 30 | 60 | 825 | | Parsoneault | 27 | 620 | 350 |
| 200 | 2.0E-04 | 30 | 60 | 875 | | Weiser | 54 | 940 | 400 |
| 200 | 2.0E-04 | 30 | 60 | 805 | | Burhman | 79 | 1100 | 330 |
| 200 | 2.0E-04 | 30 | 60 | 855 | | McCormick | 71 | 1300 | 380 |
| | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | |
| | | | | | error | | | | |
| $S_{475}$ = | 114.8 | 1.44 | = | 165 | -4% | Well 17 | 159 | | |
| $S_{900}$ = | 39.6 | 1.35 | = | 53 | 9% | Well 14 | 58 | 850 | 425 |
| $S_{815}$ = | 39.6 | 1.43 | = | 57 | 5% | Norris | 60 | 770 | 340 |
| $S_{875}$ = | 39.6 | 1.37 | = | 54 | -57% | Dzielinski | 23 | 570 | 400 |
| $S_{825}$ = | 39.6 | 1.42 | = | 56 | -52% | Parsoneault | 27 | 620 | 350 |
| $S_{875}$ = | 39.6 | 1.37 | = | 54 | 0% | Weiser | 54 | 940 | 400 |
| $S_{805}$ = | 39.6 | 1.44 | = | 57 | 39% | Burhman | 79 | 1100 | 330 |
| $S_{855}$ = | 39.6 | 1.39 | = | 55 | 29% | McCormick | 71 | 1300 | 380 |

When the Single Vertical Fracture-Finite Conductivity (SVF-F) model was applied to the early time data (0 to 2000 minutes) from three house wells (Burhman, McCormick and Weiser) the T values were like those from the Norris well and well 14. At late time (0-86,400 minutes and 10,000 to 86,400 minutes), the results were also similar, except the Dzielinski (555-560 gpd/ft) and Parsoneault (536 gpd/ft) wells' values were higher than the Norris well (165 gpd/ft) and well 14 (157 gpd/ft).

As the Cooper-Jacob solution produced a slightly better statistical fit to the data than the SVF-F model, those values were used in a simulation of the drawdowns measured during the 60-d test, Table 9, and the S values were adjusted by iteration. This produced an exceptionally good fit to the drawdown data (absolute average error of 15%). Also produced was a much longer fracture (1900 feet). It was also noted that the ¼ L value of 475 feet produced a much more realistic S value (2.4E-4) than that achieved using the unrealistic calculated well-bore radius (605 feet), suggesting that ¼ L represented the effective well-bore radius of the pumping well.

**Table 9.** Time-distance-drawdown calculations 60d test well 17 using adjusted ¼ L model.

| T | S | Q | t | x | x = 1/4L+d | Map No. | Drawdowns |  | b | r | d |
|---|---|---|---|---|---|---|---|---|---|---|---|
| gpd/ft |  | gpm | day | ft |  |  | Well | ft | ft | ft | ft |
|  |  |  |  |  |  |  |  |  |  |  |  |
| 69 | 2.0E-04 | 30 | 60 | 475 | L=1900ft | 17 | Well 17 | 159 | 12 | 0.3 | 0 |
| 157 | 2.0E-04 | 30 | 60 | 900 |  | 14 | Well 14 | 58 | 10 | 850 | 425 |
| 188 | 3.0E-04 | 30 | 60 | 815 |  | D | Norris | 60 | 31 | 770 | 340 |
| 439 | 1.0E-03 | 30 | 60 | 875 |  | F | Dzielinski | 23 | 39 | 570 | 400 |
| 330 | 1.0E-03 | 30 | 60 | 825 |  | E | Parsoneault | 27 | 23 | 620 | 350 |
| 191 | 2.0E-04 | 30 | 60 | 875 |  | C | Weiser | 54 | 20 | 940 | 400 |
| 125 | 1.0E-04 | 30 | 60 | 805 |  | B | Burhman | 79 | -28 | 1100 | 330 |
| 140 | 8.0E-05 | 30 | 60 | 855 |  | A | McCormick | 71 | 4 | 1300 | 380 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s |  |  |  |  |  |  |  |
|  |  |  |  |  | error |  |  |  |  |  |  |
| $S_{475}$ = | 114.8 | 1.44 | = | 165 | -4% | 17 | Well 17 | 159 |  |  |  |
| $S_{900}$ = | 50.4 | 1.24 | = | 63 | 8% | 14 | Well 14 | 58 |  | 850 | 425 |
| $S_{815}$ = | 42.1 | 1.23 | = | 52 | -15% | D | Norris | 60 |  | 770 | 340 |
| $S_{875}$ = | 18.0 | 1.01 | = | 18 | -28% | F | Dzielinski | 23 |  | 570 | 400 |
| $S_{825}$ = | 24.0 | 0.94 | = | 23 | -17% | E | Parsoneault | 27 |  | 620 | 350 |
| $S_{875}$ = | 41.5 | 1.35 | = | 56 | 4% | C | Weiser | 54 |  | 940 | 400 |
| $S_{805}$ = | 63.4 | 1.54 | = | 98 | -19% | B | Burhman | 79 |  | 1100 | 330 |
| $S_{855}$ = | 56.6 | 1.63 | = | 92 | -23% | A | McCormick | 71 |  | 1300 | 380 |

The good fit of the ¼ L model to the drawdown achieved during the last simulation was largely due to the length of the test and the fortunate location of a fairly large number of observation wells near a relatively simple fracture system. The initial 96-hour test is more typical of those conducted in the fractured rock aquifers of Maryland. The substantial errors made estimating impacts to nearby water supplies from that test data is more like what should be expected. The final simulation also demonstrated that a single test can be affected by a significant number of flow control mechanisms that could be difficult to model using a single analytical solution. Table 10 provides the well construction characteristics of well 17 and the observations wells that might help explain the results of the investigation. The depth to bedrock in well 17 is 5 ft, followed by a limestone formation to a total depth of 500 ft, with a static water level (44 ft) below the top of bedrock. The initial 96-hr test results indicate that a low permeability leaky aquifer is present in the vicinity of well 17. During the 60-d test, the initial response (30-2000 minutes) reflected a leaky aquifer, while the late time drawdown data fit a SVF-F model with a low permeability (T = 69 gpd/ft). All the observation wells were completed in the crystalline rock Catoctin Metabasalt. Early time data (0-2000 minutes) from the 60-d test produced moderately high T values (1232-1649 gpd/ft) in all observation wells, except the Dzielinski and Parsonaeult wells, which both had highly erratic data. In two cases (Burhman and McCormick), the static water level was in bedrock indicating there may have been a lag in response to pumping from well 17. In all but two cases, any potential weathered zone was dewatered early during the 60-d test. The water level in those the Dzielinski and Parsoneault wells remained above bedrock during the test, which resulted in T values about twice those of the other observation wells.

**Table 10.** Well construction data for Middletown well 17 and observation wells.

| Well No. | Owner | Address | Depth | Rate | Casing | Bedrock | swl | b | Wbzs | Comp. | Map | Test | | | R=dist | Reported |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | gpm | ft | ft | ft | ft | ft | Date | ID | swl | Final w/l | D/D | ft | Problem |
| | | | | | | | | | | | | | | | | |
| FR-88-0944 | Dzielinski | 7769 Coblentz | 350 | 20 | 81 | 70 | 42 | 28 | 135-163-325 | 9/27/1989 | F | 41 | 63 | 22 | 570 | Turbidity |
| FR-88-0945 | Parsoneault | 7775 Coblentz | 100 | 30 | 71 | 70 | 44 | 26 | 80-90 | 9/23/1989 | E | N/R | 73E | 26E | 620 | Yield |
| FR-94-2863 | Parsoneault | 7775 Coblentz | 250 | 7 | 100 | 80 | 80 | 0 | 153-173 | 3/4/2002 | E | 47 | 73 | 26 | 620 | none |
| FR-88-0946 | Norris | 7781 Coblentz | 150 | 10 | 81 | 72 | 50 | 22 | 96-110 | 9/23/1989 | D | 40 | 99 | 59 | 770 | Hooked up |
| FR-88-0947 | Weiser | 7787 Coblentz | 150 | 20 | 72 | 64 | 52 | 12 | 110-125-140 | 9/23/1989 | C | 54 | 108 | 54 | 940 | Turbidity |
| FR-88-0948 | Buhrman | 7793 Coblentz | 250 | 15 | 42 | 34 | 70 | -36 | 74-79-200 | 9/23/1989 | B | 70 | 148 | 78 | 1100 | none |
| FR-88-0930 | McCormick | 7799 Coblentz | 250 | 15 | 82 | 71 | 86 | -15 | 205-215-244 | 9/23/1989 | A | 95 | 167 | 72 | 1300 | none |
| FR-94-1467 | Middletown | well 14 | 500 | 35 | 60 | 54 | 50 | 4 | 45-130-165 | 6/22/1999 | 14 | 21 | 80 | 59 | 850 | Interfers |
| FR-94-4362 | Middletown | well 17 | 500 | 41 | 60 | 4 | 48 | -44 | 175-245 | 11/22/2004 | 17 | 44 | 201 | 157 | 0 | N/A |

In this case, drawdowns during testing were affected by dewatering of the shallow portion of the aquifer, the presence of an extremely long fracture, and lateral variations in hydraulic constants along the primary axis of the trough of depression. The Norris residence was hooked up to the public water supply because of the substantial drawdown (17 ft) observed during the initial 96-h test. During the 60-d test, the water level data indicate that there were substantial drawdowns in the nearby wells from 23 feet (Dzeilinski well) to 78 feet (Buhrman well). None of the homeowners indicated having yield problems, except that Mr. Parsoneault reported that the shallow (100-foot) well that he uses for lawn irrigation went dry. From the water level in his potable well, the estimated final water level in the irrigation well (73 feet) was near the first water bearing zone (80 feet). When the potential drawdown due to the pumping of the Parsoneault well is considered, the is possible that the moderate drawdown of about 26 feet due to pumping of well 17 could have produced the dry irrigation well. This does not mean that the yields of the other wells did not decline. Extensive dewatering of an aquifer can cause well yields to decline, but in this case the yields may still have been more than needed for domestic use and the homeowners might not have noticed any decreased yields.

Complaints of turbidity problems were received from Mr. Dzielinski and Mr. Weiser. In the case of the Weiser well, the turbidity problem occurred as the water level approached the first water-bearing zone in that well at the end of the pumping phase. Dewatering may have produced turbulent flow in the fracture mobilizing sediment and transporting it to the wellbore. Mr. Weiser reported brownish orange water in his toilet on the day when the pumping phase ended on May 5, 2006. A red color is generally associated with iron, especially hematite, an iron oxide with little or no titanium. His well water was clear the next day. There were no reports of water samples taken or a history of well problems in the information submitted by the town.

The answer to turbidity problem in the Dzielinski well is more complex, as it occurred when the water level was still more than 70 above the first water-bearing zone in that well. Since most fractures in crystalline rock aquifer are vertical, it is possibly that the fracture was dewatered away from the well bore, producing the turbulent flow, suspending the sediment, which is then conducted either by turbulent of laminar flow through the fracture to the well bore. Another possibility is that the increased drawdown may have moved water with iron or manganese in solution under reducing conditions to the well bore, which then precipitated out as Fe or Mn oxides when exposed to air. However, Mr. Dzielinski first reported his problem occurred 11 days after the start of the test, while doing a substantial amount of laundry, and that the well problem was gone the by next day. He, also, indicated that the problem had occurred during pump replacement and after super-chlorination (on an annual basis). He reported having a second turbidity problem the following week, and then installed a different filter, which apparently solved the immediate problem. Water quality analyses indicate that his water supply was high in iron and manganese on 3-30-06 and within water quality standards on 4-30-06. Though not specifically stated, it appears that the first sample was taken before, and the second sample was taken after changing the filter. The sediment had a black color, which is typical of manganese, but is also the color of magnetite, an iron-titanium oxide.

## A.C. Jets project

The A.C. Jets project was a proposed subdivision to be annexed into the Town of Middletown, but, it has never been completed. Due to the extensive multi-well testing of 5 wells in the Catoctin Metabasalt and the significant distances at which drawdowns were observed, this makes it a useful project to include in the present study.

The 5 wells (TW-1, -2, -3, -5 and -8) were drilled and completed between 7/23/2004 and 4/22/2005. A 72-hr test was conducted on each, except TW-2, between 4/18/2005 and 5/20/2005, while monitoring 3 or 5 observation wells, at distances between 555 ft and 1760 ft from a pumping well. Table 11 provides the results of AQTESOLV analyses of the data collected from those tests, with applicable well construction characteristics.

The first test analyzed was the 72-hr, 50/75 gpm test of TW-8, conducted on 5/17/05-5/20/05, Figures 12 and 13. Wells TW-2, TW-3 and TW-5 were monitored as observation wells. TW-1 and DW-1 were also monitored, but there was no drawdown observed in either well. Prior to the change in rate to 75 gpm on the first day, a derivative analysis indicates that a leaky aquifer flow regime was present. The flow regime after the increase in the pumping rate cannot be directly determined, since time derivatives require a constant rate; however, the calculated T values for TW-8 before the change in (0-1440 min), after the change (1440-4320 min) and the entire test (0-4320 min) were nearly identical for all models that provided good fits to the data, suggesting that the flow regime did not change with the increased rate. Overall, the best fit to the full drawdown record was made using the Hantush-Jacob (1955) solution producing a T of 1095 gpd/ft. For the observation wells, the Moench Case 3 model provided the best fit, producing T values of 910-973 gpd/ft, although the Hantush-Jacob model also provided good fits to the data. There was no drawdown observed in wells TW-1 and DW-1 during the test, suggesting that there is a significant decline in permeability between those two wells and TW-8. The calculated Storage Constants (S) varies from 2E-5 to 1E-6.

**Table 11.** A.C. Jets wells. Well construction characteristics and results of aquifer tests. Best fits to data are highlighted in red.

| Test | Bedrock | Csg | SWL | b | Test SWL (ft) | | | | T | S | r | s | period | solution | model | RSS | Var | S.D. | Mean | wbz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Well 8; 72-hr, 50/75-gpm Test** | ft | ft | ft | ft | TW 8 | TW 1 | TW 3 | TW 5 | gpd/ft | | ft | ft | min | | | ft$^2$ | ft$^2$ | ft | ft | ft |
| TW-8 (FR-94-4563) | 40 | 51 | 45 | 0-6 | 10.3 | | | 8.2 | 682 | - | - | 78 | 0-4320 | Moench3 | Leaky | 482 | 1.02 | 1.01 | -0.033 | 68,174 |
| | | | | | | | | | 698 | - | - | 45 | 0-1440 | Moench3 | Leaky | 65 | 0.35 | 0.59 | -0.016 | |
| | | | | | | | | | 692 | - | - | 78 | 1440-4320 | Moench3 | Leaky | 71 | 0.25 | 0.50 | 0.128 | |
| | | | | | | | | | 1095 | - | - | 78 | 0-4320 | H-J | Leaky | 230 | 0.49 | 0.70 | -0.004 | |
| | | | | | | | | | 1019 | - | - | 45 | 0-1440 | H-J | Leaky | 18 | 0.01 | 0.31 | 0.011 | |
| | | | | | | | | | 1017 | - | - | 78 | 1440-4320 | H-J | Leaky | 95 | 0.34 | 0.58 | -0.0005 | |
| | | | | | | | | | 1116 | - | - | 78 | 0-4320 | G-R | SVF | 451 | 0.94 | 0.97 | -0.020 | |
| | | | | | | | | | 1127 | - | - | 45 | 10-1440 | G-R | SVF | 174 | 1.04 | 1.02 | 0.44 | |
| | | | | | | | | | 1114 | - | - | 78 | 1440-4320 | G-R | SVF | 257 | 0.89 | 0.95 | 0.036 | |
| TW-2 (FR-94-4113) | 70 | 80 | 44 | 26-36 | 42.5 | 33.3 | 38.1 | 39.9 | 910 | 1E-06 | 1315 | 29 | 0-4320 | Moench3 | Leaky | 21 | 0.05 | 0.21 | 0.024 | 89,113,130,189 |
| | | | | | | | | | 910 | 1E-06 | 1315 | 29 | 0-4320 | H-J | Leaky | 23 | 0.05 | 0.22 | 0.018 | |
| | | | | | | | | | 1183 | 9E-06 | 1315 | 29 | 0-4320 | G-R | SVF | 208 | 0.44 | 0.66 | 0.030 | |
| TW-3 (FR-94-4114) | 50 | 60 | 50 | 0-10 | 49.4 | 39.2 | 42.5 | 46.4 | 973 | 3E-06 | 1760 | 26 | 0-4320 | Moench3 | Leaky | 14 | 0.03 | 0.17 | 0.027 | 217,243,390 |
| | | | | | | | | | 1052 | 5E-06 | 1760 | 26 | 0-4320 | H-J | Leaky | 27 | 0.06 | 0.24 | 0.049 | |
| | | | | | | | | | 1285 | 6E-06 | 1760 | 26 | 0-4320 | G-R | SVF | 208 | 0.44 | 0.66 | -0.017 | |
| TW-5 (FR-94-4494) | N/R | 65 | N/R | N/R | 39.3 | 35.3 | 36.1 | 37.8 | 925 | 2E-05 | 770 | 25 | 0-4320 | Moench3 | Leaky | 14 | 0.03 | 0.17 | 0.008 | N/R |
| | | | | | | | | | 954 | 3E-05 | 770 | 25 | 0-4320 | H-J | Leaky | 19 | 0.04 | 0.21 | 0.024 | |
| | | | | | | | | | 1563 | 2E-05 | 770 | 25 | 0-4320 | G-R | SVF | 95 | 0.21 | 0.45 | -0.009 | |
| No drawdown in wells TW 1 and DW 1 | | | | | | | | | | | | | | | | | | | | |
| **TW 3; 72-hr, 20.4-gpm Test** | | | | | | | | | | | | | | | | | | | | |
| TW-3 (FR-94-4114) | 50 | 60 | 50 | 0-10 | 49.4 | 39.2 | 42.5 | 46.4 | 196 | - | | 77 | 0-4317 | Moench3 | Leaky | 465 | 0.91 | 0.95 | 0.139 | |
| | | | | | | | | | 196 | - | | 77 | 10-4317 | Moench3 | Leaky | 321 | 0.70 | 0.84 | -0.0014 | Best Visual |
| | | | | | | | | | 326 | - | | 77 | 10-4317 | H-J | Leaky | 330 | 0.72 | 0.85 | 0.0001 | |
| TW-2 (FR-94-4113) | | | | | | | | | 467 | 2E-05 | 555 | 21 | 50-4320 | Moench 3 | Leaky | 20 | 0.046 | 0.21 | -0.002 | |
| | | | | | | | | | 436 | 4E-06 | 555 | 21 | 50-4320 | H-J | Leaky | 25 | 0.057 | 0.24 | -0.0025 | |
| TW-5 (FR-94-4494) | | | | | | | | | 1004 | 2E-05 | 1,167 | 7 | 50-4320 | Moench 3 | Leaky | 1.4 | 0.003 | 0.06 | -0.001 | |
| | | | | | | | | | 982 | 2E-05 | 1,167 | 7 | 50-4320 | H-J | Leaky | 1.5 | 0.003 | 0.06 | -0.0017 | |
| **TW 5; 72-hr, 30.5-gpm Test** | | | | | | | | | | | | | | | | | | | | |
| TW-5 (FR-94-4494) | N/R | 65 | N/R | N/R | 39.3 | 35.3 | 36.1 | 37.8 | 207 | - | | 91 | 0-1000 | Moench3 | Leaky | 716 | 3.94 | 1.98 | 0.659 | |
| | | | | | | | | | 258 | - | | 91 | 0-1000 | H-J | Leaky | 451 | 2.47 | 1.57 | 0.236 | |
| TW-2 (FR-94-4113) | | | | | | | | | 557 | 4E-05 | 630 | 17 | 100-4320 | Moench | Leaky | 23 | 0.045 | 0.21 | -0.006 | |
| | | | | | | | | | 533 | 4E-05 | 630 | 17 | 100-4320 | H-J | Leaky | 25 | 0.049 | 0.22 | -0.008 | |
| TW-3 (FR-94-4114) | | | | | | | | | 796 | 2E-05 | 1167 | 10 | 0-4320 | Moench | Leaky | 1.3 | 0.002 | 0.05 | -0.002 | |
| | | | | | | | | | 1025 | 3E-05 | 1167 | 10 | 0-4320 | H-J | Leaky | 1.9 | 0.004 | 0.06 | -0.003 | |
| TW-8 (FR-94-4563) | | | | | | | | | 1049 | 2E-05 | 770 | 10 | 0-4320 | Moench | Leaky | 14 | 0.027 | 0.16 | -0.010 | |
| | | | | | | | | | 1166 | 3E-05 | 770 | 10 | 0-4320 | H-J | Leaky | 12 | 0.023 | 0.15 | -0.005 | |
| **TW 1; 72-hr, 39-gpm Test** | | | | | | | | | | | | | | | | | | | | |
| TW-1 (FR-94-4112); 72-hr, 39-gpm | 70 | 80 | 47 | 23-33 | 42.8 | 42.5 | 43.4 | 41.9 | 213 | - | | 4 | 0-2 | Moench3 | Leaky | 0.44 | 0.029 | 0.17 | -0.013 | 110,135,165,200 |
| | | | | | | | | | 34 | - | | 48 | 400-4320 | Moench3 | Leaky | 5.7 | 0.015 | 0.12 | -0.005 | |
| | | | | | | | | | 3990 | - | | 6 | 0-10 | H-J | Leaky | 1.9 | 0.038 | 0.19 | 0.037 | |
| | | | | | | | | | 365 | - | | 48 | 400-4320 | H-J | Leaky | 58 | 0.148 | 0.38 | -0.030 | |
| | | | | | | | | | 768 | - | | 48 | 30-4320 | G-R | SVF | 459 | 1.04 | 1.02 | -0.034 | |
| No drawdown observed in TW-2, TW-3 & TW-5 | | | | | | | | | | | | | | | | | | | | |

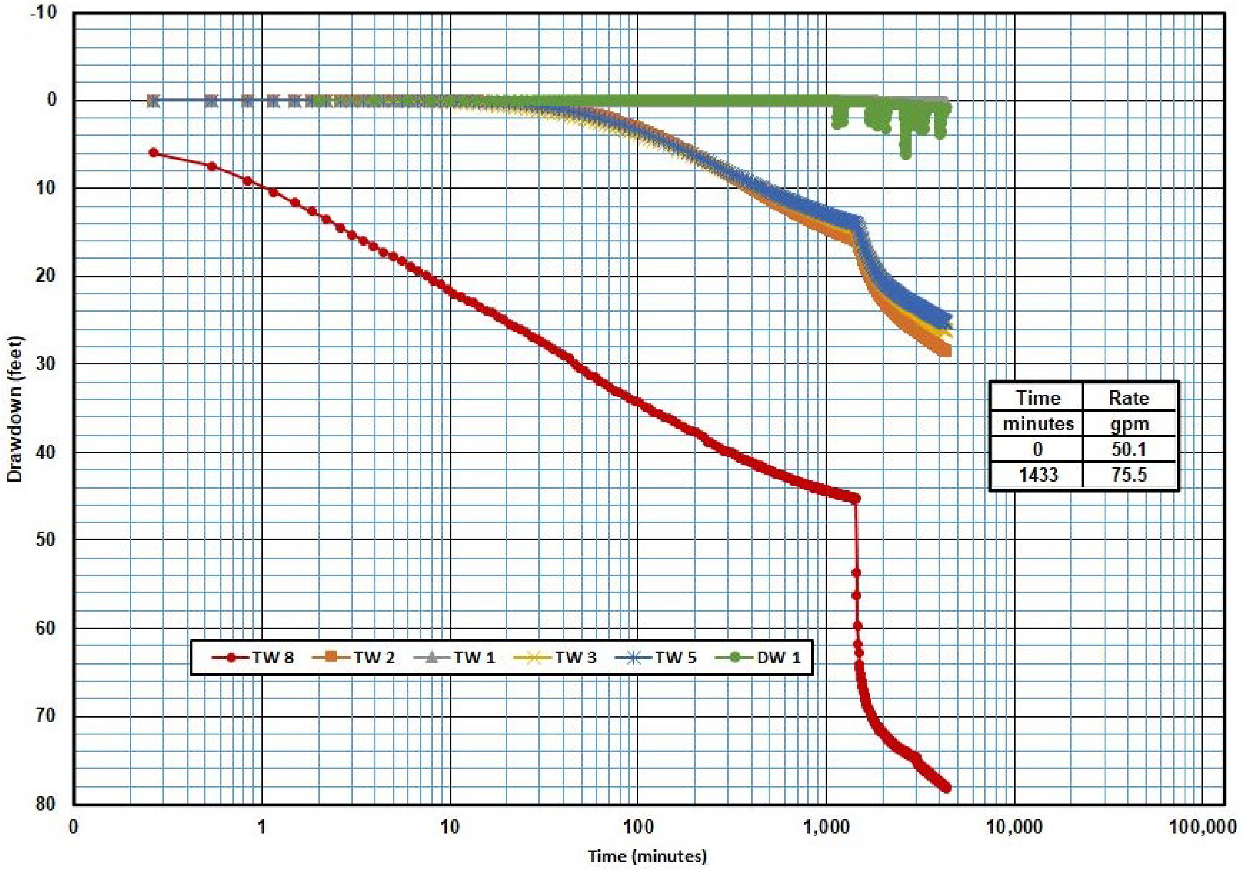

**Figure 12.** Middletown A.C. Jets TW-8. Semi-log plot of drawdown for pumping well TW-8 and observation wells from a 72-h, 50.1/75.5-gpm aquifer test.

A 72-hr, 20.4 gpm test of TW-3 was conducted on 4/26/05-4/29/05, while monitoring observation wells TW-2 and TW-5, Figure 14. The T value for TW-3 (196 gpd/ft) was much less than that from the test of TW-8 (973 gpd/ft). One explanation is that the T from the TW-8 test represents the average value between TW-8 and TW-3, while the lower T from the TW-3 test reflects a lower permeability in the immediate vicinity of TW-3 and the potential effects of aquifer dewatering, as the drawdown in TW-3 (77 ft) was much greater than the drawdown observed during the test of TW-8 (26 ft). The T value for TW-2 was higher (467 gpd/ft) but less than that from the test of TW-8 (910 gpd/ft), suggesting that the aquifer between TW-2 and TW-3 has a lower permeability than that between TW-2 and TW-8. The S for TW-2 (2E-5) is higher than that from the TW-8 test (1E-6). The T for TW-5 (1004 gpd/ft) is somewhat higher than that of the TW-8 test (925 gpd/ft), while the S (2E-5) is the same as that from the TW-8 test, suggesting that the aquifer between TW-5 and TW-3, and between TW-5 and TW-8 has similar hydraulic characteristics.

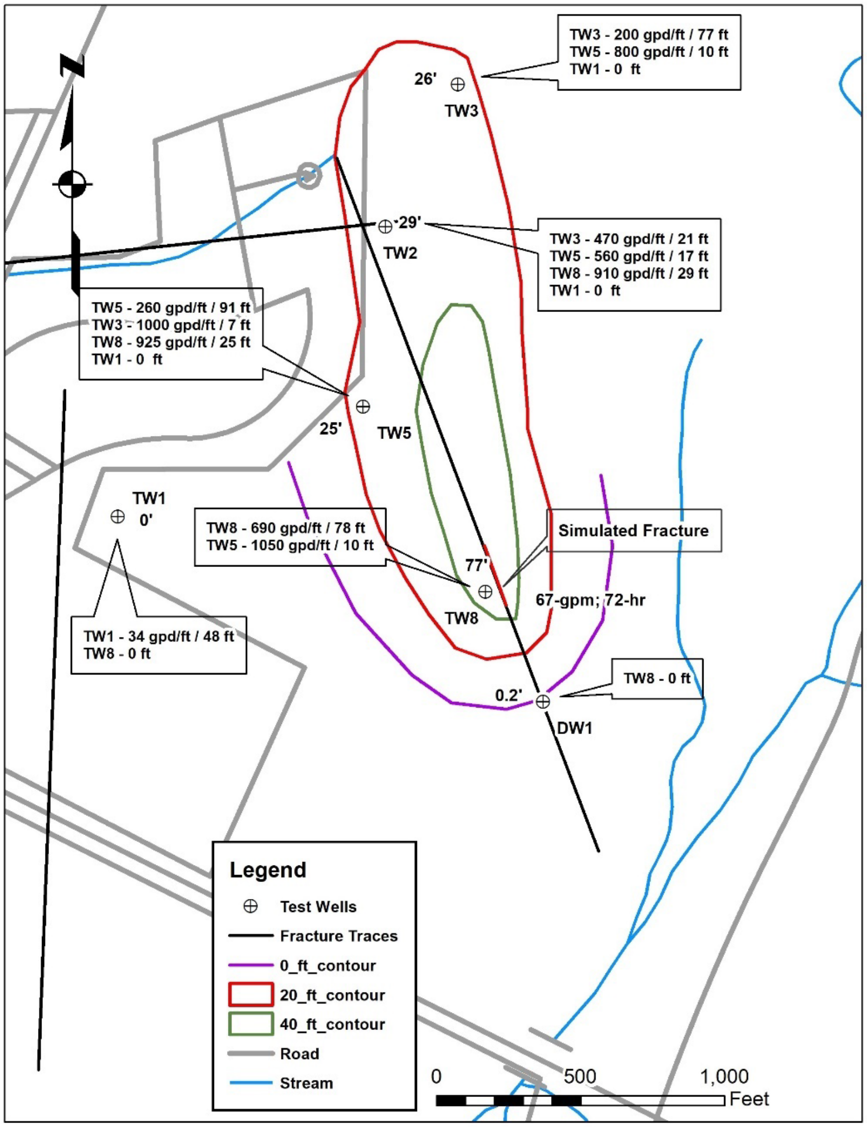

**Figure 13.** Middletown A.C. Jets TW-8 aquifer test, with drawdown contours. Text boxes contain T values and drawdowns at the end of each aquifer test. The simulated fracture was derived from the Time-Distance-Drawdown calculations.

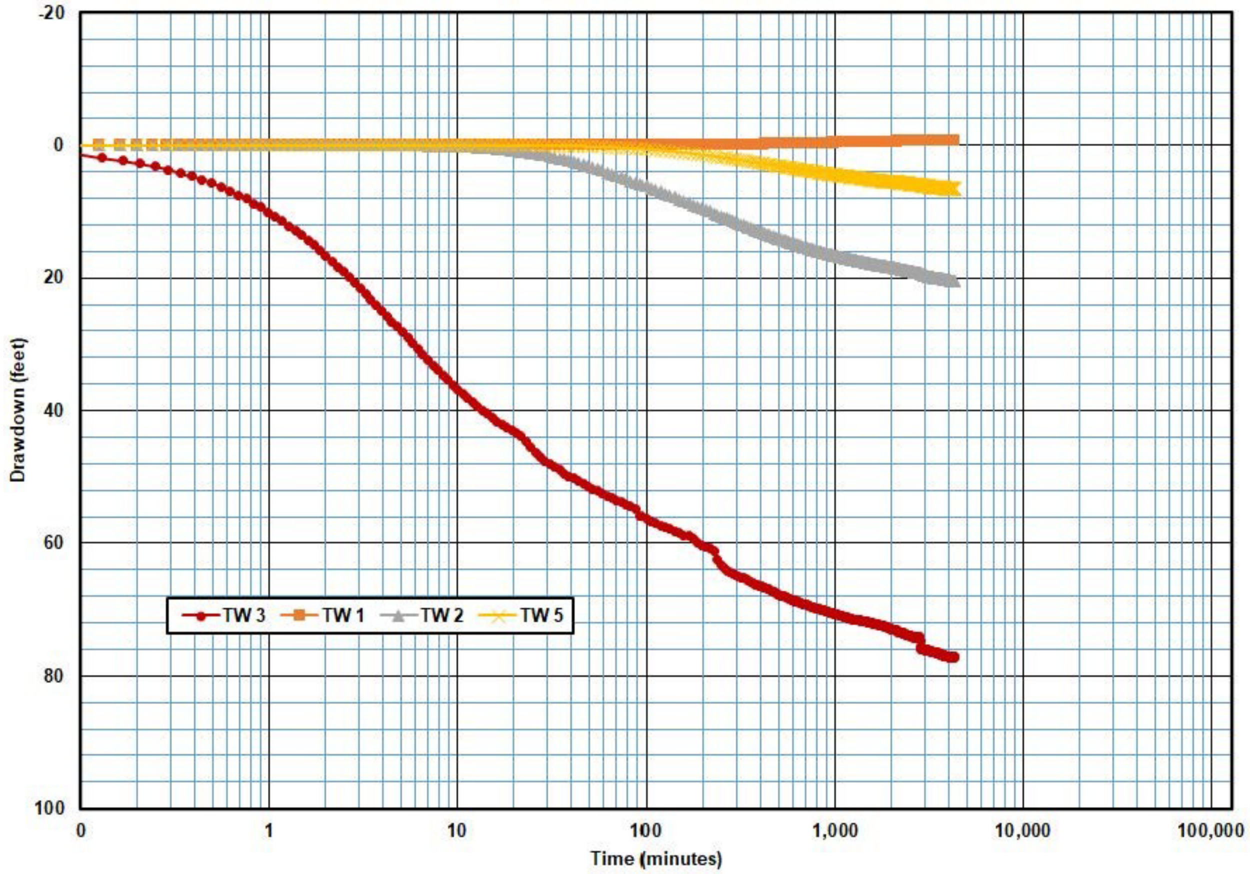

**Figure 14.** Middletown A.C. Jets TW-3. Semi-log plot of drawdown data for pumping well TW-3 and observation wells from a 72-h, 20.4-gpm aquifer test.

A 72-hr, 30.5 gpm aquifer test of TW-5 was conducted on 5/9/05-5/12/05, while monitoring observation wells TW-2, TW-3 and TW-8, Figure 15. The T value for TW-2 (557 gpd/ft) was somewhat more than that from the TW-3 but less than that from the TW-8 test. The T for TW-3 (796 gpd/ft) was higher than from the test of TW-3, but less than that from the test of TW-8. The T of TW-8 (1166 gpd/ft) is like that of the test of TW-8 (1095 gpd/ft). These variations again reflect the average T values of the representative volumes of the aquifer during the three tests.

Finally, a 72-hr, 39 gpm test of TW-1 was conducted on 4/18/05-4/21/05, Figure 16. The T value for TW-1 was very low (34 gpd/ft) and no drawdown was observed in any of the monitoring wells, TW-2, TW-3, or TW-5. This is the type of response that might be expected in a low permeability aquifer, where a steep, narrow trough or cone of depression is produced.

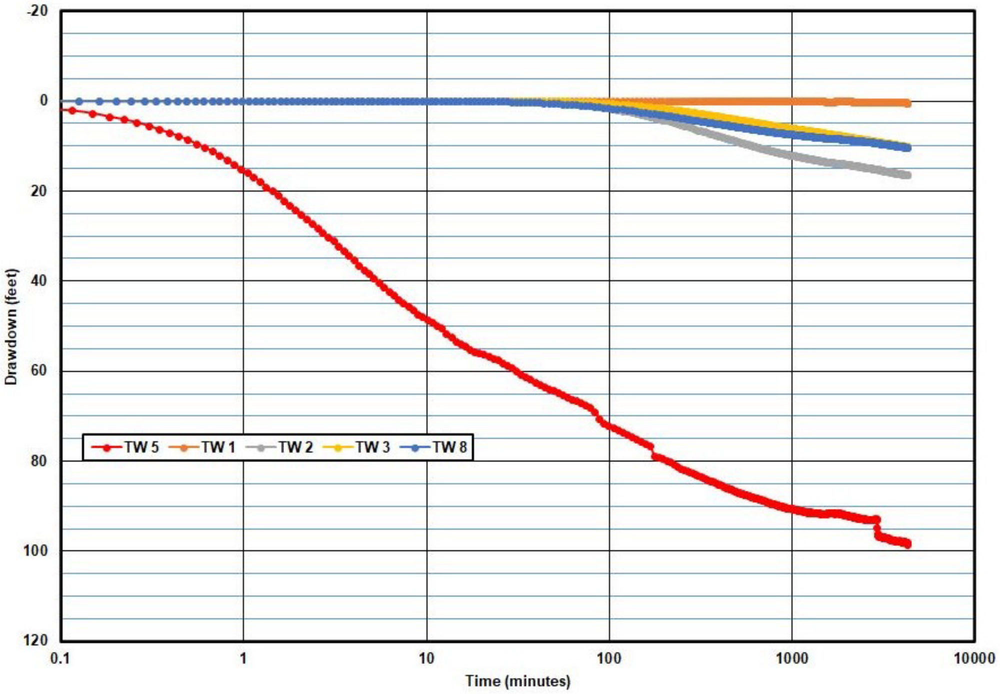

**Figure 15.** Middletown A.C. Jets TW-5. Semi-log plot of drawdown of drawdown data for pumping well TW-5 and observation wells from a 72-h, 30.5-gpm aquifer test.

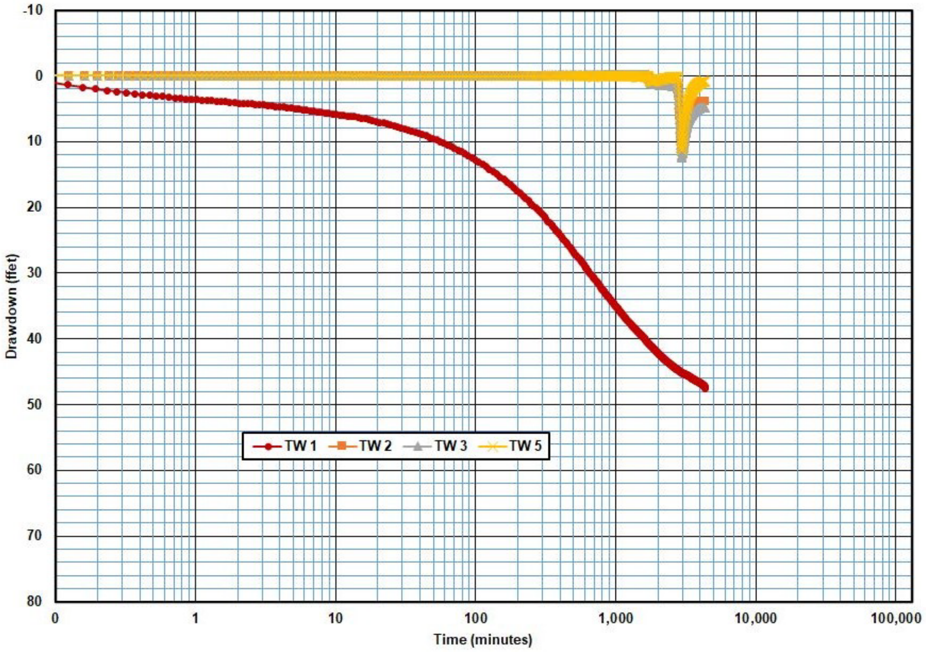

**Figure 16.** Middletown A.C. Jets TW-1. Semi-log plot of drawdown of drawdown data for pumping well TW-1 and observation wells from a 72-h, 39-gpm aquifer test.

## Time-Distance-Drawdowns (T-D-D) Calculations

The distribution of the T values indicates that the aquifer is anisotropic in all lateral and vertical directions and ground water flow is affected by a discrete vertical fracture; consequently, it is expected that there would be significant errors when using available analytical models to calculate T-D-D for withdrawals from the A.C. Jets wells. The model for an anisotropic aquifer uses a tensor to determine distribution of drawdowns. It assumes that there is a maximum and minor axis with two different T values; however, the T values are constant in each direction. The ¼ fracture length model assumes that the aquifer is isotropic. The best solution would likely be achieved using a numerical groundwater flow model; however, that is generally considered to be too costly and time consuming to be used to evaluate water appropriation and use permit applications.

For this evaluation, the ¼ fracture length model will be used, with adjustments in T and S values at the individual wells; but first, T-D-D are calculated using the Theis radial flow model and the data collected from the test of TW-8, Table 12. The hydraulic constants for TW-2, TW-3, TW-5, and TW-8 derived from the test data were inserted for those wells. Since there was no drawdown in TW-1 or DW-1, those constants were derived by an iterative process until a forced drawdown near 0 ft was achieved. The results for TW-1 and DW-1 were consistent with the low T values measured during the individual tests of TW-1, TW-3, and TW-5. The average error was 35%, disregarding the T-D-D for TW-1 and DW-1.

It is noted that the simulated drawdowns in the pumping and observation wells (TW-2, TW-3, and TW-5) were substantially over-estimated. Şen (1994) indicated that the lag in response in observation wells can lead to underestimated S values. The S values were increased by ½ order in magnitude and the T-D-D were re-calculated producing the results shown in Table 13. The average error was 23% indicating an improvement in the simulated drawdowns.

**Table 12.** Time-Distance-Drawdown calculations from 72-hr test of TW-8, radial flow model.

| T | S | Q | t | x | x = 1/4L+d | d | r | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | Well | ft | |
| | | | | | | | | | | |
| 1100 | 3E-05 | 67 | 3 | 0.3 | L= 0 ft | - | 0.3 | TW-8 | 78 | |
| 950 | 1E-06 | 67 | 3 | 1315 | | - | 1315 | TW-2 | 29 | |
| 950 | 3E-06 | 67 | 3 | 1760 | | - | 1760 | TW-3 | 26 | |
| 950 | 2E-05 | 67 | 3 | 770 | | - | 770 | TW-5 | 25 | |
| 200 | 9E-05 | 67 | 3 | 1400 | | - | 1400 | TW-1 | 0 | |
| 180 | 1E-03 | 67 | 3 | 400 | | - | 400 | DW-1 | 1 | |
| | | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | | |
| | | | | | | | | | | Error |
| $S_{0.3}$ = | 16.0 | 8.56 | = | 137 | | | | TW-8 | 78 | 43% |
| $S_{1315}$ = | 18.5 | 2.69 | = | 50 | | | | TW-2 | 29 | 42% |
| $S_{1760}$ = | 18.5 | 1.96 | = | 36 | | | | TW-3 | 26 | 28% |
| $S_{770}$ = | 18.5 | 1.86 | = | 34 | | | | TW-5 | 25 | 26% |
| $S_{1400}$ = | 88.0 | 0.01 | = | 1 | | | | TW-1 | 0 | Nil |
| $S_{400}$ = | 97.8 | 0.01 | = | 1 | | | | DW-1 | 1 | Nil |

**Table 13.** Time-Distance-Drawdown calculations from the 72-hr test of TW-8, using the radial flow model and S values increased by ½ order of magnitude.

| T | S | Q | t | x | x = 1/4L+d | d | r | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | Well | ft | |
| | | | | | | | | | | |
| 1100 | 2E-04 | 67 | 3 | 0.3 | L= 0 ft | - | 0.3 | TW-8 | 78 | |
| 950 | 5E-06 | 67 | 3 | 1315 | | - | 1315 | TW-2 | 29 | |
| 950 | 2E-05 | 67 | 3 | 1760 | | - | 1760 | TW-3 | 26 | |
| 950 | 1E-04 | 67 | 3 | 770 | | - | 770 | TW-5 | 25 | |
| 200 | 9E-05 | 67 | 3 | 1400 | | - | 1400 | TW-1 | 0 | |
| 180 | 1E-03 | 67 | 3 | 400 | | - | 400 | DW-1 | 1 | |
| | | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log 0.3Tt/$x^2$S | = | s | | | | | | |
| | | | | | | | | | | Error |
| $S_{0.3}$ = | 16.0 | 7.87 | = | 126 | | | | TW-8 | 78 | 38% |
| $S_{1315}$ = | 18.5 | 2.00 | = | 37 | | | | TW-2 | 29 | 22% |
| $S_{1760}$ = | 18.5 | 1.26 | = | 23 | | | | TW-3 | 26 | -13% |
| $S_{770}$ = | 18.5 | 1.16 | = | 21 | | | | TW-5 | 25 | -19% |
| $S_{1400}$ = | 88.0 | 0.01 | = | 1 | | | | TW-1 | 0 | Nil |
| $S_{400}$ = | 97.8 | 0.01 | = | 1 | | | | DW-1 | 1 | Nil |

Next, the ¼ fracture length model was applied using the T for TW-8 derived from the using Hantush-Jacob model and the adjusted S values from the radial flow model, Table 14. A short fracture length of 8 ft was derived and an improved average error of 15% was produced.

**Table 14.** Time-Distance-Drawdown calculations from the 72-hr test of TW-8, using the ¼ L flow model and S values increased by ½ order of magnitude.

| T | S | Q | t | x | x = 1/4L+d | d | r | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | Well | ft | |
| | | | | | | | | | | |
| 1100 | 2E-04 | 67 | 3 | 8 | L = 32 ft | - | - | TW-8 | 78 | |
| 950 | 5E-06 | 67 | 3 | 1291 | | 1283 | 1315 | TW-2 | 29 | |
| 950 | 2E-05 | 67 | 3 | 1736 | | 1728 | 1760 | TW-3 | 26 | |
| 950 | 1E-04 | 67 | 3 | 746 | | 738 | 770 | TW-5 | 25 | |
| 200 | 1E-04 | 67 | 3 | 1308 | | 1300 | 1400 | TW-1 | 0 | |
| 200 | 1E-03 | 67 | 3 | 392 | | 360 | 400 | DW-1 | 1 | |
| | | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log 0.3Tt/$x^2$S | = | s | | | | | | |
| | | | | | | | | | | Error |
| $S_8$ = | 16.0 | 4.89 | = | 78 | | | | TW-8 | 78 | 1% |
| $S_{1291}$ = | 18.5 | 2.01 | = | 37 | | | | TW-2 | 29 | 22% |
| $S_{1736}$ = | 18.5 | 1.15 | = | 21 | | | | TW-3 | 26 | -24% |
| $S_{746}$ = | 18.5 | 1.19 | = | 22 | | | | TW-5 | 25 | -14% |
| $S_{1308}$ = | 88.0 | 0.02 | = | 2 | | | | TW-1 | 0 | Nil |
| $S_{392}$ = | 88.0 | 0.03 | = | 2 | | | | DW-1 | 1 | Nil |

Then, again using the ¼ L model, the T derived using Moench 3 solution for TW-8 and the adjusted S values, an average error of 10% was produced, Table 15. It is not clear why the Moench 3 and Hatush-Jacob model produced different T values for TW-8, since the assumptions each of the models is the same (i.e., upper constant head aquifer, leaky aquitard, and lower aquifer with aquitard at the base). It may be related to dewatering of the both the upper and lower aquifers and/or the reduced drawdown in the pumping well caused by a discrete fracture.

**Table 15.** Time-Distance-Drawdown calculations from the 72-hr test of TW-8, using the ¼ L flow model, S values increased by ½ order of magnitude and T for TW-8 from the Moench 3 model.

| T | S | Q | t | x | x = 1/4L+d | d | r | Drawdowns | | |
|---|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | Well | ft | |
| | | | | | | | | | | |
| 700 | 2E-04 | 67 | 3 | 50 | L = 200 ft | - | - | TW-8 | 78 | |
| 950 | 5E-06 | 67 | 3 | 1165 | | 1115 | 1315 | TW-2 | 29 | |
| 950 | 2E-05 | 67 | 3 | 1610 | | 1560 | 1760 | TW-3 | 26 | |
| 950 | 1E-04 | 67 | 3 | 620 | | 570 | 770 | TW-5 | 25 | |
| 200 | 1E-04 | 67 | 3 | 1350 | | 1300 | 1400 | TW-1 | 0 | |
| 200 | 1E-03 | 67 | 3 | 410 | | 360 | 400 | DW-1 | 1 | |
| | | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | | |
| | | | | | | | | | | Error |
| $S_{50}$ = | 25.2 | 3.10 | = | 78 | | | | TW-8 | 78 | 0% |
| $S_{1165}$ = | 18.5 | 2.10 | = | 39 | | | | TW-2 | 29 | 26% |
| $S_{1610}$ = | 18.5 | 1.22 | = | 23 | | | | TW-3 | 26 | -13% |
| $S_{620}$ = | 18.5 | 1.35 | = | 25 | | | | TW-5 | 25 | 0% |
| $S_{1350}$ = | 88.0 | -0.01 | = | 0 | | | | TW-1 | 0 | Nil |
| $S_{410}$ = | 88.0 | -0.01 | = | -1 | | | | DW-1 | 1 | Nil |

Since this simulation (Table 15) produced the least error, the hydraulic constants from it were used to determine the potential impacts of a withdrawal from well TW-8 of 40 gpm over a 90-d period without recharge from the aquifer, Table 16. The drawdowns appear to be reasonable, except for those of TW-1 and DW-1, that were greater than the pumping well TW-8, which is not physically possible.

Reasonable results were achieved for TW-1 and DW-1 when the T value (950 gpd/ft) used for the other observation wells were substituted into the equations for those two wells, Table 17. It is not immediately clear why this is the case. One explanation is that the representative equivalent volume affecting flow to each observation well determines the amount of drawdown that would occur during a pumping phase. During the 72-hr test, groundwater was flowing to the pumping well from the area of high T and no water is flowing from the low permeability areas near TW-1 and DW-1. As pumping continues during the 90-d simulations, then water starts flowing from the low-permeability areas; however, the drawdowns in TW-1 and DW-1 reflect the cumulative effects of flow from both the high and low T areas. This concept could best be demonstrated with a numerical groundwater flow model, which is beyond the scope of this study.

**Table 16.** Time-Distance-Drawdown simulation pumping TW-8 at 40-gpm for 90 days, using ¼ L model, S values increased ½ order of magnitude and T for TW-8 from the Moench 3 model.

| T | S | Q | t | x | x = 1/4L+d | d | r | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | |
| | | | | | | | | |
| 700 | 2E-04 | 40 | 90 | 50 | L = 200 ft | - | - | TW-8 |
| 950 | 5E-06 | 40 | 90 | 1165 | | 1115 | 1315 | TW-2 |
| 950 | 2E-05 | 40 | 90 | 1610 | | 1560 | 1760 | TW-3 |
| 950 | 1E-04 | 40 | 90 | 620 | | 570 | 770 | TW-5 |
| 200 | 1E-04 | 40 | 90 | 1350 | | 1300 | 1400 | TW-1 |
| 200 | 1E-03 | 40 | 90 | 410 | | 360 | 400 | DW-1 |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | |
| | | | | | | | | |
| $S_{50}$ = | 15.1 | 4.58 | = | 69 | | | | TW-8 |
| $S_{1165}$ = | 11.1 | 3.58 | = | 40 | | | | TW-2 |
| $S_{1610}$ = | 11.1 | 2.69 | = | 30 | | | | TW-3 |
| $S_{620}$ = | 11.1 | 2.82 | = | 31 | | | | TW-5 |
| $S_{1350}$ = | 52.8 | 1.47 | = | 78 | | | | TW-1 |
| $S_{410}$ = | 52.8 | 1.47 | = | 77 | | | | DW-1 |

**Table 17.** Time-Distance-Drawdown simulation pumping TW-8 at 40-gpm for 90 days, using ¼ L model, S values increased ½ order of magnitude. and T for TW-8 from the Moench 3 model. The T values for TW-1 and DW-1 increased to 950 gpd/ft.

| T | S | Q | t | x | x = 1/4L+d | d | r | |
|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | ft | ft | |
| | | | | | | | | |
| 700 | 2E-04 | 40 | 90 | 50 | L = 200 ft | - | - | TW-8 |
| 950 | 5E-06 | 40 | 90 | 1165 | | 1115 | 1315 | TW-2 |
| 950 | 2E-05 | 40 | 90 | 1610 | | 1560 | 1760 | TW-3 |
| 950 | 1E-04 | 40 | 90 | 620 | | 570 | 770 | TW-5 |
| 950 | 1E-04 | 40 | 90 | 1350 | | 1300 | 1400 | TW-1 |
| 950 | 1E-03 | 40 | 90 | 410 | | 360 | 400 | DW-1 |
| | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | |
| | | | | | | | | |
| $S_{50}$ = | 15.1 | 4.58 | = | 69 | | | | TW-8 |
| $S_{1165}$ = | 11.1 | 3.58 | = | 40 | | | | TW-2 |
| $S_{1610}$ = | 11.1 | 2.69 | = | 30 | | | | TW-3 |
| $S_{620}$ = | 11.1 | 2.82 | = | 31 | | | | TW-5 |
| $S_{1350}$ = | 11.1 | 2.15 | = | 24 | | | | TW-1 |
| $S_{410}$ = | 11.1 | 2.14 | = | 24 | | | | DW-1 |

## Westminster well 8 (Votech/TW-A) and Maplecrest Subdivision Incident

In 1999, the Carroll County Health Department had identified Maple Crest, a 30-year-old subdivision south of Westminster, as a community having water supply problems. The neighborhood residents relied on private wells, some which run low part of the year and others that go dry during periods of drought. More than a few had dried up, causing those residents to truck in water. In 2000, the Carroll commissioners held a public hearing on the possibility of extending water lines to the community. A survey of property owners in the neighborhood indicated the most severe problems were affecting residents of Wayne Avenue and Woodland Drive, Figure 17. Twenty-nine of fifty-nine homeowners, most of them residents of those two roads, supported extending water lines to the neighborhood. In 2002, the county extended water lines to about 25 homeowners on Wayne Avenue and Woodland Drive.

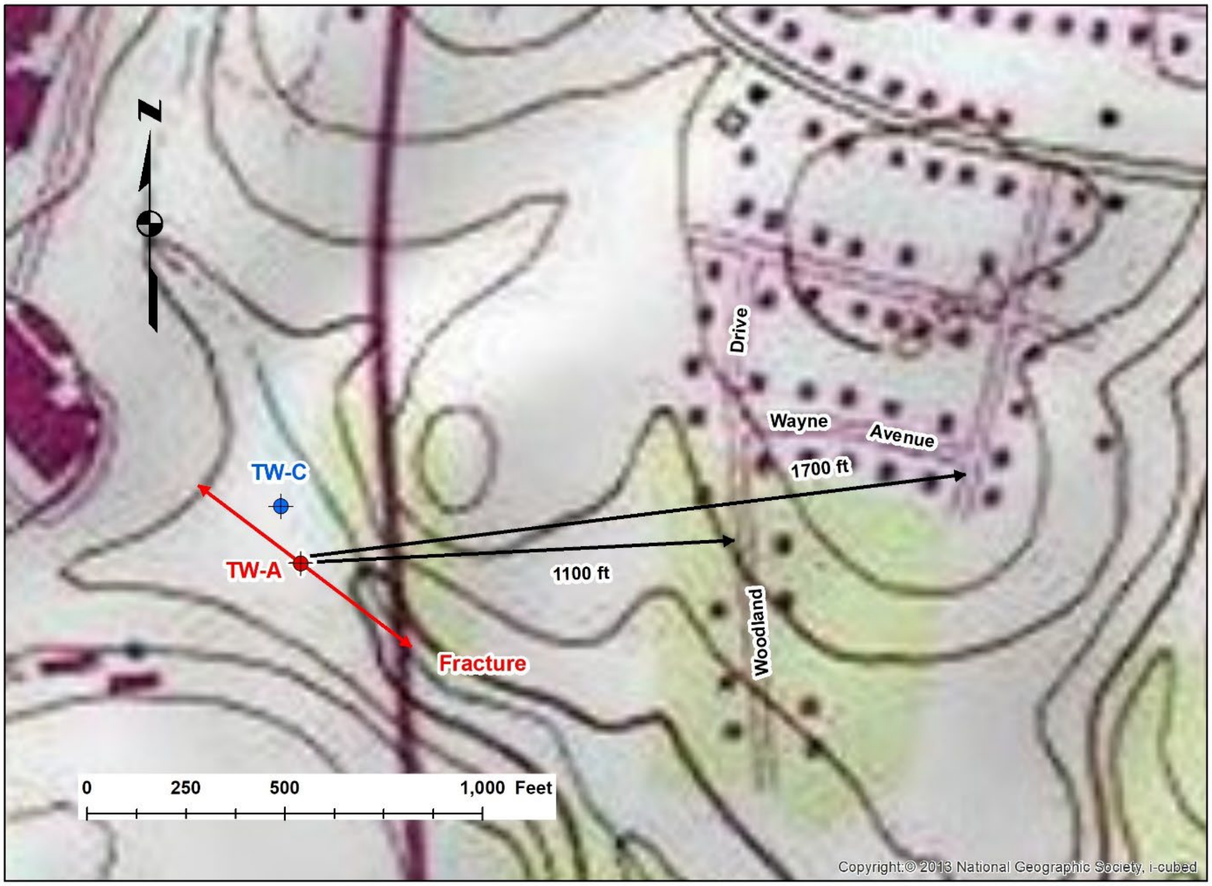

**Figure 17.** Location map for Votech well (TW-A) aquifer test and the Maplecrest Subdivision. The simulated fracture was derived from the Time-Distance-Drawdown calculations.

Westminster's nearby well 8 (TW-A, Votech well) was completed on 6/28/1987 and two aquifer tests were conducted in August 1987 (96-h, 400 gpm) and January 1988 (14-d, 205 gpm), while monitoring one observation well (TW-C), located 150 feet from TW-A, Figure 17. The well was placed in service in 1995 at a reduced capacity and reached the full estimated yield of a 101-gpm yearly average / 221-gpm max month in 1997. By 2001, the yield had declined to 92 gpm avg / 111 gpm max and has continued to be pumped at less than those amounts to date. Hammond (2018) attributed the initial high yield to substantial aquifer storage capacity and the following decline in yield to a limited recharge area.

The water supply problems noted at the Maplecrest Subdivision occurred shortly after the high use from the Votech well; however, those problems were not reported to the MDE Water Appropriation Division, so no investigation of potential impacts due to withdrawals from the Votech well was conducted. The methods developed in the present study will be used to see if it is possible that any unreasonable impacts had occurred.

The Votech well was completed in the crystalline rock Ijamsville Formation. The consultant described the lithology in the well as being heavily weathered to a depth of 55 ft. Figure 18 is a semi-log plot that shows the results of the two aquifer pumping tests. During the first test, several shallow water-bearing zones were dewatered between 30.8 ft and 54 ft BTOC, which probably resulted in the high turbidity noted by the consultant. The shallow fractures were then cased off and the second test was conducted. Hammond (2018) observed differing responses between the two tests and attributed this to the shallow, water-bearing zones that were directly connected by a short-circuit through the well-bore to the primary fracture system during the first test; while during the second test, water from the then isolated shallow zones had to leak into the bedrock fracture system and then flow to the well-bore.

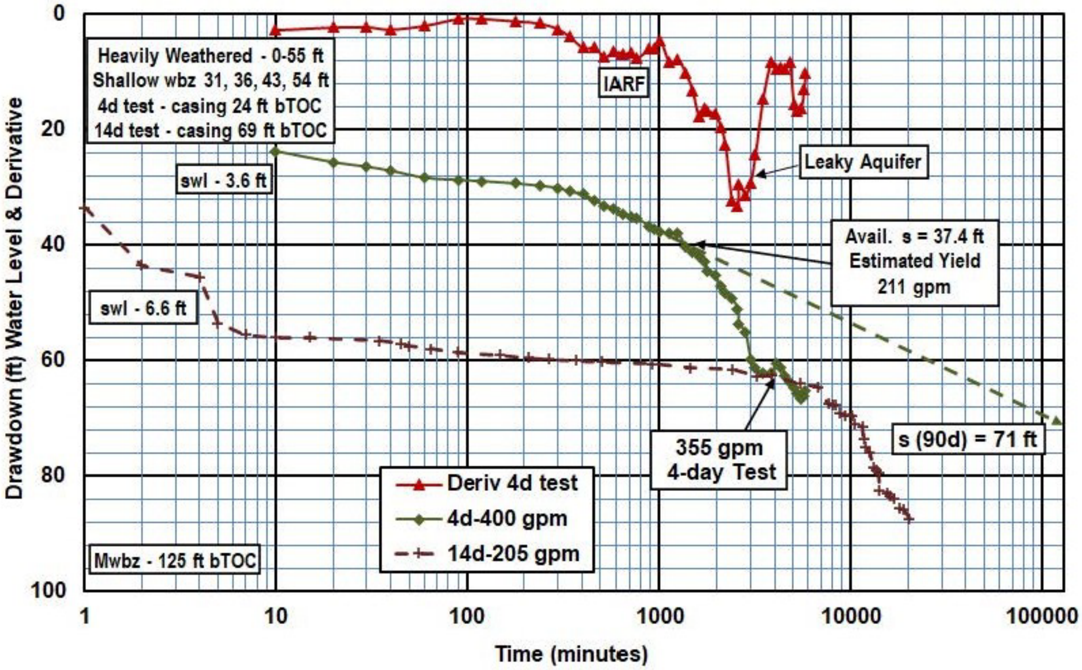

**Figure 18.** Westminster Vo-tech well – Semi-log plot of drawdown and its logarithmic derivative for 4-d and 14-d pumping tests.

The derivative analysis of the first test indicated that an IARF segment began after about four hours of pumping and lasted for about 13 hours. This was followed by a leaky aquifer response at a drawdown of 37.4 ft. The end of the test was affected by aeration in the flowmeter reportedly due to clogging of the pump intake screen, which required a reduction in the pumping rate to 355 gpm. Based on the results of the second test, it appeared that the well could supply a reliable yield of 200 gpm. Hammond (2018) extrapolated the drawdown from an IARF segment from the first test to 90 days and calculated an estimated yield of 211 gpm.

Application of the Dougherty-Babu (1984) double porosity solution to the data, in English measurement units, from the first step-drawdown test produced a poor visual fit, but good statistical results, Table 18. Substantial differences occurred when the International System of Units (S.I. or metric) were assigned, such that the T value in English units was about four times greater and the well efficiency (W.E.) about ½ of the results using S.I. units. When the Hantush-Jacob solution was applied, the T value using English units was only twice as high as the result with S.I. units.

Better visual and statistical fits were achieved by correcting the data for the effects of aquifer dewatering of the weathered zone, using the Dougherty-Babu model and a saturated thickness of 43 ft (13 m), producing similar T and W.E. results for both the English and S.I. unit calculations. When the Hantush-Jacob model was applied, the value resulting from use of the English unit results were ½ of those for the S.I. units.

Application of the Dougherty-Babu solution to the data in English units from the second step-drawdown test produced good visual and statistical results; however, the W.E. was only 15 percent. S.I. units produced a W.E. of 64 percent; however, there was more than an order of magnitude difference in the T values between the two units of measurement calculations. When the Hantush-Jacob model was applied, there was a better agreement, but still a significant difference between the results of the two units of measurement. The best fit to those data was achieved by correcting it for the effects of dewatering, using a saturated thickness of 36 ft (11 m) and producing a W.E. of 71 percent (English) and 77 per cent (S.I.) and similar T values. The Hantush-Jacob model also produced comparable results from application of the two units of measurement, except that the T values were about ½ of those produced by the Dougherty-Babu solution, while the W.E. results, 81 per cent (English) and 99 per cent (S.I.), were greater.

These results indicate that there was not a proportional relationship between the U.S. English and S.I. units for the uncorrected step-test data; however, when corrected for estimated aquifer thicknesses of the weathered zone, the U.S. English and S.I. units are directly proportional, within the limits of rounding errors. It is not entirely clear as to why this is the case, but Hammond (2018) indicated that it may simply be an artifact related to one or both of the following factors: 1. the nonlinear coefficient (C) in the step drawdown equation was derived empirically and has peculiar units ($T^2/L^5$), and, more likely, 2. Step-drawdown test equations do not include a factor for nonlinear losses due to aquifer dewatering effects.

These results suggest that casing off the upper, water-bearing zones may have increased the well efficiency by reducing the turbidity and eliminating clogging of the pump intake.

**Table 18.** Hydraulic constants Votech well 1st and 2nd step tests.

| Well | Period | Model | Units | RSS | V | S.D. | Mean | T | Tconv | W.E. | s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | min | Type | | $ft^2$ or $m^2$ | $ft^2$ or $m^2$ | ft or m | ft or m | gpd/ft or $m^2$/d | gpd/ft or $m^2$/d | % | ft or m |
| 1st -S1-4 uncorr | 0-240 | D-B | Eng | 1.6 | 0.06 | 0.24 | -0.026 | 3.9E+04 | 484 | 29 | 17.2 |
| 1st -S1-4 uncorr | 0-240 | D-B | S.I. | 1.8 | 0.07 | 0.25 | -0.001 | 130 | 1.0E+04 | 61 | 5.2 |
| 1st -S1-4 uncorr | 0-240 | H-J | Eng | 5.3 | 0.19 | 0.44 | -0.01 | 2.1E+04 | 257 | 30 | 17.2 |
| 1st -S1-4 uncorr | 0-240 | H-J | S.I. | 1.9 | 0.07 | 0.26 | 0.0008 | 130 | 1.0E+04 | 53 | 5.2 |
| | | | | | | | | | | | |
| 1st -S1-4 corr(43ft) | 0-240 | D-B | Eng | 0.7 | 0.02 | 0.15 | -0.007 | 2.4E+04 | 300 | 84 | 13.7 |
| 1st -S1-4 corr(13m) | 0-240 | D-B | S.I. | 1.3 | 0.05 | 0.22 | 0.008 | 329 | 2.7E+04 | 99 | 4.2 |
| 1st -S1-4 corr(43ft) | 0-240 | H-J | Eng | 4.2 | 0.15 | 0.39 | -0.02 | 1.4E+04 | 176 | 72 | 13.7 |
| 1st -S1-4 corr(13m) | 0-240 | H-J | S.I. | 1.3 | 0.05 | 0.22 | 0.007 | 329 | 2.7E+04 | 99 | 4.2 |
| | | | | | | | | | | | |
| 2nd -S1-4 uncorr | 0-240 | D-B | Eng | 8.1 | 0.25 | 0.50 | -0.009 | 1.2E+04 | 152 | 15 | 25.7 |
| 2nd -S1-4 uncorr | 0-240 | D-B | S.I. | 14.3 | 0.46 | 0.68 | 0.037 | 3.3 | 266 | 64 | 7.8 |
| 2nd -S1-4 uncorr | 0-240 | H-J | Eng | 11.0 | 0.36 | 0.60 | -0.08 | 6212 | 77 | 20 | 25.7 |
| 2nd -S1-4 uncorr | 60-240 | H-J | S.I. | 13.3 | 0.74 | 0.86 | -0.07 | 43.8 | 3526 | 84 | 7.8 |
| | | | | | | | | | | | |
| 2nd -S1-4 corr(36ft) | 0-240 | D-B | Eng | 9.8 | 0.31 | 0.55 | -0.06 | 9805 | 122 | 71 | 16.5 |
| 2nd -S1-4 corr(11m) | 0-240 | D-B | S.I. | 1.4 | 0.04 | 0.20 | -0.02 | 135 | 10,859 | 77 | 5.0 |
| 2nd -S1-4 corr(36ft) | 60-240 | H-J | Eng | 7.2 | 0.40 | 0.63 | -0.27 | 4592 | 57 | 81 | 16.5 |
| 2nd -S1-4 corr(11m) | 60-240 | H-J | S.I. | 0.5 | 0.03 | 0.16 | -0.02 | 49 | 3945 | 99 | 5 |

The hydraulic constants derived from the AQTESOLV program for the 96-h, 400 gpm aquifer test of the Votech (TW-A) well are presented in Table 19. There are three segments to the drawdown curve developed from the data collected in TW-A. The Moench 3 leaky aquifer solution provides the best fit to the 10- to 200-minute segment, producing a T value for the U.S. English units that is about a ½ order of magnitude greater that for the S.I. units, an indication of aquifer dewatering. In the second segment (300-1000 minutes), there is better agreement, in that the T value for the U.S. English units was only about 50 per cent greater than that for the S.I. units. When the Gringarten-Ramey solution for a finite single vertical fracture (SVF-F) was applied to that data, the T values using both the U.S. English units and S.I. units were similar (+/-20%), except the T values are nearly ½ order of magnitude greater than those derived using the Moench 3 model.

The early time (0-400 min) drawdown data for the observation well TW-C best fit the Moench3 leaky aquifer solution and produced similar results for both units of measurement, indicating that there was no dewatering effect. This was possibly related to the limited drawdown in the well, which was less than the 20 precent of the aquifer thickness where a correction for dewatering is not needed. Another possibility is that there was lag in response to pumping of the water level in the observation well, producing a flat curve and the extremely high calculated T value. The late-time (600-5760 min) data best fit the SVF-F solution, but the T value of the U.S. English unit calculation was about ½ of the S.I. unit calculations, suggesting some effects due to dewatering.

**Table 19.** Hydraulic constants Votech well 96-h, 400 gpm test.

| Well | Period | Model | Units | RSS | V | S.D. | Mean | T | Tconv | S | s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | min | Type | Eng/S.I. | ft$^2$or m$^2$ | ft$^2$or m$^2$ | ft or m | ft or m | gpd/ft or m$^2$/d | gpd/ft or m$^2$/d | | ft or m |
| TW-A | 10-200 | Moench3 | Eng | 0.15 | 0.04 | 0.19 | 0.005 | 1.1E+04 | 137 | - | 30 |
| TW-A | 10-200 | Moench3 | S.I. | 0.24 | 0.06 | 0.25 | 0.005 | 27 | 2174 | - | 9 |
| TW-A | 300-1000 | Moench3 | Eng | 0.77 | 0.11 | 0.33 | 0.007 | 2343 | 29 | - | 38 |
| TW-A | 300-1000 | Moench3 | S.I. | 0.06 | 0.008 | 0.089 | 0.001 | 19 | 1530 | - | 11.5 |
| TW-A | 300-1000 | SVF-F | Eng | 0.61 | 0.09 | 0.3 | 0.0001 | 8490 | 105 | - | 38 |
| TW-A | 300-1000 | SVF-F | S.I. | 0.06 | 0.008 | 0.09 | 1E-06 | 87 | 7003 | - | 11.5 |
| TW-A | 1365-2565 | SVF-F | Eng | 1.69 | 0.28 | 0.53 | 0.001 | 2549 | 32 | - | 51 |
| TW-A | 1365-2565 | SVF-F | S.I. | 0.32 | 0.05 | 0.23 | -0.01 | 33 | 2657 | - | 16 |
| | | | | | | | | | | | |
| TW-C | 0-400 | Moench3 | Eng | 0.01 | 0.002 | 0.05 | 0.001 | 5.4E+04 | 676 | 0.009 | 1.7 |
| TW-C | 0-400 | Moench3 | S.I. | 0.004 | 0.0007 | 0.03 | -0.005 | 821 | 6.6E+04 | 0.007 | 0.5 |
| TW-C | 600-5760 | SVF-F | Eng | 0.17 | 0.009 | 0.093 | 0.002 | 2.2E+04 | 273 | 0.099 | 6 |
| TW-C | 600-5760 | SVF-F | S.I. | 0.02 | 0.0008 | 0.028 | 0.0007 | 533 | 4.3E+04 | 0.072 | 1.8 |

Table 20 provides the hydraulic constants calculated from the 14-d, 200 gpm test of TW-A. Two segments to the drawdown data for TW-A were identified, an early time one from 6 to 1000 minutes and a following late-time period from 10,000 to 20,000 minutes. The Moench 3 and Hantush Jacob (with and without aquitard storage) solutions produced reasonable fits to the early-time data and nearly identical T values, except the T values calculated in S.I. units were about three times greater than those in U.S. English units. This indicates that aquifer dewatering was a factor effecting the early-time data. The Theis radial flow and SVF-F models both provided good solution to the late-time data and similar calculated T values (average of 897 gpd/ft) that are significantly less that the early time T results, suggesting that they were representative of the bedrock portion of the aquifer and unaffected by dewatering.

The early-time (0-500) drawdown data from TW-C best fit the Moench 3 solution and the derivative was characteristic of a leaky aquifer. The data between 500 and 1000 minutes were erratic due to a possible recharge event. The Moench 3 model provided a reasonable solution for the late time (10,000 to 20,000 minutes) with similar results using either S.I. or US English units, indicating no effects of aquifer dewatering. The derivative indicated that there was no leakage which may explain why the Theis radial flow and SVF-F both produced better results. The T values in either S.I. or US English units were identical which is not unexpected, since the Theis and SVF-F type curves merge at late time.

**Table 20.** Hydraulic constants Votech well 14-d, 200 gpm test

| Well | Period | Model | Units | RSS | V | S.D. | Mean | T | Tconv | S | s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | min | Type | | ft$^2$or m$^2$ | ft$^2$or m$^2$ | ft or m | ft or m | gpd/ft or m$^2$/d | gpd/ft or m$^2$/d | - | ft or m |
| TW-4 | 6-1000 | Moench3 | Eng | 23 | 2.3 | 1.5 | -0.005 | 1731 | 22 | - | 60 |
| TW-4 | 6-1000 | Moench3 | S.I. | 2.8 | 0.23 | 0.48 | 0.04 | 63 | 5072 | - | 18 |
| TW-4 | 6-1000 | H-J/A.S. | Eng | 43 | 4.3 | 2.1 | 1.2 | 1731 | 22 | - | 60 |
| TW-4 | 6-1000 | H-J/A.S. | S.I. | 0.9 | 0.08 | 0.28 | 0.013 | 65 | 5233 | - | 18 |
| TW-4 | 6-1000 | H-J | Eng | 280 | 16.5 | 4.1 | 1.0 | 1639 | 20 | - | 60 |
| TW-4 | 6-1000 | H-J | S.I. | 8.5 | 0.77 | 0.88 | 0.66 | 67 | 5394 | - | 18 |
| TW-4 | 10K-20K | Theis | Eng | 41 | 3.0 | 1.7 | -0.08 | 1024 | 13 | - | 87 |
| TW-4 | 10K-20K | Theis | S.I. | 2.4 | 0.2 | 0.42 | -0.013 | 11 | 886 | - | 27 |
| TW-4 | 10K-20K | SVF-F | Eng | 24 | 2 | 1.4 | -0.017 | 792 | 10 | - | 87 |
| TW-4 | 10K-20K | SVF-F | S.I. | 2.5 | 0.21 | 0.46 | -0.008 | 11 | 886 | - | 27 |
| | | | | | | | | | | | |
| TW-C | 0-500 | Moench3 | Eng | 0.01 | 0.001 | 0.036 | 0.012 | 5.0E+04 | 615 | 0.013 | 0.8 |
| TW-C | 0-500 | Moench3 | S.I. | 0.001 | 0.0001 | 0.01 | 0.004 | 614 | 4.9E+04 | 0.045 | 0.25 |
| TW-C | 2K-17K | Moench3 | Eng | 0.30 | 0.01 | 0.11 | 0.05 | 5911 | 73 | 0.06 | 5 |
| TW-C | 2K-17K | Moench3 | S.I. | 0.02 | 0.0007 | 0.026 | 0.017 | 67 | 5394 | 0.21 | 1.6 |
| TW-C | 2K-17K | Theis | Eng | 0.07 | 0.003 | 0.05 | -0.002 | 7506 | 93 | 0.25 | 5 |
| TW-C | 2K-17K | Theis | S.I. | 0.007 | 0.0002 | 0.016 | -0.0006 | 93 | 7506 | 0.25 | 1.6 |
| TW-C | 2K-17K | SVF-F | Eng | 0.07 | 0.003 | 0.05 | -0.002 | 7506 | 93 | 0.24 | 5 |
| TW-C | 2K-17K | SVF-F | S.I. | 0.007 | 0.0003 | 0.016 | -0.0006 | 93 | 7506 | 0.25 | 1.6 |

For this evaluation, the ¼ fracture length model was applied to the test data. The best results obtained in the previous case studies were achieved by using late-time data. Since the upper water bearing zones were cased off prior to the 14-d, 200 gpm test, the late-time T values for TW-A and TW-C would be representative of the aquifer characteristics. Those T values were held constant, and the S values were adjusted by an iterative method to match the drawdowns observed at the end of the test, with the results given in Table 21. In this case, there was no calculated drawdown along either Woodland Drive or Wayne Avenue. The homes between Woodland Drive/Wayne Avenue and the Votech well along Campus Court/Alumni Drive were supplied with public water when they were built in 1989 (Zachary Neal, Carroll County Government, personal communication, 2019).

**Table 21.** Time-Distance-Drawdown simulation of 14-d, 200 gpm test of the Votech well (TW-A)

| T | S | Rate | t | x | x = 1/4L+d | Drawdowns | | r | d |
|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | Well | ft | ft | ft |
| | | | | | | | | | |
| 900 | 1.0E-02 | 200 | 14 | 170 | L=680ft | TW-A | 66 | 0.3 | 0 |
| 7500 | 1.2E-01 | 200 | 14 | 245 | 1/4L=170ft | TW-C | 5 | 150 | 75 |
| 7500 | 1.2E-01 | 200 | 14 | 1020 | | Woodland Dr | | 1100 | 850 |
| 7500 | 1.2E-01 | 200 | 14 | 1620 | | Wayne Ave | | 1750 | 1450 |
| | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | |
| | | | | | error | | | | |
| $S_{170}$ = | 58.7 | 1.12 | = | 66 | 0% | TW-A | 66 | 0.3 | 0 |
| $S_{245}$ = | 7.0 | 0.64 | = | 5 | 0% | TW-C | 5 | 150 | 70 |
| $S_{1020}$ = | 7.0 | -0.60 | = | -4 | N/R | Woodland Dr | N/R | 1200 | 960 |
| $S_{1620}$ = | 7.0 | -1.00 | = | -7 | N/R | Wayne Ave | N/R | 1750 | 1400 |

Since the simulation (Table 21) produced no error, the hydraulic constants from it were used to determine the potential impacts of a withdrawal from well TW-A (Votech well) of 200 gpm over a 90-d period, without recharge to the aquifer. The results, Table 22, indicate that there would be no impacts to the domestic wells along Woodland Drive and Wayne Avenue.

**Table 22.** Time-Distance-Drawdown simulation pumping the Votech well for 90-d at 200 gpm.

| T | S | Rate | t | x | x = 1/4L+d | Drawdowns | | r | d |
|---|---|---|---|---|---|---|---|---|---|
| gpd/ft | | gpm | day | ft | | Well | ft | ft | ft |
| | | | | | | | | | |
| 900 | 1.0E-02 | 200 | 90 | 170 | L=680ft | TW-A | 66 | 0.3 | 0 |
| 7500 | 1.2E-01 | 200 | 90 | 245 | 1/4L=170ft | TW-C | 5 | 150 | 75 |
| 7500 | 1.2E-01 | 200 | 90 | 1020 | | Woodland Dr | | 1100 | 850 |
| 7500 | 1.2E-01 | 200 | 90 | 1620 | | Wayne Ave | | 1750 | 1450 |
| | | | | | | | | | |
| $S_x$ = | 264Q/T X | Log $0.3Tt/x^2S$ | = | s | | | | | |
| | | | | | error | | | | |
| $S_{170}$ = | 58.7 | 1.92 | = | 113 | -22% | TW-A | 93 | 0.3 | 0 |
| $S_{245}$ = | 7.0 | 1.45 | = | 10 | N/R | TW-C | N/R | 150 | 70 |
| $S_{1020}$ = | 7.0 | 0.21 | = | 1 | N/R | Woodland Dr | N/R | 1200 | 960 |
| $S_{1620}$ = | 7.0 | -0.19 | = | -1 | N/R | Wayne Ave | N/R | 1750 | 1400 |

Since there was no long-term monitoring data from the domestic wells along Woodland Drive and Wayne Avenue, additional information needs to be considered to verify that no unreasonable impacts had occurred. Most telling is that water use from the Votech well declined from a peak of 200 gpm in July 1997 to about 80-110 gpm from 1998-2002, Figure 19, when the Maplecrest water supply problems were first reported, and continued at less than an average of 100 gpm to date, Table 23. After the houses along Woodland Drive and Wayne Avenue were provided with public water in 2002, it is expected that that production from the Votech would increase to the previous maximum yield of 200 gpm. Hammond (2018) indicated that, upon depletion of aquifer storage, the reduced yield after 1997-98 was due to recharge from a limited area (148 acres) in the vicinity of the well. The water system supervisor during the period of the incident also indicated that she had no knowledge of impacts to the Maplecrest house wells (Paula Martin, retired, personal communication, 2021) and suggested that the available recharge area may have been reduced by impermeable surfaces at several major facilities in the watershed (Carroll County Career & Technology Center-Votech and Public Safety Training Center), Figure 20. This information and the Time-Distance-Drawdown calculations indicate that there were no impacts to the Maplecrest house wells due to withdrawals from the Votech well.

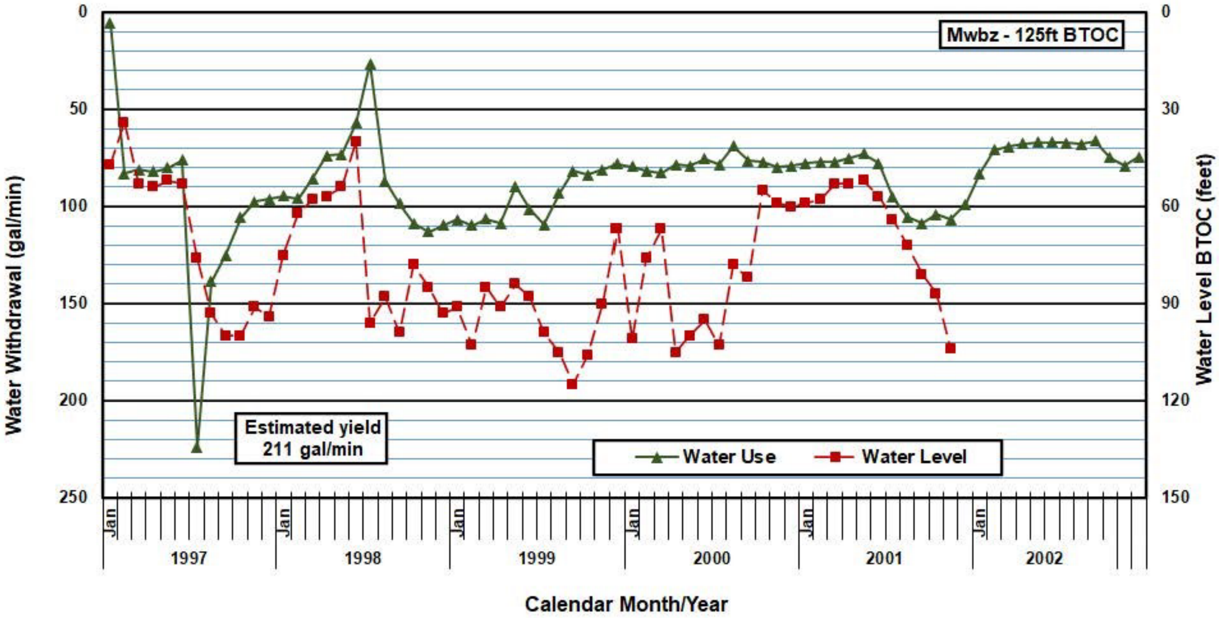

**Figure 19.** Westminster Votech well – Water use and water level data.

**Table 23.** Reported pumpage (water use) from the Votech well, 1989-2020.

**Permit: CL1977G736** **Total Pumpage Reports: 0**

| Year | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Annual Total Usage | Annual Average | Annual % Overage | High Month | High MonthAvg Gal Per | Monthly % Overage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1989 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | | | 0.00 |
| 1990 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | | | 0.00 |
| 1991 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | | | 0.00 |
| 1992 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 110 | 310 | 420 | 1 | 0.00 | 12 | 10 | 0.00 |
| 1993 | 300 | 280 | 310 | 300 | 310 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 1,640 | 4 | 0.00 | 2 | 10 | 0.00 |
| 1994 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 275,000 | 313,000 | 588,000 | 1,611 | 0.00 | 12 | 10,097 | 0.00 |
| 1995 | 63,200 | 14,500 | 44,400 | 24,500 | 54,300 | 42,100 | 1,220,084 | 2,663,538 | 5,841,525 | 4,603,791 | 2,751,889 | 3,305,340 | 20,629,167 | 56,518 | 0.00 | 9 | 194,718 | 0.00 |
| 1996 | 2,227,057 | 3,527,029 | 2,931,197 | 3,171,066 | 3,522,099 | 2,660,477 | 820,800 | 969,900 | 3,606,430 | 2,926,760 | 3,048,190 | 2,337,210 | 31,748,215 | 86,744 | 0.00 | 2 | 121,622 | 0.00 |
| 1997 | 245,910 | 3,415,980 | 3,695,170 | 3,612,330 | 3,640,250 | 3,471,850 | 9,859,020 | 6,313,740 | 5,517,760 | 4,811,680 | 4,294,860 | 4,380,710 | 53,259,260 | 145,916 | 22.62 | 7 | 318,033 | 10.43 |
| 1998 | 4,310,400 | 3,943,180 | 3,904,420 | 3,257,240 | 3,336,300 | 2,595,890 | 1,164,040 | 3,953,060 | 4,336,830 | 4,953,520 | 4,979,230 | 4,998,360 | 45,732,470 | 125,294 | 5.29 | 11 | 165,974 | 0.00 |
| 1999 | 4,862,560 | 4,502,960 | 4,848,910 | 4,782,350 | 4,071,580 | 4,614,780 | 4,809,810 | 4,237,010 | 3,598,650 | 3,812,510 | 3,571,170 | 3,558,010 | 51,270,300 | 140,467 | 18.04 | 2 | 160,820 | 0.00 |
| 2000 | 3,608,360 | 3,481,570 | 3,757,740 | 3,461,420 | 3,597,660 | 3,438,210 | 3,458,140 | 3,128,660 | 3,371,190 | 3,505,400 | 3,517,950 | 3,595,700 | 41,922,000 | 114,541 | 0.00 | 3 | 121,217 | 0.00 |
| 2001 | 3,543,780 | 3,169,090 | 3,508,510 | 3,310,010 | 3,316,560 | 3,536,040 | 4,197,660 | 4,798,460 | 4,784,080 | 4,736,800 | 4,705,160 | 4,491,890 | 48,098,040 | 131,775 | 10.74 | 9 | 159,469 | 0.00 |
| 2002 | 3,776,700 | 3,229,060 | 3,149,890 | 3,070,100 | 3,044,650 | 3,048,460 | 3,068,130 | 3,089,570 | 3,018,470 | 3,398,350 | 3,593,530 | 3,382,870 | 38,869,780 | 106,493 | 0.00 | 1 | 121,829 | 0.00 |
| 2003 | 2,318,680 | 2,650,820 | 3,094,260 | 2,537,340 | 3,830,310 | 3,517,430 | 3,475,140 | 3,472,950 | 3,053,170 | 3,256,260 | 3,309,870 | 3,358,530 | 37,874,760 | 103,766 | 0.00 | 5 | 123,558 | 0.00 |
| 2004 | 3,308,950 | 2,600,900 | 3,359,850 | 3,503,040 | 3,730,510 | 3,572,330 | 3,643,350 | 3,658,070 | 3,528,530 | 3,634,710 | 3,399,800 | 3,465,040 | 41,405,080 | 113,129 | 0.00 | 5 | 120,339 | 0.00 |
| 2005 | 2,962,390 | 3,309,760 | 3,849,780 | 3,726,790 | 3,901,300 | 3,808,110 | 3,956,170 | 2,864,630 | 3,611,570 | 3,609,320 | 3,370,230 | 0 | 38,970,050 | 106,767 | 0.00 | 7 | 127,618 | 0.00 |
| 2006 | 3,093,610 | 2,691,680 | 3,441,750 | 3,377,140 | 3,461,330 | 3,223,650 | 3,118,770 | 2,913,550 | 2,791,240 | 1,641,250 | 0 | 0 | 29,753,970 | 81,518 | 0.00 | 4 | 112,571 | 0.00 |
| 2007 | 0 | 0 | 0 | 0 | 0 | 0 | 3,301,200 | 3,993,400 | 2,818,100 | 3,965,700 | 3,801,700 | 3,595,100 | 21,475,200 | 58,836 | 0.00 | 8 | 128,819 | 0.00 |
| 2008 | 3,033,600 | 2,927,700 | 3,471,300 | 3,048,300 | 3,332,600 | 3,488,500 | 2,689,100 | 3,904,400 | 4,148,300 | 4,203,800 | 3,466,000 | 3,572,400 | 41,286,000 | 112,803 | 0.00 | 9 | 138,277 | 0.00 |
| 2009 | 4,027,400 | 2,925,500 | 3,994,500 | 4,027,400 | 3,763,300 | 3,889,200 | 2,094,200 | 3,987,400 | 3,220,600 | 1,761,400 | 690,000 | 3,189,200 | 37,570,100 | 102,932 | 0.00 | 8 | 134,247 | 0.00 |
| 2010 | 3,768,600 | 3,460,300 | 2,723,700 | 3,380,700 | 3,339,300 | 3,185,600 | 2,803,400 | 2,542,200 | 2,199,300 | 341,300 | 4,152,900 | 1,846,106 | 33,743,406 | 92,448 | 0.00 | 11 | 138,430 | 0.00 |
| 2011 | 2,724,590 | 2,707,880 | 2,976,195 | 546,530 | 0 | 1,510,188 | 3,639,202 | 1,759,372 | 2,009,123 | 0 | 3,530,715 | 3,046,399 | 24,450,194 | 66,987 | 0.00 | 11 | 117,691 | 0.00 |
| 2012 | 1,878,411 | 947,449 | 1,773,020 | 2,291,564 | 0 | 0 | 0 | 1,964,021 | 3,580,845 | 3,651,146 | 3,949,031 | 4,191,990 | 24,227,477 | 66,195 | 0.00 | 12 | 135,225 | 0.00 |
| 2013 | 4,596,688 | 4,092,647 | 3,753,229 | 4,242,085 | 3,896,926 | 3,346,294 | 4,302,388 | 4,226,269 | 4,051,797 | 3,056,559 | 4,305,642 | 3,780,348 | 47,650,872 | 130,550 | 9.71 | 1 | 148,280 | 0.00 |
| 2014 | 4,315,922 | 3,750,995 | 3,307,114 | 2,395,763 | 3,562,569 | 3,224,486 | 1,484,279 | 0 | 0 | 0 | 0 | 0 | 22,041,128 | 60,387 | 0.00 | 7 | 139,223 | 0.00 |
| 2015 | 0 | 0 | 0 | 0 | 0 | 3,102,875 | 3,461,051 | 3,700,799 | 3,410,164 | 3,651,235 | 3,582,893 | 3,477,507 | 24,386,524 | 66,812 | 0.00 | 11 | 119,430 | 0.00 |
| 2016 | 3,429,380 | 3,399,684 | 3,632,460 | 3,581,106 | 4,167,858 | 3,890,278 | 3,402,079 | 4,275,457 | 4,071,500 | 4,273,403 | 4,080,956 | 4,125,336 | 46,329,497 | 126,583 | 6.37 | 8 | 137,918 | 0.00 |
| 2017 | 4,161,886 | 3,727,962 | 3,888,452 | 4,020,810 | 4,033,052 | 3,968,894 | 4,050,232 | 3,116,904 | 1,418,620 | 3,037,324 | 3,755,842 | 4,037,584 | 43,217,562 | 118,404 | 0.00 | 1 | 134,254 | 0.00 |
| 2018 | 3,714,344 | 3,324,872 | 3,385,592 | 3,856,824 | 3,924,908 | 3,532,108 | 4,101,112 | 4,193,316 | 3,990,315 | 3,995,128 | 3,231,410 | 3,927,769 | 45,177,698 | 123,775 | 4.01 | 8 | 135,268 | 0.00 |
| 2019 | 3,920,582 | 3,414,855 | 3,931,983 | 4,190,698 | 3,676,131 | 2,665,722 | 3,836,360 | 4,022,859 | 4,039,600 | 4,166,667 | 4,004,889 | 4,039,361 | 45,909,707 | 125,780 | 5.70 | 4 | 139,690 | 0.00 |
| 2020 | 3,985,848 | 3,527,960 | 4,098,135 | 3,470,685 | 3,899,144 | 3,771,945 | 3,588,354 | 3,954,693 | 3,817,637 | 2,393,454 | 0 | 0 | 36,507,855 | 99,748 | 0.00 | 3 | 132,198 | 0.00 |

**Figure 20.** Imagery map for Votech well (TW-A) aquifer tests, the Maplecrest Subdivision, Career & Technology Center (Votech) and the Public Safety Training Center. The simulated fracture was derived from the Time-Distance-Drawdown calculations in the present study.

## Waterside Subdivision Aquifer Tests

Figure 21 is a map of the Waterside Community, located just north of Frederick City. The Frederick County Department of Utilities and Solid Waste Management (DUSWM) proposed testing a high capacity well (PW, FR-94-2233) that had been completed in the Grove Limestone, with a blown yield of 2000 gpm and a primary water-bearing zone at 326 feet. Due to the potential for sinkhole development and its proximity to nearby homes, the State required that a 60-day operational test of the well be conducted.

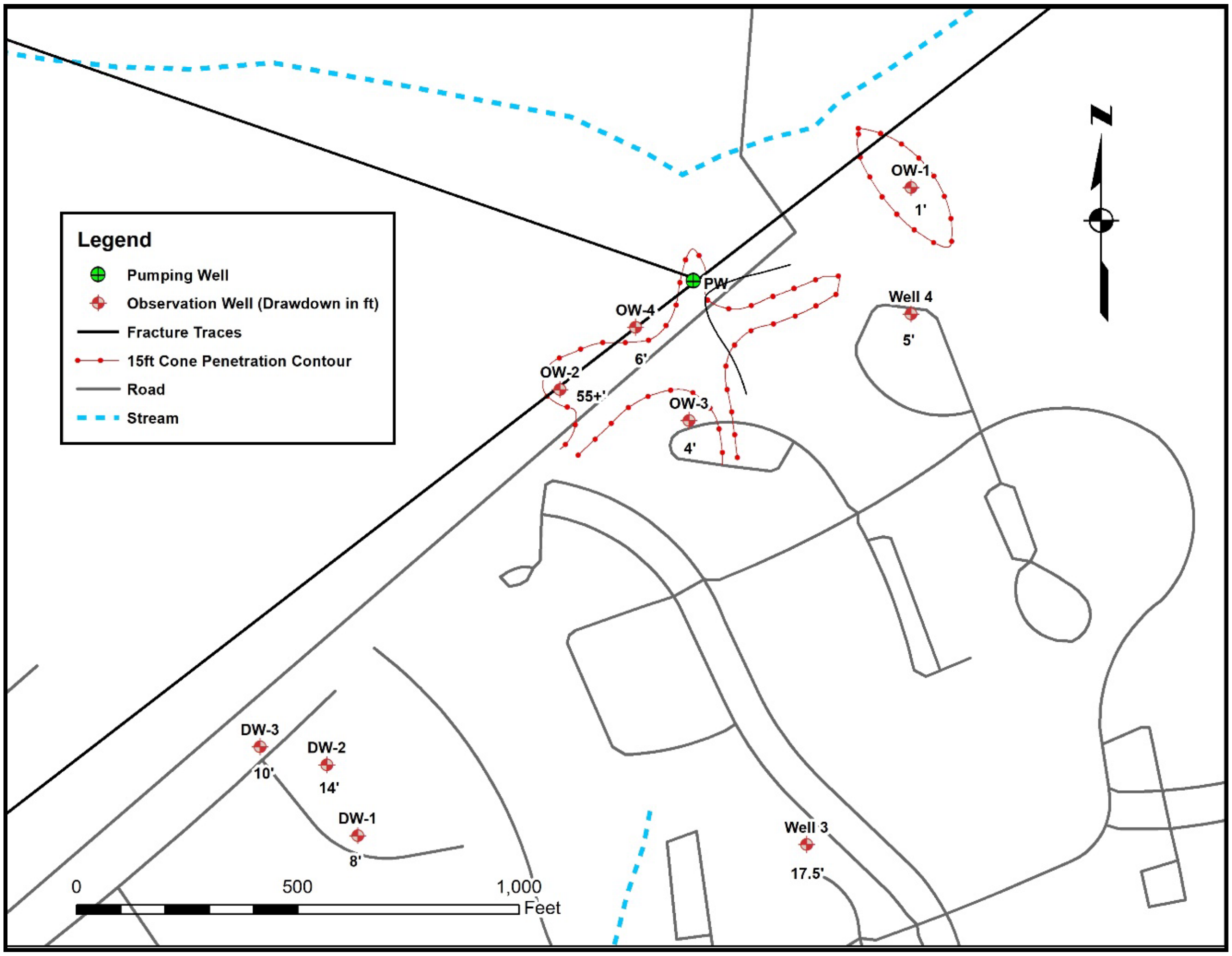

**Figure 21.** Location map for the Waterside Subdivision pumping well (PW) aquifer tests.

An initial, single well, 500-gpm, 72-hour test was conducted during which a drawdown of 20 feet occurred, from a static water level of 13 feet, Figure 22. Based on the large amount of available drawdown to the water-bearing zone at the end of the test, a 700-gpm rate was proposed for the long-term test.

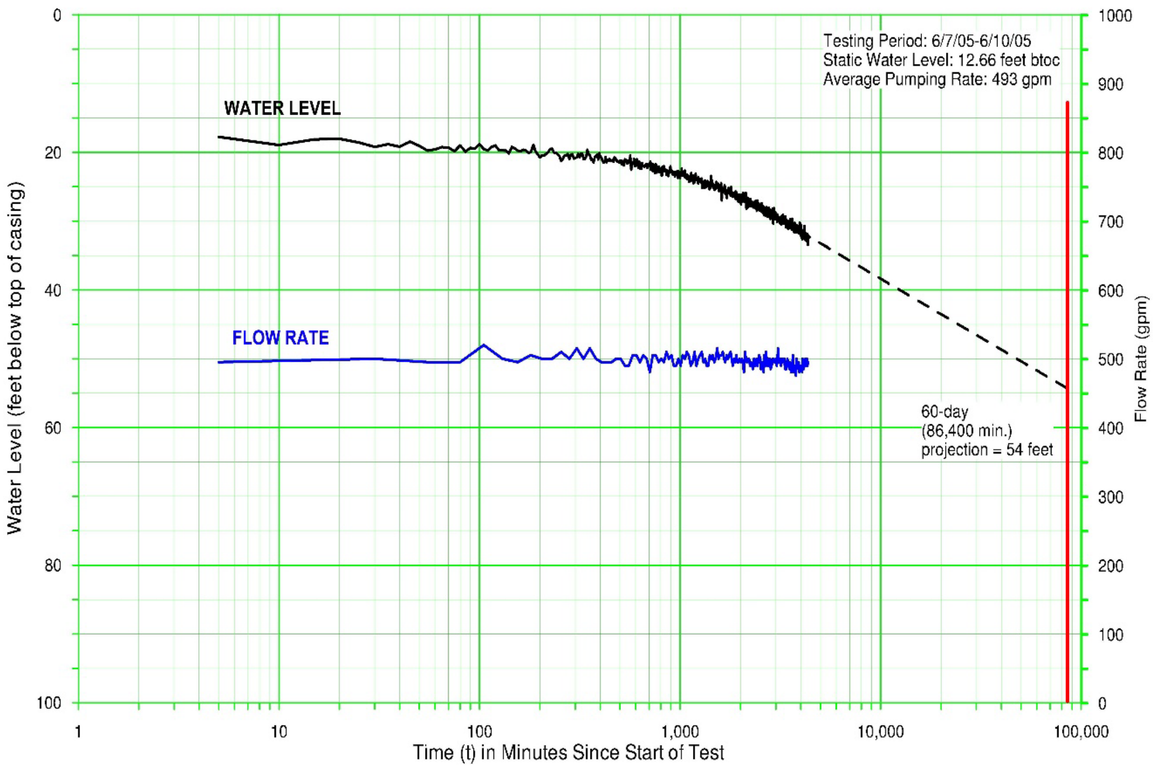

**Figure 22.** Waterside pumping well (PW) – Semi-log plot of drawdown and its flow rate a 72-h, 493 gpm pumping test.

Four observation wells (OW-1 to -4) were drilled and monitored, along with two existing unused production wells (#3 & #4), during testing. Wells OW-2 and OW-4 were located as close as possible to a gully, which was thought to be evidence of a primary conduit controlling groundwater flow. Well OW-3 was initially to be placed in a draw, which might have been another conduit; but it had to be moved out of the feature, due to the lack of permission for access to the site. During the long-term test, complaints were received from three homeowners located about 1500 feet southwest of the pumping well, and those house wells were monitored during the recovery phase.

Figure 23 is a semi-log graph of the pumping well data. As can be seen, the drawdown during the first few days was moderate, was like that which occurred during the 72-hr test and would appear to fit a linear/pseudo-radial flow model. As the pumping proceeded, the rate of drawdown increased in a steady manner, such that it was drawing down rapidly towards the end of the test, a response that was most likely due to mud clogging the pump intake screen/filter. The test had to be secured after 10 days, when the water level reached the pump intake, after about 130 feet of drawdown.

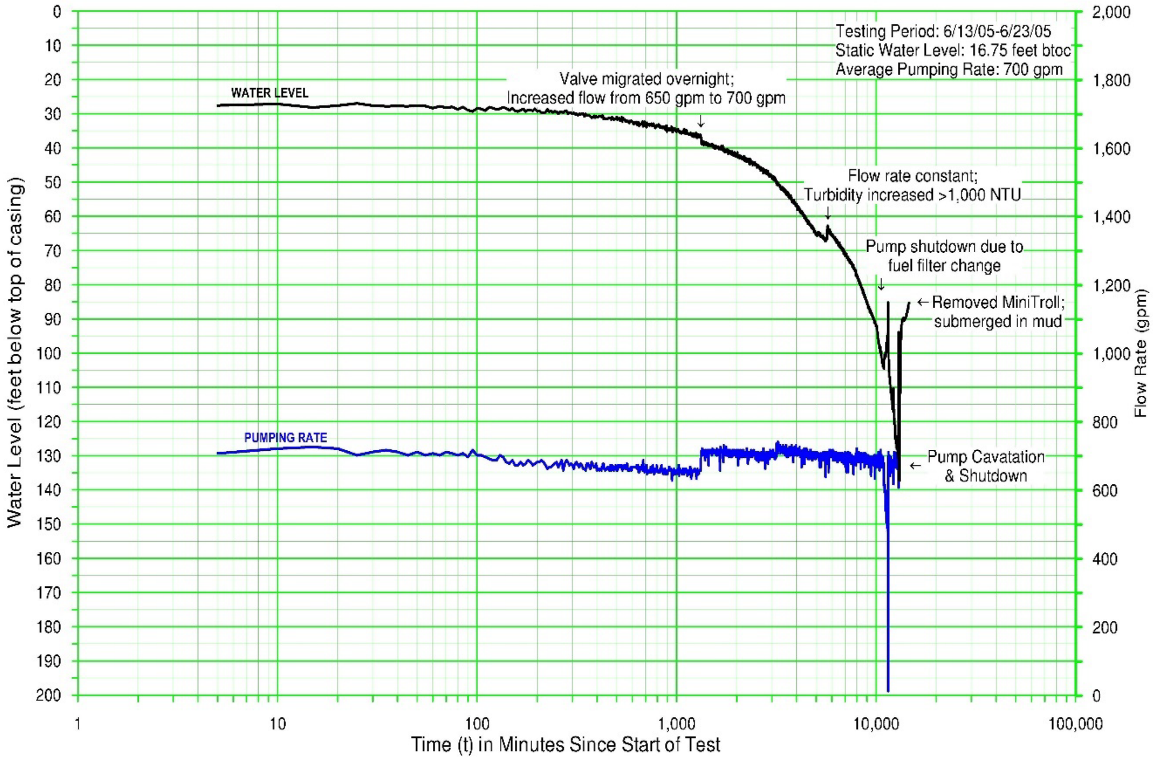

**Figure 23.** Waterside pumping well (PW) – Semi-log plot of drawdown and its flow rate for a proposed 60-d, 700 gpm aquifer test, that was secured after 10 days.

Figure 24 shows the drawdown and recovery data taken from the monitoring wells. The four observation wells were 100+/- ft deep, the house wells were 65-105 ft deep, and wells 3 and 4 were 550+/- ft deep. Data recorders were placed on the house wells after the complaints were received, so only recovery data were available. The drawdowns determined from recovering water levels, in all wells are shown on the map, Figure 21. Of interest was that the water levels recovered 15-20 ft after about one month in the house wells, located about 1400 ft from the pumping well. This was more than the recovery of 8 and 10 ft observed in wells OW-3 and -4, located 200-300 ft from the pumping well. The recovery was greatest in OW-2 (55+ ft, as the water level had fallen below the probe), located 385 ft from the pumping well. Wells OW-2 and OW-4 were located as close as possible to the gully which was thought to be a primary conduit for ground water flow. The recovery data indicate that OW-2 has a strong hydraulic connection to the conduit, the house wells are along the same trend, and OW-4 has a weak connection. Initially, OW-3 was to be placed in a draw that might be located over a conduit but had to be moved due to lack of access. The substantial recovery of water levels in well 3 (25 ft), located 1300 ft from the pumping well, relative to the recovery of 8 ft in OW-3, indicates that there was a conduit along that draw in the direction of well 3.

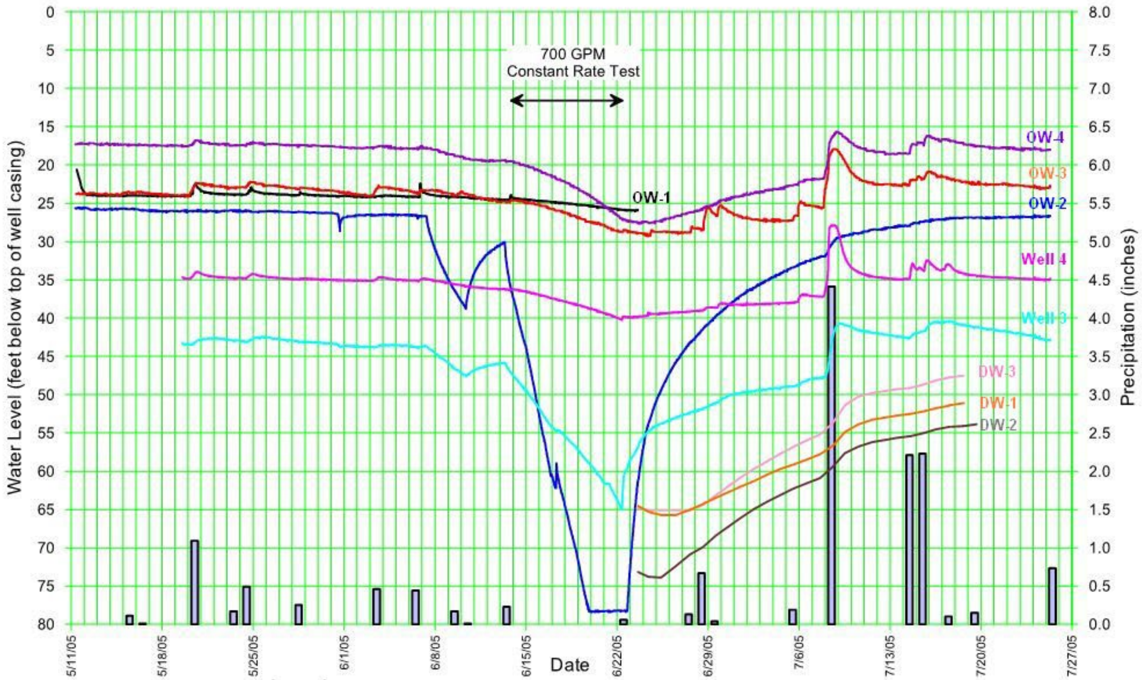

**Figure 24.** Waterside pumping well (PW) – Plots of water levels versus time for PW and the observation wells from the 10-d, 700 gpm aquifer test of well PW.

A subsequent review of the consultant's depth to bedrock map, which included data from cone penetrometer test soundings, confirms the interpretation based on the water level measurements. Although the soundings were confined to the immediate vicinity of the pumping well, the 15-foot contours on Figure 21 suggest that there were two open conduits, one in the direction of the house wells and the second towards well 3. A third conduit in the direction of well OW-1 and well 4 was closed, while a fourth in the vicinity of OW-1 was isolated from the main conduit system.

All these data suggest that you can expect to see exceptionally anisotropic formations in carbonate rocks due to the presence of highly permeable conduits in relatively impermeable bedrock. In this case, the application for the water use permit was withdrawn by the County, so no determination had to be made as to how much water could be allocated without causing any unreasonable impacts that could not be mitigated. These test data, however, provide valuable information that could be used to evaluate impacts due to water withdrawals in carbonate aquifers. To date, the only documented unreasonable impacts in carbonate formations are due to dewatering of quarries.; however, this may be due to a lack of opportunity, rather than a unique feature of this type of aquifer.

The drawdowns observed during the aquifer test of the Waterside well were simulated using the analytical techniques and iterative methods developed in this study. For the pumping well (PW) and OW-2, the drawdowns observed at the end of the 72-h, 493 gpm test were used in those simulations. The T value was derived by the Cooper-Jacob straight line method applied to the PW data. The S value was derived using an iterative method to produce the estimated fracture length and distance to the fracture for the observation wells. The following calculations present those results:

## 1/4 Fracture Length Calculation

$s_x = 264\ Q/T \log 0.3\ T\ t / x^2$

$s_x$ = drawdown (ft) Q = pumping rate (gpm)
x = distance to fracture (d) + 1/4 L
r = radial distance to pumping well
L = fracture length  t = time (days)
T = Transmissivity (gpd/ft)
S = Storage Coefficient (dimensionless)
Aquifer Constants (T&S) from:
On-site test

## Ground Water Model

Four iterations were performed to calculate the fracture length from the PW drawdown data using these S values: 0.0001, 0.001, 0.005 and 0.01. The last three provided reasonable fracture lengths (900 to 2820 ft); however, when applied to the OW-2 drawdown data, only a S value of 0.005 produced a reasonable match to the actual radial distance of 385 ft. The error of 56% is likely due to a calculated d (245 ft) that is less than the ¼ L (315 ft).

## Pumping Well

Q= 493 gpm, t = 3.0 d (72 hr), s = 19.8 ft

T = 7437 gpd/ft
S = 0.0001, 1st iteration

$s_x = 264\ (493)/7437 \log (0.3)\ (7437)\ (3.0) / x^2\ 0.0001 = 17.5 \log 66{,}933{,}000 / x^2$

$s_{2230}$ = 19.8 ft, L (1/4) = 2230 ft, L = 8,920 ft

S = 0.001, 2nd iteration

$s_x = 264\ (493)/7437 \log (0.3)\ (7437)\ (3.0) / x^2\ 0.001 = 17.5 \log 6{,}693{,}300 / x^2$

$s_{705}$ = 19.8 ft, L (1/4) = 705 ft, L = 2,820 ft

S = 0.005, 3rd iteration

$s_x = 264\ (493)/7437 \log (0.3)\ (7437)\ (3.0) / x^2\ 0.005 = 17.5 \log 1{,}338{,}660 / x^2$

$s_{315}$ = 19.8 ft, L (1/4) = 315 ft, L = 1260 ft

$S = 0.01$, 4th iteration

$s_x = 264\ (493)/7437 \log (0.3)\ (7437)\ (3.0) / x^2\ 0.01 = 17.5 \log 669{,}330 / x^2$

$s_{225} = 19.6$ ft, $L\ (1/4) = 225$ ft, $L = 900$ ft

### Observation Well OW-2

$Q = 493$ gpm      $t = 3.0$d

$T = 7437$ gpd/ft, $S = 0.005$, $s = 11$ ft, $r = 385$ ft

$s_x = 264\ (493)/7437 \log (0.3)\ (7437)\ (3.0) / x^2\ 0.005 = 17.5 \log 1{,}338{,}660 / x^2$

$s_{560} = 11$ ft, $d = x - L\ (1/4) = 560-315 = 245$ ft,
$r = x + L\ (1/4) = 560+315 = 875$ ft vs 385 ft, error 56%

### Other Observation Wells

When the T and S values from the 96-hr test when applied to the drawdowns in the remaining observation wells during the 15-d, 591-gpm test, the following simulations produced errors of -2% to 29% in the calculated to actual radial distances.

$T = 7437$ gpd/ft, $S = 0.005$

$s_x = 264\ (519)/7437 \log (0.3)\ (7437)\ (15) / x^2\ 0.005 = 18.4 \log 6{,}693{,}300 / x^2$

DW1    $r = 1432$ feet    $s = 10$ ft    $s_{1380} = 10$ ft

$S_{1380} = 10$ ft, $d = x - L\ (1/4) = 1380-315 = 1065$ ft,
$r = x + L\ (1/4) = 1380+315 = 1695$ ft vs 1432 ft, error -16%

DW2    $r = 1372$ feet    $s = 17$ ft    $s_{892} = 17$ ft

$S_{892} = 17$ ft, $d = x - L\ (1/4) = 892-315 = 577$ ft,
$r = x + L\ (1/4) = 892+315 = 1207$ ft vs 1372 ft, error 14%

DW3    $r = 1438$ feet    $s = 12$ ft    $s_{1220} = 12$ ft

$S_{1220} = 12$ ft, $d = x - L\ (1/4) = 1220-315 = 905$ ft,
$r = x + L\ (1/4) = 1220+315 = 1535$ ft vs 1438 ft, error -6%

Well 3  $r = 1300$ feet    $s = 21$ ft    $s_{5695} = 21$ ft

$S_{695}$ = 21 ft, d = x -L (1/4) = 695-315 = 380 ft,
r = x + L (1/4) = 695+315 = 1010 ft vs 1300 ft, error 29%

DW3 r = 1438 feet s = 12 ft $s_{715}$ = 12 ft

$S_{715}$ = 12 ft, d = x -L (1/4) = 715-750 = -35 ft,
r = x + L (1/4) = 715+750 = 1465 ft vs 1438 ft, error -2%

Well 3 r = 1300 feet s = 21 ft $s_{465}$ = 21 ft

$S_{465}$ = 21 ft, d = x -L (1/4) = 465-750 = -285 ft,
r = x + L (1/4) = 465+750 = 1215 ft vs 1300 ft, error 7%

Outside of quarries, most of the water withdrawn in the carbonate areas of the Maryland is from surface water for public water supplies in the Hagerstown, Frederick, and Wakefield (Westminster) valleys. In 1968, the Maryland Court of Appeals (Finley v. Teeter Stone, Inc.) affirmed that quarry withdrawals could be determined by law and regulation to be reasonable, even if they caused nearby water supplies to go dry, had diminished yields or experienced water quality problems. The legislation requiring permits for surface mines was passed in 1975. Changes of State regulations were made for water use in 1989 and surface mines ("Zone of Influence" in karst terrain) in 1991, so that quarries could be held liable for mitigation of impacts caused by dewatering activities. By that time, most quarries had been operating for decades, so any impacts that could have occurred may have already happened and there were probably few, if any, records available concerning such problems. The "Zone of Influence" delineations appear to be based solely on existing information, although monitoring programs may be required as a permit condition. The results of the Waterside test might be useful is making future "Zone of Influence" delineations and designing programs for monitoring of potentially impacted water supplies.

# Summary

## Myersville Water Treatment Plant (WTP) well

An initial 1987 test of the WTP well had to be secured early, when an excessive drawdown caused a nearby domestic well to go dry. A permit was issued after that test and that domestic well and three other homes were connected to the public water system. An increased withdrawal was requested by the Town in 1993. The Water Supply Program required additional testing; however, before it was completed, a complaint was made that another domestic well, located about 1000 feet northwest of the WTP well, had gone dry. Due to the potential impacts to the last domestic well and the relatively low estimated yield of the WTP well, a long-term test of the WTP well was conducted for 51 days in Jul-Aug 1994. VLF traces and drawdowns (155 feet) from that test indicate that there is a prominent northeast trending fracture (280 feet long) connecting the WTP well and its back-up well. The drawdown (150 feet) in the Weirer well and the VLF traces suggest that there is a compound northwest trending second fracture (280 feet long) connecting the WTP and Weirer wells. The estimated minimum total length of the primary fracture system is then 560 feet.

The results of the 54-hr and 51-d tests were used to develop the ¼ fracture length model used by the State, in lieu of costly numerical simulations, to estimate impacts to water supplies caused by groundwater withdrawals in the fractured rock aquifers of Maryland. This relatively simple analytical technique assumes an effective well radius (equal to ¼ fracture length), instead of the actual well radius, to calculate drawdowns in pumping wells. The heterogeneity of an aquifer is estimated by assigning higher storage and transmissivity values to the weathered zone relative to the bedrock portion of an aquifer to calculate drawdowns in shallow domestic wells. In those cases, the distance used in the calculations is not the distance to the pumping well, but the distance to the fracture plus ¼ L. Şen (1992) indicated that while fracture length is not directly related to transmissivity, it can affect the storage constant by as much as an order of magnitude.

There are several observations that can be taken from the results of the testing and analysis of data from the WTP well tests. The aquifer functions as one with two layers of differing hydraulic characteristics. One explanation is that an upper 100-150 ft weathered layer has a high T value and probably exists under effectively confined conditions. The deeper layer has a lower T value and, due to aquifer dewatering, is semi-confined. A second possibility is that there is a lateral variation in hydraulic properties, in that there is a high T in the immediate vicinity (about 100 ft) of the fracture and a low T off the fracture trend. Under most field conditions there will not be detailed geophysical surveys conducted, so it is possible that the errors in estimated drawdowns in potentially impacted wells may be greater than 25% and could exceed 50%.

# Middletown

## Municipal Well 17

An initial, 96-hour, 41-gpm aquifer test was conducted on the Middletown well 71, while monitoring the Town's well 14 and three nearby domestic wells. As a condition of the associated water use permit, a follow-on, 60-day, 30-gpm test was performed, while monitoring wells 14 and 17, and six domestic wells within 1300 feet of well 17.

The drawdowns in two domestic wells at the end of the initial test were about 2-3 feet, which were substantially less than the 17 feet in a third domestic well, although the first two were much closer to the pumping well. This suggested that a discrete fracture, or combination of fractures, might be affecting groundwater flow and that the fracture was much closer to the third domestic well than the other two domestic wells. The long-term test and ¼ fracture length modelling confirmed that drawdowns were affected by dewatering of the shallow portion of the aquifer, the presence of an extremely long fracture, and lateral variations in hydraulic constants along the primary axis of the trough of depression. The results indicated that declining yields in one domestic well and a lawn irrigation well, and increased turbidity in two other domestic wells were caused by withdrawals from well 17.

## Middletown A.C. Jets project

Five wells (TW-1, -2, -3, -5 and -8) were drilled and completed for the A.C. Jets project. A 72-hr test was conducted on each, except TW-2, while monitoring 3 or 5 observation wells, at distances between 555 ft and 1760 ft from a pumping well. There were no drawdowns observed in wells TW-1 and DW-1 during the TW-8 test, suggesting that there is a significant decline in permeability between those two wells and TW-8. One explanation is that the representative equivalent volume affecting flow to each observation well determines the amount of drawdown that would occur during a pumping phase. During the 72-hr test, groundwater is flowing to the pumping well from the area of high T and no water is flowing from the low permeability areas near TW-1 and DW-1. As pumping continues during the 90-d simulations, then water starts flowing from the low-permeability areas; however, the drawdowns in TW-1 and DW-1 reflect the cumulative effects of flow from both the high and low T areas. The 26 ft of drawdown in TW-3 at 1760 ft represents the maximum distance at which a significant drawdown has occurred during testing in a non-carbonate crystalline rock aquifer.

# Westminster well 8 (Votech)(TW-A) and Maplecrest Subdivsion Incident

In 1999, the Carroll County Health Department identified Maple Crest, a 30-year-old subdivision south of Westminster, as a community having water supply problems. The neighborhood residents relied on private wells, some which run low during part of the year and others that go dry during periods of drought. Most of those wells were on properties along Wayne Avenue and Woodland Drive. In 2002, the county extended water lines to about 25 homeowners on Wayne Avenue and Woodland Drive. Westminster's nearby well 8 (TW-A, Votech well) was completed on 6/28/1987 and two aquifer tests were conducted in August 1987 (96-h, 400 gpm) and January 1988 (14-d, 205 gpm), while monitoring one observation well (TW-C), located 150 feet from TW-A.

The water supply problems noted at the Maplecrest Subdivision occurred shortly after the Votech well was placed in service; however, those problems were not reported to the MDE Water Appropriation Division, so no investigation of potential impacts due to withdrawals from the Votech well was conducted. The methods developed in the present study were used to see if it is possible that any unreasonable impacts had occurred.

For this evaluation, the ¼ fracture length model was used. Since the upper water bearing zones were cased off prior to the 14-d, 200 gpm test, the late-time T values for TW-A and TW-C were likely representative of the aquifer characteristics. Those T values were held constant, and the S values were adjusted by an iterative method to match the drawdowns observed at the end of the test. In that case, there was no calculated drawdown along either Woodland Drive or Wayne Avenue. Potential impacts were estimated by pumping well TW-A (Votech well) at 200 gpm over a 90-d period, without recharge from the aquifer. The results indicate that there would have been no impacts to the domestic wells along Woodland Drive and Wayne Avenue.

Since there was no long-term monitoring data from the domestic wells along Woodland Drive and Wayne Avenue, additional information was considered to verify that no unreasonable impacts had occurred. Most telling is that water use from the Votech well declined from a peak of 200 gpm in July 1997 to about 80-110 gpm from 1998-2002, when the Maplecrest water supply problems were first reported, and continued at less than an average of 100 gpm to date. After the houses along Woodland Drive and Wayne Avenue were provided public water in 2002, it is expected that that production from the Votech would increase to the previous maximum yield of 200 gpm if impacts had occurred. Hammond (2018) indicated that, upon depletion of aquifer storage, the reduced yield after 1997-98 was due to recharge from a limited area (148 acres) in the vicinity of the well. The water system supervisor during the period of the incident also indicated that she had no knowledge of impacts to the Maplecrest house wells and suggested that the available recharge area may have been reduced by impermeable surfaces at several major facilities in the watershed (Carroll County Career & Technology Center-Votech and Public Safety Training Center), That information and the Time-Distance-Drawdown calculations indicated that there were no impacts to the Maplecrest house wells due to withdrawals from the Votech well.

## Waterside Subdivision

At the Waterside Community, located just north of Frederick City, the Frederick County DUSWM proposed testing a high capacity well that had been completed in the Grove Limestone with a blown yield of 2000 gpm. Due to the potential for sinkhole development and its proximity to nearby homes, the State required that a 60-day operational test of the well be conducted. The test was started at 700 gpm, but had to be secured after 10 days, due to excessively drawdowns that caused mud to clog the pump intake and impacts to three domestic wells at 1400 feet from the pumping well.

A consultant's depth to bedrock map, which included data from cone penetrometer test soundings, confirms the geologic interpretation based on the water level measurements from the test, which was that there were two open conduits, one in the direction of the three domestic wells and the second towards a community supply well, a third conduit was closed and a fourth was isolated from the main conduit system.

The drawdowns observed during the aquifer test of the Waterside well were simulated using the analytical techniques and iterative methods developed in this study. For the pumping well (PW) and OW-2, the drawdowns observed at the end of the 72-h, 493 gpm test were used in those simulation. The T value was derived by the Cooper-Jacob straight line method applied to the PW data. The S value was estimated using an iterative method to produce the estimated fracture length (1260 ft) and distance to the fracture for the observation wells. The error for r = x + L (1/4) of OW-2 equals -56%, likely because the distance to the fracture (245 ft) is less than L (1/4) (315 ft). The errors for the other observation wells vary from -2% to +29%.

# REFERENCES

**Bachman, L.J., Lindsey, B., Brakebill, J. and Powars, D.S.**, 1998, Ground-water discharge and base-flow nitrate loads of nontidal streams, and their relation to a hydrogeomorphic classification of the Chesapeake Bay Watershed, middle Atlantic coast: U.S. Geological Survey Water-Resources Investigations Report 98-4059, 71 p. https://doi.org/10.3133/wri984059

**Barker, J.A.**, 1988, A generalized radial flow model for hydraulic tests in fractured rock: Water Resources Research: 24(10), pp.1796-1804. https://doi.org/10.1029/WR024i010p01796

**Brezinski, D.K.,** 2004, Stratigraphy of the Frederick Valley and its relationship to karst development: Maryland Geological Survey Report of Investigations No. 75, 101 p.

**Cleaves, E.T., Edwards, J. and Glaser, J.D.**, 1968, Geologic map of Maryland: Maryland Geological Survey, Baltimore, Maryland, scale 1:250,000.

**Cooper Jr, H.H. and Jacob, C.E**., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Eos, Transactions American Geophysical Union, 27(4), pp.526-534. http://dx.doi.org/10.1029/TR027i004p00526

**Dougherty, D.E. and Babu, D.K.**, 1984, Flow to a partially penetrating well in a double-porosity reservoir: Water Resources Research, 20(8), pp.1116-1122. https://doi.org/10.1029/WR020i008p01116

**Duffield, G.M.**, 2007, AQTESOLV® for Windows Version 4.5 User's Guide. HydroSOLVE, Reston, VA.

**Duigon, M.T. and Dine, J.R.**, 1987, Water resources of Frederick County, Maryland: Maryland Geological Survey Bulletin 33.

**Fleming, B.J., Hammond, P.A., Stranko, S.A., Duigon, M.T., and Kasraei, S.**, 2012, A science plan for a comprehensive assessment of water supply in the region underlain by fractured rock in Maryland: U.S. Geological Survey Scientific Investigations Report 2012–5160, 29 p. https://doi.org/10.3133/sir20125160

**Gringarten, A.C. and Ramey Jr, H.J.**, 1974, Unsteady-state pressure distributions created by a well with a single horizontal fracture, partial penetration, or restricted entry: Society of Petroleum Engineers Journal, 14(04), pp.413-426. https://doi.org/10.2118/3819-PA

**Gringarten, A.C. and Witherspoon, P.A.**, 1972, A method of analyzing pump test data from fractured aquifers. Percolation through fissured rock, Deutsche Gesellschaft fur Red and Grundbau, Stuttgart, pp. T3B1-T3B8.

**Hammond, P.A.**, 2018, Reliable yields of public water-supply wells in the fractured-rock aquifers of central Maryland, USA: Hydrogeology Journal, 26(1), pp.333-349. https://doi:10.1007/s10040-017-1639-4

**Hammond, P.A. and Field, M.S.**, 2014, A reinterpretation of historic aquifer tests of two hydraulically fractured wells by application of inverse analysis, derivative analysis, and diagnostic plots: Journal of Water Resource and Protection, 6(05), p.481. https://doi.org/10.4236/jwarp.2014.65048

**Hanson, E.R.**, 2009, Public community water systems groundwater interference project. Final report. Prepared for the Vermont Rural Water Association, Essex Junction, VT on June 30, 2009, 160 p.

**Hantush, M.S. and Jacob, C.E.**, 1955, Non-steady radial flow in an infinite leaky aquifer: Eos, Transactions American Geophysical Union, 36(1), pp.95-100. https://doi.org/10.1029/TR036i001p00095

**Hydrosolve, Inc.**, 2007, AQTESOLV® (ARCADIS, Geraghty and Miller, Inc.), Version 4.50.002, Aquifer Test Analysis Software, Reston, Virginia, U.S.A.

**Kohurt, A.P., Foweraker, J.C., Johanson, D.A., Tradewell E.H. and Hodge, W.S.**, 1983, Pumping effects of wells in fractured granitic terrain: Groundwater 21(5), pp. 564-572. https://doi.org/10.1111/j.1745-6584.1983.tb00762.x

**Moench, A.F.**, 1985, Transient flow to a large-diameter well in an aquifer with storative semiconfining layers: Water Resources Research, 21(8), pp.1121-1131. https://doi.org/10.1029/WR021i008p01121

**Nutter, L.J.**, 1975, Hydrogeology of the Triassic rocks of Maryland: Maryland Geological Survey Report of Investigations no. 26

**Otton, E.G.**, 1981, The availability of ground water in western Montgomery County, Maryland: Maryland Geological Survey Report of Investigations no. 34

**Prats, M.**, 1961, Effects of vertical fractures on reservoir behavior-incompressible fluid case: Society of. Petroleum Engineers Journal 1(02), pp. 105-118. https://doi.org/10.2118/1575-g

**Rushton, K.R. and Chan, Y.K.**, 1976, Pumping Test analysis when parameters vary with depth. Groundwater 14(2), pp. 82-87. https://doi.org/10.1111/j.1745-6584.1976.tb03637.x

**Sen, Z.**, 1992, Unsteady ground-water flow toward extended wells: Groundwater 30(1), pp.61-67. https://doi.org/10.1111/j.1745-6584.1992.tb00812.x

**Sen, Z.**, 1994, Hydrogeophysical concepts in aquifer test analysis: Hydrology Research 25(3), pp. 183-192. https://doi.org/10.2166/nh.1994.0003

**Stewart, M. and Langevin, C.**, 1999, Post audit of numerical prediction of wellfield drawdown in a semi-confined aquifer system: Groundwater 37(2), pp. 245-252. https://doi.org/10.1111/j.1745-6584.1999.tb00980.x

**Theis, C.V.**, 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Eos, Transactions American Geophysical Union, 16(2), pp.519-524. https://doi.org/10.1029/TR016i002p00519

**Tiedeman, C.R. and Hsieh, P.A.**, 2001, Assessing an open-well aquifer test in fractured crystalline rock: Groundwater 39(1), pp. 68-78. https://doi.org/10.1111/j.1745-6584.2001.tb00352.x

**Van Tonder, G.J., Botha, J.F., Chiang, W.H., Kunstmann, H. and Xu, Y.**, 2001a, Estimation of the sustainable yields of boreholes in fractured rock formations: Journal of Hydrology, 241(1-2), pp.70-90. https://doi.org/10.1016/S0022-1694(00)00369-3

**Vecchioli, J.**, 1967, Directional hydraulic behavior of a fractured shale aquifer in New Jersey. International Symposium on Hydrology of Fractured Rocks, Dubrovnik, Yugoslavia: Proc. Intern. Assoc. Sci. Hydrology Publ. 73(1), pp. 318-325.