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DEVELOPMENT OF AN APPROACH TO EVALUATE FRACTURED CRYSTALLINE BEDROCK WATER RESOURCE SUPPLY AND SUSTAINABILITY

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Development of an Approach to Evaluate Fractured
Crystalline Bedrock Water Resource Supply and Sustainability

Helen E. Spera

B.S., University of Connecticut, 1983

A Thesis

Submitted in Partial Fulfillment of the

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2011

APPROVAL PAGE

Development of an Approach to Evaluate Fractured
Crystalline Bedrock Water Resource Supply and Sustainability

Master of Science Thesis

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2011

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ABSTRACT

Groundwater derived from fractured crystalline bedrock is an important resource in Connecticut. Despite its importance we know very little about this resource. This study was conducted at the Plant Science and Landscape Architecture Research and Education Facility, University of Connecticut, Storrs, CT. The objectives of this study were: to improve the characterization of the hydrogeology of the facility; to develop a method to determine the amount of recharge to the bedrock from the overburden during pumping and non-pumping periods; and to develop an approach that can be used in evaluating the sustainability and zone of contribution of bedrock pumping wells. The study entailed installation of bedrock and overburden wells, conducting pump and slug testing, initiating a real-time ground water level monitoring system and estimating ground water flow conditions. The study developed detailed information on the overburden and bedrock hydrogeologic characteristics. Water levels were monitored under pumping and non-pumping conditions to access zones of contribution to wells. The recession rates of the overburden and bedrock were used to estimate the recharge rate to the bedrock under non-pumping conditions. As a conservative estimate of the recharge rate during pumping, the non-pumping vertical gradient was used. Three types of zones of contribution were developed based on the effects of pumping and hydraulic divides. Essential results include: under non-pumping conditions, 30 to 50 percent of the water that recharges the overburden recharges the bedrock; predicted flow amounts to pumping wells were within 30% of the actual amount pumped; using

the most conservative area of contribution, the estimated recharge from the overburden matched within 10% of the water being pumped. The methods developed in this study can be used at other locations as a means of estimating the availability and sustainability of groundwater in the fractured crystalline bedrock.

1 INTRODUCTION

Background

Groundwater derived from fractured crystalline bedrock is an important resource in Connecticut. The State has more than 4,000 public water supply wells and some 400,000 domestic wells in bedrock (CT DEP 2009 a). Much of the new development in the State has occurred in rural areas where water derived from the bedrock is the sole source of water supply (USGS 2004, CT DEP 2009 b).

Given the importance of the water derived from fractured crystalline bedrock wells, the supply needs to be sustained and protected. This requires knowing the recharge rates to the bedrock in relation to usage and the areas of contribution of pumping wells (source area). The latter is important in protecting the wells from contamination and assessing well interferences. Because of the complex nature of bedrock fractures, it is difficult to characterize their hydrogeologic conditions to perform quantitative resource assessments. The bulk porosity of unweathered, crystalline rock is very low and typically ranges from 0.1 to 1% (Singal and Gupta 2010). Therefore, the flow path and storage of water in the rock is through interconnected fractures. Not only do these fractures need to be interconnected, but whether flow will occur and its rate are dependent on the fracture aperture width. As summarized by Doe and Pedler (1998) the amount of flow increases by approximately the cube of the width of the fracture. Therefore, a fracture that has an aperture that is slightly larger than one nearby will carry much more of the flow. Even though a well may intersect many fractures only a small number of the wider fractures may be water contributing. As noted by Berkowitz (2002), the matter is complicated even further by material filling the fractures. Also, fractures that intersect a well may have many different orientations, densities and degrees of interconnectiveness which are dependent on complex,

unpredictable factors. These factors include the method of formation of the rock, the physical properties of the rock, and fractures formed during diagenesis (Nelson 2001).

The water available in crystalline bedrock aquifers in New England ultimately comes from precipitation falling on the ground and infiltrating through overlying glacial material, or in rare cases, directly onto the bedrock. The water then flows through the fractures into wells that penetrate these fractures. In order to determine the source area of the water and the amount of water available to the bedrock from the overburden, a thorough characterization of the surficial material and underlying bedrock need to be completed. In Connecticut, there have been few studies that have addressed the recharge issue. Ellis (1909) was the first to characterize the hydrogeology of Connecticut. He described the surficial and bedrock geology of Connecticut, and the groundwater quality and availability associated with these environments. The bedrock aquifers were characterized by their structure and composition; this included bedding planes and the spacing and orientation of typical joints found. He evaluated how water would flow in and through these rocks. This study was extended more recently by Starn and Stone (2005). They developed a fractured rock conceptual model used to classify possible ground water flow conditions and modeled groundwater flow using computer simulations representing various geological settings and well locations. They determined a generalized shape and size of the source area to a well. Another study by Mullaney (2004) entailed conducting a water budget and hydrogeologic model for 32 small basins in the Greenwich area of Connecticut, where crystalline bedrock is located. He used computer simulations and hydrogeologic data to determine the groundwater availability with a groundwater recharge rate depending on the type of overburden and estimated hydraulic conductivity of the bedrock. Lyford et al. (2007) did a similar study in the Pomperaug River Basin, a regional drainage basin in western Connecticut, using computer models to delineate the recharge areas to public supply wells for sustainability and water quality analysis.

The two studies above that estimated groundwater recharge rate (Mullaney 2004, and Lyford et al. 2007) lumped both the recharge to the overburden and to the bedrock; they did not compute the amount of water recharging the bedrock from the overburden. Not all the water entering the overburden will necessarily flow into the bedrock aquifer, so the actual recharge rate to the bedrock may be much less than what they estimated. Other studies completed in similar settings in other parts of New England have addressed the bedrock recharge rate. Harte and Winter (1995) used a computer simulation of a crystalline rock aquifer overlain by glacial deposits in hilly terrain typical of the New England located in the Central Highlands. They estimated that for most geological conditions, the recharge rate from the overburden to the bedrock does not exceed 10 percent of the precipitation and is mostly between 1 to 3 inches/year out of an annual 44 inches of precipitation. They also found that the source areas to the wells were affected the most by topography and horizontal heterogeneities found in the bedrock. Tiedemann et al. (1998) used a computer simulation in the drainage basin at Mirror Lake, New Hampshire to estimate the recharge to the bedrock. The study area is in the highlands where glacial deposits overlie metamorphic rock and granitic intrusions. They found that 40% of the groundwater recharge stayed in the glacial overburden and 60% of it recharged the bedrock. Robbins et al. (2009) conducted a study at a farm owned by the University of Connecticut, “The Plant Science and Landscape Architecture Research and Education Facility,” to determine if additional water could be withdrawn from the bedrock aquifer without deleterious results. They conducted a water budget to estimate the groundwater recharge rate to the bedrock. The range of flow to the bedrock under non-pumping conditions was estimated by taking 10%, 50% and 90% percent of the typical recharge rate to the till on the site. They used Darcy’s Law and estimated values of contributing areas, vertical hydraulic gradient, specific yield of the overburden, and porosity of the bedrock to estimate the flow to the fractured rock under pumping conditions at a hypothetical pumping rate of 31,000 gallons of water per day. The estimates were used to calculate a recession rate for the overburden which compared favorably to the observed recession

rate. In addition to estimating the recharge to the bedrock aquifer, the groundwater flow from the farm to the surrounding areas during non-pumping periods was determined to see if an increase pumping would impact areas bordering the farm.

Problem Statement

This study builds on that of Robbins et al. (2009). Despite the importance of the fracture rock for water supply, key pieces of information are missing in our knowledge that is needed to evaluate the sustainability of the bedrock water supply. This study, using data collected at the University farm, strives to develop an approach useful for filling in those blanks.

Study Objectives

The main objectives of this study are:

- To improve the characterization of the geology and hydrogeology of the agricultural farm located at the University of Connecticut;
- To develop a method to determine the amount of recharge to the bedrock from the overburden during pumping and non-pumping periods; and
- To develop an approach that can be used in evaluating the sustainability and zone of contribution of bedrock pumping wells.

2 SITE DESCRIPTION

Geographic Location and Topography

The University of Connecticut agronomy farm, called the Plant Science Research and Education Facility, is located on Agronomy Road in Mansfield, Connecticut, about one mile south of the main campus at Storrs. Figure 2-1 shows the location of the farm in Connecticut (CT DEP 1994a, CT DEP 1994b, CT DEP 1994c, CT DEP 1999a, CT DEP 1999b, CT DEP 2006a, CT DEP 2006b, CT DEP 2009c, US DEPT of Commerce 2008a). This farm is primarily used for research and teaching in plant and soil science by the Department of Plant Sciences (UCONN Dept. of Agriculture, 2011). Currently 50 acres are under cultivation (UCONN Dept. of Agriculture, 2011) and in 2009 the farm supported 3.5 million dollars in research funding and 35 plant science projects (Robbins et al. 2009). Figure 2-2 shows the site with the local drainage basin, water bodies, topographic contours, local roads, farm boundary and the new and existing bedrock wells (CT DEP 1988, CT DEP 1999c, CT DEP 2000a, U.S. DEP of Commerce 2008, Parent J. 2011). The farm is located in the geological Eastern Uplands of Connecticut on the top and side of a northwest-southeast trending hill called Spring Hill. The surface elevation ranges from about 550 to 680 feet above mean sea level. The hill is comprised of glacial till overlying crystalline bedrock. The area of focus for this study is 153 acres of the farm located north of East Road.

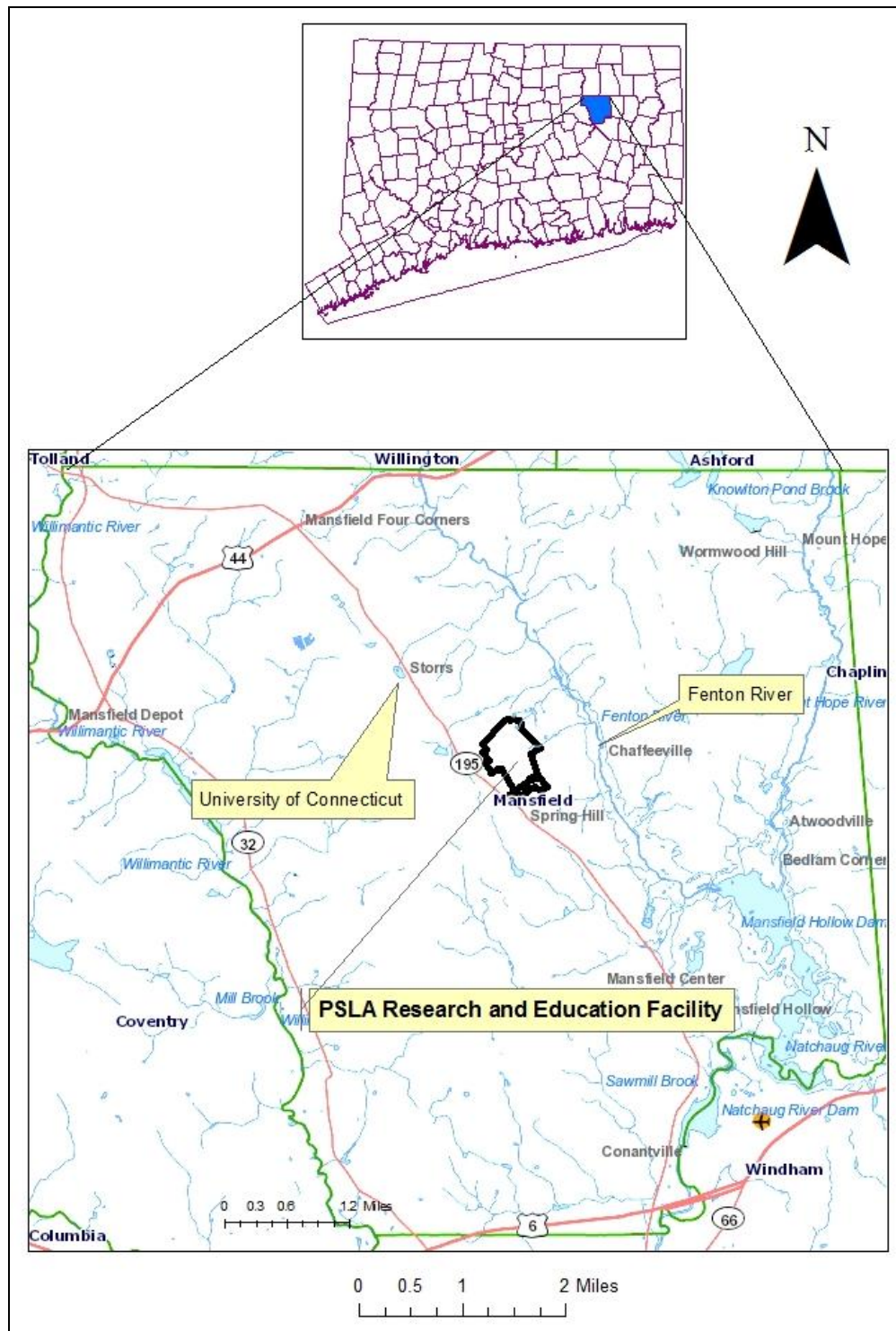


Figure 2-1 Location of the PSLA Research and Education Facility. Insert map data from DEP (1994b, 1994c). Main map data from Parent (2011) and <http://www.ctecoapp2.uconn.edu/arcgis/services>

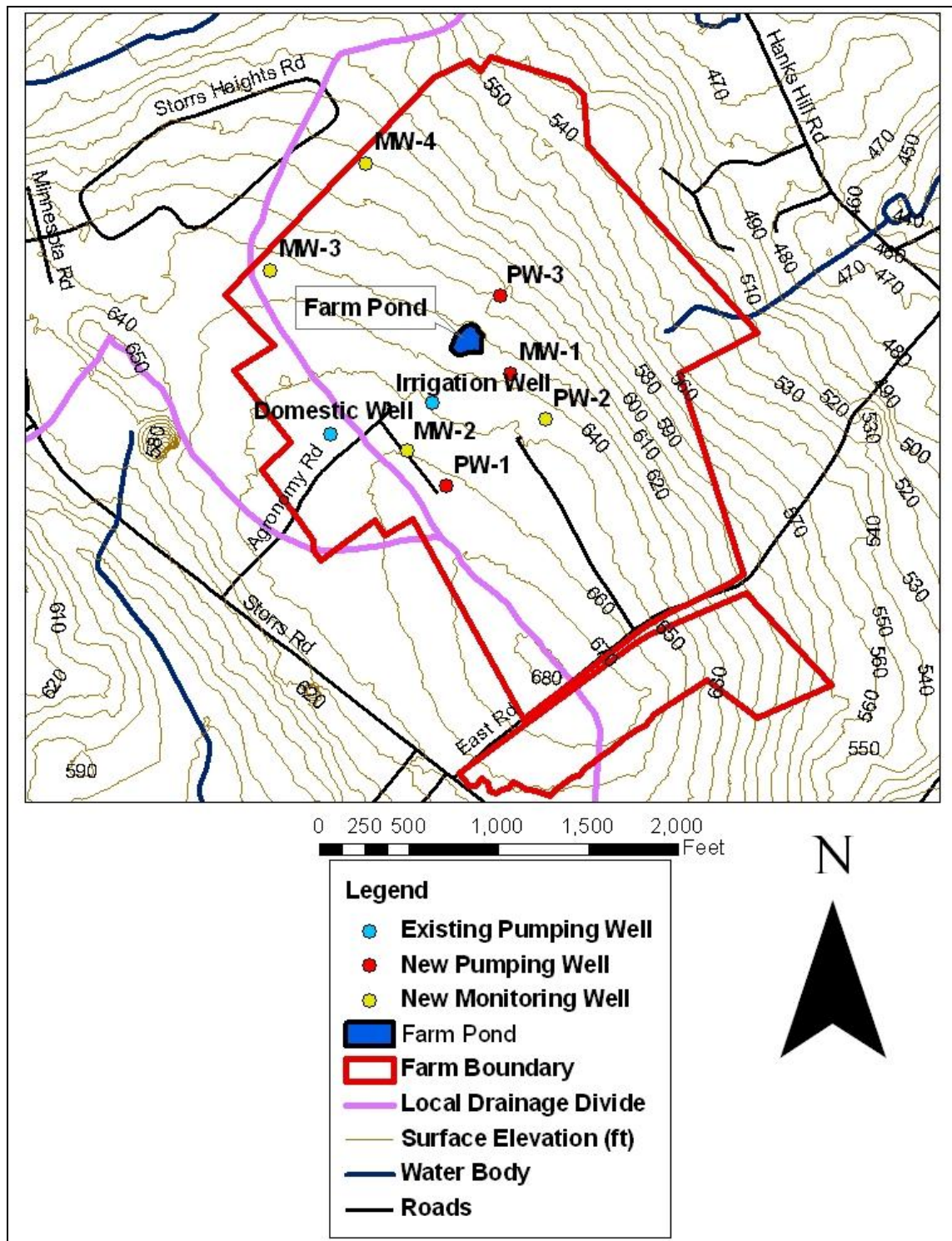


Figure 2-2 PSLA Research and Education Facility. Local drainage basin data from CT DEP (1998), water body data from CT DEP (1999c), topographic contours from CT DEP (2000a), local road data from U.S. DEP of Commerce (2008) and farm boundary from Parent (2011).

Soil composition and surface water hydrology

The farm is located in the Fenton River watershed (see Figure 2-1). The Fenton River is located approximately 3,500 feet to the northeast of the farm and the runoff from the farm flows to it from the three local drainage basins that divide the farm (Figure 2-2). Most of the farm is located west of one local drainage divide, causing most of the runoff to flow in a northeasterly direction to the Fenton River. This local drainage basin is the focus of this study and will be referred to as the “main drainage basin”.

The surface water on the farm primarily flows over fine, sandy loams that cover the site. Figure 2-3 is a soil map of the area (U.S Dept. of Agriculture 2007) overlaying NAIP imagery (USDA-FSA-APFO 2010). The majority of the soils are classified as either Montauk or Woodbridge. There is also an area of hydric soils in a wooded area, up-gradient from the farm pond.

This pond is a dug pond used for storing water for irrigation purposes. It is filled by direct precipitation and surface water flowing from a gravel filled drainage ditch that diverts water to it. The surface water empties from an uphill area of approx 551,200 ft² (Robbins et al. 2009). About 35% of this area is located in a wooded area consisting mostly of hydric soils. These soils are extremely stony and poorly drained (US Dept. of Agriculture 2007) which maximizes run-off to the pond. Previous to this study, the pond had a capacity of 325,800 gallons and was situated on at least 11 feet of relatively impermeable clayey gravelly till (Robbins, 2006). It had an earthen dike around its perimeter and a concrete spillway. (Robbins et al. 2009). In the fall of 2009, the pond was expanded from 1/3 acre to 1/2 acre.

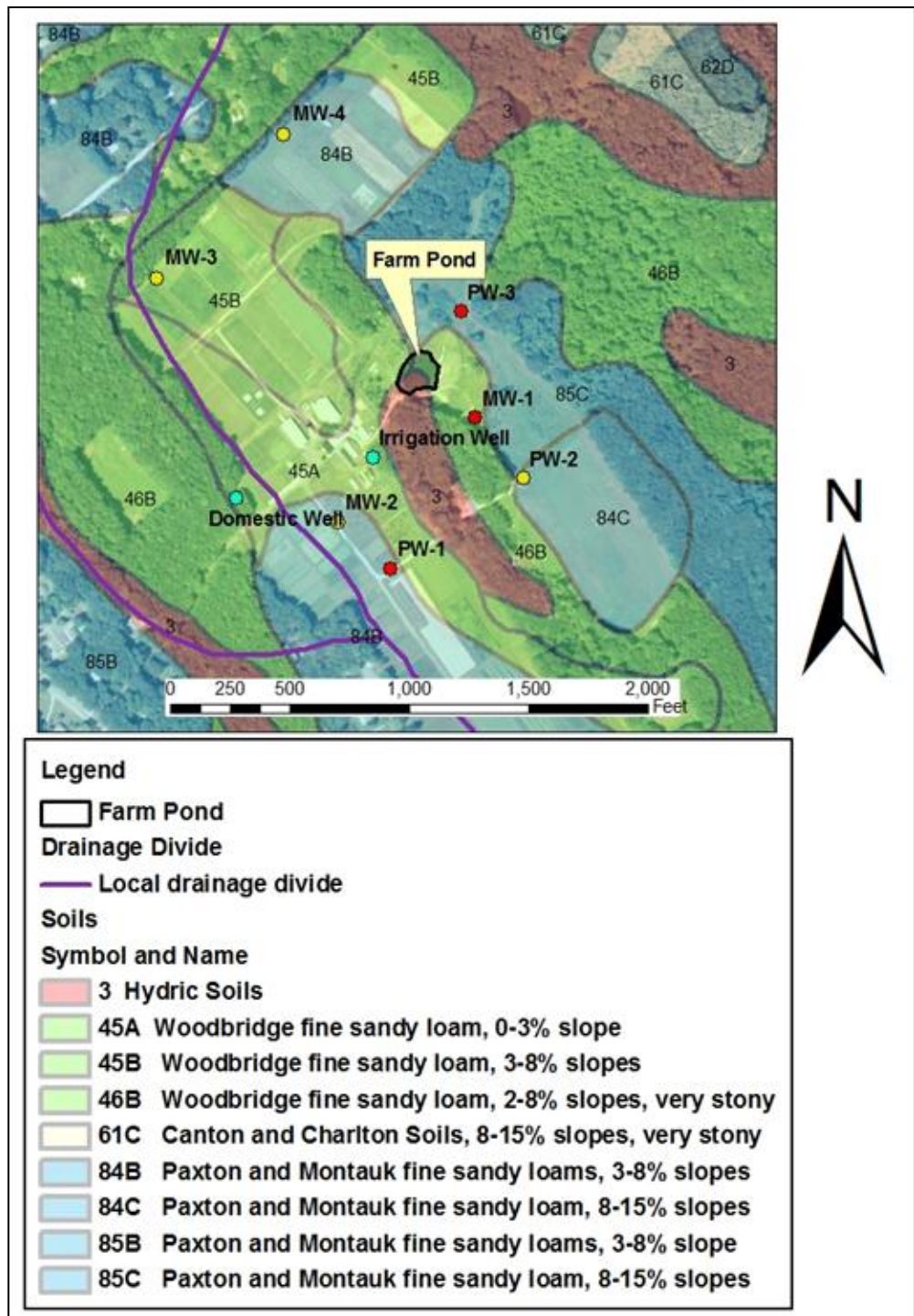


Figure 2-3 Soils map with NAIP imagery. Soil data from the U.S Dept. of Agriculture (2007), NAIP imagery from USDA-FSA-APFO (2010), and drainage basin data from CT DEP (1988).

Shallow ground water hydrogeology

Glacial till underlies the fine sandy loam and hydric soils on the farm (CT DEP 1995a, CT DEP 1995b) as shown in Figure 2-4. Till consists of non-sorted and non-stratified deposits with particle sizes ranging from clay to boulders. Most of it on site is classified as “thick till” which is greater than 10-15 feet thick. “Thin till” is defined as having a thickness less than 10-15 feet, and is found on the northeastern side of the farm.

The shallow groundwater in the overburden most likely mimics the surface topography and therefore has the same drainage patterns as the surface runoff. As shown in the topographic map in Figure 2-1, most of the shallow ground water on the farm likely flows downhill to the northeast. Since the groundwater is flowing through till which has a hydraulic conductivity range between 10^{-06} and 10^{-04} cm/sec (or 3×10^{-1} to 3×10^{-3} ft/day) (Fetter 2001) the groundwater moves very slowly. The low permeability of the till on the site was confirmed by a hydraulic test in a shallow monitoring well near the irrigation pond (Robbins 2006).

Bedrock groundwater hydrogeology

The bedrock that underlies the overburden on the farm is classified as Hebron Gneiss (CTDEP 1985a, CTDEP 1985b) (Figure 2-4). The rock layers have a shallow dip of about 20-25 degrees to the north-northwest (Pease 1988). There are no known major faults in the bedrock of the farm; the closest major fault zone is over 6,000 feet from the farm (Robbins et al. 2009). In the 2009 study it was found that the bedrock surface and water level mimicked the surface topography. Therefore, the groundwater would flow in a downhill direction, making the surface drainage divide also a divide for groundwater flow. This was supported by the fact that a well located to the west of the main drainage divide (the Domestic Well) (see Figure 2-3) was not

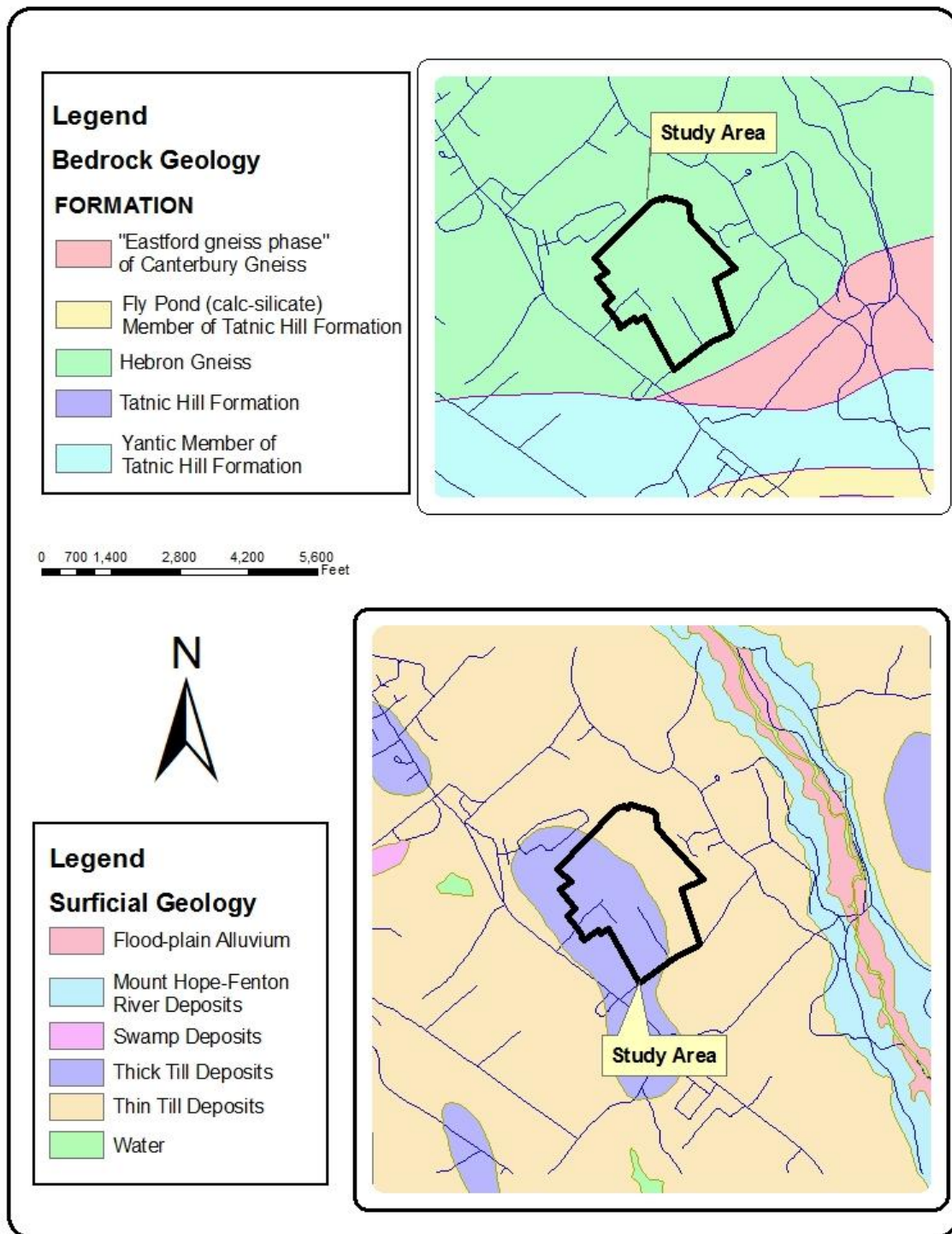


Figure 2-4 Bedrock and surficial geology maps. Bedrock data from CTDEP (1985a, 1985b) surficial geology data from CT DEP (1995a, 1995b), and local road data from U.S. DEP of Commerce (2008).

affected by a 72 hour pumping test in a well on the east side of the divide (the Irrigation Well). The transmissivity of the bedrock aquifer near the Irrigation well during the 72 hour test was relatively high at 5.3×10^{-3} ft.²/min. compared to the Domestic Well on the west side of the main drainage divide which had a transmissivity of 1.67×10^{-3} ft.²/min (found by using a method using specific capacity by Huntley et al. 1992).

Bedrock groundwater issues and study

The intense use of the land by the farm requires that they irrigate during dry periods in the summer and early fall. Prior to 2009, they relied on the 1/3 acre pond to irrigate the fields. When needed, water was pumped by a submersible pump to an underground irrigation system located under 4 acres of fields (Robbins et al. 2009) or into an overhead, portable sprinkler that irrigated about 1.5 acres (Olsen 2010). In addition to the pond, they used two deep bedrock wells approximately 600 feet deep to obtain water. One well, called the “Irrigation Well”, was used primarily for watering greenhouse plants; the other well, called the “Domestic Well”, was used for domestic water and some irrigation in the greenhouse. Both wells were also used to increase the supply of water in the pond when it was low.

During the dry periods in the summer and fall, they found that the two bedrock wells could not supplement enough water to the pond so that the water level in the pond decreased to the point that no more water could be withdrawn. The farm required more than 25,000 gallons of water a day and as much as 214,000 gallons per week (Robbins et al. 2009). Because of the insufficient supply of water, the farm needed to find additional sources. The 2009 study by Robbins et al. as discussed above, was completed to determine if the bedrock aquifer on the farm could supply their need for water. It collected data from 7 wells in the surrounding residential community and 2 on the farm and conducted a 72 hour pumping test in a well on the farm. The study concluded that three new pumping wells could be pumped sequentially at 15 gallons per

minute for as long as 8 hours per day, supplying a total of 21,600 gallons per day. The irrigation well could make up the difference if necessary to reach the 30,000 gallon demand.

3 METHODOLOGY

Bedrock Wells

Three additional pumping wells (PW-1, MW-1 (now titled PW-2), and PW-3) and four monitoring wells (MW-2, MW-3, MW-4, and PW-2 (now titled MW-1)) were installed on the farm as recommended in the previous study (Robbins et al. 2009). An aerial photograph (US DEPT of Commerce 2008b, USDA-FSA-APFO 2010) showing the existing and new bedrock wells can be found in Figure 3-1. After drilling, one of the pumping wells, PW-2, collapsed, so monitoring well MW-1 was made into a pumping well and PW-2 became a monitoring well. The nomenclature for these two wells remained the same in this report after the collapse; however, the University of Connecticut renamed MW-1 to PW-2, and PW-2 to MW-1, in order to avoid the confusion of using an abbreviation of PW (pumping well) for a monitoring well.

The wells were installed by air percussion drilling and have the design of a typical domestic well (Figure 3-2). These 6-inch diameter wells have a steel casing sealed into the bedrock with grout and have a well cap on the top.

Table 3-1 shows a summary of the well completion data for the new and existing wells on the farm. All the pumping wells were drilled to a depth of about 600 feet. The two monitoring wells, MW-3 and MW-4, located in the northwest corner of the farm, were drilled to 250 feet. Although PW-2 was drilled to 600 ft, because of collapse, this well is 110 feet deep. MW-2 was drilled to 600 feet. The original well completion reports can be found in Appendix D “Bedrock Well Completion”. They contain the depth, condition, and composition of the bedrock, depth to rock, depths of water contributing fractures and the yield obtained at different depths.

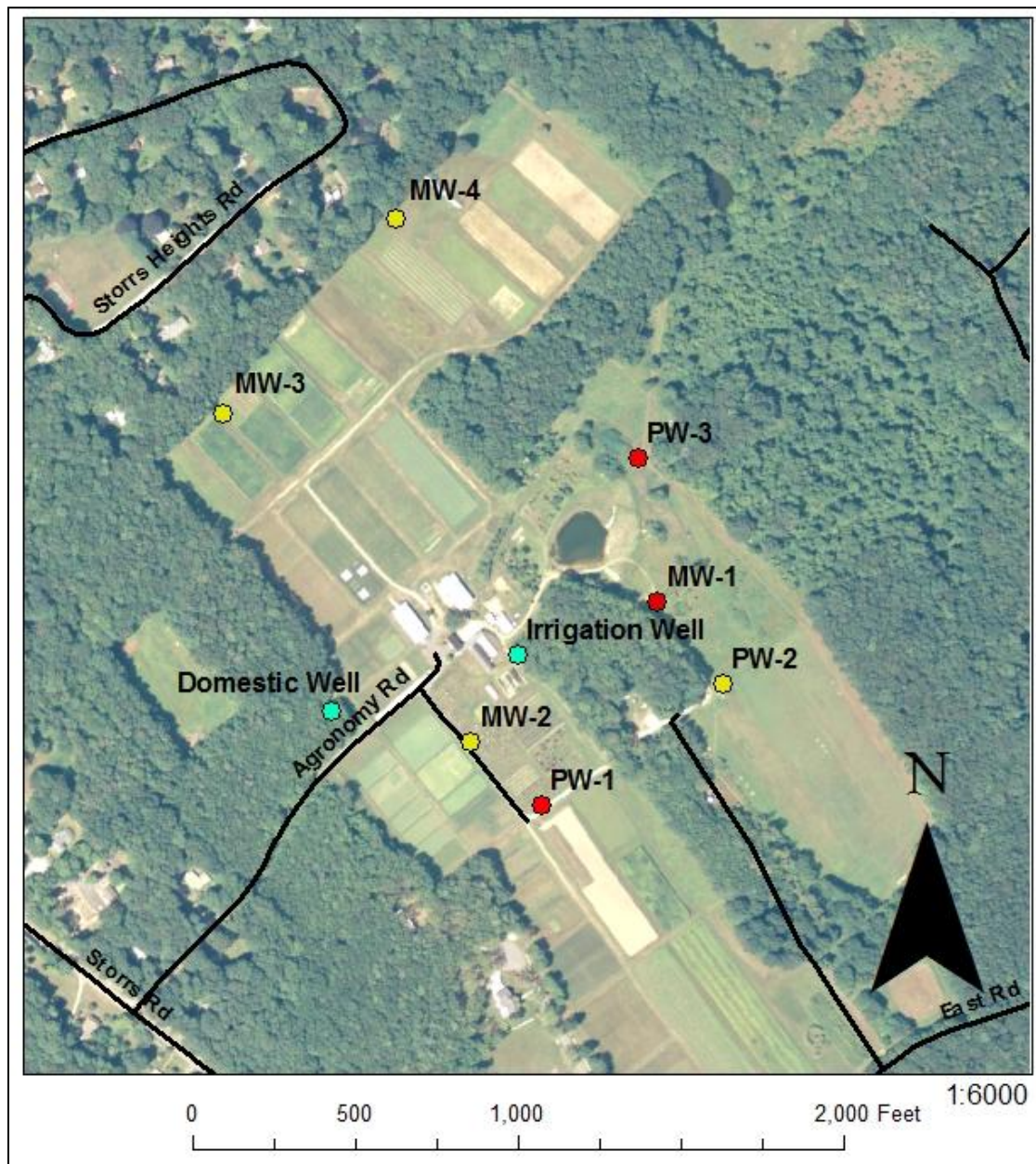


Figure 3-1 Aerial photo with bedrock wells. Red symbol indicates pumping well, yellow indicates monitoring well, and blue the existing pumping wells. NAIP imagery from NAIP imagery from USDA-FSA-APFO (2010) and road data from U.S. Dept. of Commerce (2008).



Figure 3-2 Typical bedrock well drilled for study

Table 3-1 Bedrock Well Completion

Well	Northing (ft)**	Easting (ft)**	Surface Elevation (ft)	Height of Casing (ft)	Well Depth (ft)	Elevation of Bottom of Well (ft)	Depth to Bedrock (ft)	Bedrock Elevation (ft)
PW-1	850471.4	1142473.3	663.0	1.8	620	43	43	620
PW-2	850844	1143026.7	646.4	2.4	620*	26*	73	573
PW-3	851530.8	1142769.6	614.1	0.8	620	-6	28	586
MW-1	851093.4	1142826.7	637.5	2.1	600	38	37	601
MW-2	850663.6	1142254.1	659.8	0.5	620	40	32	628
MW-3	851668	1141490.5	635.6	2.4	250	386	37	599
MW-4	852260.5	1142024.4	600.8	3.0	250	351	54	547
Irrigation Well	850930.2	1142397.4	647.6	1.2	600	48	30	618
Domestic Well	850758.6	1141824.5	654.1	1.4	505	149	48	606
*The well collapsed to a depth of 110 feet due to weathered bedrock.								
**CT State Plane Coordinate System								

The geographical coordinates of all the new bedrock wells were determined by using a Trimble Juno® hand held global positioning system unit. The coordinates were projected onto a ArcGIS® map in Connecticut State Plane coordinate system (NAD 83) after they were differentially corrected using the GPS station in Mansfield. The elevations of the wells were then determined by using ESRI point cloud data (LiDAR) of the Spring Hill Quadrangle SW-NE from the CLEAR website (University of CT College of Agriculture and Natural Resources 2000).

These data were then converted to a raster file using the conversion tool in ArcGIS®. The elevation of each well was determined by using the Identity tool on the raster file at each location and recording the elevation in feet. The original map containing the raster file and well locations that were imported from the Trimble Juno® can be found in Appendix L, “GIS Maps”.

A depth to bedrock and bedrock elevation map of the farm and the surrounding community was produced using the well data from the farm and from the surrounding community. The bedrock data from the surrounding community was collected from a previous PLSA Research Facility study (Robbins et al. 2009), the drainage basins and surface contours from the Connecticut Department of Environmental Protection (1988, 2000a) and roads from the US Dept. of Commerce (2008b). These data can be found in Appendix D and the original GIS map can be found in Appendix L.

Hydraulic Testing

Pumping tests and slug tests were used to determine the hydraulic characteristics of the bedrock.

Driller’s Pumping Tests

Eight hour pumping tests were completed in PW-1, PW-2 and MW-1 by the drilling company in October, 2009. The drillers’ recorded the date, depth to pump, pumping rate, elapsed time, depth to water, and the drawdown every 30 minutes to 1 hour. The original data can be found in Appendix E, “Bedrock Pumping Tests”. The water level change during the test was monitored by pressure transducers placed in the other bedrock wells as part of this study. The Instrumentation Northwest Smart Sensor PT2X® pressure transducers were first disinfected with bleach and then placed in the wells about 100 feet down. They were set to record every minute during the test. The original data can be found in Appendix E.

AQTESOLV™ software was used to analyze the pumping tests. In order to use the software, it was necessary to input the drawdown in each observation well, the distance of the observation well to the pumping well, and the pumping well rates.

To find the drawdown with time for the pumping tests in PW-1 and PW-2, the absolute pressure transducer readings needed to be compensated for atmospheric pressure and then converted to depth to water. The readings from an INW Smart Sensor PT2X® barometric probe placed in a building on the farm were subtracted from the absolute readings of the pressure transducer to obtain the pressure due to the height of water above the instrument. The depth to water measurements were determined by taking the initial depth to water, read with a water level sounder, and adding it to the initial compensated pressure reading, then subtracting from that subsequent pressure compensated readings. The drawdown was then calculated by taking the drawdown in the observation well at the beginning of the test and subtracting from that the subsequent drawdown values. This calculation and the drawdown curves produced for each test can be found in Appendix E.

To find the drawdown in the observation wells during testing in MW-1, it was necessary to use a different method because the wells were still recovering from the pumping test in PW-1 the day earlier. A graph of the depth to water and time prior and during the test in MW-1 was produced as seen in an example in Figure 3-3 of the curve for observation well PW-2. An extension of the recovery curve from the test in PW-1 the day before was extrapolated linearly for each hour for the entirety of the test in MW-1. The drawdown was then calculated by taking the difference between the depth to water on the recovery curve and the observed hourly depth to water. The exception to this method occurred in PW-1, for it had little pre-pumping data from which to extrapolate. A recovery curve was approximated by hand instead of by linear extrapolation. The graphs produced can also be found in Appendix E.

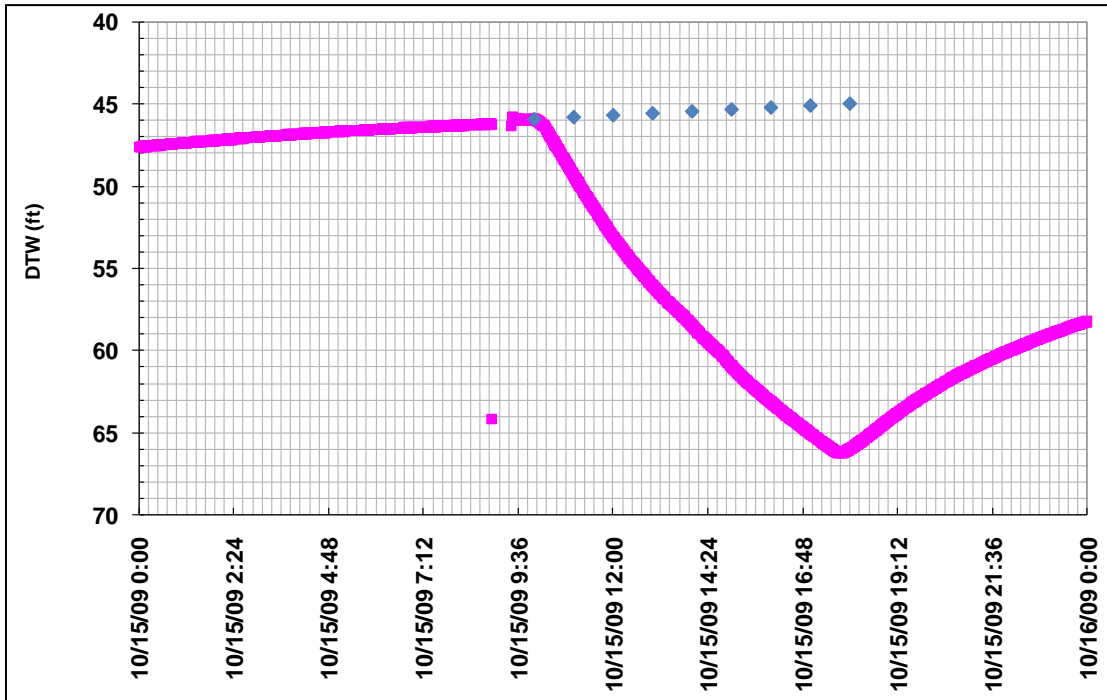


Figure 3-3 Graphical compensation for MW-1 test. Red curve is the observed depth to water in observation well PW-2. Blue dots are the data points for the recovery curve.

The distance of each observation well from the pumping well was determined by using the measuring tool on ARCGIS map with location of the wells on it. The pumping rates for each well were determined by taking the time weighted average of the pumping rates during the test.

The drawdown observed in each observation well during each test was analyzed for transmissivity and storativity using the Theis model for a confined aquifer (Theis 1935). Only the late time data were used in order to avoid wellbore storage effects. The drawdown observed in pumping well PW-1 were also analyzed to determine transmissivity. The transmissivity of the other two pumping wells could not be analyzed during pumping. Pumping well MW-1 was still recovering from the PW-1 test the day earlier and did not have enough pre-test recovery measurements to graphically compensate the readings. Water levels in PW-2 did not fluctuate

during its test, so the Theis solution could not be used. The geometric mean of the transmissivity and storativity values determined for each test were calculated and used as the transmissivity of the tested well. For the wells that were not tested, the geometric mean of these parameters found while observing the pumping tests were taken. These calculations can be found in Appendix E.

Drawdown maps showing the total drawdown for each test were produced using ArcGIS® mapping program.

Bedrock Slug Tests

Slug tests were performed in MW-3 and MW-4. In MW-3, a slug-out test was performed using a bailer system (Figure 3-4). It consisted of three one-inch diameter, three foot long bailers tied together with one three-inch diameter, three-foot long bailer attached in tandem. This configuration caused a 1.3 foot displacement of the water column in the 6-inch well. The response in the well was monitored from data obtained from the PSLA Research and Education Facility Website (website <http://www.canr.uconn.edu/nrme/agfarm/>). This website displays hourly water level data for the new monitoring wells on the farm.

A slug-in test was performed in MW-4 using 4-5 gallons of clean tap water. This caused a displacement of 2.6 feet. It was also monitored using the above mentioned website. Both slug tests were analyzed using AQTESLOV™ software. The Bouwer and Rice model (Bouwer and Rice 1976) for a confined aquifer with a fully penetrating well was used. The workbook with the original and processed data, original AQTESLOV™ analysis, and testing summary can be found in Appendix F, “Bedrock Slug Tests”.



Figure 3-4: Bailer system for bedrock well slug testing

From the data collected and analysis completed, a transmissivity map of the farm and the surrounding community was produced using ArcGIS® software. Data from the surrounding community was obtained from the previous study of the farm (Robbins et al. 2009) and added to the data in this report to produce a composite map. The additional data obtained can be found in the “2009 Agfarm Report Data” folder in Appendix D.

Pre-pumping Water Level Monitoring

Instrumentation Northwest™ (INW™) absolute pressure transducers were placed in all the bedrock wells except PW-3 on May 26, 2010, to monitor the water levels until the farm started irrigating at the beginning of July. The irrigation well was also monitored by an INW™

pressure transducer placed in the well during the previous year. All the wells were set to record hourly. A table with the pressure transducer installation data can be found in Appendix G, “Bedrock Well Monitoring”.

The pressure transducer data produced was converted to water elevation measurements. First, the readings were compensated for atmospheric pressure using the INW™ barometric pressure gauge. Then the depth to water from the top of the casing was calculated in the same manner as described for the pumping test data. This depth to water was then converted to depth to water from the ground surface by subtracting the height of the casing above the ground. Then the depth to water was subtracted from the ground elevation to obtain the water surface elevation. The processed data can be found in Appendix G.

New Pumping and Monitoring System

A new pumping and monitoring system was installed at the farm during the summer of 2010. Pumps capable of pumping at least 20 gallons per minute were placed in PW-1, MW-1 and PW-3. The pumping wells were connected to water lines that bring the water to a pumping station in a small building near the irrigation pond. The pumping schedule and the rate of flow from each well are controlled by a Teloger Enterprise® computer system. The water is then piped to the irrigation pond. Between July and mid-September, the pumps ran on a 24 hour schedule, with each well pumping at approximately 15 gallons per minute for 8 hours a day. The pumping rates and time for each well is then sent by wireless signal to Telog Enterprise, Inc. where the data is tabulated in online forms.

The new monitoring system also included placing pressure transducers in four of the monitoring wells, MW-2, MW-3, MW-4 and PW-2 in the beginning of July. The pressure transducers were barometrically compensated instruments (gauge pressure transducers) except for MW-4, which was compensated with a separate barometric probe. The pressure transducer

readings are sent by wireless signal to the farm building and uploaded onto the farm website every hour (<http://www.cag.uconn.edu/plsc/plsc/facilities.html>). A table listing pressure transducer placement data can be found in Appendix G.

Horizontal flow in the bedrock during ambient conditions

Water elevation maps and depth to water maps using ArcGIS® were produced with the elevation data collected on July 7, 2010 to analyze the flow during ambient conditions. The natural neighbor interpolation method found in the software program was utilized. The irrigation well was eliminated in these maps because it was recovering from pumping at the time of data collection.

The horizontal flow in the bedrock, $Q_{h(br)}$, during the non-pumping period was determined by using Darcy's Law with the data collected on 7/7/10:

$$Q_{h(br)} = w * T * dh/dl_{(br)} \quad (3.0)$$

Where w =width of flow: The width of flow was assumed to be the length of the drainage divide to the west parallel to the surface contours encompassing the area as water would flow downgradient topographically. The drainage divide for the bedrock is assumed to be the same as the surface water divide.

T, transmissivity: The geometric mean of the transmissivity values found in the bedrock pumping tests and slug tests. The calculation of the mean can be found in Appendix E.

$dh/dl_{(br)}$: It was calculated as the average of all the horizontal hydraulic gradients on 7/7/10 near each well found by a line drawn between adjacent contours on a bedrock water level map. The calculation of these averages can be found in Appendix H, "Recharge to Rock Analysis".

Post-pumping Water Level Monitoring

Water levels in all the bedrock wells, with the exception of PW-3, were continually monitored during the pumping period from July 8, 2010 to August 27, 2010, although full scale pumping of the new wells occurred on July 26. This data can be found in Appendix G. The water level in PW-3 was recorded in the field notebook on July 8 and on August 27. The notebook can be found in Appendix K, "Field Notebook". Water elevation and depth to water maps were produced with data collected on August 27 at 10:00 AM using the same method as described above. The irrigation well was included in these maps and the original GIS maps with the data can be found in Appendix L.

During the pumping season the wells reached steady state drawdown. The maximum, minimum and average water levels achieved during pumping were approximated for each well. The average water level was approximated by taking the average of the two highest levels as close to the 8/25/10 as possible, but between the dates 8/24-8/27, and averaging this value with the two lowest elevations in the same time period. The exception was for monitoring well PW-2; where the lowest water level had to be approximated due to the water level exceeding the pressure transducer depth. The range of water levels before it was exceeded (13 feet) was subtracted from the highest average water levels. The worksheet with the original pressure transducer data for the time period and the calculations used can be found in Appendix J, "Contribution Area".

Shallow Overburden Wells

Six shallow wells were installed in the spring of 2010 to monitor the water levels in the overburden. Each well was installed within five feet of a bedrock well in order to determine the hydraulic gradient between the overburden and the bedrock. MW-2 already had a USGS

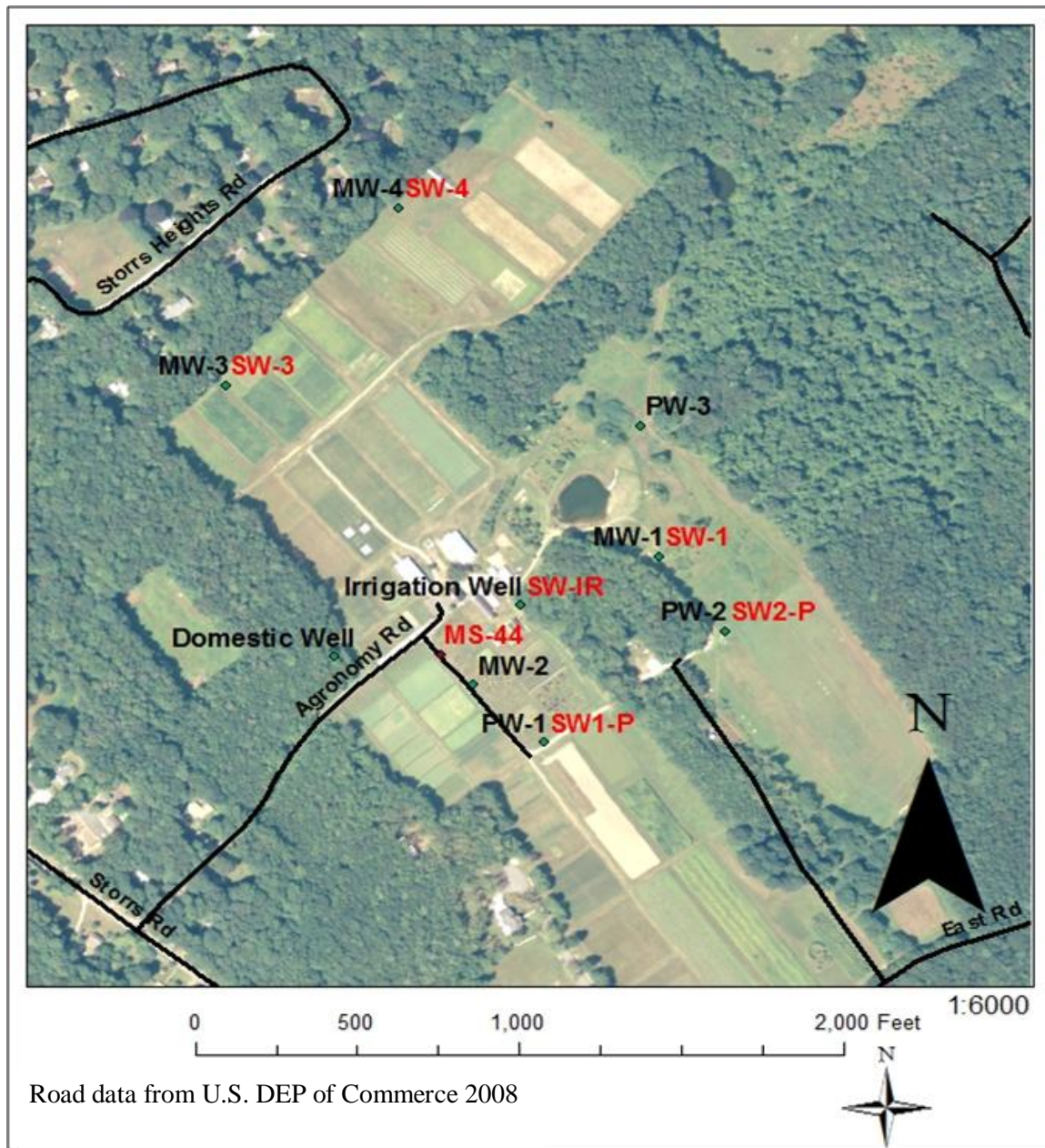


Figure 3-5 Aerial photo of study area. Red labels denote shallow wells and black labels bedrock wells .NAIP imagery from USDA-FSA-APFO (2010) and road data from U.S. DEP of Commerce (2008).

shallow well within 150 feet, so it was unnecessary to drill another one there. This well, MS-44, is part of the National Water Information System run by the USGS. The water level from this well is constantly monitored and data is uploaded hourly to the following website:

http://waterdata.usgs.gov/nwis/nwisman/?site_no=414741072134501&agency_cd=USGS. All the

new overburden wells begin with the prefix SW- and can be seen in Figure 3-5. The shallow monitoring wells were installed on April 16 and 17, 2010 using a track mounted Geoprobe® direct push machine from the University of Connecticut’s Center for Environmental Sciences and Engineering (see Figure 3-6). The holes were cored to about 20 feet using a Macro-Core®



Figure 3-6 Shallow Well Installation with Geoprobe®

soil sampler and logged in the field. One-inch diameter PVC casing with 5 foot long pre-packed stainless steel were installed, except in SW-3 and SW-4, where 10 foot PVC #10 slotted screens were used. The screens were placed at the bottom of the well, and the hole was packed with #2 sand from the bottom of the well to a few inches above the screen. A few inches of fine sand was then added and then bentonite to the surface. If the well collapsed above the screen, #2 sand was added to a few feet above the surface. Table 3-2 shows the details on the well construction. Boring logs of the individual wells can be found in Appendix A, “Shallow Well Installation”.

Table 3-2 Shallow Well Construction Specifications

Shallow Well	Nearby Well	Actual Screen Length (ft)	Casing Radius (ft)	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Depth to Bottom of Well (ft)
SW1-P	PW-1	5	0.042	9.4	14.4	14.5
SW2-P	PW-2	5	0.042	9.7	14.7	14.8
SW-1	MW-1	5	0.042	10.4	15.4	15.5
SW-IR	Irrigation Well	5	0.042	10.4	15.4	15.5
SW-3	MW-3	10	0.042	9.9	19.9	20.0
SW-4	MW-4	10	0.042	9.9	19.9	20.0



Figure 3-7 Shallow well construction pictures. Left to right: Sealed protective covering, opened protective covering, and a view inside.

After the wells were installed, a special protective apparatus for the pressure transducers was set up in all the wells except SW-3 and SW-4 so they could be kept out of the weather (Figure 3-7). A 2.5 -inch diameter cast iron pipe with metal threading was placed around the PVC well casing sticking above ground. A cast iron flange with threads was attached to the top of the pipe and fixed with screws to a 5 gallon bucket with a hole in the bottom. With the top of the well casing inside the bucket, the pressure transducer could be lowered into the well and the cable stored in the bucket. Whenever readings were taken, the bucket was opened and the end of the transducer was connected to the computer. The protective covering for SW-3 and SW-4 was a standard four-inch steel stick-up casing that was cemented in place and fixed with a locking cap.

The locations and elevations of each new shallow well was assumed to be equal to the bedrock well nearby. The location for MS-44 was determined by placing its approximate location on NAIP imagery (USDA-FSA-APFO 2009) using ARCGIS® software.

The overburden was characterized by soil logging, mapping, and by hydraulic testing in each of the newly installed wells. Continuous core samples were obtained while drilling the shallow wells. Boring logs were produced with the data using the M-Tech Geographics 2009® program. The original files and PDF versions can be found in Appendix A.

The overburden descriptions from the boring logs were grouped into five general categories to correlate them between wells: 1. Peat (topsoil) 2. Sandy silt and silty sand 3. Low and high plasticity clays 4. Fine to medium sands 5. Clayey gravel to coarse gravel. These descriptions were used to create generalized logs that were then used to develop fence diagrams for the site using the M-Tech Geographics® software program. The original logs and modified log files and PDF versions can be found in Appendix A.

Hydraulic Testing

Before the wells were tested, they were developed by surging and plunging until the water turbidity was 175 NTU or less. The hydraulic conductivities of the overburden wells were determined by conducting slug tests of various types depending on the rate of well recovery. A summary of the test types and parameters can be found in Table 3-3. If a well responded slowly, a slug-out test using a one-half inch bailer and a pressure transducer to record water level changes was utilized. If the water level rose fast enough to record with a water level sounder, it was used. If the response was very rapid, as in SW-4, a pneumatic slug out test was conducted.

The pneumatic slug test in SW-3 was conducted using a Pneumatic Slug Test Kit from Geoprobe®. This kit was modified by adding an isolation valve, a pressure gauge, regulator valve, and a pump capable of producing pressure or a vacuum as seen in Figure 3-8. The head changes over time recorded during slug testing were analyzed using Aqtesolv™ software using various models. If the screen was fully submerged in one stratigraphic unit, the Hvorslev's Full Ellipsoid model (Hvorslev 1951) was used. The Hvorslev's Half Ellipsoid model was used if the screen was not fully penetrating one stratigraphic unit. Since Aqtesolv™ did not have that model, the Full Ellipsoid Model was used with one-half the value of the intake radius. The original slug testing data can be found in Appendix B, "Shallow Well Slug Tests".

Table 3-3 Shallow Well Hydraulic Test Parameters and Test Types

Shallow Well	Screen Length (ft)	Casing Radius (ft)	Intake Radius (ft)	Screen Length Used for Aqtesolv ®	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Depth to Bottom of Well (ft)	Model Used	Test Type	Equipment Used
SW1-P	5	0.042	0.094	5	9.4	14.4	14.5	Hvorslev's Full-Ellipsoid	Slug Out	Bailer & Pump
SW2-P	5	0.042	0.094	5	9.7	14.7	14.8	Hvorslev's Full-Ellipsoid	Slug Out	Bailer & Pump
SW-1	5	0.042	0.094	5	10.4	15.4	15.5	Hvorslev's Full-Ellipsoid	Slug Out	Bailer & Pump with P-Transducers
SW-IR	5	0.042	0.047	4	10.4	15.4	15.5	Hvorslev's Half-Ellipsoid	Slug Out	Slug Out/Bailer & Pump
SW-3	10	0.042	0.135	10	9.9	19.9	20.0	Hvorslev's Full-Ellipsoid	Slug Out	Pump & P-Transducers
SW-4	10	0.042	0.070	6	9.9	19.9	20.0	Hvorslev's Half-Ellipsoid	Slug Out	Pneumatic Test Kit

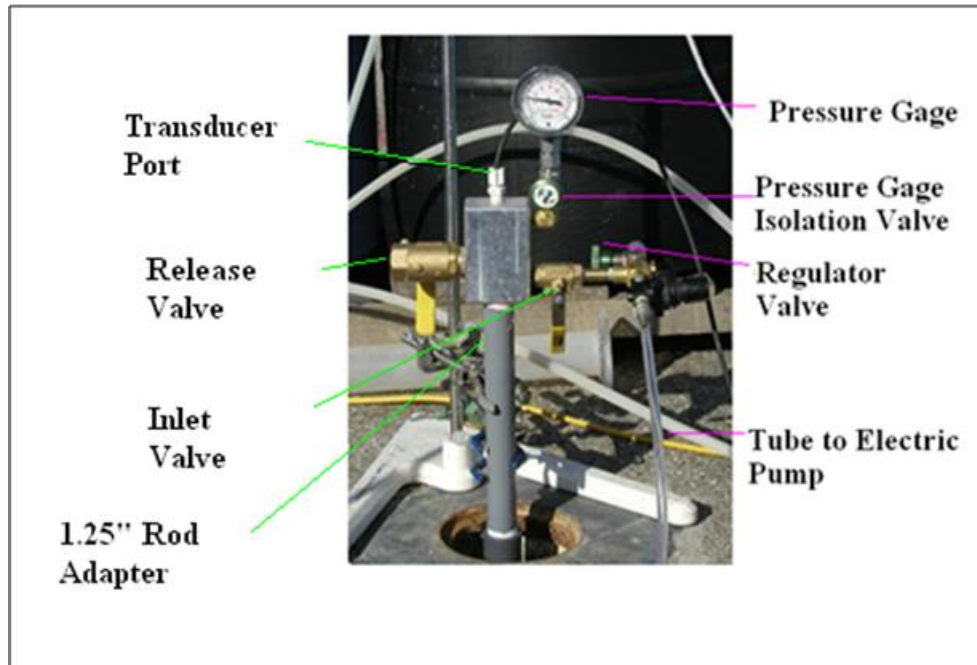


Figure 3-8 Pneumatic slug test kit from Geoprobe® and modified kit. Original components from Geoprobe® 2011 labeled with green line and modified components labeled with pink line. Picture from Robbins (2010).

Installation of Pressure Transducers

In-Situ Inc. Level TROLL® 300 pressure transducers were placed in the shallow wells SW1-P, SW2-P, and SW-1, and an INW Smart Sensor® PT2X was placed in SW-IR. They were placed in the wells on May 26, 2010, the same day that the transducers were placed in the bedrock wells for pre-pumping monitoring. SW-3 and SW-4, the two wells closest to Storrs Heights Road, were not monitored. A table showing a summary of the data during installation can be found in Appendix C, “Shallow Well Monitoring”.

The absolute pressure transducers by In-Situ Inc. ® were compensated with a BaroTROLL® 500® barometric pressure gauge and the pressure transducer by INW® was compensated with INW Smart BV® PT2X. Both barometric gauges were placed in the main farm building.

Water level monitoring

The water levels were monitored from May 26 to August 27. The water elevation and depth to water from the ground was calculated the same way as described earlier for the pumping wells. The water levels were graphed juxtaposed with precipitation data obtained from the PLSA Research and Education Facility used to monitor the response of the water levels to precipitation. The water levels in SW-3 and SW-4 were collected on July 7 and August 27 in order to produce water level and depth to water maps that will be discussed later in the report. This processed data, the raw data, and water level summaries can be found in Appendix C.

Horizontal flow in the overburden in ambient conditions

The horizontal flow in the overburden in the area encompassing the well field was determined by using Darcy's Law:

$$Q_{(h)ob} = w * K_{(ob)} * b * dh/dl_{(ob)} \text{ (ft}^3\text{/day)} \quad (3.1)$$

Where:

w, width of flow (ft): The length of the drainage divide to the west, parallel to the surface contours encompassing the area as water would flow down gradient topographically to the wells. The drainage divide for the surface water is assumed to be the same as the overburden water divide.

b, depth of the overburden aquifer (saturated thickness) (ft): Taken as difference between the average of the depth in feet to bedrock found in the well completion reports and the average depth to water in the overburden on the east side of the main drainage divide on 7/7/10. These calculations can be found in Appendix H.

$K_{(ob)}$, *hydraulic conductivity (ft/day)*: The geometric mean of the conductivity values found during slug testing in the overburden. These calculations can be found in Appendix H.

$dh/dl_{(ob)}$, *the horizontal hydraulic gradient (ft/ft)*: It was taken as the average of all the horizontal hydraulic gradients on 7/7/10 near each well found by a line drawn between adjacent contours. A map of these gradients can be found in Appendix L, and the calculations of the averages can be found in Appendix H.

Recharge to bedrock aquifer analysis

Area of contribution in ambient conditions

In order to determine the recharge of the overburden to the bedrock during ambient conditions, the area of contribution to these formations needed to be determined. This area of recharge was drawn on a water elevation map using ArcGIS® with data collected on 7/7/10 in the overburden aquifer before active pumping began and can be found in Appendix L. It was drawn with the assumption that the bedrock has the same drainage divides as the surface water as seen on Figure 2-2. Therefore, the main drainage divide shown in pink was used as a border on the west and drawn with an area that encompassed all the wells in the well field as water would flow down-gradient from the drainage divide. In the area drawn, the bedrock wells would not be recharged from the other side of the local drainage divide to the west and are only recharged from the overburden directly up-gradient. In addition to observing a water level map to determine the area of contribution, a depth to water map was produced using data from 7/7/10 to help determine areas of the overburden where recharge is more likely to occur.

Recharge to bedrock aquifer

The method used to calculate the flow from the overburden to the bedrock aquifer in ambient conditions is based on mass balance. If the water level in a given volume of overburden

is not changing, the amount of water coming into it through the overburden must be equal to the amount going out. If there is a water level decline observed, then there is a change of storage; there is more water leaving the site than coming into it. *If there is no additional water added to*

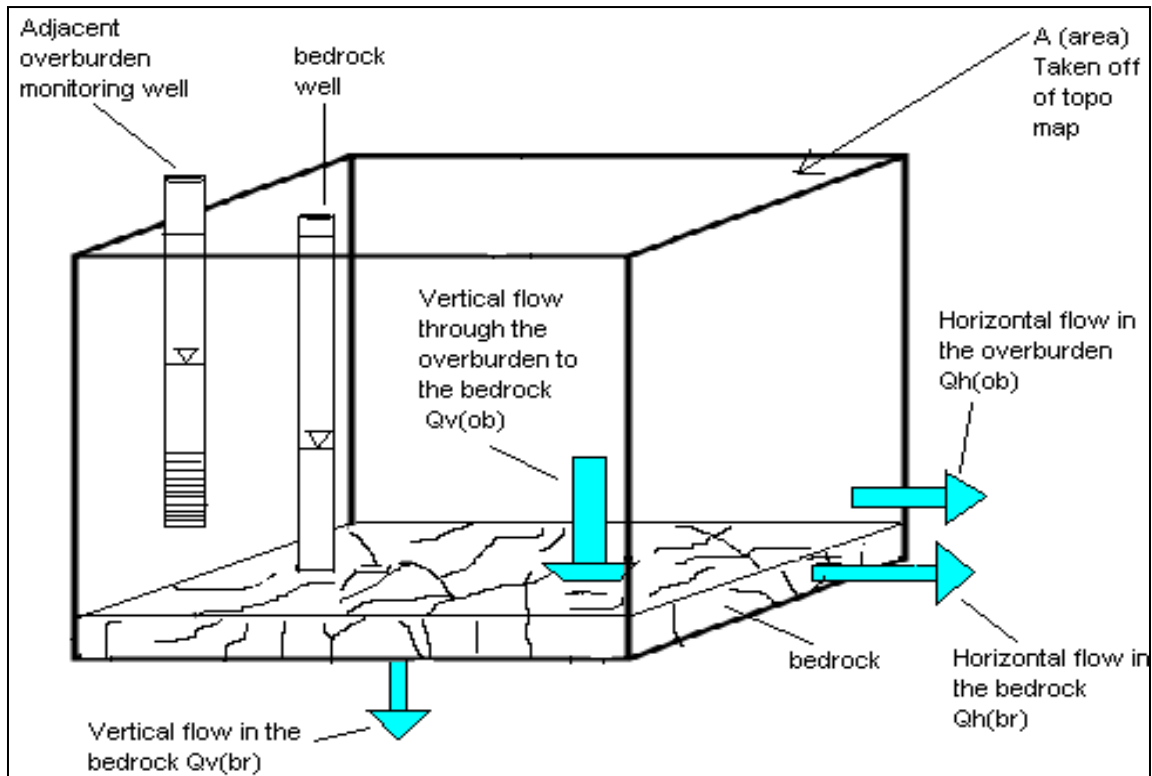


Figure 3-9 Flow of ground water in overburden and bedrock

the aquifer, then the water level of the aquifer decreases due to the volume of water leaving.

Water leaves the overburden aquifer either down gradient in the horizontal direction or vertically downward due to gravity (see Figure 3-9).

The total discharge, $Q_{t(ob)}$, can be calculated by the following formula:

$$Q_{t(ob)} = Q_{h(ob)} + Q_{v(ob)} \text{ (ft}^3\text{/day)} \quad (3.2)$$

$$Q_{h(ob)} = \text{horizontal flow in the overburden (ft}^3\text{/day)}$$

$Q_{(v)(ob)}$ = vertical flow in the overburden (ft³/day)

Using Darcy's Law, the vertical saturated flow downward into the bedrock is equal to the following:

$$Q_{(v)(ob)} = A'_r * dh/dz * K_{(ob)} \text{ (ft}^3\text{/day)} \quad (3.3)$$

A'_r = the effective recharge area of the bedrock (ft²)

$K_{(ob)}$ = the geometric mean of the hydraulic conductivity in the overburden (ft/day)

dh/dz = the vertical hydraulic gradient between the overburden and the bedrock (ft/ft)

Substituting 3.1 and 3.3, the total amount of flow in 3.2 becomes the following:

$$Q_{t(ob)} = w * K_{(ob)} * b * dh/dl_{(ob)} + A'_r * K_{(ob)} * dh/dz \text{ (ft}^3\text{/day)} \quad (3.4)$$

The recession rate observed in the overburden is related to the total quantity of flow leaving the site when there is no recharge by precipitation:

$$Q_t = RR_{(ob)} * A * S_y \text{ (ft}^3\text{/day)} \quad (3.5)$$

$RR_{(ob)}$ = recession rate observed in the overburden (ft/day)

A = total contributing area to the overburden (ft²)

S_y = specific yield of the unconsolidated aquifer

Combining 3.4 and 3.5 and solving for the recession rate

$$RR_{(ob)} = (w * K_{(ob)} * b * dh/dl_{(ob)} + A'_r * dh/dz * K_{(ob)}) / (A * S_y) \text{ (ft/day)} \quad (3.6)$$

All of the parameters in the equation for the recession rate can be estimated by completing field studies of the character of the overburden except for the effective recharge area of the rock. By comparing the observed recession rate in the field with the calculated rate above,

this value can be estimated. Then the recharge rate to the bedrock can be calculated by equation 3.3.

For this study, parameters in 3.6 were determined as previously discussed or described below. All the individual calculations for these parameters can be found in Appendix H, “Recharge to Rock Analysis” unless otherwise noted.

A, Area of contribution (ft²): Determined as discussed above.

w, width of flow (ft): Determined as discussed above

dh/dl_(ob), the horizontal hydraulic gradient in the overburden (ft/ft): The average horizontal hydraulic gradient on the 7/7/10 water level map.

RR_(ob), recession rate in the overburden (ft/day): The average recession rate observed between 7/21/10-7/23/10 before the regular bedrock pumping schedule. The recession rate plots can be found in the processed data in Appendix G, and the averages calculated in Appendix H.

dh/dz, the vertical hydraulic gradient (ft/ft): The average vertical hydraulic gradient between each overburden well and the adjacent bedrock well. The following formula was used:

$$dh/dz = \frac{(\text{water elevation of shallow well} - \text{water elevation of adjacent bedrock well})}{(\text{bottom elevation of shallow well} - \text{bottom elevation of adjacent bedrock well})}$$

The pre-pumping water elevations in the bedrock and shallow wells found on 7/7/10 were used.

b, depth of the saturated overburden aquifer (ft): Calculated as the average difference between the depth to water on 7/7/10 and the depth to bedrock found in the well completion reports for all the wells on the farm (See Appendix H, “Recharge to Rock Analysis”)

K_(ob), hydraulic conductivity (ft/day): The geometric mean of the hydraulic conductivity values found during slug testing in the overburden

S_y , *specific yield*: The average specific yield of clay of 2% (Fetter 2001), and the lower limit of the specific yield of silt at 3% (Fetter 2001) were both used separately. The hydraulic conductivity found during slug testing was within the value of silt, but the majority of boring logs contained a clay layer at the base, so both values were used for comparison purposes.

Vertical bedrock aquifer flow in ambient conditions

The vertical flow in the bedrock aquifer can be determined by mass balance, similar to the method used to find the overburden recharge to the rock discussed previously, except in this case there is additional water being added to the volume of aquifer from the overburden (see Figure 3-9). Therefore, the recession rate observed in the bedrock is equal to the change of storage of the bedrock aquifer. This change of storage is the difference between the water flowing out of the bedrock both horizontally and vertically and the water flowing into it (the recharge from the overburden). The calculations for the vertical flow can be found in Appendix H.

$$\Delta S_{(br)} = Q_{out(br)} - Q_{in(br)} \text{ (ft}^3/\text{day)} \quad (3.7)$$

$$\Delta S_{(br)} = \text{change of storage in the bedrock (ft}^3/\text{day)}$$

$$Q_{out(br)} = \text{flow leaving the aquifer (ft}^3/\text{day)}$$

$$Q_{in(br)} = \text{the recharge from the overburden (Qv(ob)) (ft}^3/\text{day)}$$

Where:

$$\Delta S_{(br)} = RR_{(br)} * A'_r \text{ (ft}^3/\text{day)} \quad (3.8)$$

$$RR_{(br)} = \text{recession rate in the bedrock (ft/day)}$$

$$A'_r = \text{the effective recharge area of the bedrock (ft}^2\text{)}$$

Combining 3.6 with 3.7 and solving for $Q_{out(br)}$:

$$Q_{out(br)} = Q_{in(br)} + RR_{(br)} * A'_r \text{ (ft}^3/\text{day)} \quad (3.9)$$

The amount of flow leaving the aquifer is comprised of both vertical and horizontal flow:

$$Q_{out(br)} = Q_{v(br)} + Q_{h(br)} \text{ (ft}^3/\text{day)} \quad (3.10)$$

$Q_{v(br)}$ = the vertical flow in the bedrock (ft³/day)

$Q_{h(br)}$ = the horizontal flow in the bedrock (ft³/day)

$Q_{in(br)}$ = $Q_{v(ob)}$ as determined in equation 3.2

Combining 3.9 with 3.8, and solving for vertical flow, the vertical flow in the bedrock can be determined using field data and the effective recharge area to the bedrock found earlier:

$$Q_{v(br)} = Q_{in(br)} + RR_{(br)} * A'_r - Q_{h(br)} \text{ (ft}^3/\text{day)} \quad (3.11)$$

For this study, the parameters in 3.10 were determined by:

A'_r , *area of contribution (ft²)*: The effective recharge area of the rock that was determined in the calculations for the recharge to the bedrock discussed above. Two different values were used depending on the specific yield used in the recharge to bedrock calculations.

$Q_{in(br)}$, *Vertical flow into the bedrock (ft³/day)* : The amount of recharge to the bedrock found earlier using the two different rates depending on specific yield used.

$RR_{(br)}$, *recession rate in the bedrock (ft/day)*: The recession rate observed between 6/15/10 to 7/2/10. The calculations can be found in Appendix H.

Area of Contribution during Pumping and Potential Recharge Rates

Three different potential contributing areas while each well was pumping were delineated. They are named “Area A”, “Area B”, and “Area C” and were produced by using different boundary conditions. “Area A” is the area enclosed by the zero drawdown contour on drawdown maps produced for each pumping well from 7/7/10 to 8/25/10. “Area B” and “Area C” are based on the minimum water elevation achieved during pumping on 8/25/10, with “Area B” bounded to the south by a minor drainage divide on the farm, and “Area C” bounded by the main mapped drainage divide. Figure 3-10 shows a map with the boundaries for Areas “B and C”. These three areas represent a conservative zone of influence, and assume a well connected network of fractures. In reality the fractures in these wells could extend beyond these boundaries, even to, or beyond, drainage divides that determine regional flow. Details on how the drawdown maps were produced and the boundaries determined can be found in Appendix J, “Contribution Area”.

After the boundaries for the three contributing areas were drawn for each pumping well, the potential amount of recharge from the overburden using these areas was approximated. The recharge rates determined during the recharge to bedrock analysis were multiplied by each contributing area to determine the potential flow to the bedrock from the overburden in each case ($Q = \text{recharge rate} * \text{contributing area}$). Flow calculated in this manner is conservative because while pumping, the vertical hydraulic gradient between the overburden and the bedrock increases. The recharge rate used was based on a vertical gradient during non-pumping conditions, so in reality more water would be potentially drawn into the well while pumping. The amount of potential recharge to each well was compared to the average rate of pumping to see which area of contribution would supply enough water to sustain pumping and would therefore be the most likely contributing area.

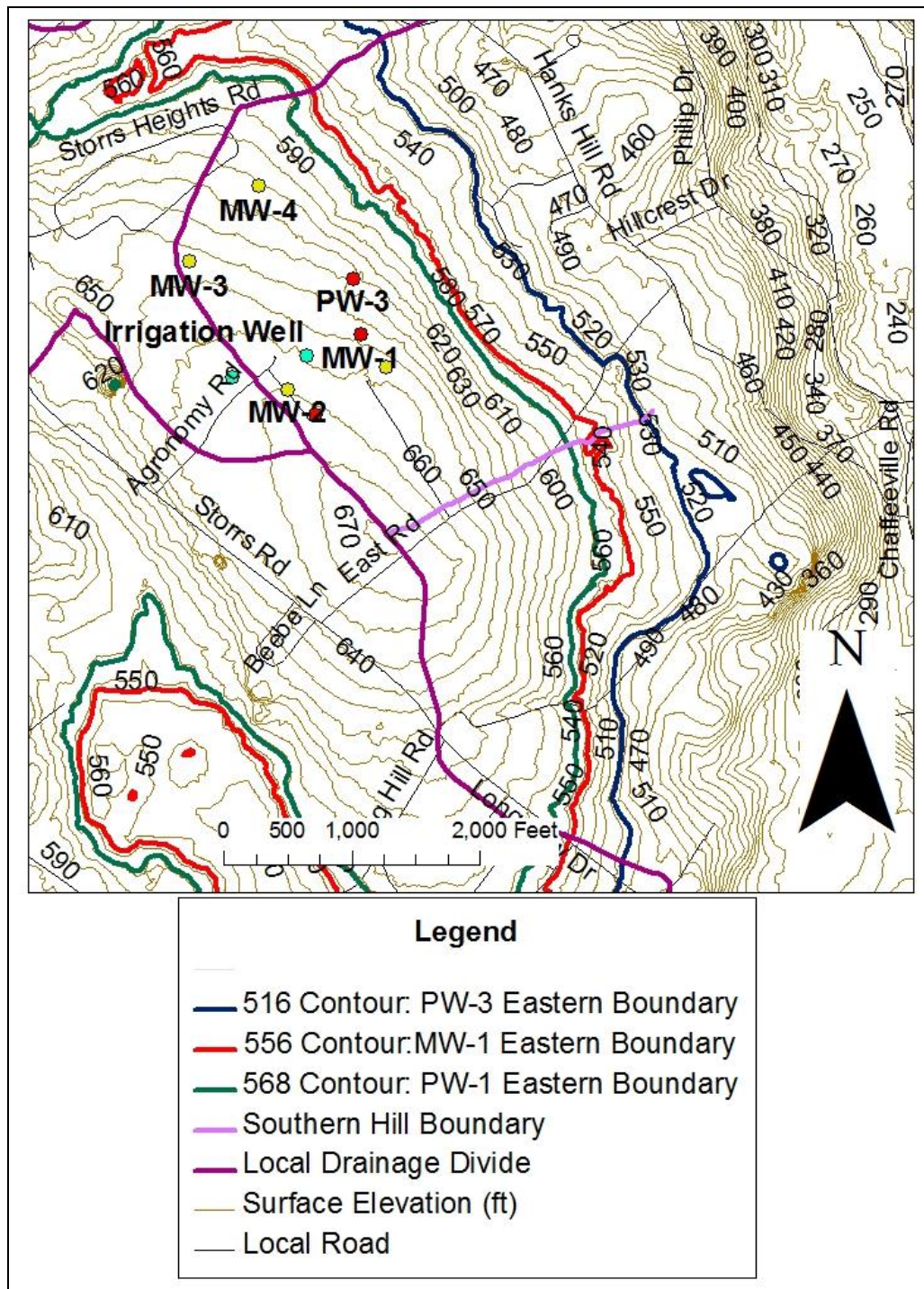


Figure 3-10 Boundaries used for determination of possible contributing areas. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

Flow to bedrock wells during pumping

Water elevation maps were produced for each pumping well in order to calculate the flow to each well at the time of maximum drawdown. In addition to the three pumping well maps, another map was produced using water elevations at 10:00AM on 8/27/10 while MW-1 was in the middle of pumping and PW-3 was recovering from pumping four hours earlier. This is the only map of the four that contains a measured water level in PW-3. These water elevation maps take into account the slope of the water table and would make flow estimations more accurate than the drawdown maps drawn for the contribution areas. Water level data on 8/25/10 were used and obtained as discussed above. The maps were produced in the same manner as with the drawdown maps except that limited hand interpolation was used in the absence of data. Where interpolation was needed, the drainage divide to the west was used as a western boundary, and in the other directions, the existing gradient in a given direction was extended, or the lines were extended naturally from one point to another, assuming no change in the gradient. Of these three maps, the map produced for 8/27/10 and pumping well MW-1 was the least uncertain; for it was more centrally located and contained data from all directions. A fair amount of hand interpolation was needed for the bordering wells PW-1 and PW-3.

The flow from each direction was calculated using Darcy's law. The width of flow (w) was taken from a given contour on the water elevation map that would require the least amount of interpolation overall for the well. The line to calculate the hydraulic gradient (dh/dl) was drawn perpendicular to this water elevation contour and extended to an adjacent 10 foot contour. On some maps, 5 foot contours were utilized to draw the gradient lines. The maps showing the parameters for flow can be found in Appendix L.

Since it was determined that the transmissivity was not constant across the aquifer, the flow from each direction to the pumping well was calculated using the geometric mean of the transmissivities of the wells in that direction. For example, in the elevation map for MW-1, the observation wells PW-2, MW-2, PW-1 and the Irrigation Well are located to the south and the transmissivity values of these wells were geometrically averaged for the calculation of the flow in that direction.

To determine the flow from the west when PW-1 was pumping, the average transmissivity of the domestic well and two wells on Agronomy Road on the western side of the main drainage divide were used. The transmissivity to the south of PW-1 was assumed to be the same as the north in order to match the water elevation contours which were interpolated to be the same as the north due to the absence of data. To the west of pumping well MW-1, there was little data and the water elevation contours were close to each other, so it was assumed that the transmissivity was low. Therefore, the geometric average of the entire well field was used. The transmissivity of the bedrock in the easterly direction while PW-3 was pumping was employed the same manner as MW-1, since it was located even farther to the east than MW-1.

4 RESULTS AND DISCUSSION

Hydrogeologic Characterization of the Overburden

Surficial Geology

The overburden is greater than 15 feet thick over the entire farm and is classified as “thick till” (CT DEP, 1995b). As seen in the depth to bedrock map in Figure 4-1, it is 30-40 feet thick on the north east flank near the top of the hill, and between 50-70 feet thick near MW-4 and PW-2. An analysis of the stratigraphy shows that most of the well field is underlain by a sandy silt layer with a clay layer underneath. Figure 4-2 is a fence diagram for the site looking east and Figure 4-3 looking north. The deepest silt layer is found at top of the hill near PW-1 (SW1-P), extending to near the farm buildings and Irrigation Well. This sandy silt would allow percolation of water down through the overburden and would be a good area of recharge being situated near the top of the hill. The lateral extent of this layer to the higher elevation of the farm is unknown due to lack of data. If this permeable layer does extend in that direction, then an appreciable amount of recharge occurs near the top of the hill.

The clay underneath this silt layer varies in depth across the farm, with the deepest portion found on the southeast and eastern part of well field where it is from 32 to 66 feet thick between SW2-P and SW-1. The presence of this relatively impermeable layer is confirmed by the fact that this area tends to be wet and no early crops can be grown there in early spring according to the Farm Manager (personal communication, Olson 2010). This region of thick clay most likely extends west to the area of hydric soils shown in Figure 2-3. In addition, it may extend to the northwest, down-gradient of the farm pond to PW-3, where it was wet until late spring. This

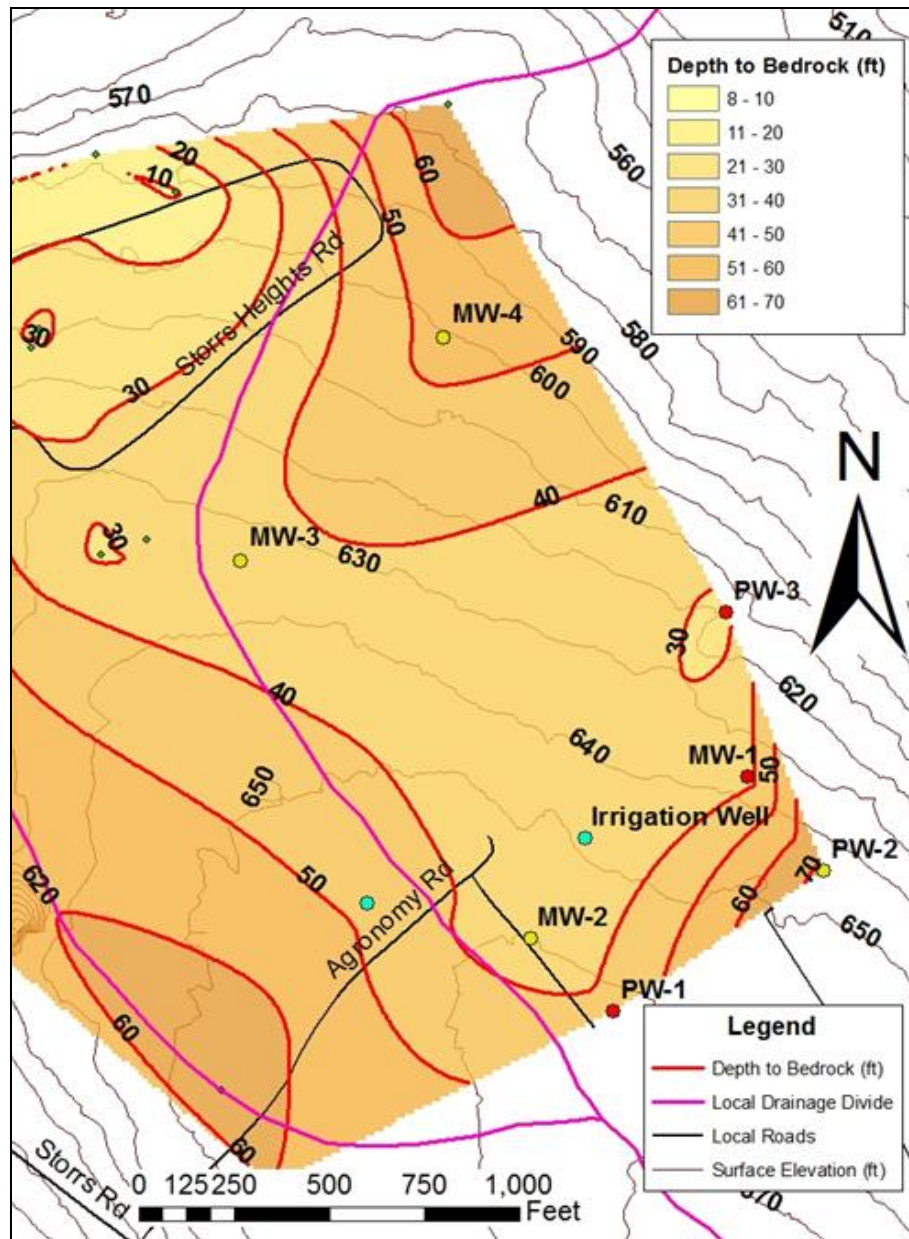


Figure 4-1 Depth to bedrock. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008). Off site depth to bedrock data from Robbins et al (2009).

area has thinner till, and the moisture is most likely caused by springs. Since clay is relatively impermeable, the areas just described would not be good areas of recharge.

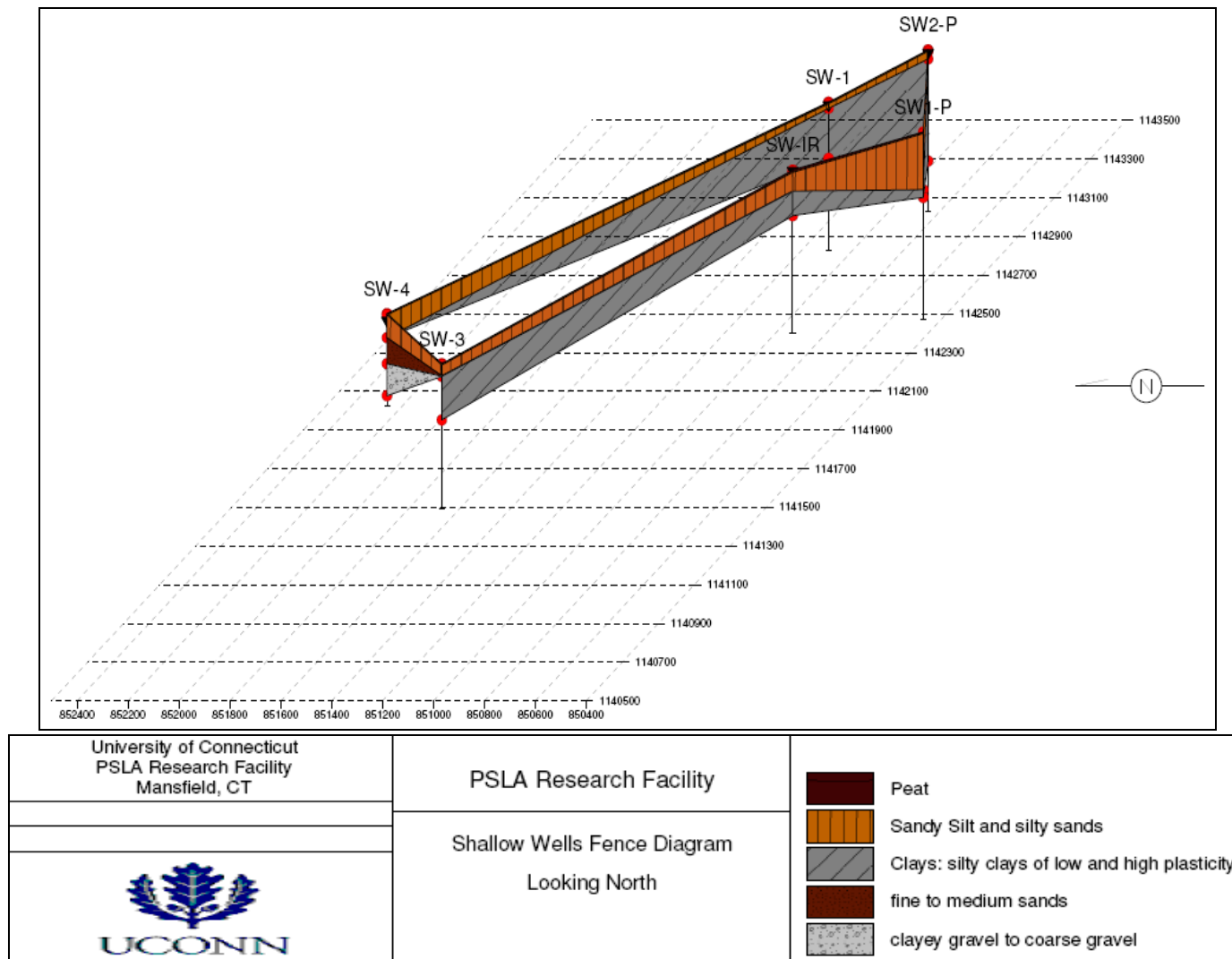


Figure 4-2 General overburden characteristics interpolated between wells. View looking east.

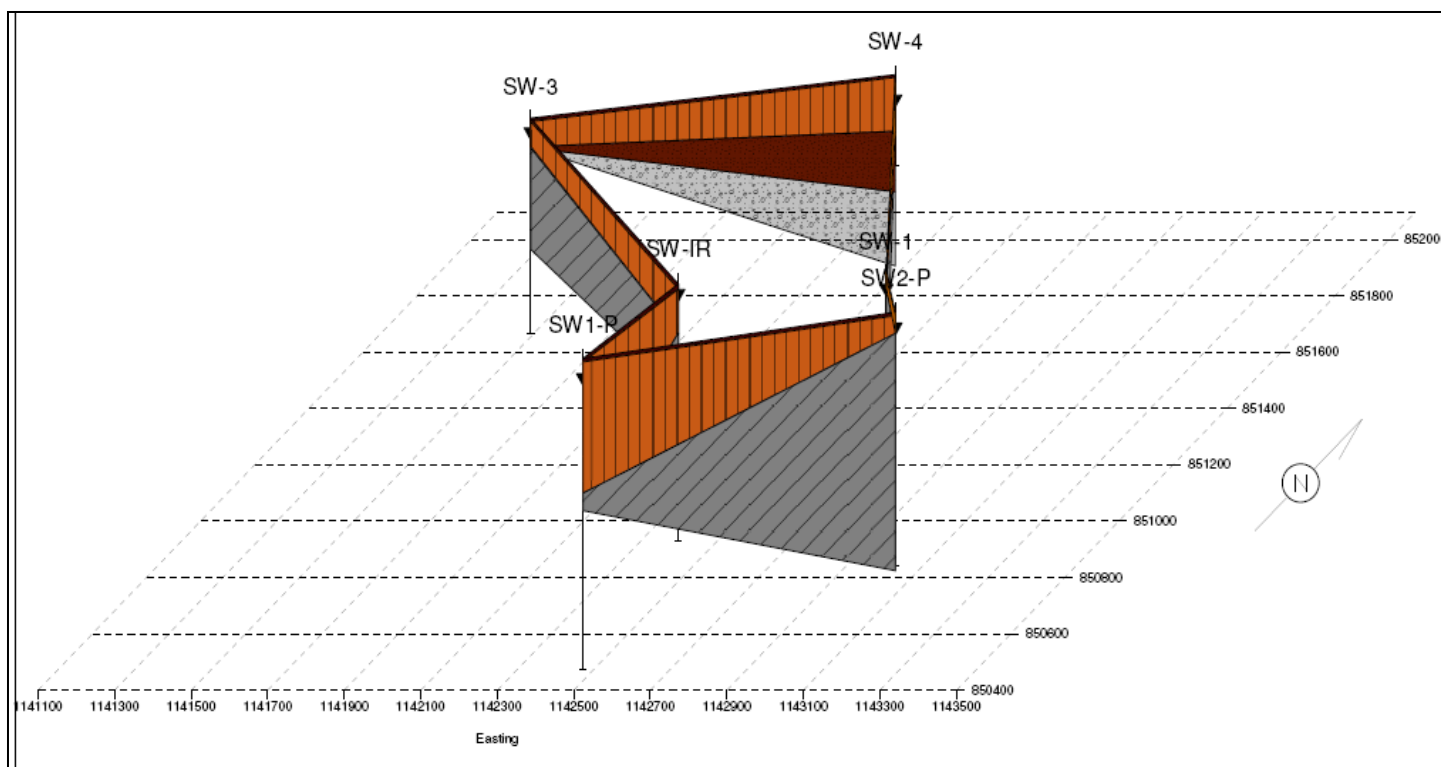


Figure 4-3 General overburden characteristics interpolated between wells. View looking north.

Most of the remaining wells contained a combination of clay and silt. This mixture would allow more percolation through the overburden than just clay. The north east portion of the farm near SW-4 is the most permeable location on the farm. As shown in Figure 4-3, there are thick layers of sand and gravel underneath the thick silt layer. Since this well is located in an area of thick till, and there is no clay layer at this location, this area would be an excellent area of potential recharge.

Slug Test Results

Figure 4-4 shows an AQTESOLV™ analysis plot for a typical test. Appendix B, “Shallow Well Slug Tests” contains the data and results of the multiple tests completed in each

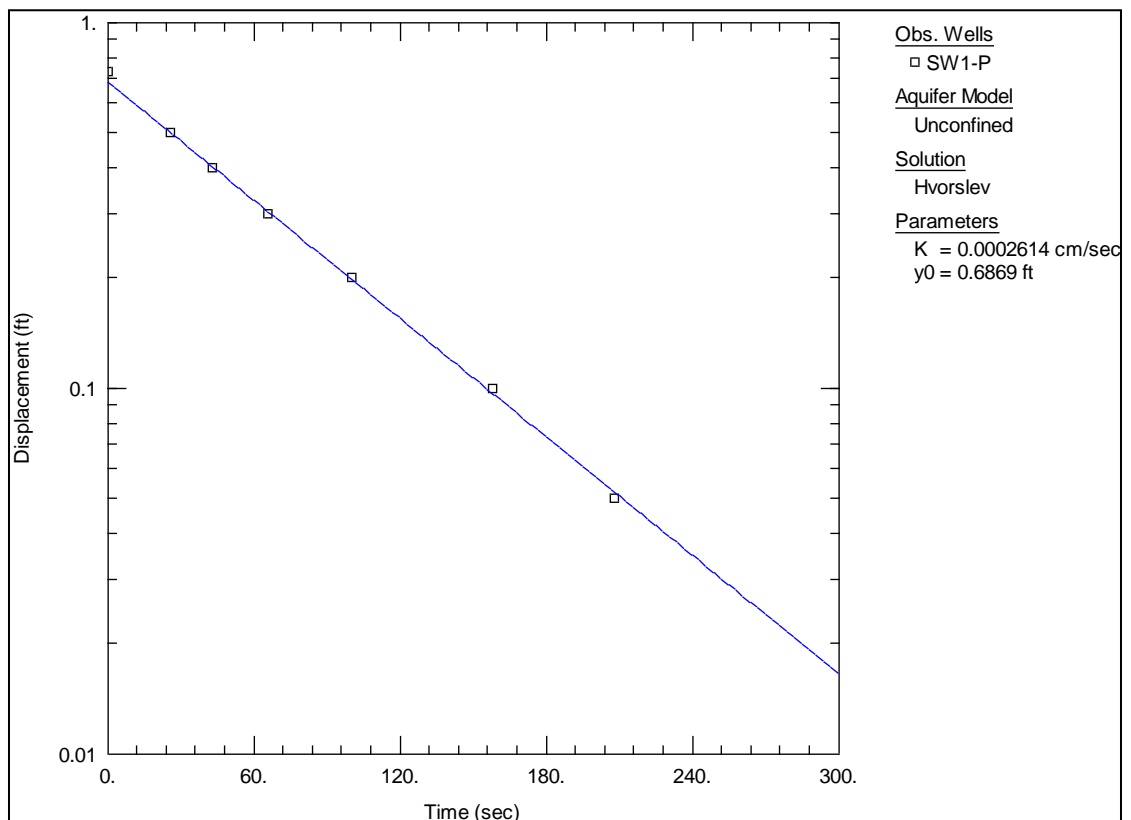


Figure 4-4 Typical shallow well response to slug testing

Table 4-1 Shallow Well Hydraulic Conductivity

Shallow Well	Hydraulic Conductivity (ft/day)	Hydraulic Conductivity (cm/sec)
SW1-P	7.16E-01	2.53E-04
SW2-P	1.02E-01	3.60E-05
SW-1	3.53E-03	1.25E-06
SW-IR	4.00E-01	1.41E-04
SW-3	6.19E-03	2.18E-06
SW-4	1.93E+01	6.80E-03
geometric mean	1.50E-01	5.36E-05

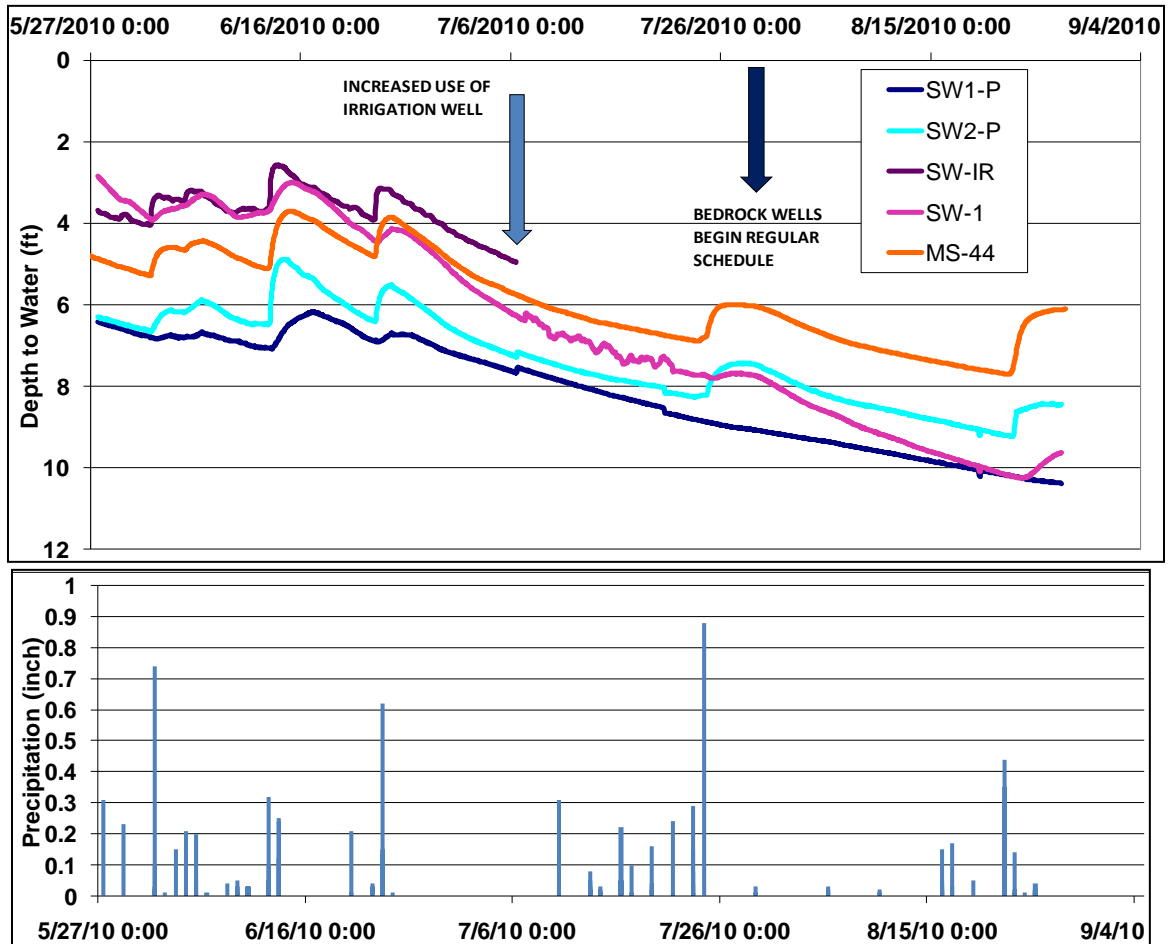


Figure 4-5 Depth to water in shallow wells and precipitation data 5/27/10-8/27/10.
 Precipitation data obtained from the PLSA Research and Education Facility in Mansfield, CT.

well. The slug tests results for hydraulic conductivity are shown in Table 4-1. The geometric mean of the hydraulic conductivity of the wells was $5.36\text{E-}05$ cm/sec , or 0.15 ft/day. This value is in the middle of the range of 10^{-4} to 10^{-6} cm/s found in tills (Fetter 2001). The conductivity values obtained for the wells were consistent with the sediment types observed in installing the wells and the classification by the DEP on the Surficial Geology Map (Figure 2-4) (CT DEP 1995a&b).

Shallow Well Pre-pumping Monitoring Results

Figure 4-5 shows the depth to water in the shallow monitoring wells as a function of time and in response to precipitation. The depth to water was relatively shallow, ranging from 3-10 feet. This close proximity to the ground surface enables the wells to respond rapidly to rain events. There was no response to the tides, which confirms the lack of a confining unit in the boring logs. The highest water levels generally occurred around June 15th, near the end of the spring rainy period. The water level started an overall decline for the rest of the monitoring period. There was no recharge to the overburden near the start of the pumping period (7/26/10) until mid August, due to a severe drought.

The rate of the response to rain events in the individual wells did vary. The water level in wells SW-1 and SW1-P had delayed and muted responses to precipitation events through June compared to other overburden wells, owing to the low permeability of the soils in their vicinity. The delayed response in SW-1-P could also be due to it having the deepest depth to water on the farm; recharge would take longer to reach the water table.

There was a steady overall decline in water level in the shallow wells from late June 23 to July 23, near the end of the pre-pumping monitoring period (Figure 4-5). The summer was dry and included a long time period from 6/24/10 to 7/10/10 with no rain at all. After the dry period,

there was a period of rain events from July 10 up to July 22 which affected the water levels in the wells differently than before the dry spell. SW-1 had the largest and most rapid response to precipitation compared to the other wells, all of which showed little or no response. This is an opposite reaction to rain compared to before the dry period. This could be due to the presence of clay in SW-1, which when dry may have desiccation cracks and a higher permeability than courser material, such as sand (Fetter 2001). Therefore, rainwater would flow vertically downward at a more rapid rate than in the areas of the other wells.

The recession rate in the shallow wells was at its lowest near the end of the pre-pumping monitoring period, from 7/21/10-7/23/10, at 0.05 ft/day as shown in Table 4-2. There was little rain for the month prior, and most of the recent rain events did not affect the majority of the wells as seen in Figure 4-5.

Table 4-2 Shallow Well Hydraulic Gradients and Recession Rates during the Pre- and Post-Pumping Period

	PRE-PUMPING			POST-PUMPING		
Shallow Well	7/7 Water Elevation (ft)	Horizontal Hydraulic gradient dh/dl 7/7 (ft/ft)	Recession Rate 7/ 21-7/23 (ft/day)	8/27 Water Elevation (ft)	Horizontal Hydraulic gradient 8/27 (dh/dl) (ft/ft)	Recession Rate Week of 8/20 (ft/day)
SW1-P	655.33	0.029	0.059	652.6	0.031	0.04
SW2-P	639.12	0.038	0.037	637.9	0.042	0.05
SW-1	631.10	0.042	0.058	627.9	0.043	0.07
MS-44	649.46	0.030	0.047	647.9	0.065	0.04
SW-3	629.55	0.047	N/A	625.1	0.052	N/A
SW-4	591.64	0.050	N/A	585.9	0.055	N/A
SW-IR	642.63	0.036	N/A	N/A	N/A	N/A
	AVERAGE	0.039	0.05		0.05	0.05

As shown in Figure 4-6, the depth to water on 7/7/10 before active pumping is lowest near MS-44 and SW-IR, near the top of the hill. This indicates an area of recharge, seeing that the corresponding water elevation map shown in Figure 4-7 shows that the water level is parallel to the topography and the water would flow downhill from that location. The area near SW1-P, even though it is located on the top of the hill had a greater depth to water. This area would not be a good area of recharge compared to the area near MS-44. The data used to generate these two maps can be found in Appendix G.

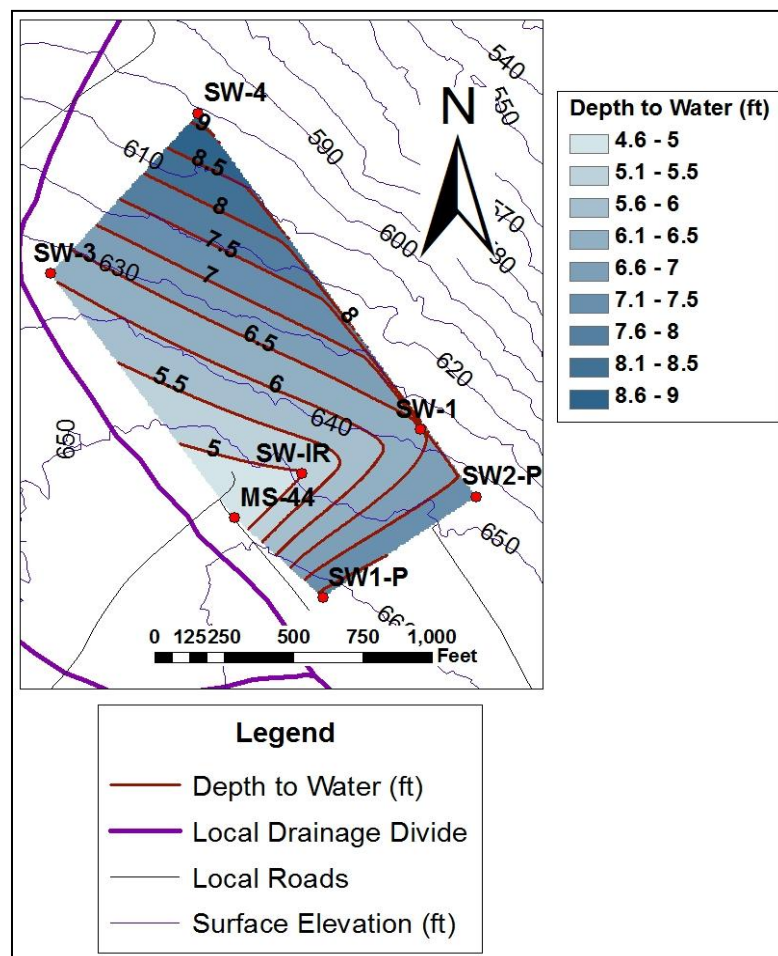


Figure 4-6 Depth to water in overburden in ambient conditions. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

Horizontal Flow in the Overburden in Ambient Conditions

The horizontal flow of water in the overburden starts at the local drainage divide on the farm and flows downhill in the northeast direction. As shown in Table 4-3, the average horizontal hydraulic gradient was 0.039 ft/ft which is approximately the same as the slope of the topographic surface. The amount of flow from the study area in the horizontal direction was about 2650 gallons per day.

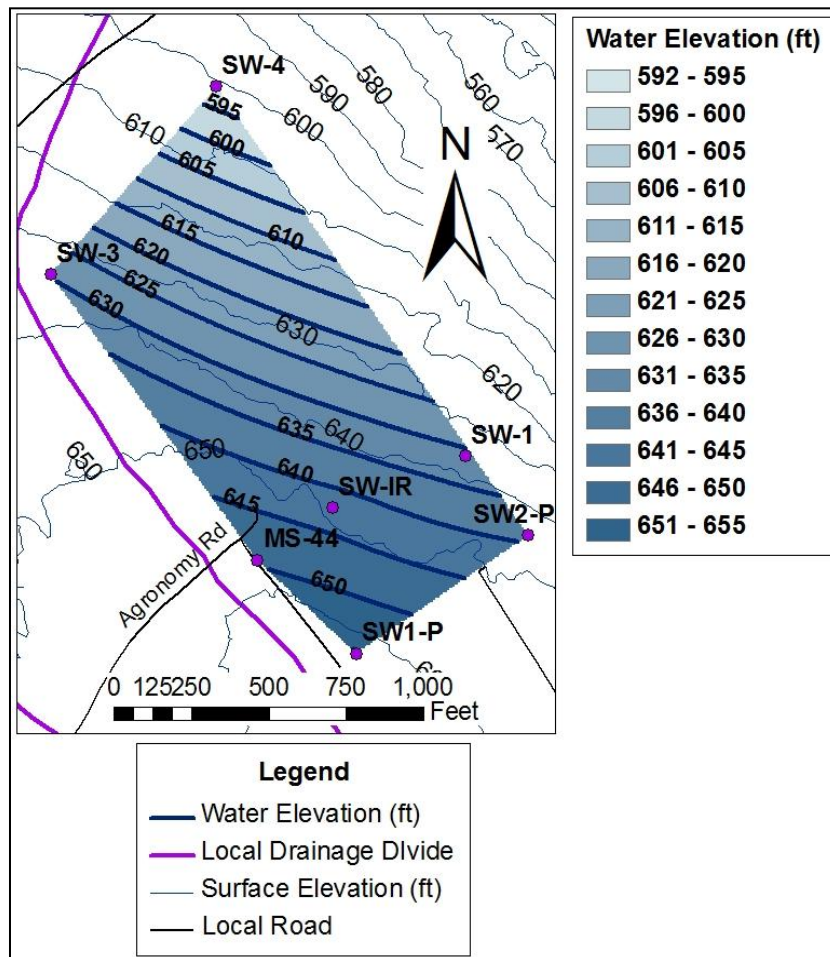


Figure 4-7 Water elevation in overburden during ambient conditions. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

Table 4-3 Horizontal Gradient and Flow in Overburden

Pre-pumping		Post Pumping	
Horizontal Hydraulic Gradient (ft/ft)	Horizontal Flow 7/7(gal/day)	Horizontal Hydraulic Gradient (ft/ft) (8/27)	Horizontal Flow 8/27 (gal/day)
0.0388	2,623	0.0478	2,655

Post pumping shallow monitoring well results

There was an overall decline in water level in the wells from mid June to the end of the monitoring period as seen in Figure 4-5. During the pumping period, there were two main rain events that increased the water level in these wells occurring at the end of July and August. Smaller rain events between these dates never made it to the water table.

The water level recession rate was lowest the week of 8/23/10 as shown in Table 4-2. The lowest recession rates observed between 0.04 to 0.05 ft/day occurred in SW1-P, SW2-P and MS-44 the wells located at the highest elevation. The highest recession rate of 0.07 ft/day occurred in SW-1, the well at the lowest elevation.

None of the shallow well water levels appeared to be influenced by pumping of the bedrock wells. Figure 4-8, Figure 4-9, and Figure 4-10 shows the comparison of the water levels in the shallow monitoring wells with the adjacent bedrock wells. None of the shallow wells show response to pumping. This may be due to a lack of hydraulic connection with the fractures that provide water to the bedrock wells, or due to the low hydraulic conductivity of the overburden.

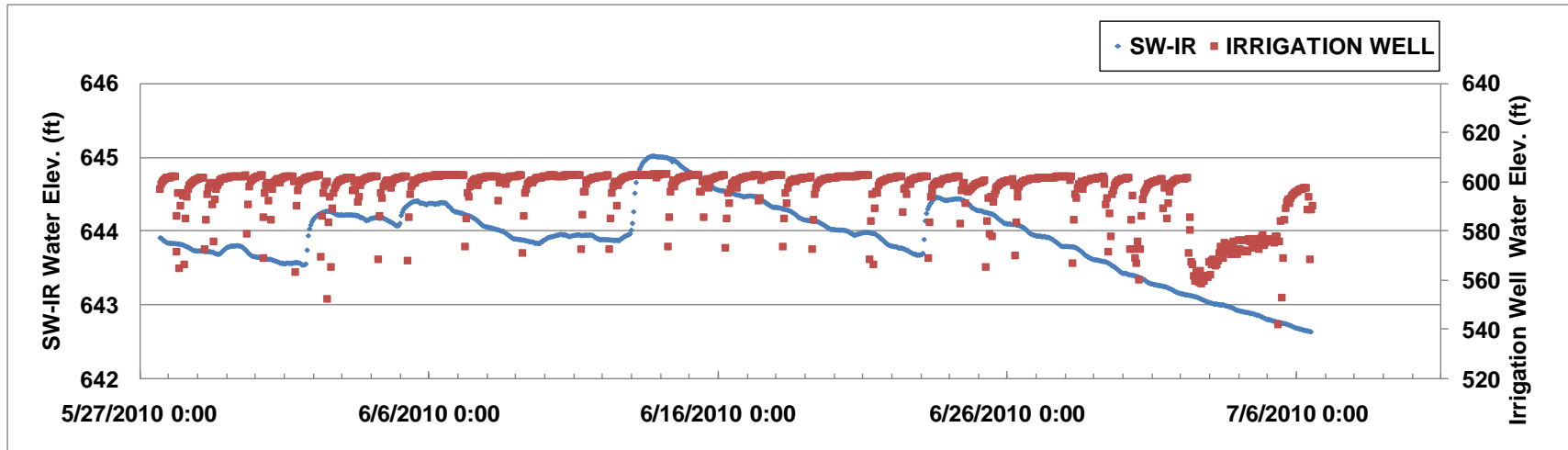


Figure 4-8 Water level in shallow well SW-IR and corresponding bedrock well before new well field pumping.

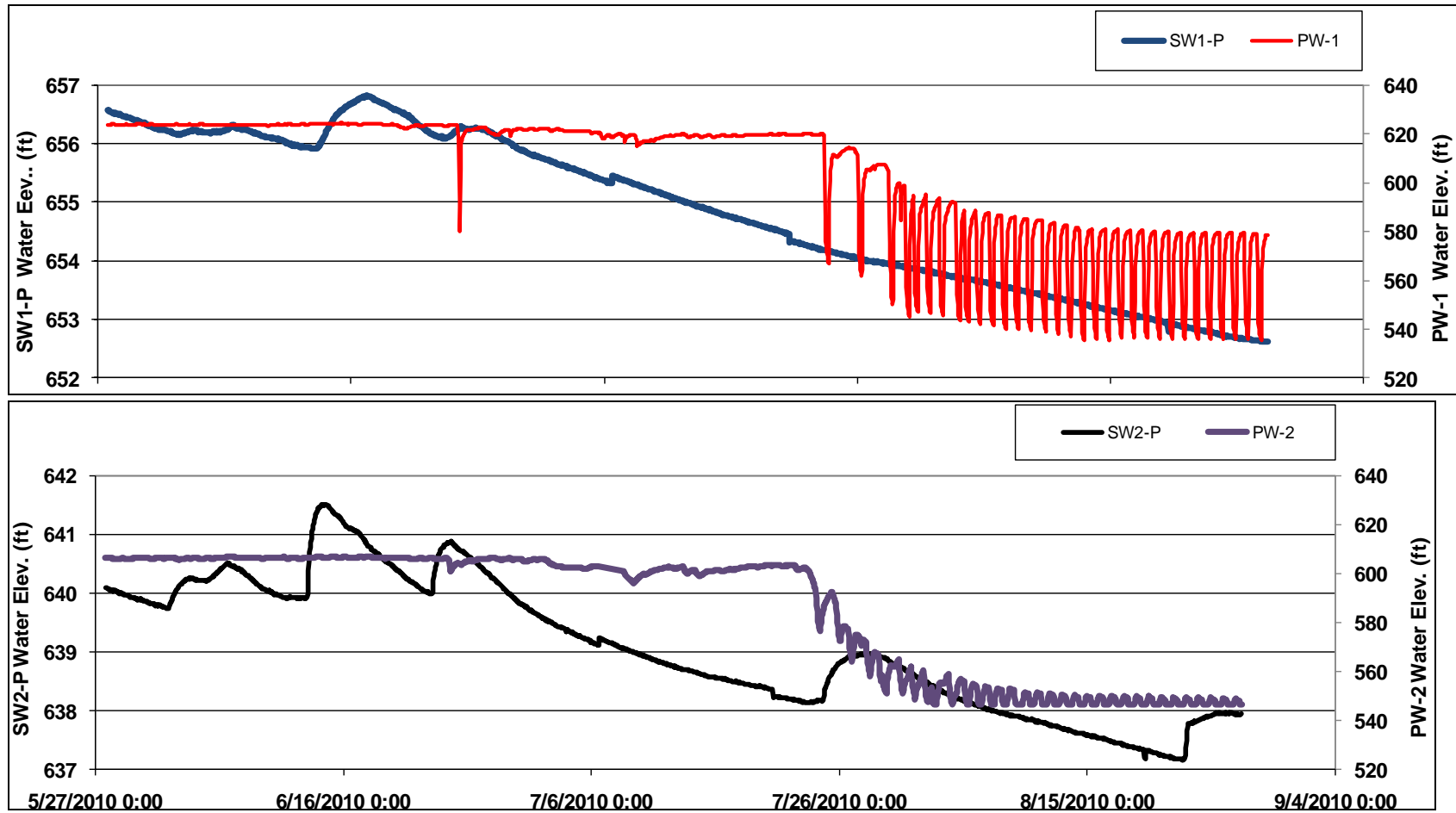


Figure 4-9 Figures comparing water levels in bedrock wells with those in adjacent overburden wells. Top is pumping in PW-1 and the nearby shallow well SW1-P, and below is bedrock monitoring well PW-2 and nearby Shallow well SW2-P.

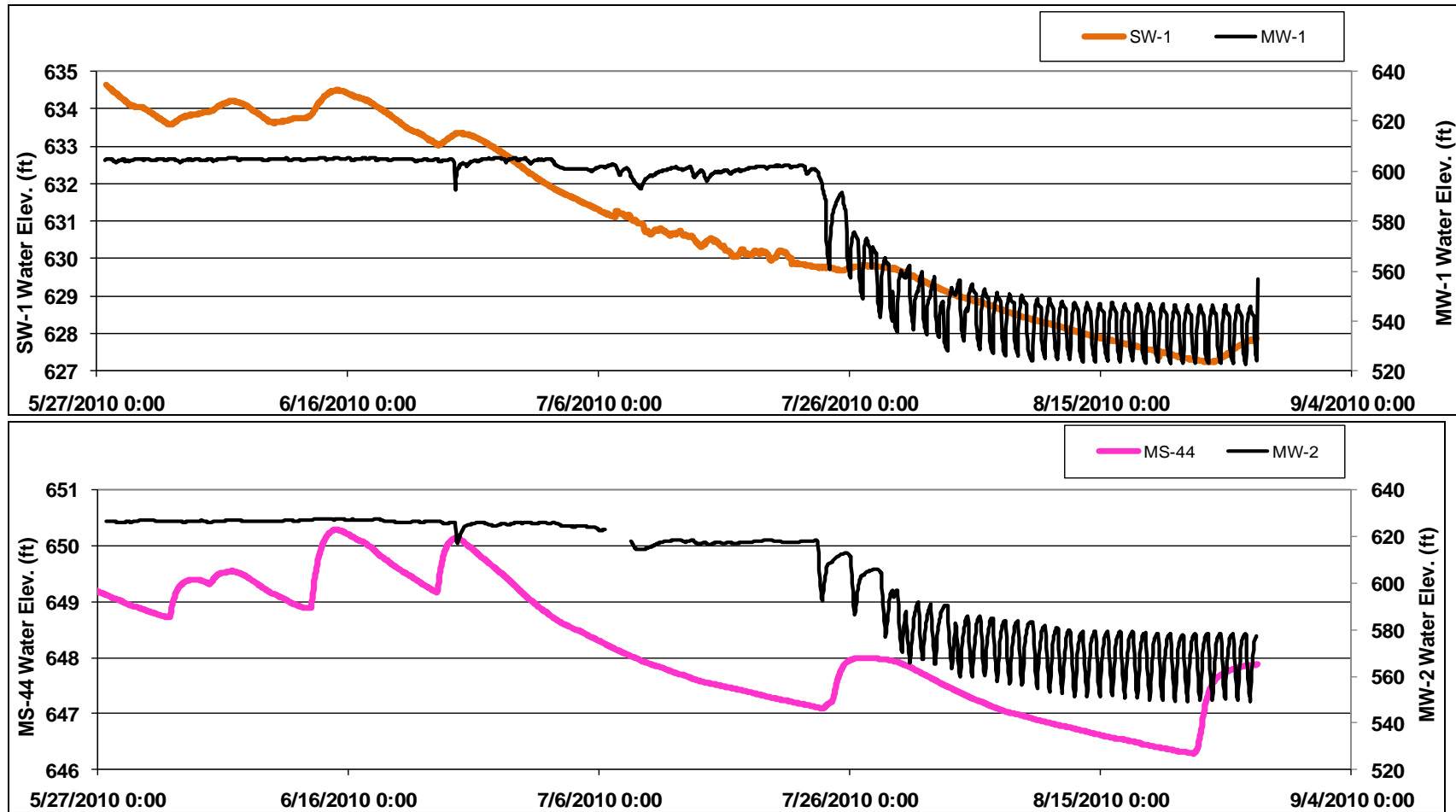


Figure 4-10 Figures comparing water levels in bedrock wells with those in adjacent overburden wells. Top is pumping in MW-1 and the nearby shallow well SW1 and below is bedrock monitoring well MW-2 and nearby Shallow well MW-44.

The depth to water contour map of the overburden on 8/27/10 shown in Figure 4-11a was similar to the pre-pumping depth to water shown in Figure 4-6. There were a series of rain events in the few days prior, and at the time of the sampling, the water levels were increasing as seen in Figure 4-5. The 8/27/10 map shows the same area of recharge as the map completed on 7/7/10. The only difference between the two maps was that there was a greater depth to water in August, due to a general lack of rain from late July to mid August.

Horizontal Flow in the Overburden

There was no change in the direction of overburden groundwater flow while pumping from the bedrock aquifer; the water elevation contours were still parallel to the topographic contours as shown in Figure 4-11b. The water that did not recharge the bedrock still flowed downhill as it did before pumping. As shown in Table 4-3, the hydraulic gradient, and therefore horizontal flow, did not change appreciably before and after pumping.

Hydrogeologic Characterization of the Bedrock Aquifer

As shown in Figure 4-12, the bedrock surface mimics the topography. The well completion reports show that the Hebron Gneiss under the overburden had aerially extensive water yielding fractures. A summary of these fractures can be found in Table 4-4. The elevation of the bottom of the pumping wells was near sea level, but the locations of the main contributing fractures identified by the drillers were between 250-370 feet below the ground surface, or between 270-390 feet elevation. The average yield while drilling the pumping wells at this elevation was high, at 34 gallons/minute. Another zone of fractures occurred between 510 to 575 feet elevation. All the monitoring wells and one of the pumping wells had a recorded fracture here.

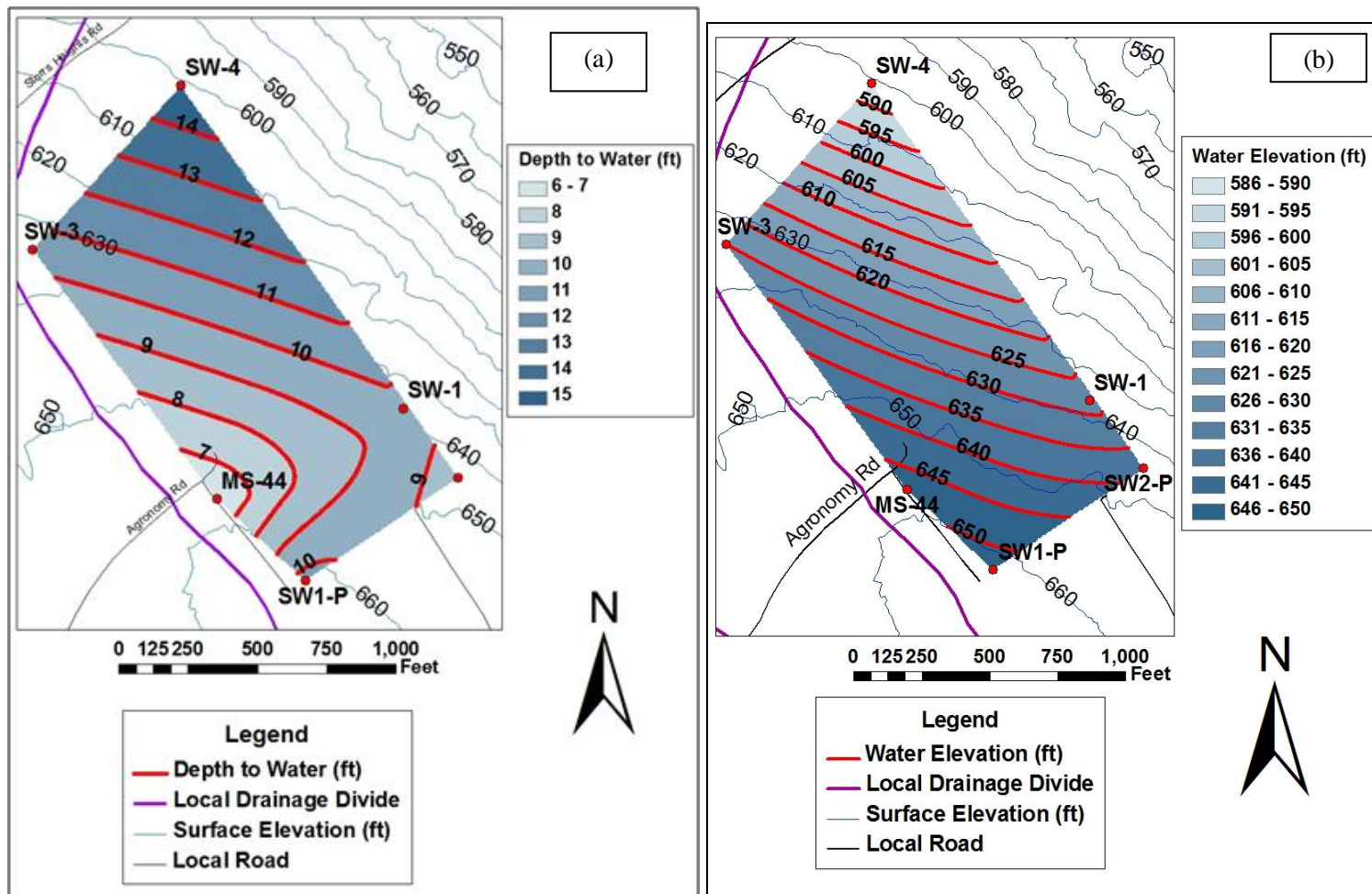


Figure 4-11 Water Level and Depth to Water in Overburden During Pumping 8/27/10. (a): Depth to water (b) Water Elevation. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

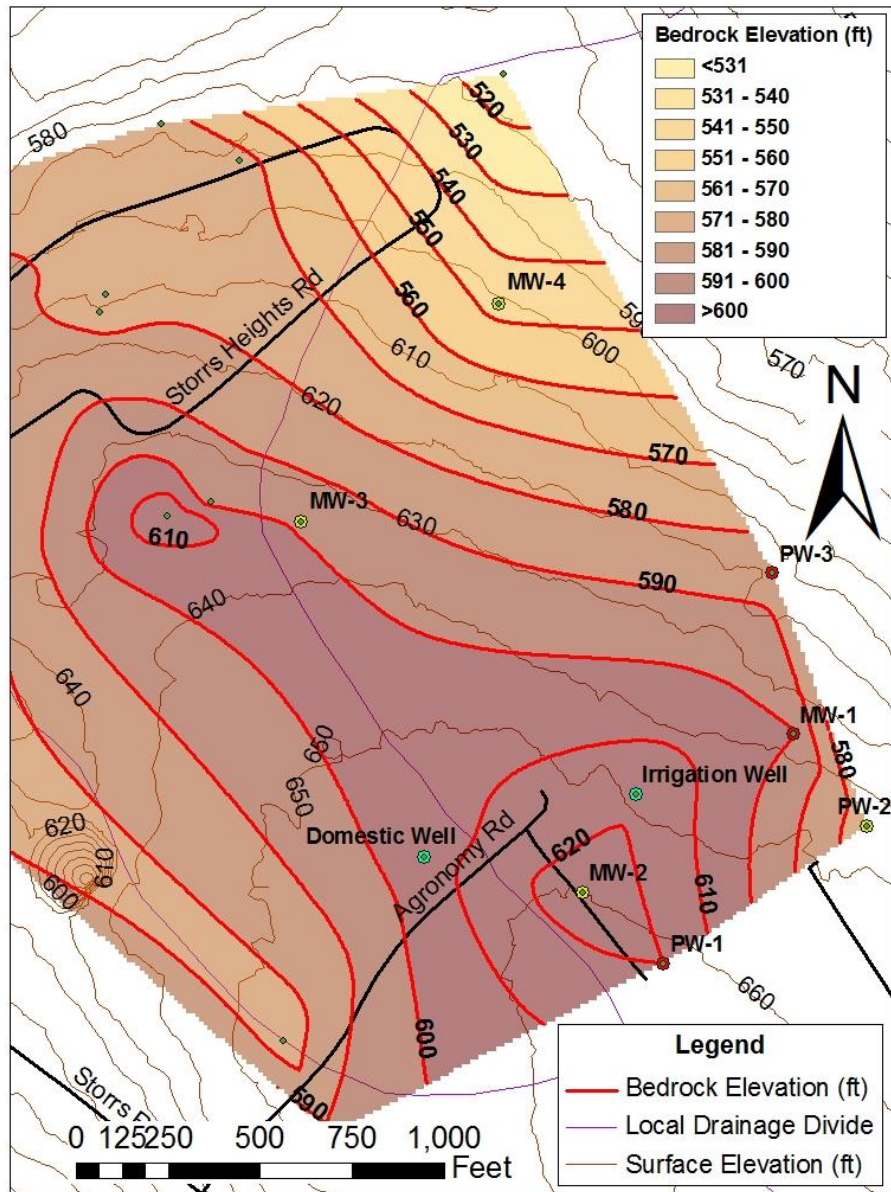


Figure 4-12: Bedrock elevation map. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008). Off site bedrock elevation data from Robbins et al. (2009).

Table 4-4 Bedrock Fracture Locations and Yield based on Driller Reports

Well	Surface Elevation (ft)	Depth to Water Contributing Fracture (ft)	Elevation of Fracture (ft)	Elevation of Bottom of Well (ft)	Yield (GPM)
PW-1	663	340-360	323-303	43	40
PW-2	646	140	506	26*	8
		360	286		18
PW-3	614	240	374	-6	12
MW-1	638	80-100	558-538	38	8-10
		360-370	278-268		50
		600	38		70
MW-2	654	?	?	40	?
MW-3	636	100	536	386	0.25
		250	386		0.25
MW-4	601	?	?	351	?
*The well subsequently collapsed to a depth of 110 feet due to weathered bedrock.					
?: Not determined					

This water bearing fracture zone in PW-2, located at 512 feet, has special significance. This fracture, 140 feet down, is located near the intersection between the weathered and un-weathered bedrock at 506 feet elevation. After drilling, the well subsequently collapsed to 110 feet down, or at elevation 536 feet, 30 feet above the water bearing fracture. Despite the collapse, the well readily responds to pumping indicating there is still continuity with fractures below the collapse zone.

MW-1 had the most fractures (3) recorded from the drillers and the highest yield over all. It also had the deepest water contributing fracture recorded in all the wells, at 15 feet elevation. MW-2 and MW-4 had no recorded water bearing fractures found as they drilled. MW-2 however, readily responds to pumping, whereas MW-4 only marginally responds.

The presence of two sets of fractures located at similar elevations in the bedrock wells could be evidence of a particular type of fracture found in the Hebron Gneiss. Starn and Stone (2005) in their study of Connecticut geology, found that gently dipping layered metamorphic

rocks have unroofing fractures occurring between their natural layers. These layers can be zones where water can flow in the rock. Unroofing fractures located around 300 feet elevation could be the main source of water to these bedrock wells.

Pumping Test

Figure 4-13 shows the pumping rate and drawdown in pumping well PW-1 during testing. The figure shows the transmissive nature of the well; a constant yield of 25 gallons was obtained and the drawdown in the well almost reached steady state near the end of the test.

The pumping rate and drawdown graphs for MW-1 also attest to the relatively high transmissivity of the fractured rock in this area as seen in Figure 4-14. The discharge reached 25 gallons per minute within the first minute of the test; much quicker than PW-1 which took 90 minutes to reach this rate. But unlike PW-1, the drawdown increased continually and did not reach steady state.

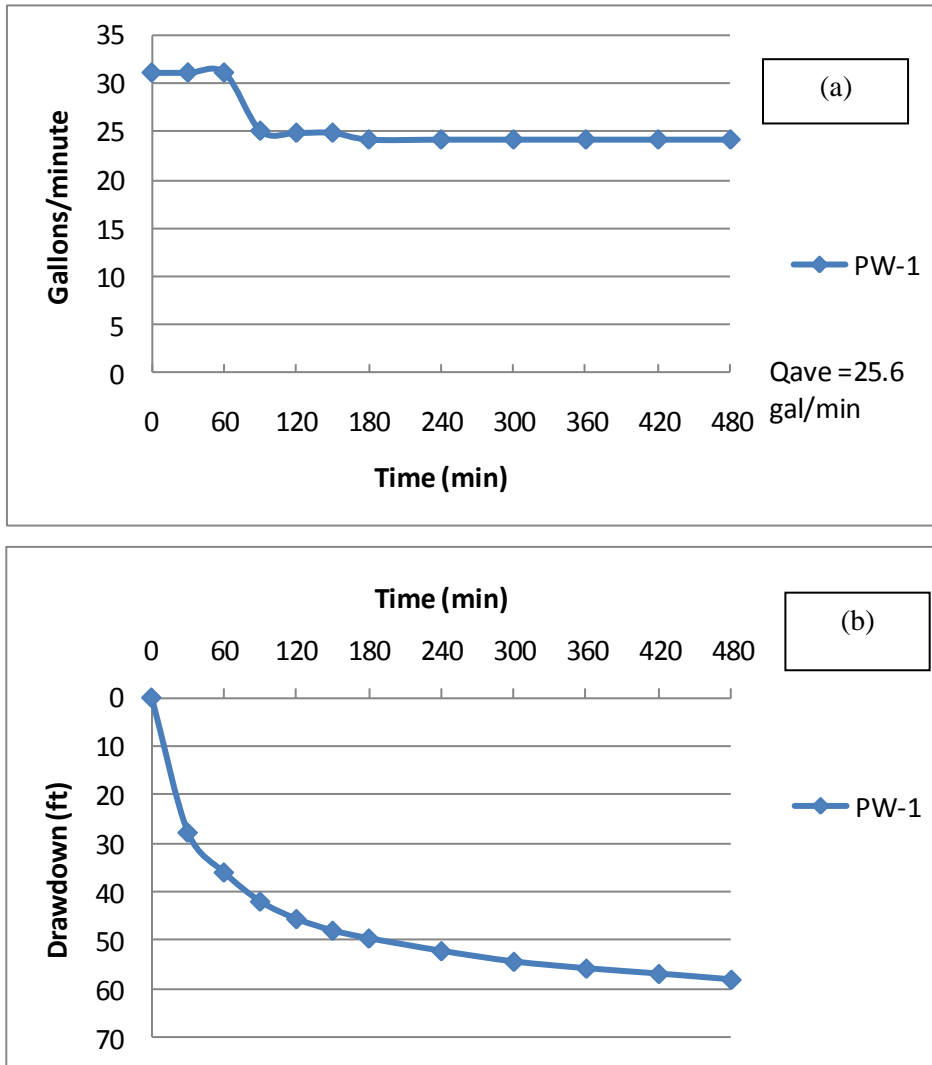


Figure 4-13 Pumping well PW-1 during testing. (a) Discharge vs. time (b) Drawdown vs. time

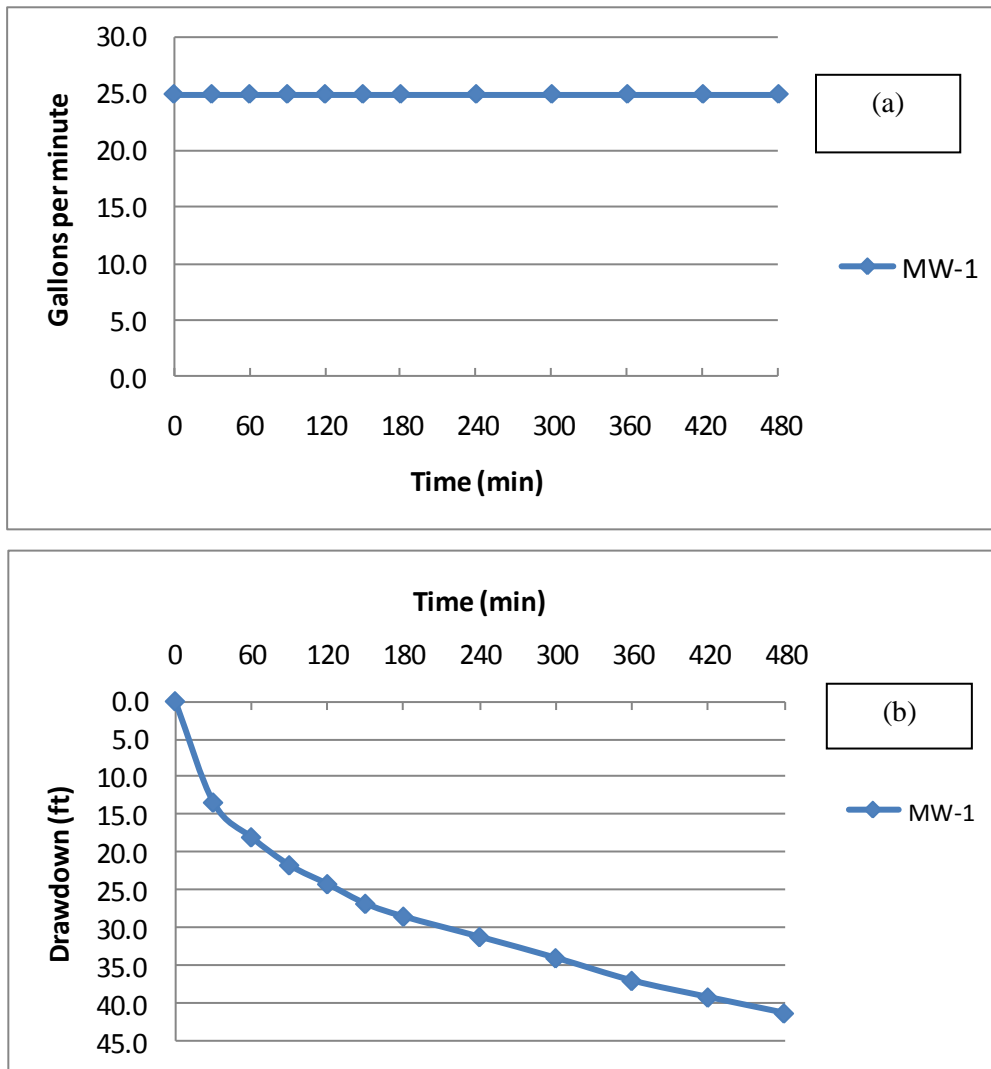


Figure 4-14 Pumping well MW-1 during testing. (a) Discharge vs. time (b) Drawdown vs. time

Figure 4-15 shows the discharge and drawdown in PW-2. They were affected by the fact that the well had collapsed and the pump in this well was placed above the collapse, only 95 feet down. After pumping 20 gallons per minute for about 30 minutes, the drawdown was 47 feet, which was within 5 feet of the pump. The pumping rate was reduced over the next two hours to 10 gallons per minute to keep the pump submersed.

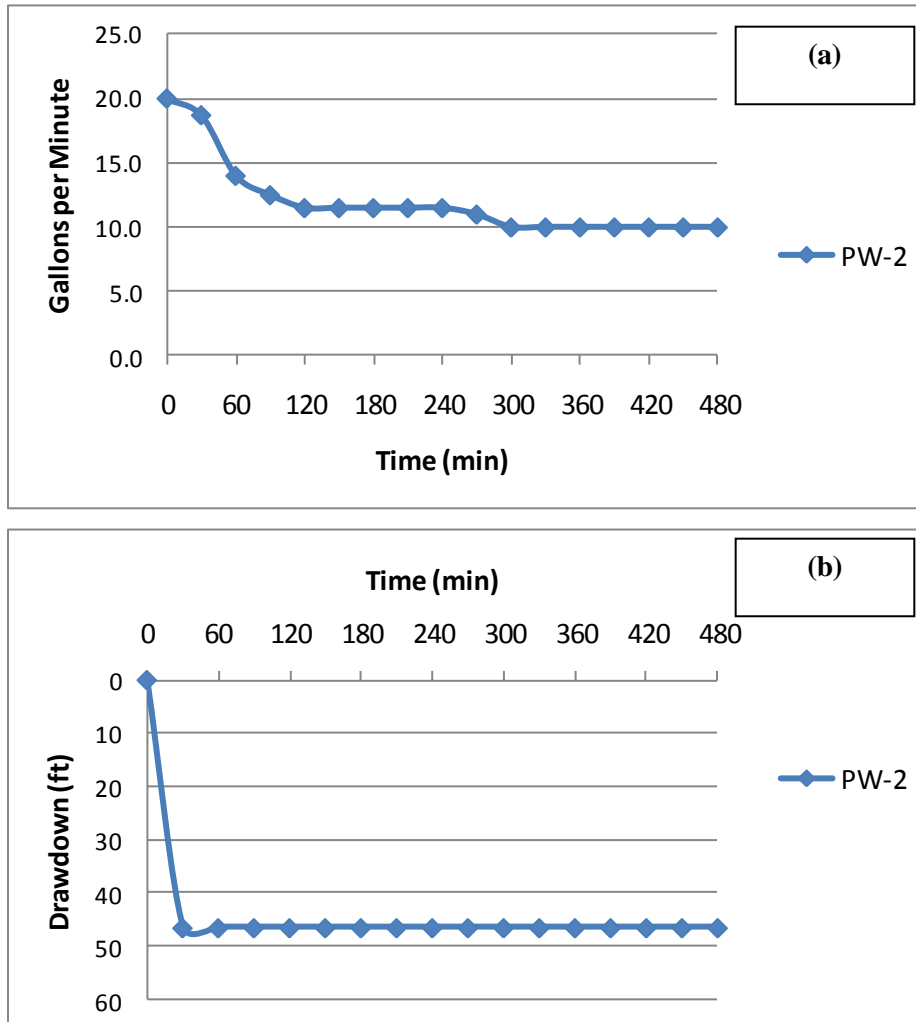


Figure 4-15 Pumping well PW-2 during testing. (a) Discharge vs time (b) Drawdown vs time

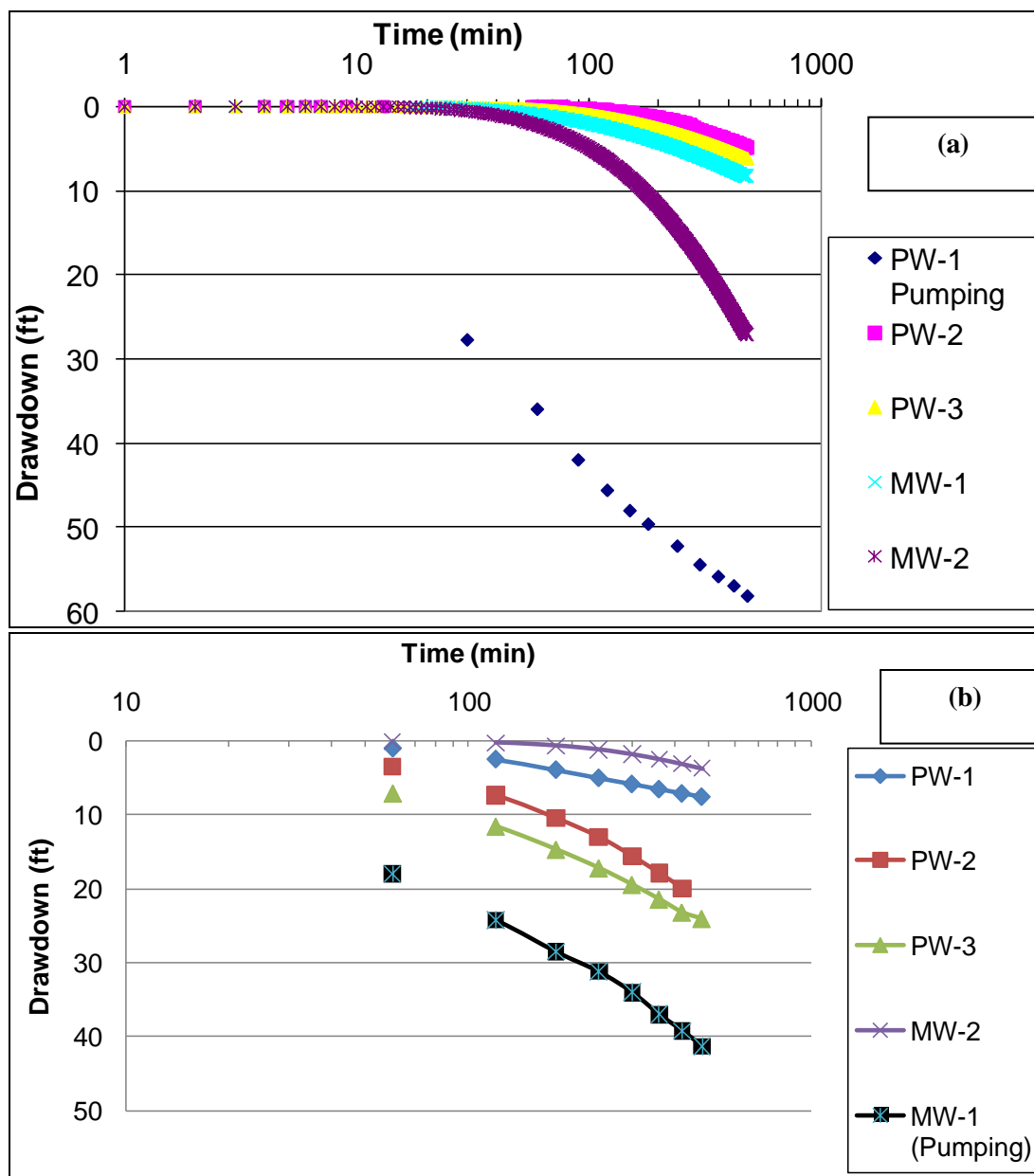


Figure 4-16 Water levels in bedrock wells during testing. (a) PW-1 test (b) MW-1 test

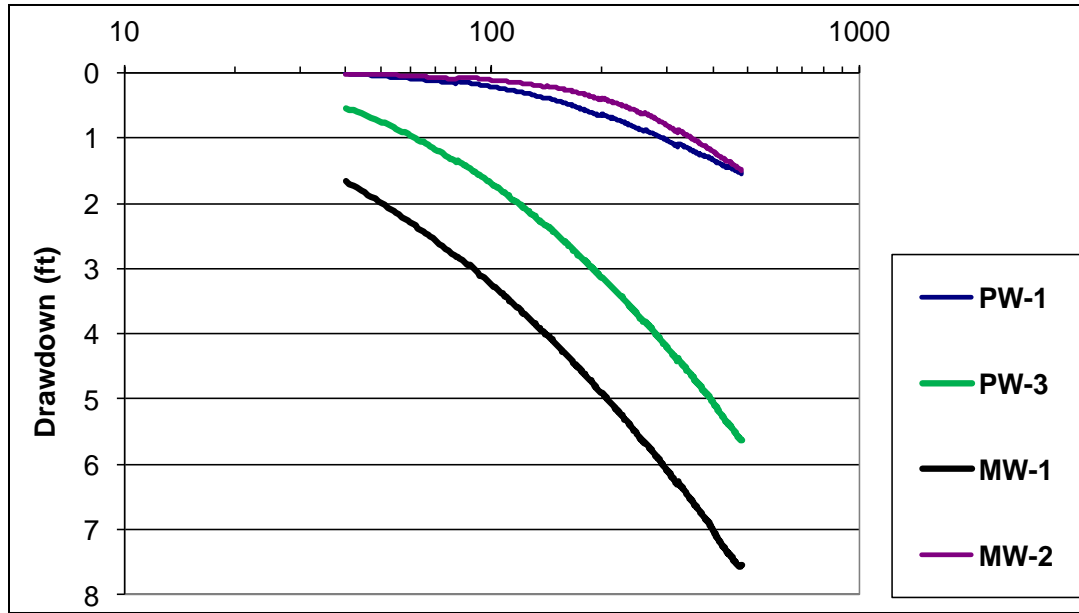


Figure 4-17 Water levels in bedrock wells during PW-2 testing

The drawdown in the observation wells during each test can be found in Figure 4-16 and Figure 4-17. All of them exhibited semi-log linear drawdown responses after about 200 minutes of testing. This late time data fit the Theis (1935) curve in the AQTESOLV™ program in all the wells. An example of a typical result can be found in Figure 4-18. Additional program results can be found in Appendix E. Early non-linear data due to wellbore storage effects was omitted. The observation wells located the farthest away showed no change in the water level during the tests.

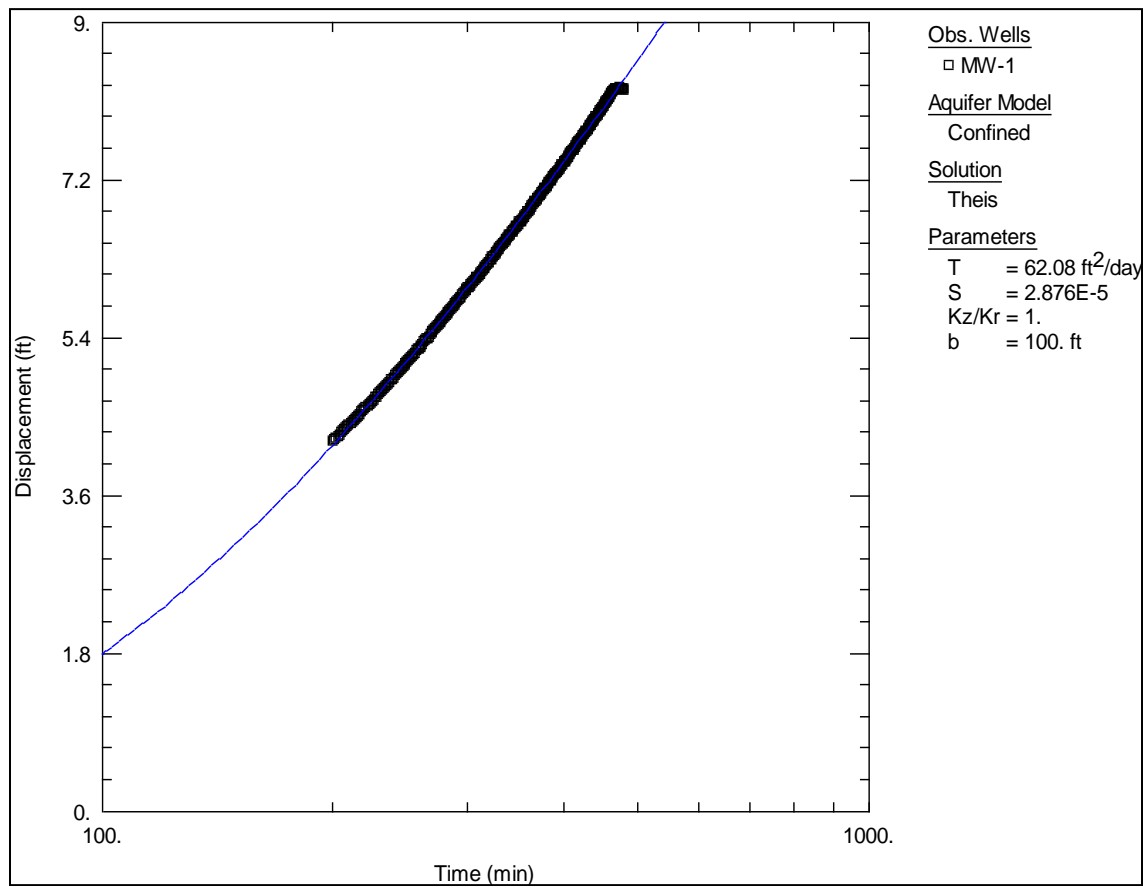
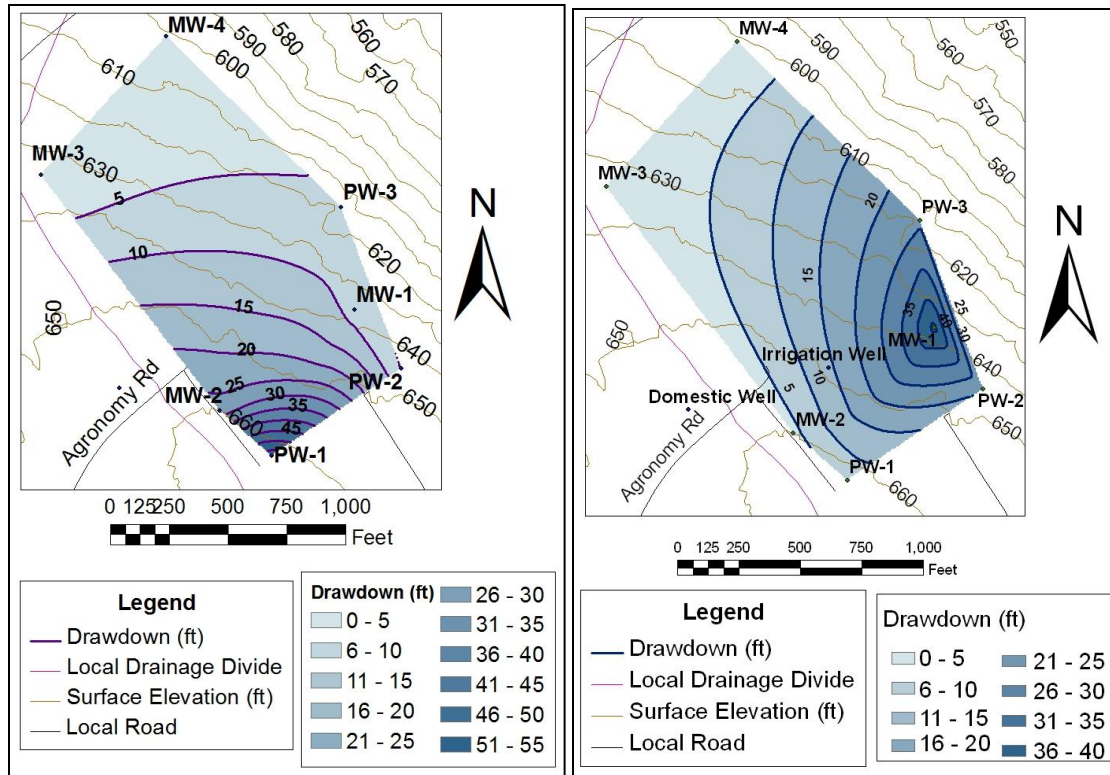


Figure 4-18 Calibration of late time data using AQTESOLV™ software. MW-1 is the observation well while pumping PW-1.



Maps of the maximum drawdown during each pumping test can be found in Figure 4-19 and Figure 4-20. The drawdown contours are not symmetrical around the pumping wells; they are all elongated to the north or northeast. This shows the anisotropy of the transmissivity of the well field. Larger distances between the contours in one direction verses another indicate that the fractures are more transmissive in that direction.

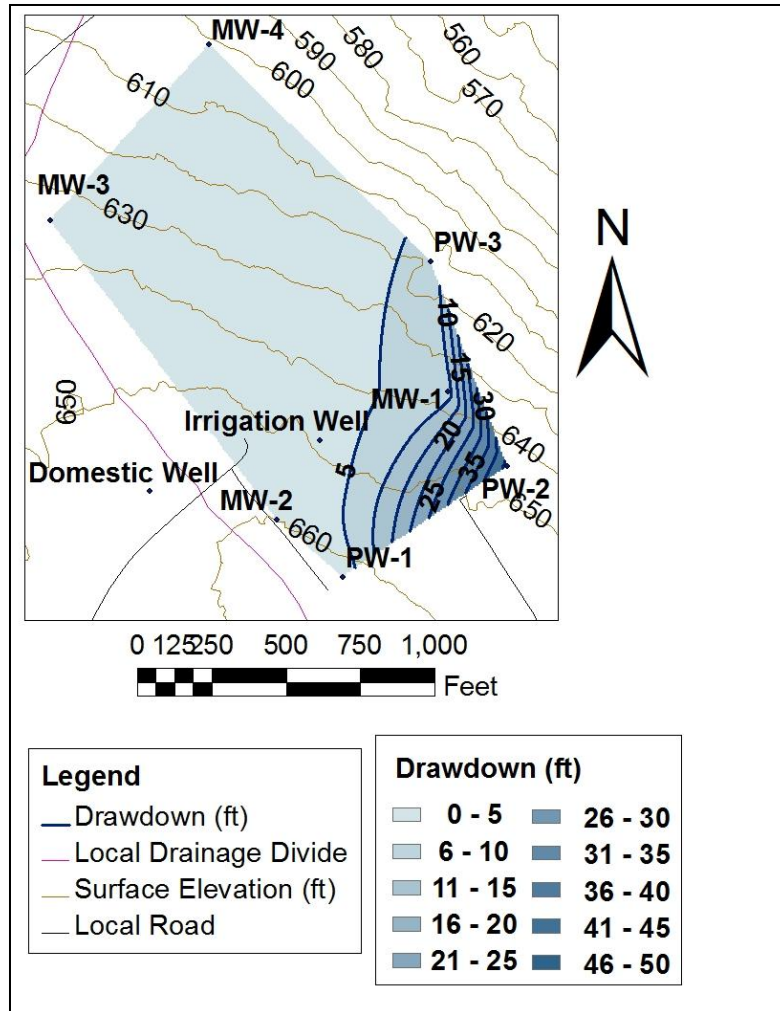


Figure 4-20 Drawdown in pumping test conducted in PW-2 after 8 hours. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

The mean value of the transmissivity from the pumping tests was $49 \text{ ft}^2/\text{day}$, which is about a factor of seven larger than the existing Irrigation Well which was tested at $7.6 \text{ ft}^2/\text{day}$ (Table 4-5). The test completed in PW-2 yielded the highest overall average transmissivity value of the three tests at a value of $67 \text{ ft}^2/\text{day}$. This high average value was due in part to the transmissivity of $116 \text{ ft}^2/\text{day}$ observed in PW-1.

Table 4-5 Transmissivity of New Bedrock Wells from Pumping Tests

	T (ft ² /day) Observation Well MW-1	T (ft ² /day) Observation Well MW-2	T (ft ² /day) Observation Well PW-1	T (ft ² /day) Observation Well PW-2	T (ft ² /day) Observation Well PW-3	Pumping Tests Average T (ft ² /day)
PW-1 Test	62	15	43	55	61	42
PW-2 Test	53	61	116		52	67
MW-1 Test		42	86	27	35	43
Overall Average T (ft²/day)	57	34	75	39	48	49

Table 4-6 Storativity of New Bedrock Wells from Pumping Tests

Well	Pumping Test PW-1	Pumping Test PW-2	Pumping Test MW- 1	Average for wells
PW-1		9.50E-05	2.55E-05	6.02E-05
PW-2	6.85E-05		5.09E-05	5.97E-05
PW-3	1.88E-05	1.68E-05	1.58E-05	1.71E-05
MW-1	2.88E-05	4.65E-05		3.76E-05
MW-2	5.93E-05	7.20E-05	7.23E-05	6.78E-05
Average	4.38E-05	5.76E-05	4.11E-05	
Average of all tests		4.75E-05		

As seen in Table 4-6, the storativity values found in the tests were all within the order of magnitude of 10^{-5} . This indicates that this bedrock aquifer is confined and basically incompressible.

An anomaly was found in the values of the transmissivity obtained between two wells depending upon which one was pumping and which one was observing. In a homogeneous and isotropic medium and horizontal water elevation, the transmissivity should be equal; in this study, it was found not to be the case. About twice the transmissivity was observed in PW-1 and MW-1 when PW-2 was pumping (116 ft²/day and 53 ft²/day, respectively) than was observed in PW-2 when either PW-1 or MW-1 was pumping (55 ft²/day and 27 ft²/day, respectively). One

possibility causing this difference could be the heterogeneous nature of the fracture conditions in the rock. The cone of depression formed by PW-2 could draw in a source of recharge from a fracture not encountered when the other two wells were pumping and PW-2 was observing. This would cause a smaller drawdown produced by PW-2 which would create a larger observed transmissivity in the other wells. This source of recharge could be from fractures located in the 40 feet of weathered and broken rock near PW-2, or from a more distant source. Another possibility could be due to the relative positions of the wells in the well field. PW-2 and MW-1 are at a lower elevation than PW-1 as seen in Figure 2-2. While PW-2 pumps, it would have the advantage of the water flowing down gradient which would increase the transmissivity observed in PW-1. While PW-1 pumps, it would be working against the hydraulic gradient so a smaller transmissivity would be observed in PW-2. While this explains the difference between PW-1 and PW-2, this is not the case between PW-2 and MW-1. PW-2 is at a higher elevation than MW-1, so the higher transmissivity observed in MW-1 while PW-2 was pumping cannot be explained by the elevation difference.

The anomaly in the transmissivity between PW-1 and MW-1 was not as dramatic, but still noticeable. While MW-1 was pumping, the observed transmissivity in PW-1 was slightly larger than the reverse by about 32 percent (86 ft²/day vs. 62 ft²/day). Perhaps MW-1, located near PW-2, encountered the same source of recharge while pumping to produce a larger observed transmissivity in PW-1. The weathered rock layer may extend near that well. The difference in could also be explained by the difference in elevation as discussed earlier, for MW-1 is at lower elevation than PW-1.

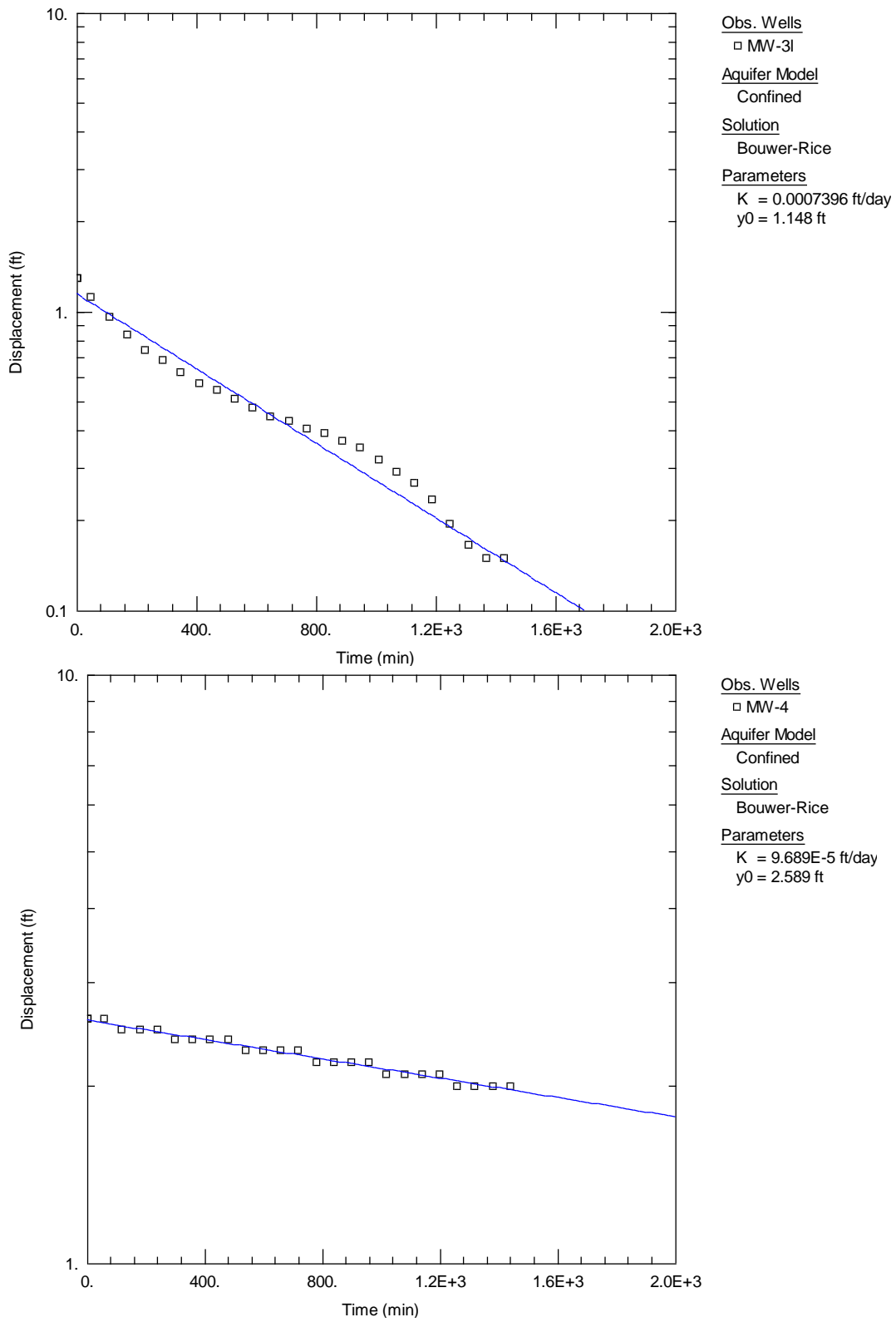


Figure 4-21 Slug test analysis and results in bedrock wells MW-3 and MW-4.

Bedrock Slug Test Results

The slug tests performed in MW-3 and MW-4 can be found in Figure 4-21. During the 24 hour monitoring period, the water level in MW-3 oscillated somewhat, likely due to the affect of the earth tides. The results of all the hydraulic tests completed on the farm can be found in Table 4-7. MW-3 and MW-4 are the least transmissive by 2 to 3 orders of magnitude, respectively. This large difference in transmissivity could be due to the fact that these two wells are less than half of the depth of the other new bedrock wells and therefore would intersect fewer fractures.

Table 4-7: Bedrock Well Transmissivity Results from all Testing

Well	Geometric Average T (ft²/day)
Mw-1 Test	43
MW-2	34
PW-1 Test	42
PW-2 Test	67
PW-3	48
MW-3	0.44
MW-4	0.058
Irrigation Well	7.6
Geometric Average of Farm Wells	8.9

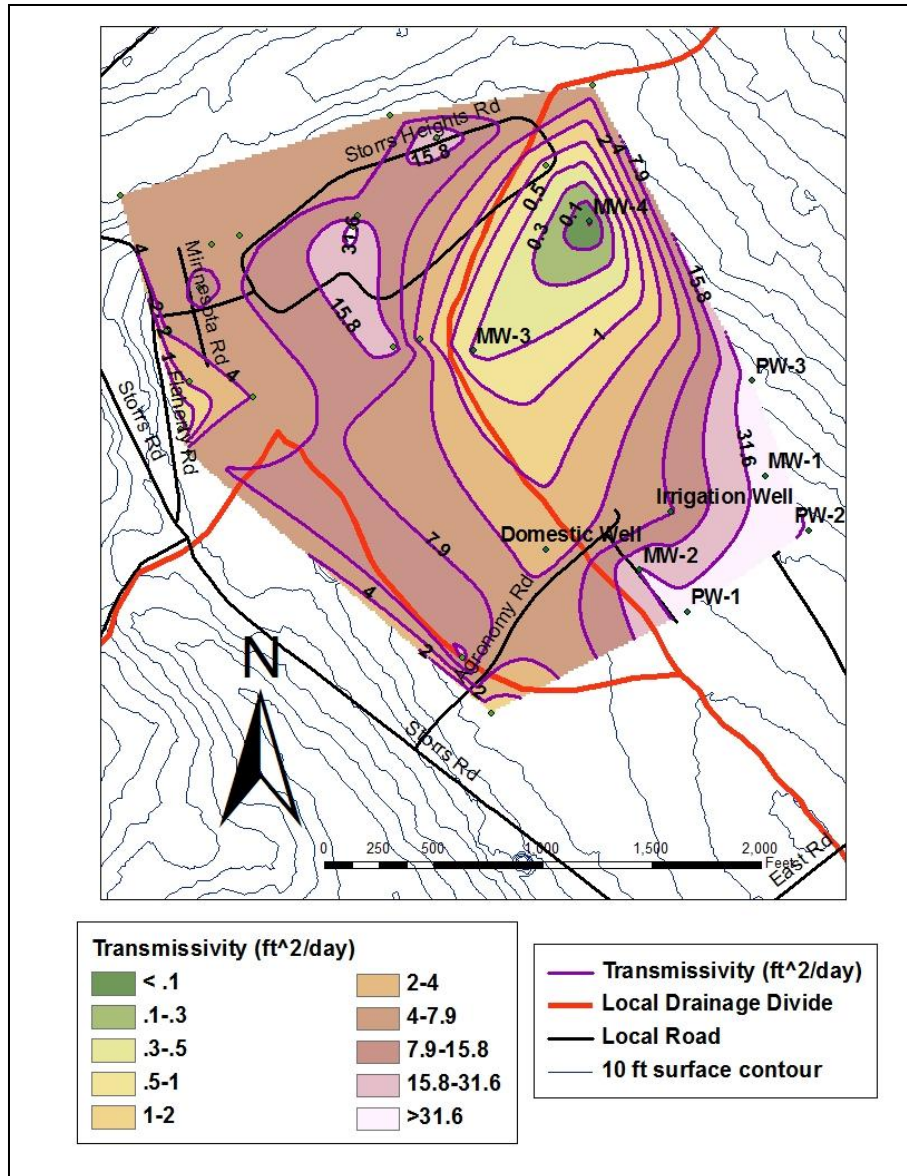


Figure 4-22 Transmissivity of bedrock. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008). Off-site transmissivity data from Robbins et al. (2009).

The distribution of the transmissivity of the bedrock on the farm and surrounding areas can be found in Figure 4-22. Central to the map, and encompassing the majority of the farm nearest to the drainage divide, is a north-south elongated area with lower transmissivity of less than 8 ft²/day. This area is mapped as the green to yellow areas on the map. To the west and east

of this strip are areas of higher transmissivity between 8 to over 30 ft²/day, located in the pinkish area on the map. The new wells on the farm are located in one of these mapped high transmissive strips. Since there is a large area with no wells between the majority of the wells on the farm and bordering wells, MW-3 and MW-4, the transmissive area could extend farther to the north and west. The areas of high transmissivity could be due to the presence of transmissive fracture zones or highly weathered rock parallel to the rock layers that trend north and south.

Caution must be used in the interpretation of this map. The map was developed using wells that are completed at different depths and would therefore intersect different amounts of fractures. The average depths of the wells in the various neighborhoods range from about 240 to 440 feet (Robbins et al. 2009), so some wells have the opportunity to intersect more water bearing fractures than others.

Bedrock Wells Water Levels in Ambient Conditions

The water level in the bedrock wells over the pre-pumping period increased until mid June during the time of spring rains and started receding when rainfall decreased and evapotranspiration increased (see Figure 4-23). The Irrigation Well was pumping daily during this time period. The affects of this pumping can be seen in all the wells except MW-3 and MW-4. In addition, pumping well PW-1 was briefly pumped on 6/24/10, and again, all the wells responded with the exception of MW-3 and MW-4. The lack of response is due to the combination of distance and low transmissivity of the fractures that intersect the well. The bedrock wells did not exhibit any discernable response to individual precipitation events.

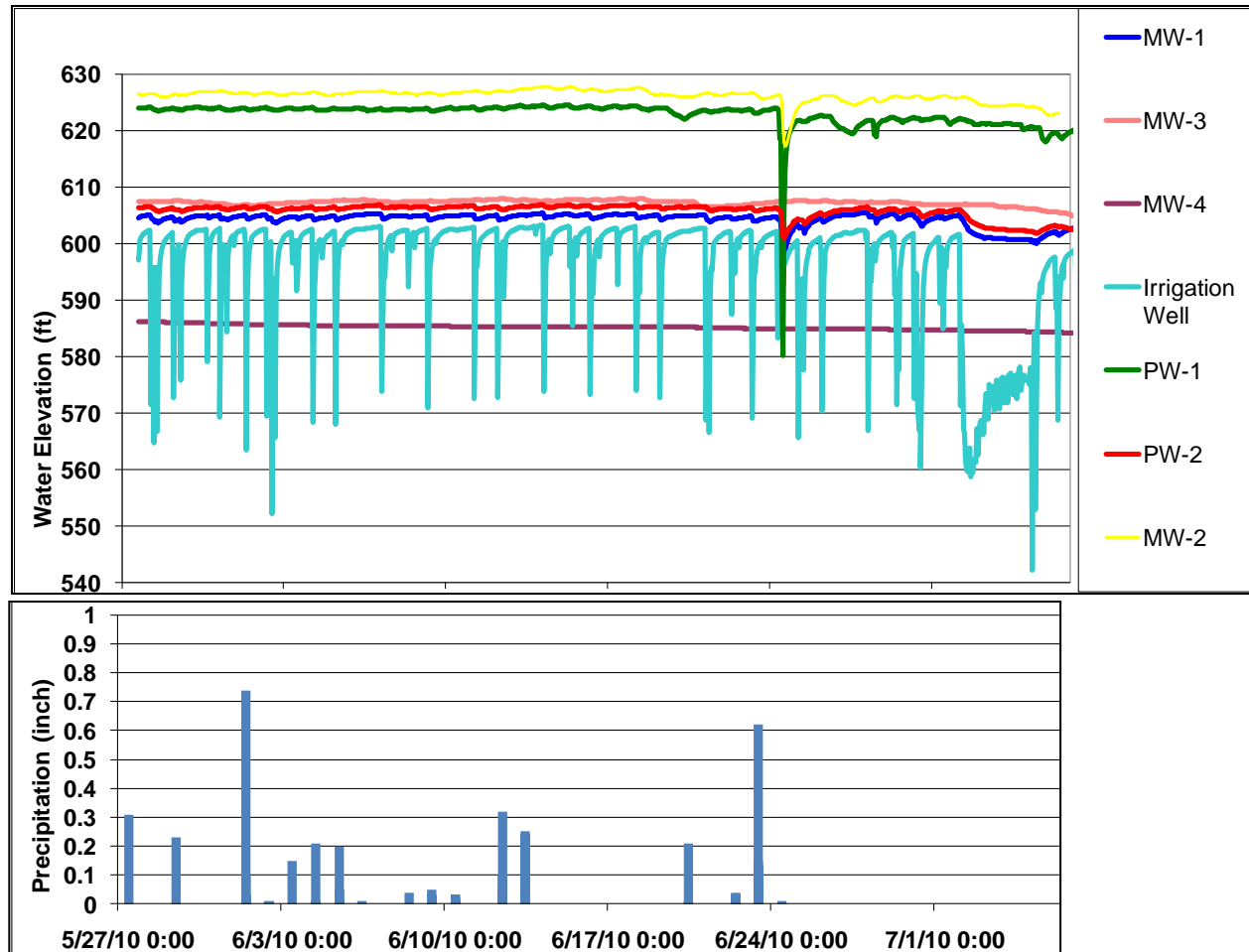


Figure 4-23 Bedrock Water Elevations in Pre-pumping Period with Precipitation Data. Precipitation data obtained from the PLSA Research and Education Facility in Storrs, CT.

The water level in MW-3 was affected by neighboring residential use (see Figure 4-24). The arrows on the map point to weekends when there was a lowering of the water level due to increased water use by homeowners. In addition, there were smaller, daily drawdowns starting in the late afternoon and ending near midnight, a time period when most residents are home. None of the other farm wells were affected by these residential wells.

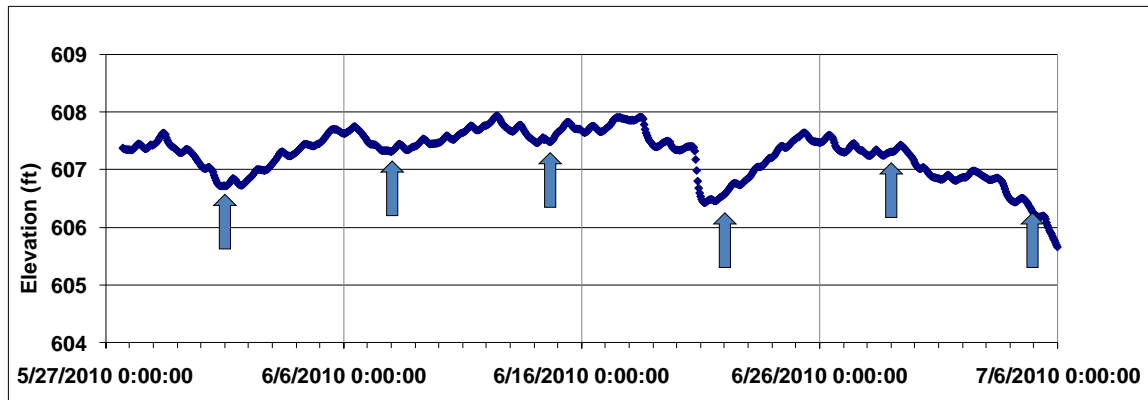


Figure 4-24 Water levels in MW-3 showing the effect of nearby domestic well usage. Blue arrows indicate weekends.

All the bedrock wells, with the exception of MW-4, were affected by earth tides. These twice daily oscillations can be seen in Figure 4-25 that displays the time period in mid June, nearest to the maximum water level in the bedrock wells. The top graph shows the water level in the irrigation well for comparison. During the periods of recovery from pumping in the irrigation well, the other wells shown have oscillations in their water level. These occur at the same time in all the wells. The irrigation well also shows these oscillations when viewed at a larger scale. These tidal influences, along with the low storativity values, show that the water contributing fractures behave like confined aquifers. The lack of earth tidal influences in MW-4 is due to its low transmissivity.

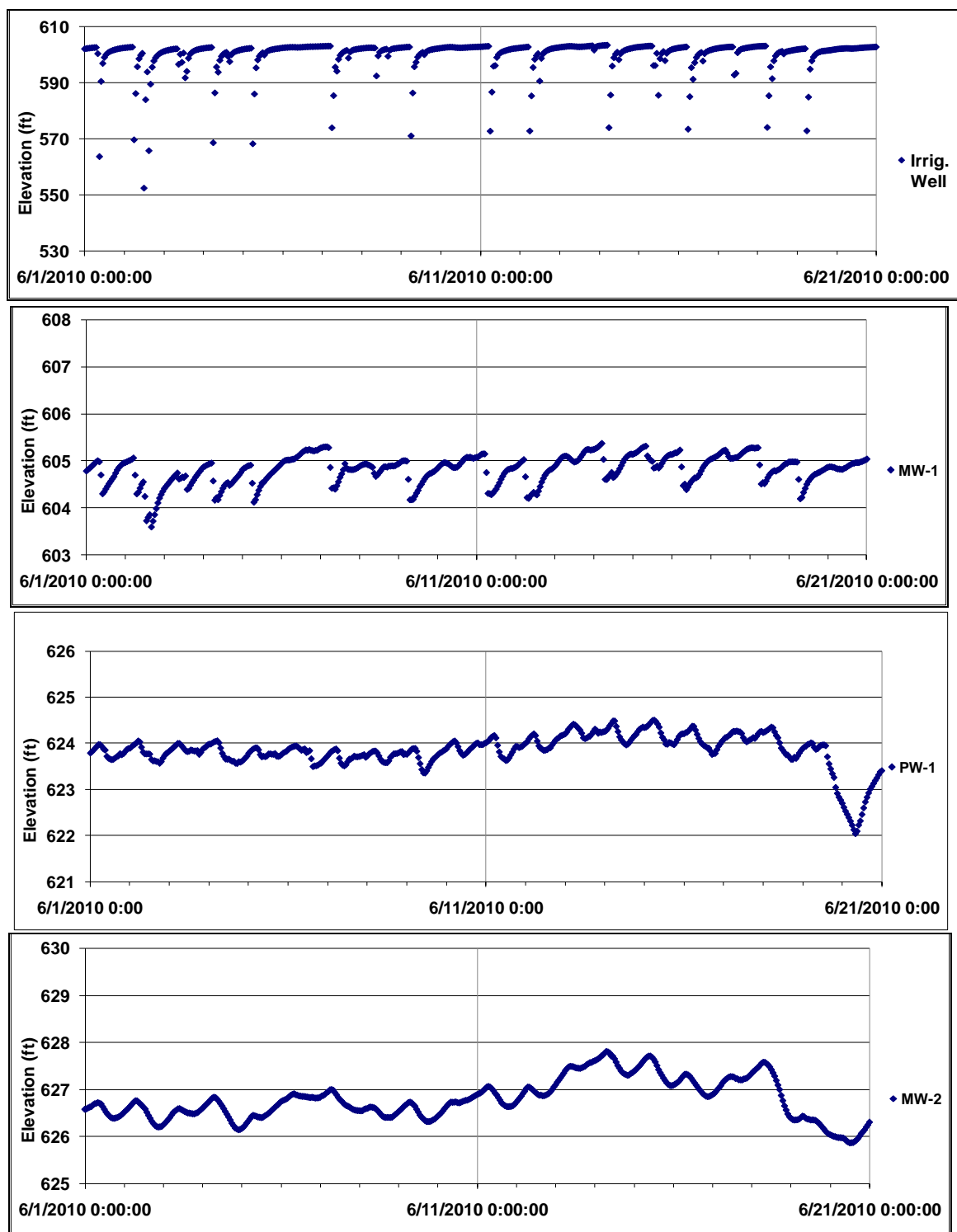


Figure 4-25 Water Elevations in Bedrock Wells Closest to the Irrigation Well in June

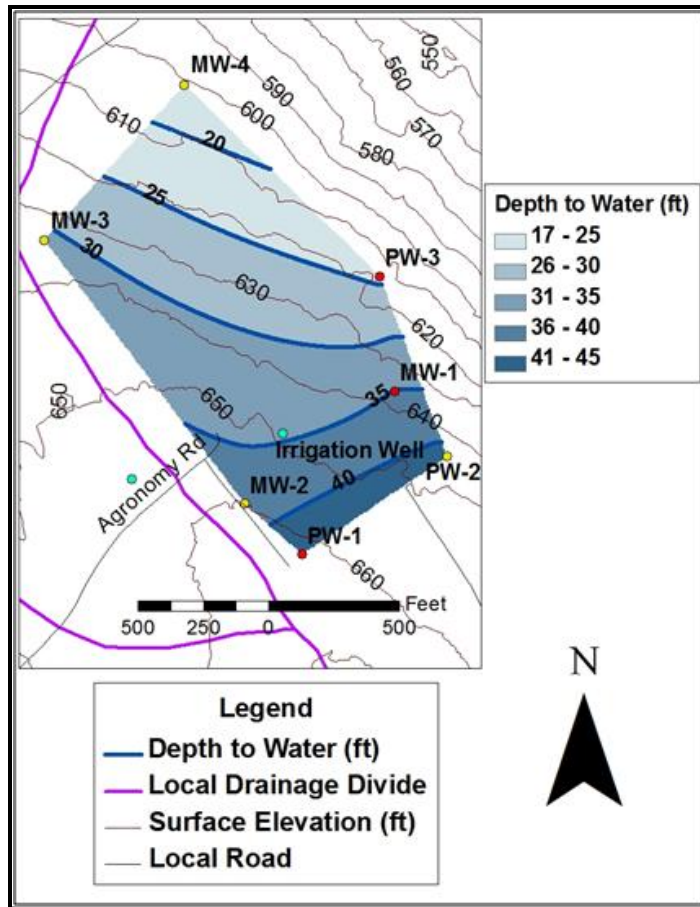


Figure 4-26 Bedrock depth to water under ambient conditions (7/7/10). Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

The depth to water map shown in Figure 4-26 indicates that the depth to water in the bedrock is greater at the top of the hill. The contours on this map are also more or less parallel to the topographic contours.

Horizontal flow in the bedrock

The gradient in the bedrock was similar to the topographic contours in July before pumping began as seen in Figure 4-27a. This would cause the water to flow in the topographic downhill direction.

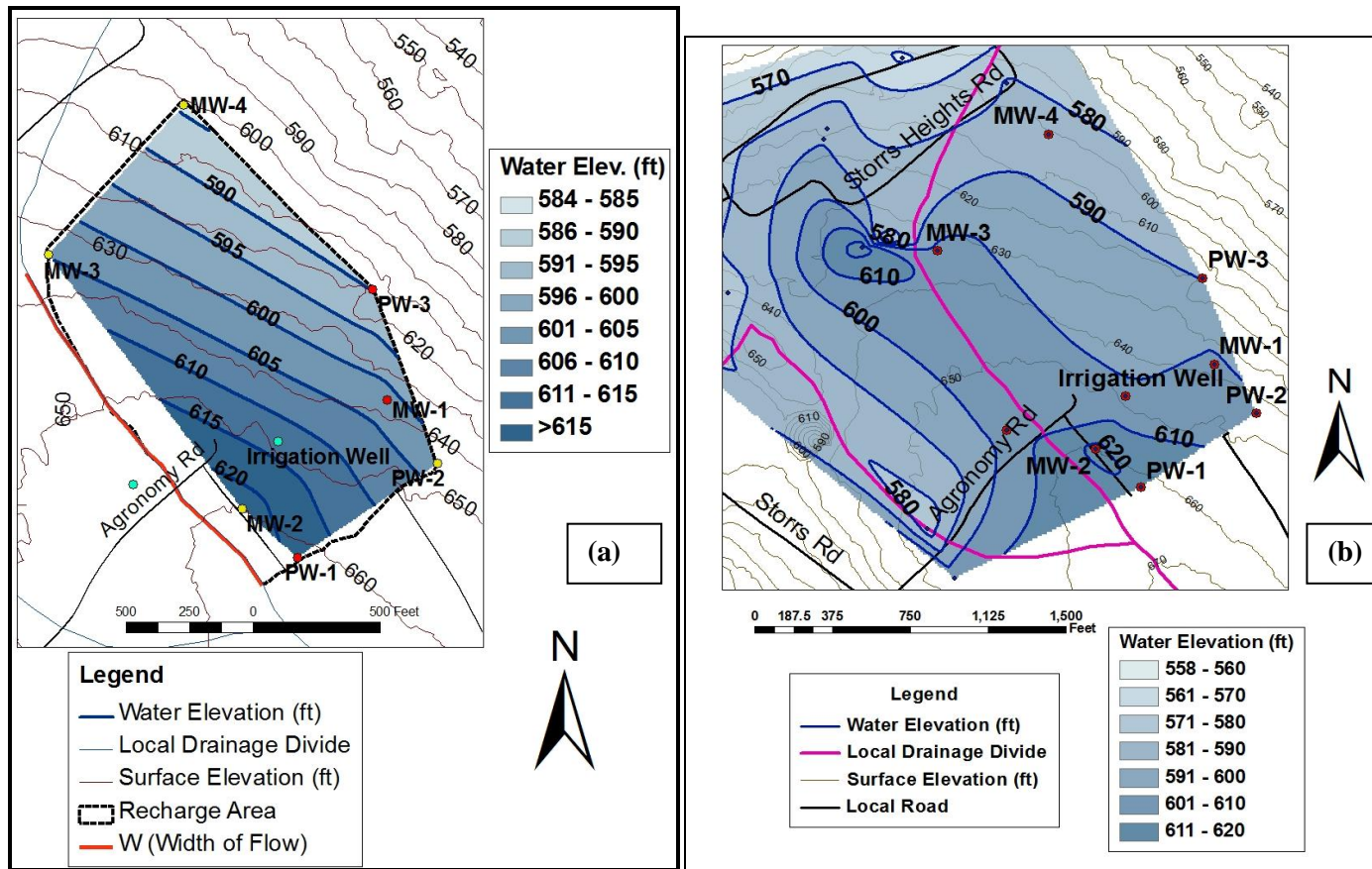


Figure 4-27 Water level in bedrock aquifer in ambient conditions. (a): Map using data from this study (b): Map using data from study and surrounding area (Robbins et al. 2009). For both maps: drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

When the bedrock water levels from the nearby residents were added to water elevation map as shown in Figure 4-27b, the water level and topographic contours were still parallel to each other on the other side of the main surface water divide. The bedrock groundwater would flow in the downhill directions which confirm the fact that the crest of the hill acts as a boundary for groundwater flow in the bedrock in this area.

The amount of horizontal flow and hydraulic gradient in the bedrock was similar to the values found in the overburden as shown in Table 4-8

Bedrock Well Water Levels during Pumping

Figure 4-28 and Figure 4-29 show the depth to water in the wells from the beginning of monitoring through 8/27/10. All of them responded to the new pumping schedule except MW-4. This shows that they are connected to common fractures. MW-4 exhibited a steady decline throughout the period (Figure 4-29), reflecting a seasonal trend. The lack of MW-4 response to pumping is likely due to its distance and the low transmissivity of the rock in the vicinity of the well.

From the time of active pumping to the end of the period, all the water levels in the wells reached a quasi steady state. The effect of the pumping schedule overall on the water level in the wells was relatively small, considering the wells are between 250-600 feet deep and have an average ambient depth to water of 33 feet. The average drawdown from pre to post pumping ranged from 6 to 68 feet as summarized on Table 4-9. These ranges represent the maximum affect of the pumping wells because even without pumping, there would be a decline in the water levels due to the lack of recharge during this relatively dry period. MW-3 was affected the least at 6 feet, while the other wells ranged from 54-68 feet. MW-1 had the largest water level

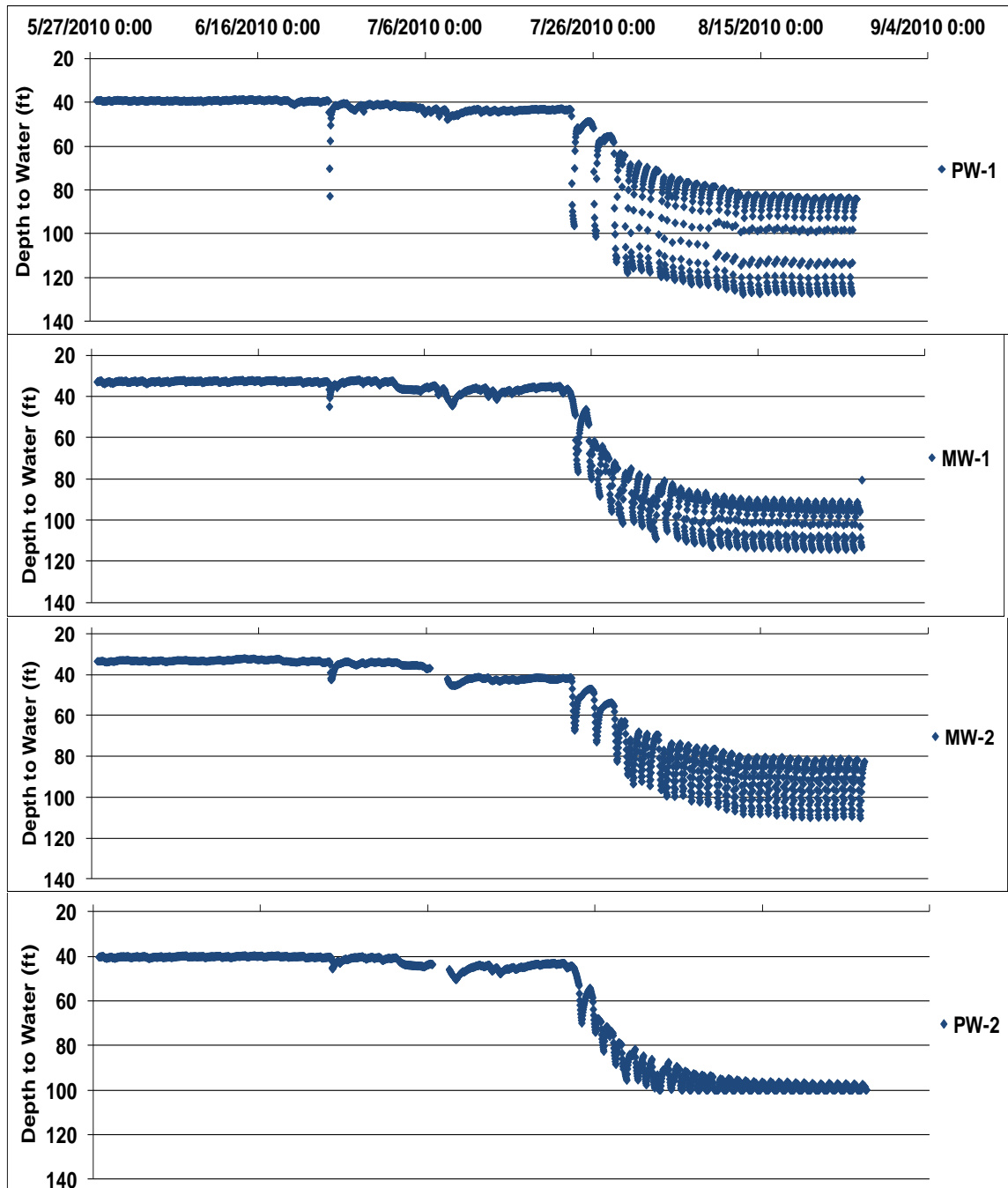


Figure 4-28 Water level in new pumping wells and nearby monitoring wells during entire monitoring period. From the top: pumping wells PW-1 and MW-1 nearby monitoring wells MW-2 and PW-2.

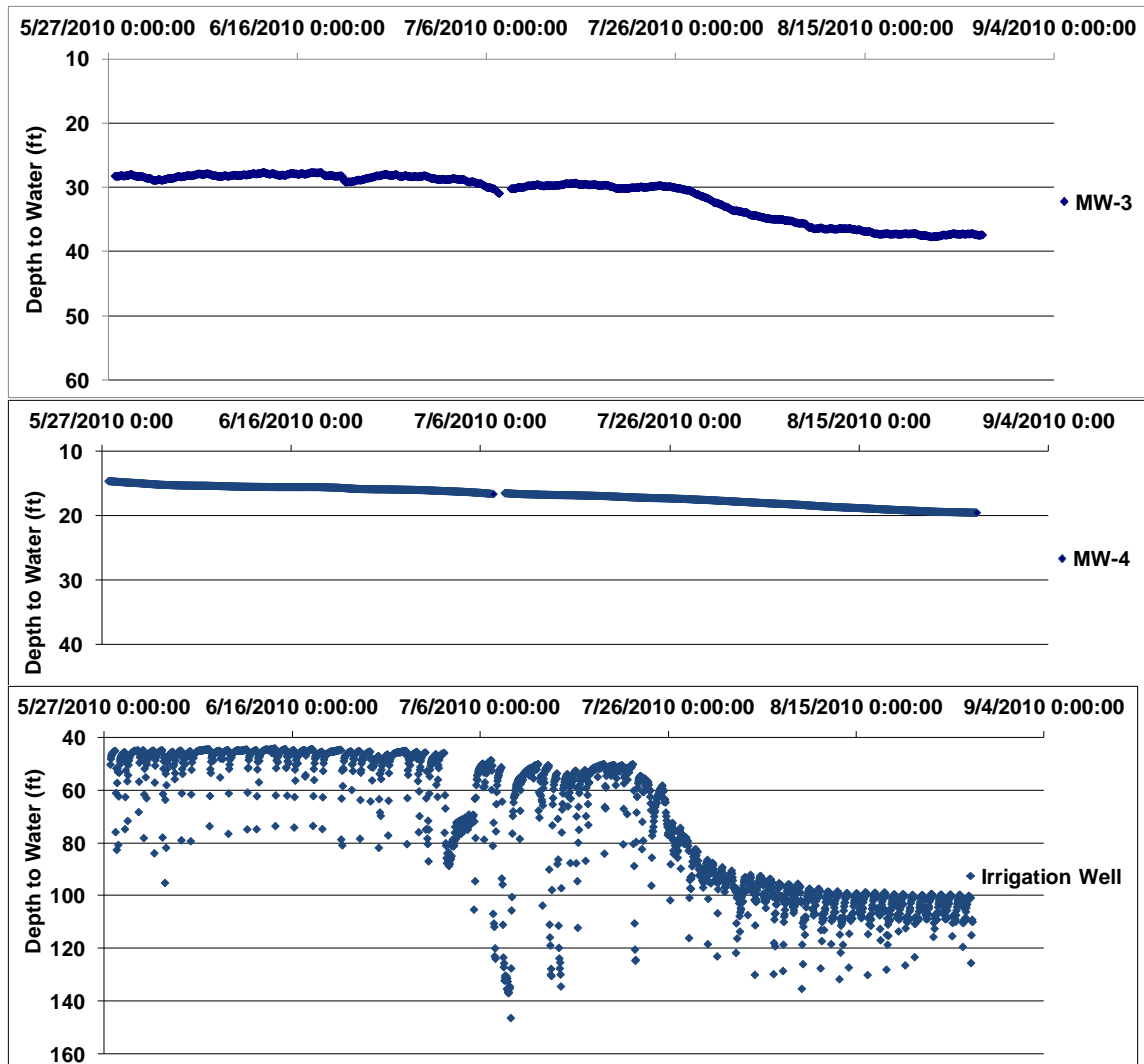


Figure 4-29 Water level in distant bedrock monitoring wells and the Irrigation well during entire monitoring period.

change overall from the beginning of pumping to steady state. This may be due to the central location of the well in the pumping well field where most of the water is being withdrawn.

Table 4-8 Horizontal Flow in Ambient Conditions in Overburden and Bedrock

	Horizontal Hydraulic Gradient (ft/ft)	Horizontal Flow (gal/day)
Overburden	0.0388	2,623
Bedrock	0.0290	3,004

Table 4-9 Bedrock Monitoring Water Level Summary May to August 27

Well	Maximum Water Level Change From May to 7/7/10	Water Level Change at Steady State (ft)	Average Water Level Change Pre- to Post-Pumping (ft)
PW-1	6	43	54
PW-2	4	13*	55
PW-3			N/A
MW-1	3	23	68
MW-2	5	28	59
MW-3	2	0.2	6
MW-4	2	0.5	3
Irrigation well	3	21	64
*Approximated Value			

Horizontal flow to bedrock wells during pumping

Pumping caused changes in the direction of the bedrock groundwater flow. Figure 4-30 shows the water levels found on 8/27/10 at 10:00AM, a time when MW-1 had been pumping for 4 hours and PW-3 finished pumping four hours earlier. The water flows from all directions to the well field near the two wells.

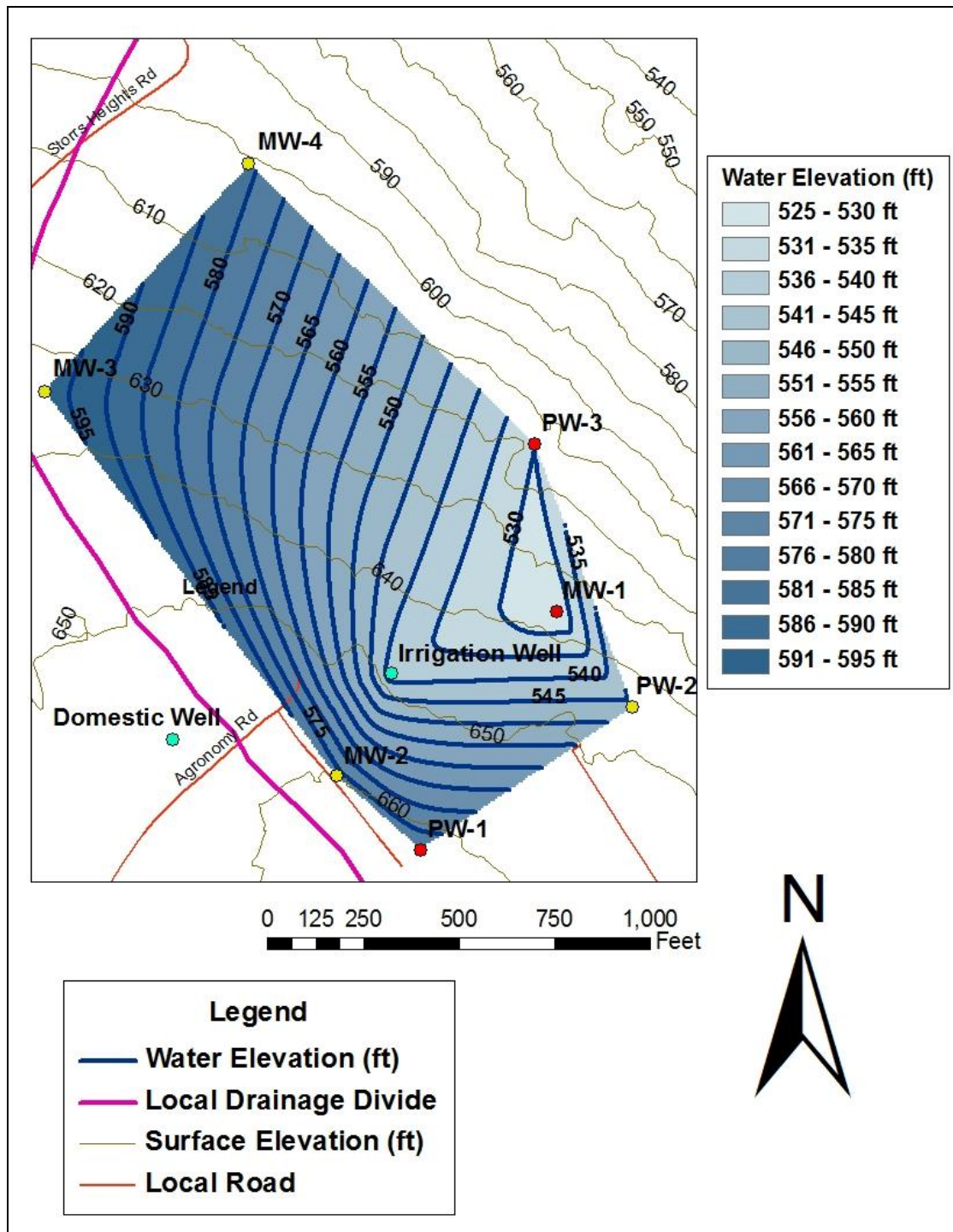


Figure 4-30 Bedrock water elevations in feet during pumping 8/27/10 at 10:00 AM. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

Recharge Analysis

Recharge to Bedrock from Overburden in Ambient Conditions

The recharge from the overburden to the bedrock during ambient conditions comes from an area shown in the dotted line in the water elevation map in Figure 4-27a. The amount of flow was determined by matching the observed recession rate with a calculated one using Equation 3-5 (also shown in Table 4-10) by varying the effective recharge area of the bedrock, a value not determined in the study. This process was completed two times, each using a different value of specific yield. The overburden consisted of a thick clay layer underlying most of the site, so the average specific yield for clay of 2% was used (Fetter 2001). For comparison, the lower end of the range of specific yield of silt at 3% was used (Fetter 2001), seeing that the average hydraulic conductivity of the overburden was within the range of silt, but the thick clay layer underneath would impede drainage. The parameters used to calculate the recession rate and the results of the iterations are presented in Table 4-10. Using a specific yield of 2%, the effective recharge area of the bedrock was iterated to match the recession rate and was estimated to be 143,100 ft², or 9% of the total overburden recharge area of 1,645,000 ft²; a specific yield of 3% produced an effective recharge area of 236,900 ft², or 14% of the total overburden recharge area.

The total amount of flow into the bedrock aquifer from the overburden using the two recharge rates and Equation 3-5 can be found in Table 4-11. These values are compared to the total amount of recharge into the overburden using the average recharge rate for the drainage basin as found in Mazzaferro et al. (1979). The result is 30 percent of the total overburden water flows into the bedrock using a specific yield of 2%. This flow amounts to 9,630 gallons per day over the well field, which is 48% of the total amount pumped at the present pumping rate of about 20,300 gallons per day. Using the larger specific yield, the percent of overburden water

Table 4-10 Calculations and Results for Determining Recharge Rate to Bedrock Aquifer from Overburden

Given Values Used for Calculations				
RR = observed recession rate in overburden	0.05	ft/day		
A = contribution area	1645000	ft ²		
Qh(br) = horizontal flow in the overburden	2.66E+03	gal/day		
w = width of flow	1.56E+03	ft		
K = hydraulic conductivity of overburden	0.150	ft/day		
b = thickness of saturated overburden	39	ft		
dh/dl = horizontal hydraulic gradient	0.039	ft/ft		
dh/dz = vertical hydraulic gradient	0.060	ft/ft		
Results	Specific Yield of 2%		Specific Yield of 3%	
Effective recharge area of bedrock (A _r)	143,100	ft ²	236,900	ft ²
Recharge to Bedrock (Q _{in})	9.63E+03	gal/day	1.59E+04	gal/day

Table 4-11 Recharge Rate to Bedrock Aquifer during Ambient Conditions

Specific Yield Used (percent)	Average Recharge to Overburden by Mazzaferro et al. (1979) (gal/day)	Calculated Recharge from Overburden to Bedrock (Q_v(ob)) (gal/day)	Estimated Percentage of Overburden Recharge that Recharges Bedrock	Percentage of Recharge to Bedrock to the Amount Pumped	Average Pumping Rate in August (Gal/day)
2	3.E+04	9.63E+03	30	48	2.03E+04
3	3.E+04	1.59E+04	49	79	2.03E+04

recharging the rock increases to 15,900 gal/day, which is 79 percent of the total amount pumped. Since this flow was calculated using the vertical hydraulic gradient during ambient conditions, it represents the lowest vertical flow that would occur during pumping. During active pumping the vertical hydraulic gradient would be greater, and more water would flow from the overburden into the rock.

The recharge rates to the bedrock aquifer found are within the range of other studies completed in similar settings. A low recharge rate between 1-3 inches per year was determined by Harte and Winter (1995). On the higher end, Tiedemann et al. (1998) reported a rate of 60% of the overburden water recharging the bedrock, amounting to about 7 inches per year using the 10-13 inch per year recharge rate for this location. In this report, it was about 3 inches per year using

the specific yield of 2% and about 6 inches per year when using the specific yield of 3%. This new method does have reasonable results and may be a good approximation of the amount of recharge to the bedrock. As was stated earlier, the value using the specific yield of 2% is more likely given the large amount of clay on the site.

Vertical Bedrock Groundwater Flow

Table 4-12 shows that during recession conditions, there is a large change of storage in the bedrock aquifer; more flow is shown going out of the aquifer than going into it. Most of this water leaves the site vertically and very little leaves horizontally. The amount leaving vertically is much more than the vertical recharge from the overburden or the amount pumped when the farm irrigates. This water is most likely flowing down fractures that are a part of the regional flow system.

Table 4-12 Flow in and Out of Bedrock Aquifer in Ambient Conditions with Parameters Used

Given Values Used for Calculations				
RR = bedrock recession rate	0.063	ft/day		
Qh(br) = horizontal flow in bedrock	3.00E+03	gal/day		
A' _r = effective area of recharge of the bedrock (2% specific yield)	143,100	ft ²		
A' _r = effective area of recharge of the bedrock (3% specific yield)	236,900	ft ²		
Recharge to Bedrock (Qin) (2% specific yield)	9.63E+03	gal/day		
Recharge to Bedrock (Qin) (3% specific yield)	1.59E+04	gal/day		
Results				
	Specific Yield of 2%		Specific Yield of 3%	
Change of Storage in Bedrock ($\Delta S(\text{br}) = \text{RR} * A'_r$)	6.74E+04	gal/day	1.12E+05	gal/day
Total Flow Out of Bedrock ($Q_{\text{out}}(\text{br}) = Q_{\text{in}} + \Delta S(\text{br})$)	7.71E+04	gal/day	1.28E+05	gal/day
Vertical Flow in Bedrock ($Q_v(\text{br}) = Q_{\text{out}}(\text{br}) - Q_h(\text{br})$)	7.41E+04	gal/day	1.25E+05	gal/day

Bedrock Zone of Contribution Analysis

The potential zones of contributions for each pumping well are shown in Figure 4-31. “Area A”, shown with a green border, is the maximum area affected by pumping based on drawdown observations from 7/7/10 to 8/25/10 with some interpolations. PW-3 shows the largest area affected by pumping compared to the other two wells. This may be due in part to the large amount of interpolated data down gradient of PW-3. In reality, there would be less water drawn from this direction compared to water upgradient. MW-1 has the smallest contributing “Area A”.

As shown in Table 4-13, “Area A” is approximately two or three times larger than the area of contribution when the wells are not pumping (1,645,000 ft²). This additional area increases the potential recharge to the wells. Using the two recharge rates estimated in this report, the total recharge flow to each contributing area can be found in Table 4-13. The approximate amount of recharge from the overburden to “Area A” met or exceeded the amount pumped using a specific yield of clay (2%) except for MW-1, where the recharge rate was only 18,552 gallons per day compared to the approximate value of 20,300 gallons per day rate that is pumped from the aquifer. Since this difference is less than 10 percent of the total amount pumped, “Area A” is a good approximation for the area of contribution. In addition, since the recharge rates were calculated using the ambient vertical hydraulic gradient, the recharge rate calculated would be higher, requiring a smaller contribution area. Using a specific yield of 3%, the amount of recharge is more than enough to sustain pumping in every case.

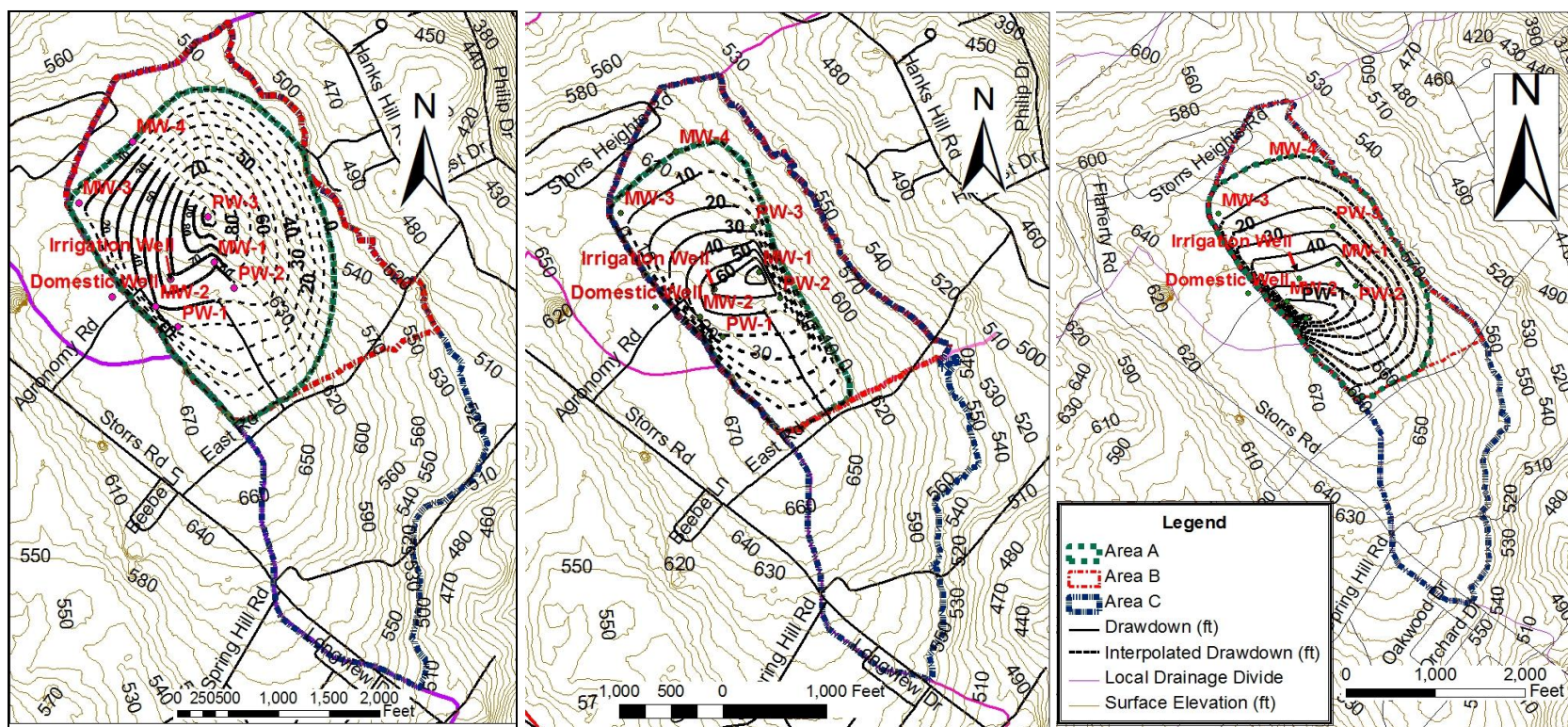


Table 4-13 Recharge to Bedrock Aquifer From Overburden During Pumping

	Area A: Drawdown Contours				
Pumping Well	Area (ft²)	Percent Change from Ambient Conditions	Recharge Using 2% Sy (gal/day)	Recharge Using 3% Sy (gal/day)	Lowest Elevation(ft)
PW-1	4,112,023	250	24,083	39,862	568
MW-1	3,167,636	193	18,552	30,707	576
PW-3	5,402,802	328	31,643	52,375	516
	Area B: Lowest Elevation to Hill				
Pumping Well	Area (ft²)	Percent Change from Ambient Conditions	Minimum Recharge Using 2% Sy (gal/day)	Minimum Recharge Using 3% Sy (gal/day)	Lowest Elevation(ft)
PW-1	4,967,000	302	29,091	48,150	568
MW-1	5,471,473	333	32,046	53,041	556
PW-3	7,421,000	451	43,464	71,940	516
	Area C: Lowest Elevation to Drainage Divides				
Pumping Well	Area (ft²)	Percent Change from Ambient Conditions	Minimum Recharge Using 2% Sy (gal/day)	Minimum Recharge Using 3% Sy (gal/day)	Lowest Elevation(ft)
PW-1	8,028,000	488	47,019	77,824	568
MW-1	8,968,979	545	52,530	86,946	556
PW-3	12,363,000	752	72,408	119,848	516

The recharge area calculated using “Area B”, had the lowest water elevation during pumping and using the boundary of the hill and drainage divide, increased the contribution area by a factor of 3 to 4.5 depending on which well was pumping. This increased the recharge potential to the pumping wells and caused an excess of 8.8 to 23 thousand gallons of potential recharge per day using the specific yield of clay. This area would be likely if the actual recharge to the bedrock was up to approximately 45% less than calculated and the water needed to be drawn from a greater area. Since this area is mostly on the farm’s property, few neighboring wells would be affected by the increased pumping with this more conservative scenario. In addition, since the wells pump only three months in a year, there is plenty of water to supply these wells in either case.

Area C, using the entire area west of the drainage divide and the lowest water elevation during pumping, was about twice the area of “Area B”. This large area would be likely if the actual recharge rate was $\frac{1}{2}$ to $\frac{1}{3}$ of the amount found in this study.

Even though the recharge rate to the bedrock aquifer was sufficient to meet the pumping demand, the actual recharge rate could be much less and the contributing area much larger. A larger contributing area for the pumping areas was attempted by extending the lowest water elevation contour past the local drainage divide using the assumption that it is not a bedrock groundwater divide. The area produced was extremely large, extending miles to the north, and extending east to the eastern area of the drainage basin for the Fenton River and west to the sides of the drainage divide for the Willimantic River. The contribution area could extend to this regional flow region to some extent for the wells farthest from the drainage divide if the subhorizontal fractures in the gneiss had few vertical fractures. A computer simulation in a study by Starn and Stone (2005) found that a well located on the side of a hill intersecting a large subhorizontal fracture received water from areas of regional flow. In this study, PW-3 and MW-1 have a possibility of receiving this flow.

Flow to Bedrock Wells During Pumping

The water elevation during pumping of the three wells is shown in Figure 4-32. The water elevation maps for PW-1 and MW-1 (Figure 4-32) are similar in shape to the drawdown maps produced during pumping tests the year before (Figure 4-16 and Figure 4-17). The contours in both sets of maps are elongated to the northeast. The estimated rate of flow to the pumping wells can be found in Table 4-14 compared to the approximate pumping rate.

All the estimated rates of flow to the wells were within 30% of the actual flow, with all of them over predicting the flow except in PW-3. The most accurate estimate was for the data collected on 8/27/10 at 10:00 AM. This could be due to the fact that a water level measurement was taken in PW-3 at the time, whereas on the other maps it was estimated. Also, there were more data points surrounding the well which resulted in more accurate mapping of the gradients and widths of flow.

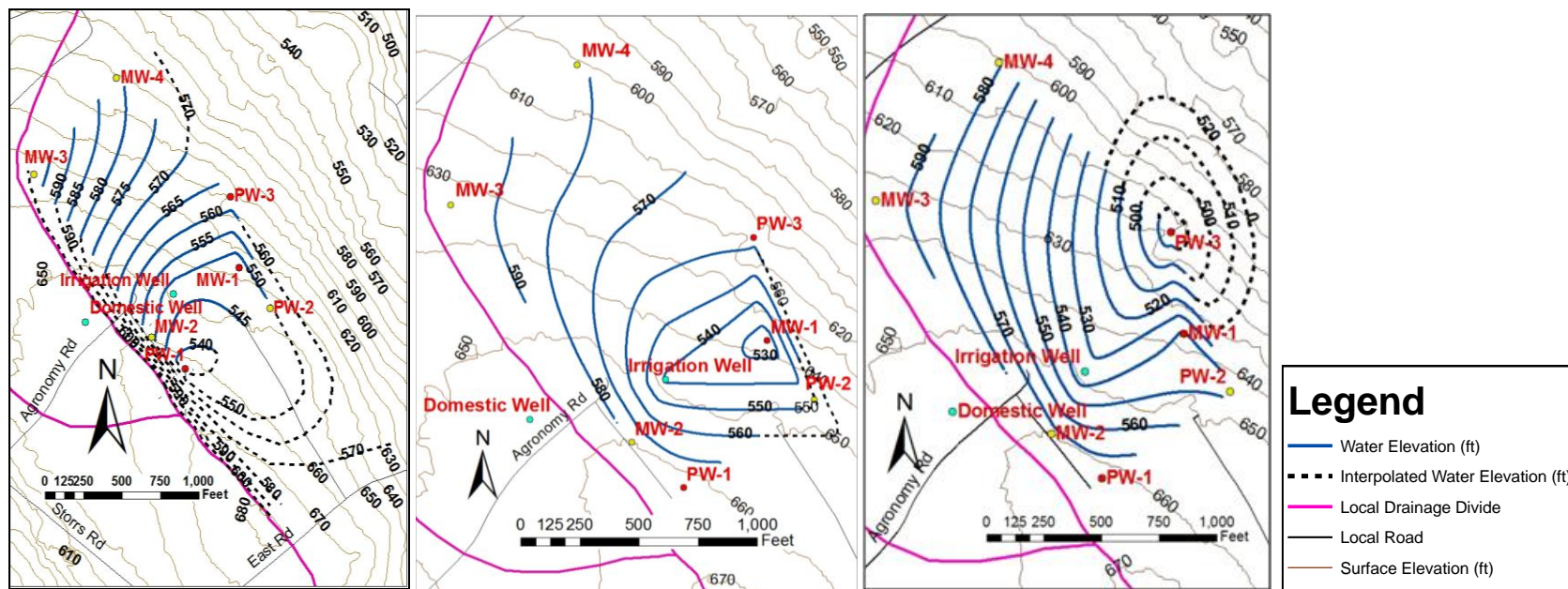


Figure 4-32 Water Elevation in Bedrock Aquifer While Pumping 8/25/10. Drainage basin data from CT DEP (1988), surface elevation data from CT DEP (2000a), and local road data from U.S. Dept. of Commerce (2008).

Table 4-14 Calculated and Actual Amount of Water Pumped from Wells in August, 2010

	Total Estimated Flow to Well (Gal/day)	Approx. Amount Pumped (Gal/day)	Percent Diff.
PW-1	1.55E+04	20250	26
MW-1	2.74E+04	20250	30
PW-3	1.95E+04	20250	4
Pumping on 8/27/10 at 10:00 AM	2.08E+04	20250	3

Table 4-15 shows the transmissivity used to determine the flow from each direction to each pumping well. The flow rate calculated from each direction can be found in Table 4-16. The vast majority of the water comes from the east and south. This orientation is similar to the areas that have the highest transmissivity as shown in Figure 4-22. In general, less than 20% of the flow to the wells comes from the north and the west. This lack of flow is due to the low transmissivities found in MW-3 and MW-4, and the presence of the drainage divide.

With the combination of the flow from each direction and the contribution area “A”, the most likely contribution area, it can be seen that most of the water comes from the farm property and that most of the flow comes from the west and south, the two directions of the least possible influence on neighboring residential wells.

Table 4-15 Parameters Used to Calculate Flow to Wells during Pumping

	Direction From	Contour Interval used for Hydraulic Gradient (ft)	Length of Gradient line (ft)	Hydraulic Gradient (ft/ft)	Width of flow (ft)	Transmissivity (ft²/day)	Wells Used for Transmissivity Value
PW-1	East	10	114	0.05	962	19.2	MW-1, PW-2, and PW-3
	North	10	271	0.03	843	3.3	Irrig. Well, MW-1, MW-3, MW-4 and PW-3,
	South	10	271	0.03	479	3.3	Irrig. Well, MW-1, MW-3, MW-4, and PW-3
	West	64	180	0.36	705	4.3	Domestic Well, MW-3 and MW-2,
MW-1	East	37	121	0.31	612	8.8	Entire well field
	North	10	150	0.07	422	1.1	MW-3, MW-4, and PW-3
	South	10	110	0.09	647	29.1	PW-2, MW-2, PW-1, and
	West	10	69	0.14	385	4.8	MW2, and MW3
PW-3	East	10	89	0.11	628	8.8	Entire well field
	North	10	174	0.06	428	8.8	Entire well field
	South	10	76	0.13	401	31.5	Irrigation Well, MW-1, MW-2, PW-1 and PW-
	West	10	91	0.11	528	1.8	MW3
8/27/10 at 10:00 AM	East	10	66	0.15	944	8.8	Entire well field
	North	10	185	0.05	584	1.1	MW-3, MW-4, and PW-3
	South	10	116	0.09	554	29.1	PW-2, MW-2, PW-1, and
	West	10	185	0.05	437	4.8	MW2, and MW3

Table 4-16 Flow to Bedrock Wells While Pumping

	NORTH		SOUTH		EAST		WEST	
	Flow (Gal/day)	Percent of Total Daily Flow	Flow (Gal/day)	Percent of Total Daily Flow	Flow (Gal/day)	Percent of Total Daily Flow	Flow (Gal/day)	Percent of Total Daily Flow
PW-1	6.88E+02	4	3.91E+02	3	6.39E+03	41	8.04E+03	52
MW-1	2.25E+02	1	1.28E+04	47	1.23E+04	45	2.02E+03	7
PW-3	1.62E+03	8	1.24E+04	64	4.64E+03	24	7.95E+02	4
Pumping on 8/27/10 at 10:00 AM	2.52E+02	1	1.04E+04	50	9.34E+03	45	8.57E+02	4
Average	6.96E+02	4	9.00E+03	41	8.17E+03	39	2.93E+03	17

5 CONCLUSIONS

Characterization of the Overburden Hydrogeology

- The overburden is made of till of average thickness of 42 feet and is comprised of a heterogeneous mixture of silt ranging from 7 to 42 feet thick, clay ranging from 0-66 feet thick, and sand and gravel layers 38 feet thick in one area of the farm.
- The hydraulic conductivity of the overburden is low at an average of 5.36×10^{-5} cm/sec, which is in the range of silt.
- There is an underlying clay layer over most of the farm; where it is present, it ranges from 7 to 66 feet thick.
- The recharge rate to the rock from the overburden is partially constrained by the clay layer and occurs slowly at a rate of 3 to 6 inches per year.
- Under non-pumping conditions, 30 to 50 percent of the overburden water recharges the rock.

Characterization of the Bedrock Hydrogeology

- Water contributing fractures were found around 300 and 500 feet elevations.
- The effective area of recharge of the bedrock was estimated to be between 9 and 14 % of the total recharge area of the overburden.

- The average transmissivity of the bedrock is 8.9 ft²/day and has a range of 0.058 to 67 ft²/day.
- Zones of higher transmissivity are found, generally to the northeast-southwest direction near the new wells.
- During times of pumping for irrigation, most of the water comes from the south and east of the well field where the bedrock has high transmissivity.
- The likely zone of contribution to the bedrock wells found by the limit of the drawdown observed while pumping is two to three times larger than when the wells are not pumping.
- The recharge from the overburden to the contributing area is enough to supply water to the pumping wells.
- Since pumping only takes place four months out of the year, there is more than enough water to sustain pumping at the present rate.

Estimated Recharge to the Bedrock

- Using a specific yield of 2%, the effective area of recharge of the bedrock was 9% of the total overburden recharge area by matching the recession rate observed.
- Using a specific yield of 3%, a higher effective area of 14% of the total overburden recharge area was estimated.
- The recharge rates corresponding to the specific yields of 2 and 3% are between 3 to 6 inches per year. These values are within the range of other studies conducted in New England that have estimated the recharge rate to crystalline bedrock.

Zone of Contribution.

- Estimated flow amounts to pumping wells based on water elevations during pumping and calculated hydrogeologic parameters were within 30% of the actual amount pumped.

- The potential recharge from the overburden to the area of contribution using the observed drawdown matched within 10% of the rate that water is being taken from the aquifer.
- The fact that the groundwater levels in response to pumping reached steady state confirmed that the contribution area determined was reasonable.

Ideas for future study

- Complete a pumping test in PW-3.
- Monitor pumping well PW-3 to obtain a better area of contribution and flow map.
- Drill another shallow well near PW-3 to determine possible connectivity between the bedrock well and the overburden.
- Re-drilling Monitoring well PW-2 to obtain more complete data.
- Monitoring the Domestic Well to determine if pumping affects other side of drainage divide.
- Increase the depth of MW-4 to possibly better connect with the fractures that intersect the pumping wells.
- Continually monitor the shallow wells SW-3 and SW-4 to better characterize the overburden and to see any connection with the bedrock wells, especially in SW-4.
- Increase the depth of the overburden wells to the bedrock in order to better characterize the overburden.
- Drill another monitoring well to the east of PW-3 in order to further characterize the aquifer.
- Measure the specific yield of the overburden by conducting pumping tests.

6 REFERENCES

- Berkowitz, Brian 2002. Characterizing Flow and Transport in Fractured Geological Media: A Review. *Advances in Water Resources*, Vol. 25, Issues 8-12, August through December, pp 861-884
Elsevier. Online version available at:
<http://www.sciencedirect.com/science/article/pii/S0309170802000428>
- Bower, H., & Rice, R.C.. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. *Water Resources Research* 12: 423-28
- Connecticut Department of Environmental Protection. 1988. Datalayer Connecticut Local Drainage Basins Line
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1985a. Datalayer Connecticut Bedrock Geology Line (based on original map compiled by J Rodgers)
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1985b. Datalayer Connecticut Bedrock Geology Polygon (based on original map compiled by J Rodgers)
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1994a, 2008 ed. Connecticut Town Name, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>
- Connecticut Department of Environmental Protection. 1994b. Datalayer Town Line.
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1994c. Datalayer Town Polygon
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1995a. Datalayer Connecticut Surficial Material Line (Based on Original Map Authored by J. Stone, J. Schafer, E. London, and W. Thompson)
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- Connecticut Department of Environmental Protection. 1995b. Datalayer Connecticut Surficial Material Polygon (Based on Original Map Authored by J. Stone, J. Schafer, E. London, and W. Thompson)
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707

Connecticut Department of Environmental Protection. 1999a, 2005 ed. Connecticut Named Waterbody Polygon, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>

Connecticut Department of Environmental Protection. 1999b, Connecticut Named Waterbody Line, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>

Connecticut Department of Environmental Protection. 1999c, Datalayer Connecticut Named Waterbody Line
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707

Connecticut Department of Environmental Protection. 2000 a. Datalayer Connecticut 10 FT Contours (lidar)
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707

Connecticut Department of Environmental Protection. 2000 b. Datalayer Connecticut 2 FT Contours .
http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707

Connecticut Department of Environmental Protection. 2006a. Connecticut Geographic Names, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>

Connecticut Department of Environmental Protection. 2006b. Connecticut Geographic Places, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>

Department of Environmental Protection. 2009 a. Connecticut aquifers.
http://www.ct.gov/dep/cwp/view.asp?a=2685&q=322258&depNav_GID=1654#Bedrock
(accessed March 3, 2011)

Connecticut Department of Health. Drinking Water Assessment and Source Protection Program. 2009 b.
http://www.ct.gov/dph/lib/dph/drinking_water/pdf/SWAPWEB_05_12.pdf (accessed Dec. 9, 2009)

Connecticut Department of Environmental Protection. 2009c. Connecticut 100 Foot Contours, ARCGIS Map Service maps_Base_Map
<http://www.ctecoapp2.uconn.edu/ArcGIS/services>

Doe, Thomas, and Pedler, William H. 1998. The Problem of Fractures. *Groundwater Monitoring and Remediation*, Winter 1998 p. 74-77

- Ellis, E.E. 1909. A Study of the Occurrence of Water in Crystalline Rocks, in Gregory, H.E. Underground Water Resources of Connecticut, U.S. Geol. Survey Water Supply Paper 232
- Fetter, C.W. 2001. Applied Hydrogeology, 4th edition. New Jersey: Prentice-Hall, Inc
- Geoprobe®. 2011. Geoprobe® Pneumatic Slug Test Kit (GW 1600) Installation and Operation Instructions: Instructional Bulletin No. MW3181 Salina, Kansas
http://geoprobe.com/sites/default/files/pdfs/mk3181_pneumatic_slug_test_kit_instructions_for_gw1600.pdf
- Harte, P.T. and Winter, T.C. 1995. Simulations of Flow in Crystalline Rock and Recharge from Overlying Glacial Deposits in a Hypothetical New England Setting. *Ground Water* Vol 33, No 6: pp 953–964
- Huntley, D., Nommensen, N., and Steffey, D. 1992. The Use of Specific Capacity to Assess Transmissivity in Fractured Rock Aquifers. *Ground Water* Vol 30, No 3, pp 396-402
- Hvorslev, M.J., 1951. Time Lag and Soil Permeability in Ground-Water Observations, Bull. No. 36, Waterways Exper. Sta. Corps of Engrs, U.S. Army, Vicksburg, Mississippi, pp. 1-50.
- Lyford, F. P., C. S. Carlson, C. J. Brown, and J. J. Starn. (2007). Hydrogeologic Setting and Ground-Water Flow Simulation of The Pomperaug River Basin Regional Study Area, Connecticut, in Hydrogeologic Settings And Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001, edited by S. S. Paschke, U.S. Geol. Surv. Prof. Pap., 1737-A, pp. 6-1– 6-26. (Available at <http://pubs.usgs.gov/pp/2007/1737a/Section6.pdf>)
- Mazzaferro, D.L., Handman, E.H., and Thomas, M.P. 1979. Water Resources Inventory of Connecticut, Part 8, Quinnipiac River Basin: Connecticut. *Water Resources Bulletin*, 27, 88p
- Mullaney, John R, 2004. Water Use, Ground-Water Recharge and Availability, and Quality of Water in the Greenwich Area, Fairfield County, Connecticut and Westchester County, New York, 2000-2001. U.S. Dept of the Interior, USGS WRI report 03-4300 East Hartford
- Nelson, Ronald A. (2001). Geologic Analysis of Naturally Fractured Reservoirs (2nd Edition). Elsevier.
 Online version available at:
http://www.knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1544&
- Olsen, Stephen. 2011. Oral Communication, 10/4/10, Mansfield, CT.

- Parent, J. 2011. Plant Science Farm Boundary: deer_fence Shapefile. Mansfield, CT: University of Connecticut, Department of Natural Resources and the Environment
- Pease, M.H., 1988. Bedrock Geologic Map of the Spring Hill Quadrangle, Connecticut. United States Geological Survey, Geologic Quadrangle Map GQ-1650, scale 1:24000.
- Robbins, G. 2006. Options for Consideration for Meeting Ag Farm Water Needs, letter report to Mary Musgrave, Dept. Head, Plant Sciences, September 20, 2006.
- Robbins, Gary A, Aragon-Jose, Alejandra T, and Metcalf, Meredith J. 2009. Agricultural Farm Ground Water Study. Mansfield, CT: University of Connecticut
- Robbins, Gary A. 2010. Pneumatic Slug Test Short Course. Virtual Groundwater Academy Online Course. Ram's Horn Educational LLC <http://www.vgwacademy.com> 10/17/10
- Singal, B.B., and Gupta, R.P. 2010. Applied Hydrogeology of Fractured Rocks, 2nd edition. New York: Springer Science and Business Media B.N
- Starn, J.J., and Stone, J.R. 2005. Simulation Of Ground-Water Flow to Assess Geohydrologic Factors And Their Effect On Source-Water Areas For Bedrock Wells in Connecticut: U.S. Geological Survey Scientific Investigations Report 2004-5132, 78p.
- Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16, pp. 519-524.
- Tiedeman C R, Goode D J, Hsieh, P A . 1998. Characterizing a Ground Water Basin in a New England Mountain and Valley Terrain. *Ground Water* 36:611-620
- US Department of Agriculture. 2007. Soil Survey Geographic (SSURGO) database for the State of Connecticut-Map Unit Boundary Polygons: File Geodatabase Feature Class http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898&depNav_GID=1707
- U.S. Department of Commerce, U.S. Census Bureau, Geography Division. 2008a. Connecticut Roads, TIGER/Line Shapefile, ARCGIS Image Service <http://www.ctecoapp2.uconn.edu/ArcGIS/services>
- U.S. Department of Commerce, U.S. Census Bureau, Geography Division. 2008b. Datalayer Connecticut Roads, TIGER/Line Shapefile http://magic.lib.uconn.edu/connecticut_data.html#roads
- USDA-FSA-APFO Aerial Photography Field Office. 2010. Connecticut 2010 4 NAIP 4 Band Color, ARCGIS Image Service <http://www.ctecoapp2.uconn.edu/ArcGIS/services>

USDA-FSA-APFO Aerial Photography Field Office. 2009. Connecticut 2008 4 NAIP 4 Band Color, ARCGIS Image Service <http://www.ctecoapp2.uconn.edu/ArcGIS/services>

United States Geological Survey. 2004. Bedrock Regional Aquifer Systematics Study: Groundwater and Fractured Rock Aquifers
<http://geology.er.usgs.gov/eespteam/brass/fracturedrock.htm> (accessed March 3, 2011)

University of Connecticut College of Agriculture. 2011.
<http://www.cag.uconn.edu/plsc/plsc/facilities.html> (accessed March 4, 2011)

University of Connecticut College of Agriculture and Natural Resources, Center for Land Use Education and Research (CLEAR) 2000. 2000 Lidar Point Cloud Data
<http://clear.uconn.edu/data/index.htm>