AQUIFER PERFORMANCE TEST REPORT

St. Marys Miocene Aquifer, Camden County, Georgia

September 30-October 6, 1997

By

Bill Sharp, Sam Watson, and Rex Hodges

This report has not been reviewed for conformity with Georgia Geologic Survey editorial standards, stratigraphic nomenclature, and standards of professional practice.

DEPARTMENT OF NATURAL RESOURCES
Lonice C. Barrett, Commissioner
ENVIRONMENTAL PROTECTION DIVISION
Harold F. Reheis, Director
GEORGIA GEOLOGIC SURVEY
William H. McLemore, State Geologist

Atlanta
1998

Project Report No. 34

ABSTRACT

As part of the Geologic Survey Branch of the Georgia Environmental Protection Division's "Evaluation of the Miocene Aquifers in the Coastal Area of Georgia Project", the Department of Geological Sciences at Clemson University conducted a pump test at the Georgia Geologic Survey's St. Marys well cluster, located in the city park in the town of St. Marys, Camden County, Georgia. A test of an unnamed Miocene aquifer (aquifer X) at St. Marys, was conducted from September 30 through October 6, 1997 using St. Marys 3 as the pumping well, along with St. Marys 1 and St. Marys 2 as monitoring wells. The observation well, St. Marys 1, is located 78.75 feet away from the pumping well St. Marys 3 and is unscreened with an unknown open interval. Due to the pumping response in monitor well St. Marys 1, it is assumed that the open interval includes the same hydrogeologic interval as the pumping well (aquifer X). Transmissivity calculations were made using multiple flow rates with flow rate steps of 71.00 gpm (0-24,500 seconds) and 71.40 gpm (24,500-259,200 seconds), and a well radius of 2 inches. A storativity of 0.0001 was estimated and the pumping well was assumed to be fully screened over the entire thickness of the aquifer. A transmissivity of 538 ft^2/day (50 m^2/day) with a skin factor of 3.44 was calculated for aquifer X. Data from the observation wells was not used in the calculations because St. Marys 1 was unscreened with an unknown open interval and St. Marys 2 was not screened in the same aquifer as the pumping well. The 30 ft (9.14 m) effective aquifer thickness of Miocene aquifer X at the St. Marys test site yields a hydraulic conductivitiy of 17.95 ft/day (5.47 m/day) and a

permeability of 6.59 darcys. Observation well St. Marys 2, located approximately 95 ft away from the pump well and screened in the Miocene Upper Brunswick aquifer was monitored to detect vertical leakage across the confining unit separating the Upper Brunswick aquifer from the overlying aquifer X (pumping well). No water-level changes directly related to pumping were observed in St. Marys 2, indicating no pumping related leakage across the confining unit separating aquifer X from the Upper Brunswick aquifer. Although the test site is located in a coastal area, the well cluster is located far enough away from the St. Marys River that water level fluctuations in the river (due to ocean tidal effects) had no influence on the water levels in the test wells.

ACKNOWLEDGMENTS

Funding for this project was provide through Geologic Survey Branch of the Georgia Environmental Protection Division. Georgia Geologic Survey (William Steele and Earl Shapiro) oversaw well installation and coordinated logistical arrangements with Clemson University Geological Sciences Department Personnel to conduct the St. Marys Miocene aquifer performance test. The city of St. Marys assisted with security of the site and the Park Service provided use of their pier for gathering tidal data.

TABLE OF CONTENTS

Table of Contents (Continued)

LIST OF TABLES

Tables

LIST OF FIGURES

Figure

INTRODUCTION

Purpose of the St. Marys Miocene Aquifer Performance Test

Due to the hydrologic stress imposed on the Eocene to Oligocene age Upper Floridan aquifer, the principal water source of coastal Georgia, the Geologic Survey Branch of the Georgia Environmental Protection Division is investigating the Miocene aquifers as an additional source of ground water for the region. The test at St. Marys is the second of seven Miocene aquifer tests (Tybee Island being the first) to be conducted at selected sites in southeast Georgia. Four of the seven test sites will be located in coastal counties, and three of the sites will be located inland where agricultural ground-water use is prevalent. The purpose of the St. Marys pump test is to estimate the transmissivity and storativity of the Miocene aquifer at the test site. Eventually the hydrologic properties from each of the seven sites will be analyzed to determine if the Miocene aquifers are viable alternatives to the Upper Floridan aquifer for smaller-demand needs such as community water supply, golf courses, agricultural (lower demand or supplemental), small industries, and non-contact cooling water.

Site Conditions

Location

The coastal town of St. Marys is located in the southeast corner of Georgia, on the St. Marys River, approximately 20 miles north of Jacksonville, Florida. Figure 1 is a map of Georgia showing the location of the the St. Marys test site, the Tybee Island test site,

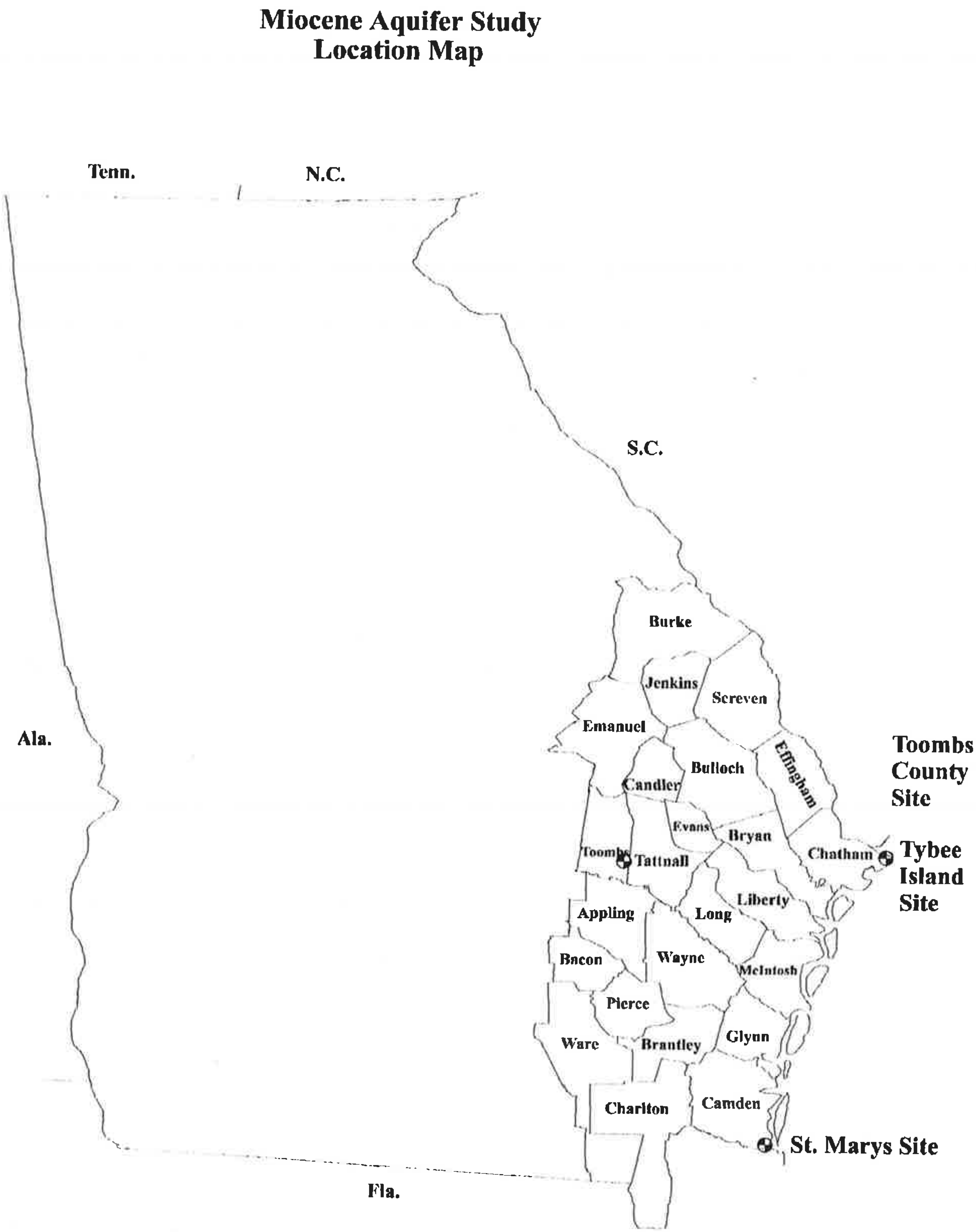

Figure 1. Map of Georgia showing the location of the St. Marys test site.

and the Toombs County test site. The well cluster is located in the city park on Gallop St., approximately 100 feet south of the railroad tracks in the town of St, Mary's, Camden County, Georgia, as illustrated in figure 2. Figure 3 is a map of the St. Marys test site showing the relative locations of the pump well and the observation wells.

Hydrogeologic Setting

The Coastal Plain sediments in the study area consist of unconsolidated to semiconsolidated layers of sand and clay and semi-consolidated to very dense layers of limestone and dolomite (Clarke, et al., 1990). Strata underlying the site dips and thickens to the southeast. The St. Mary well cluster is drilled into Coastal Plain sediments ranging in age from Eocene to post-Miocene. The hydrostratigraphy of the site consists principally of five aquifers. From deepest to shallowest, these are the Eocene Lower Floridan, the Eocene Upper Floridan, the Miocene Lower Brunswick, the Miocene Upper Brunswick and the Miocene to post-Miocene surficial aquifer (Clarke, et al., 1990). The major hydrogeologic units, geophysical well logs, and screen depth intervals of wells are shown in figure 4.

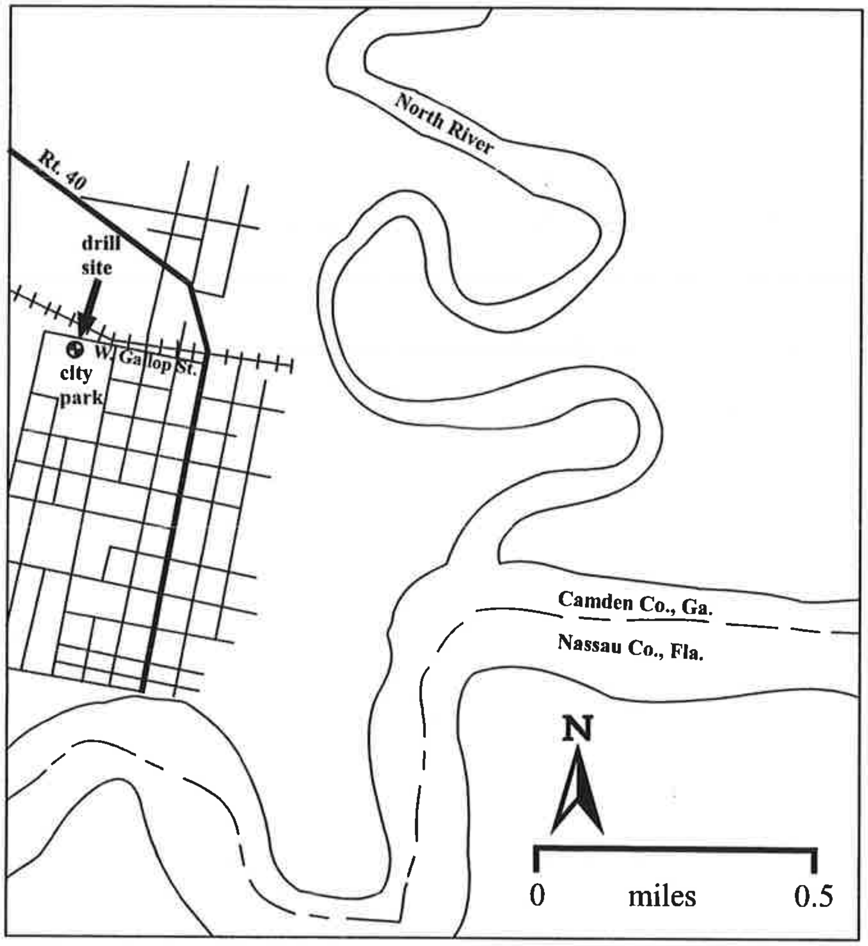

Figure 2. Map of St. Marys showing location of test site, from 7.5 minute St. Marys quadrangle.

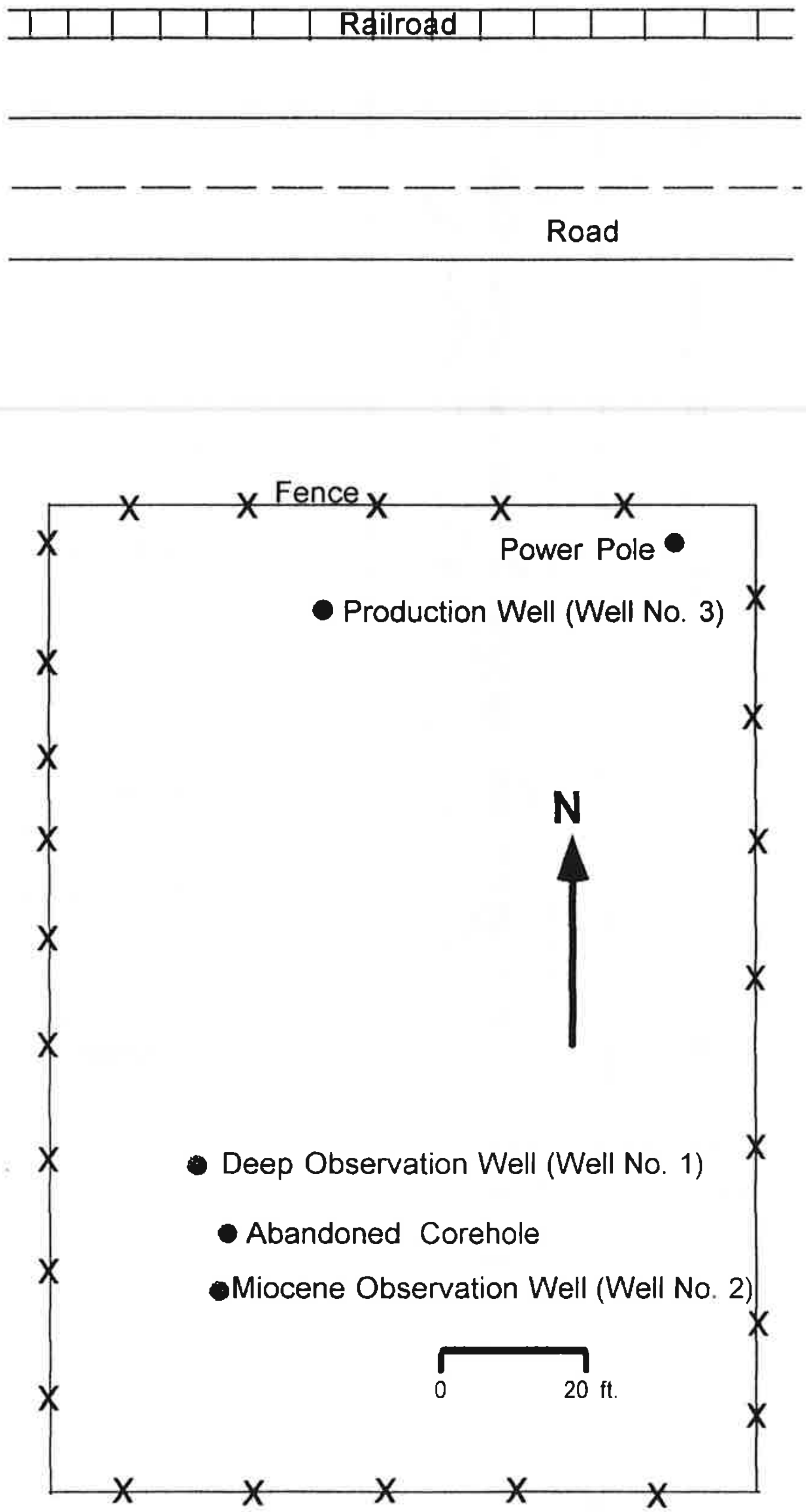

Figure 3. Map of test site showing relative locations of test wells.

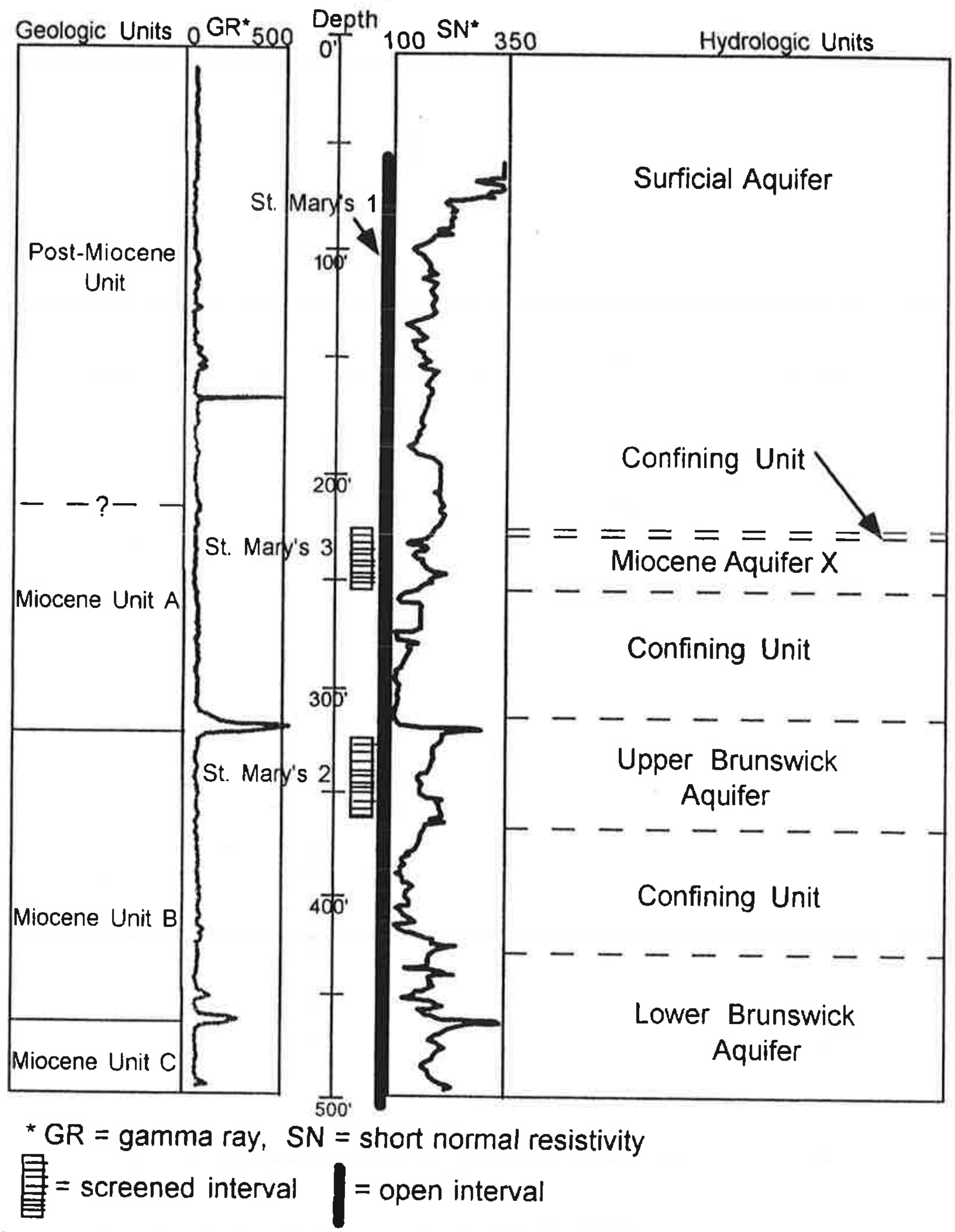

Figure 4: Geophysical well logs, geologic and hydrologic units and depth of screen intervals at the St. Marys test site.

Description of Wells Used for the Test

St. Marys 3, screened in a unnamed aquifer (aquifer X), was used as the pumping well and St. Marys 2, screened in the underlying Upper Brunswick aquifer, served as the observation well for the test in order to detect leakage. The Upper Brunswick well, St. Marys 2, was not used as the pumping well (as was the case with the Tybee Island test) because it did not yield significant quantities of water. St. Marys 1 was not screened with an unknown open interval due to losing a drill rod down the hole but was also monitored. The construction diagrams for each of the wells are shown in figures 5-7.

St. Marys Well No. 3
Production Well

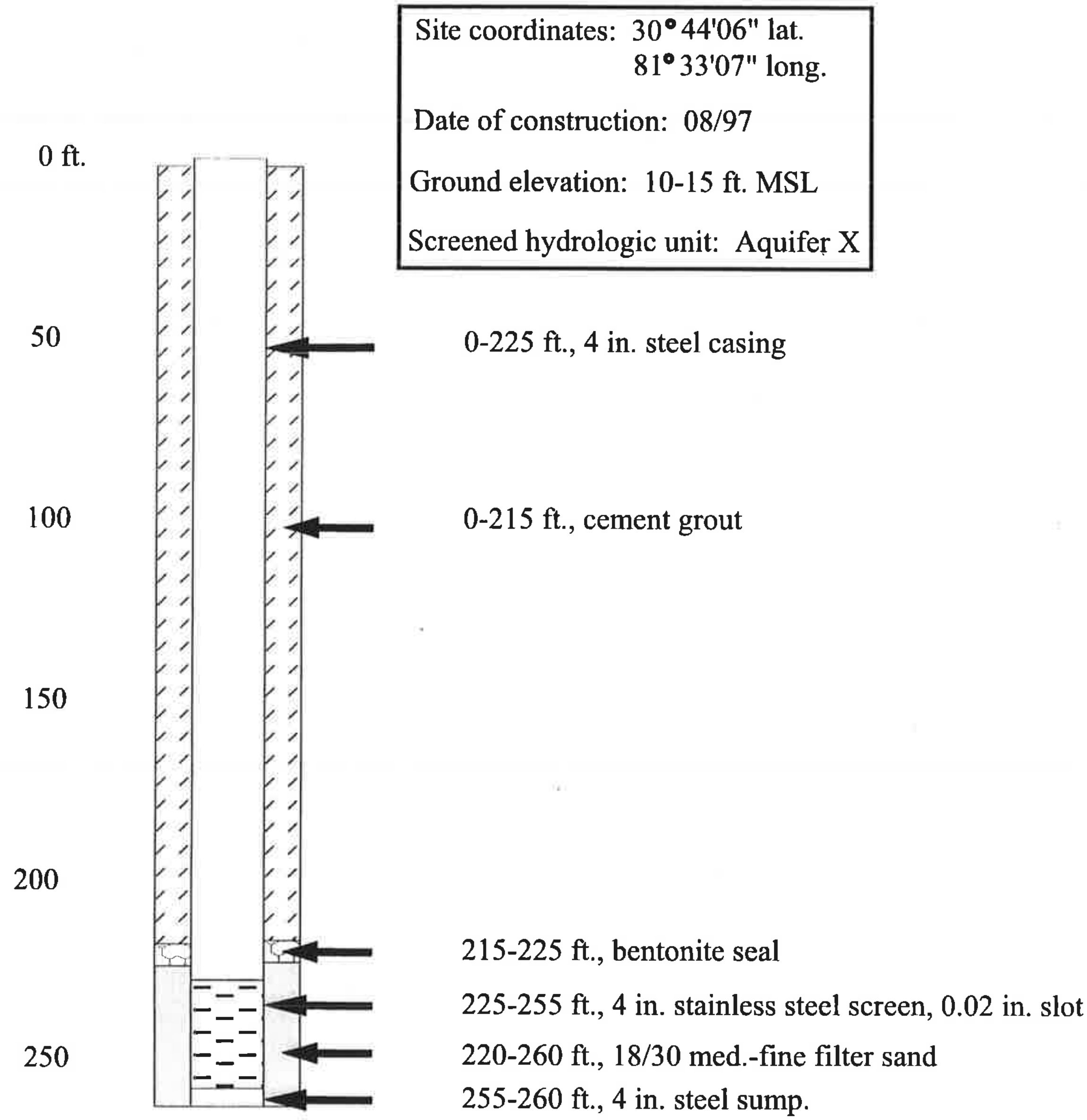

Figure 5: Well construction diagram for pumping well St. Marys No. 3.

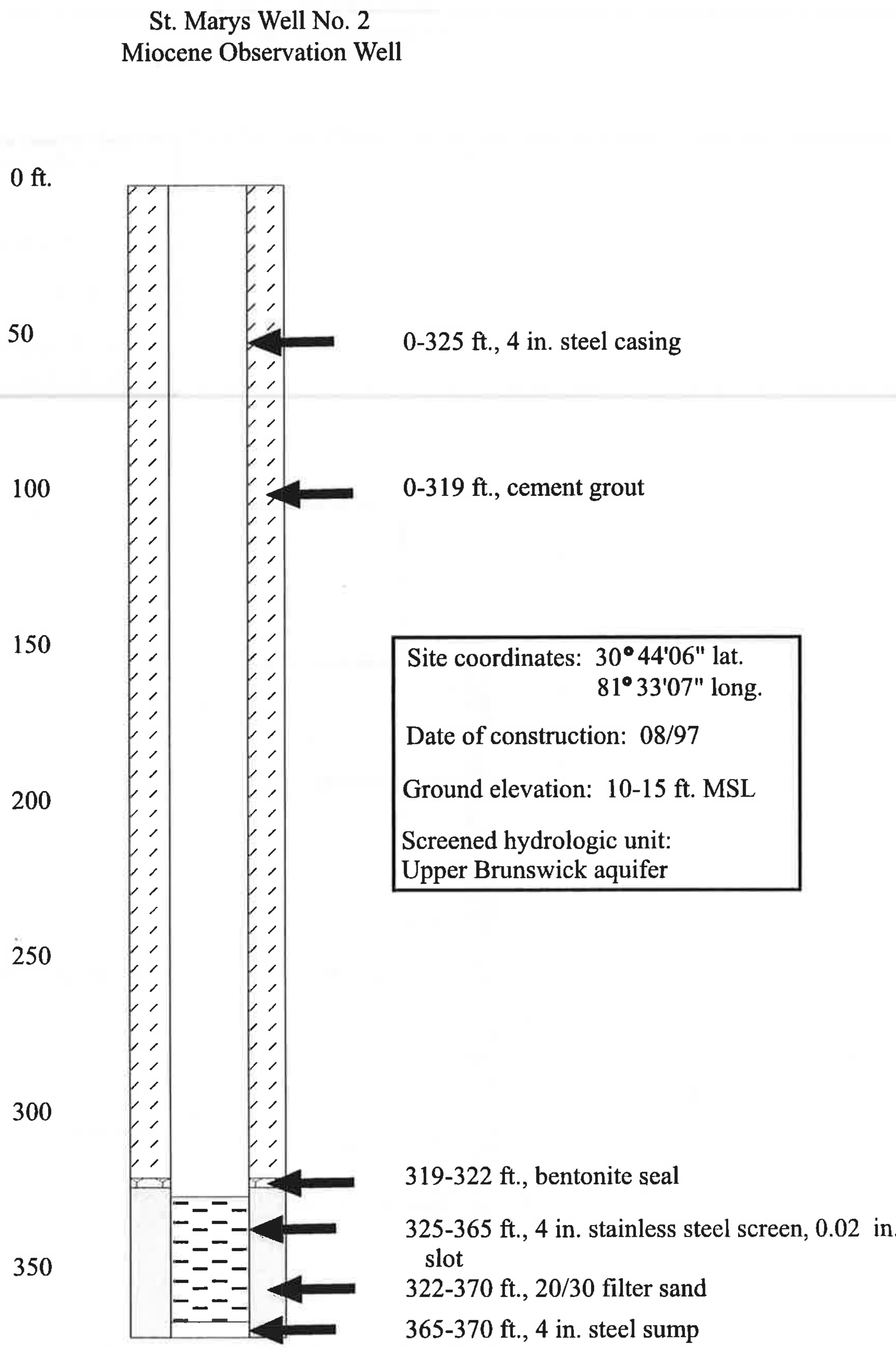

Figure 6: Well construction diagram for observation well St. Marys No. 2.

St. Marys Well No. 1
Deep Observation Well

Site coordinates: 30° 44'06" lat.
81° 33'07" long.

Date of construction: 08/97

Ground elevation: 10-15 ft. MSL

Screened hydrologic unit:
unscreened (open hole)

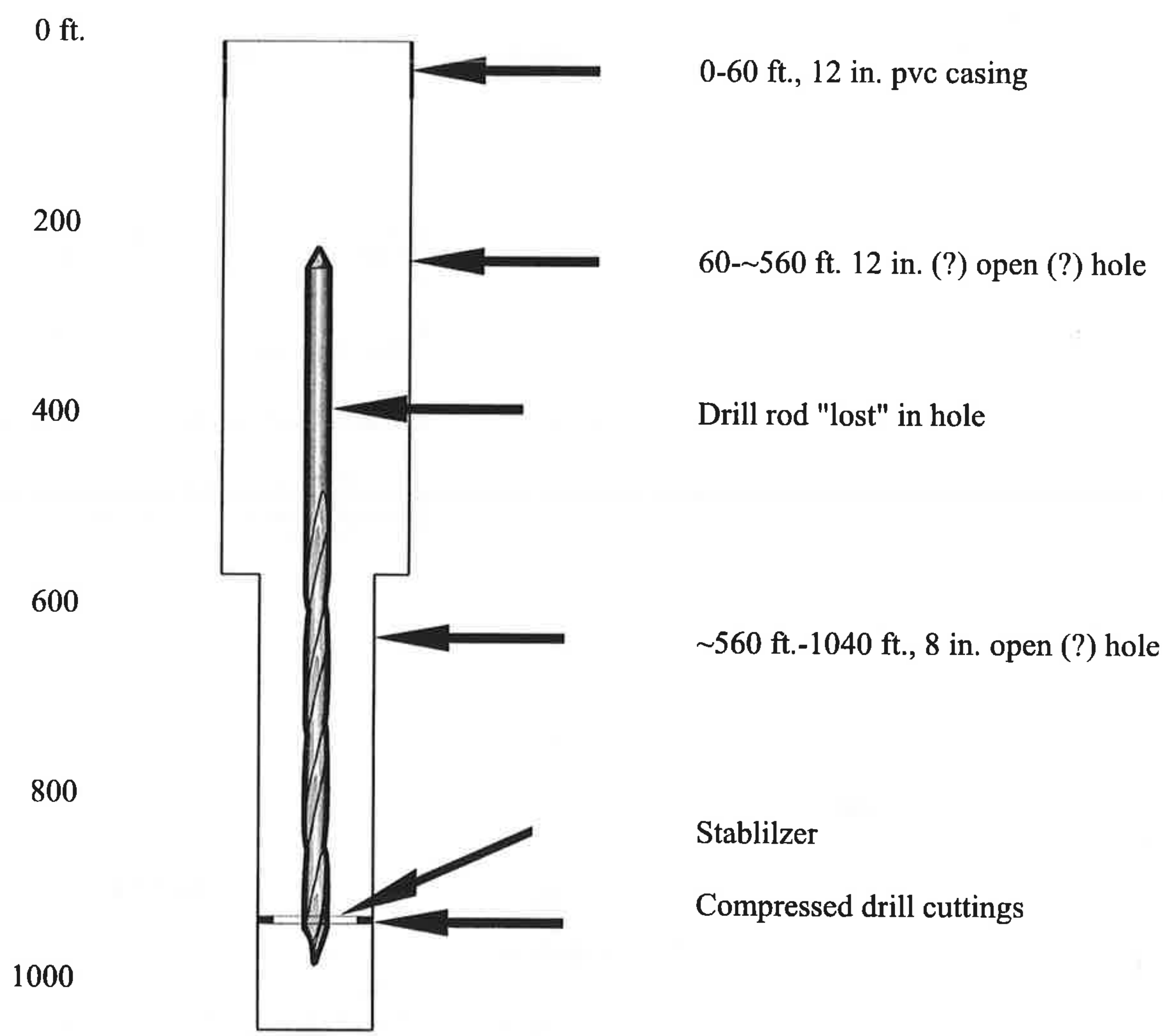

Figure 7: Well construction diagram for deep observation well St. Marys No. 1.

METHODS

Test Logistics

A pump test is composed of three periods of data collection: background pretest, pumping, and background post test (recovery). Background data are used to determine if the aquifer is in an equilibrium condition and the extent to which it is being affected by inconsistent external forces. Background data are also used to determine the barometric efficiency of the monitored aquifer so test data can be corrected for changes in atmospheric pressure. During the pumping phase of the test, the aquifer is stressed creating a pressure drawdown cone extending radially from the pumping well. After pumping stops, the aquifer is allowed to recover to pre-test conditions.

The test took place from September 30 to October 6, 1997. An unnamed Miocene aquifer (aquifer X) was pumped using St. Marys 3. The underlying Upper Brunswick aquifer was monitored to detect leakage, using St. Marys 2. St. Marys 1, unscreened and with an unknown open interval was also monitored in the test. The test consisted of 22.52 hours of background data collection, 72.00 hours of pumping and 37.78 hours of recovery data collection.

Data Acquisition Methods

Water level readings are recorded as pressure changes in meters of water relative to an initial equilibrium static water level condition. For the duration of a pump test (background through recovery), quartz crystal transducers measure water level changes in the pumping well and observation wells. Relative water level changes are recorded automatically on the computer data acquisition system at operator-specified intervals ranging from 3 seconds to 5 minutes throughout the test. An additional transducer monitors and records changes in atmospheric pressure, which are used to correct for atmospheric induced changes in water levels in the test wells.

Pumping Well Data Acquisition Methods

The pumping well, St. Marys 3, is assumed screened over the entire X aquifer from -210 to -240 ft (-64.0 to -73.6 m) MSL (figure 4). A 5 HP submersible pump was placed approximately 90 ft below the initial static water level and a 100 psi transducer was positioned 15 ft below the pump.

Observation Well Data Acquisition Methods

Observation well St. Marys 2, screened in the Upper Brunswick aquifer from -310 to -350 ft (-94.5 to -106.7 m) MSL, was monitored to detect vertical leakage. St. Marys 1, unscreened with an unknown open interval was also monitored. The relative screen positions are shown in figure 4. Pressure transducers (45 psi) were placed approximately 10 feet below the water level surface in the wells to continuously monitor water level changes.

Analysis Methods

Atmospheric Pressure Corrections

The first step in the analysis is to correct the raw well pressure data for atmospheric pressure-induced changes which can mask the small response of an aquifer in an observation well. Removal of atmospheric pressure-induced water level changes makes it easier to detect water level changes that result from pumping.

Barometric corrections are made by subtracting atmospheric pressure changes multiplied by the barometric efficiency (BE) of an aquifer from the corresponding water level measurements. The BE of an aquifer is the ratio of the change in hydraulic head in an aquifer (due to atmospheric changes) to the actual change in atmospheric pressure. A BE of 1 indicates that 100 percent of the atmospheric pressure changes have been transmitted to the aquifer. A BE of 0 would indicate that none of the atmospheric pressure changes have been transmitted to the aquifer. A typical BE for confined aquifers in the Coastal Plain of Georgia is about 0.6, ranging from 0.4 to 0.8.

Tidal Effects Corrections

The St. Marys test site is located approximately 4000 feet from the the St. Marys River. The water level on the river was found to fluctuate approximately 7 feet due to tidal effects. Water level fluctuations on the St. Marys River were measured and recorded at the Park Service Pier in the town of St. Marys using an In Situ Troll pressure transducer and data logger. The water level data from the wells showed no influence from the tidal cycle.

Well Analysis Methods

Data from an observation well screened in the same aquifer as the pumping well can be analyzed to calculate the storativity and transmissivity of the aquifer (see Test Logistics and Pumping Rates). Data from the pumping well are governed by three variables: the transmissivity and storativity of the aquifer, and the skin factor of the pumping well. If one of the three variables is known or can be estimated, the other two can be calculated. The skin factor of the pumping well is unknown and could be highly variable depending on well installation. The storativity of the aquifer is less sensitive than the transmissivity. It is estimated from analysis of observation well data (if available) or from average storativity values of similar aquifers. This storativity value is then used in the analysis of the pump well data. Variable rate curve matching of drawdown data yields a transmissivity value for the aquifer and a skin factor for the pumping well using the superposition of the Theis solution (1935) or Jacob straight-line method (Cooper and Jacob, 1946) for variable flow rates, modified for the skin factor analysis of Van Everdingen (1953) for confined aquifers with fully penetrating wells. For partial penetrating wells, data are analyzed using the Hantush (1961, 1964) solution for partial penetrating wells modified to account for the skin factor and multiple flow rate. The Hantush solution is used to calculate the transmissivity of the aquifer and the skin factor of the well, while correcting for vertical flow within the aquifer. Hydraulic conductivity is determined by dividing the transmissivity by the effective aquifer thickness. Permeability can then be calculated by multiplying the hydraulic conductivity in m/sec by a factor of 104,000 to convert to darcys (at 20° C; Fetter, 1988).

RESULTS

Duration of the Test

The pump test, using pumping well St. Marys 3 and observation wells St. Marys 1 and St. Marys 2, took place over a five day span from September 30 through October 6, 1997. The specific times for each phase of the test are shown in Table I.

Data	No. of hours	Time interval
Background Data	22.52 hours	(19:24 09/30/97 to 17:55 10/01/97)
Pump On	72.0 hours	(17:55 10/01/97 to 17:55 10/04/97)
Recovery (pump off)	37.8 hours	(17:55 10/04/97 to 07:43 10/06/97)
Total test	132.32 hours	(09:07 03/19/97 to 11:45 03/23/97)

Table I. Chart showing times for each phase of the test.

Data Acquisition Results

Pumping Rates

Drawdown in the pumping well was created by pumping water from well St. Marys 3 using a 5 hp submersible pump. Flow rates during the test were automatically measured and recorded using an Omega digital flow meter. During the pumping phase of the test, an overall variation in flow rate of approximately 1.75 gpm was observed as illustrated in Figure 8. In the analysis, multiple flow rates were used to account for the fluctuations. Flow rate steps of 71.00 gpm (0-24,500 seconds) and 71.40 gpm (24,500-259,200) seconds were used, also shown in Figure 8.

Water Level Readings

During the test, 1609 water level data points were recorded in the pumping and observation wells by the data aquisition system. Data points were recorded as frequently as every 3 seconds at times of rapidly changing water levels (i.e. at the beginning and end of pumping phase of the test), decreasing to every 5 minutes when water level changes were relatively small. Figures 9-11 shows plots of barometric corrected water level changes vs. time for respectively, the pumping well St. Marys 3, the deep observation well St. Marys 1 and the observation well St. Marys 2, over the duration of the pump test.

Water Level Change During the Test

A maximum drawdown of 16.74 meters (54.92 ft) was observed in the pumping well St. Marys 3 after 72.0 hours of pumping (Figure 9). A maximum drawdown of approximately 1.84 meters (6.04 ft) was seen in the deep unscreened observation well St. Marys 1 (Figure 10), 50 minutes after the pump was shut off.

Monitor well St. Marys 2 showed no observable changes in water level due to pumping (Figure 11) indicating a relatively effective confining layer between Miocene aquifer X and the Miocene Upper Brunswick aquifer.

Static water levels, measured from the top of the casing of the pumping and monitor wells, were taken on 09/30/97 prior to starting the test as illustrated in Table II.

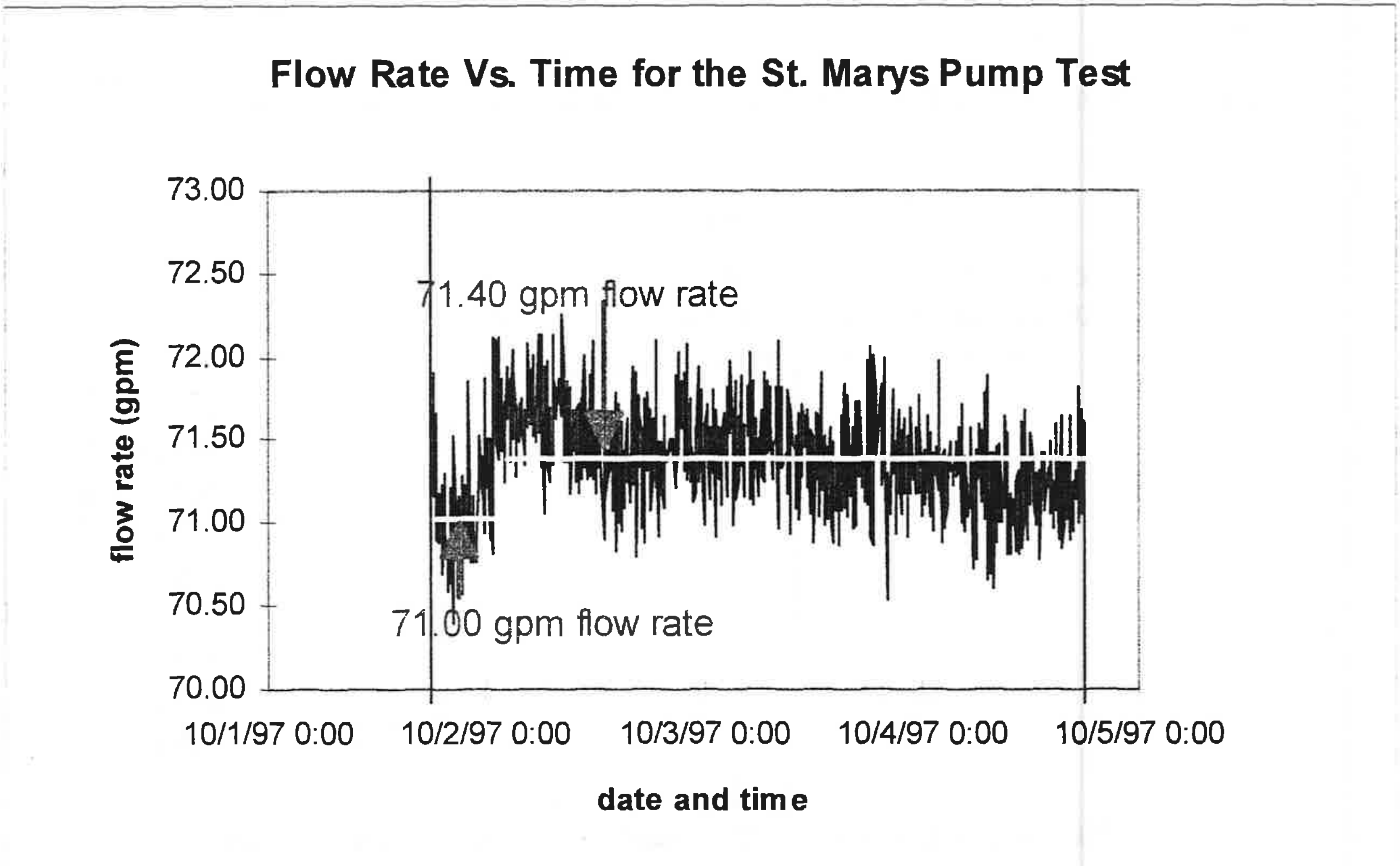

Figure 8. Graph showing flow rate versus time over the duration of the pumping phase of the St. Marys test and flow rate steps used in the analysis.

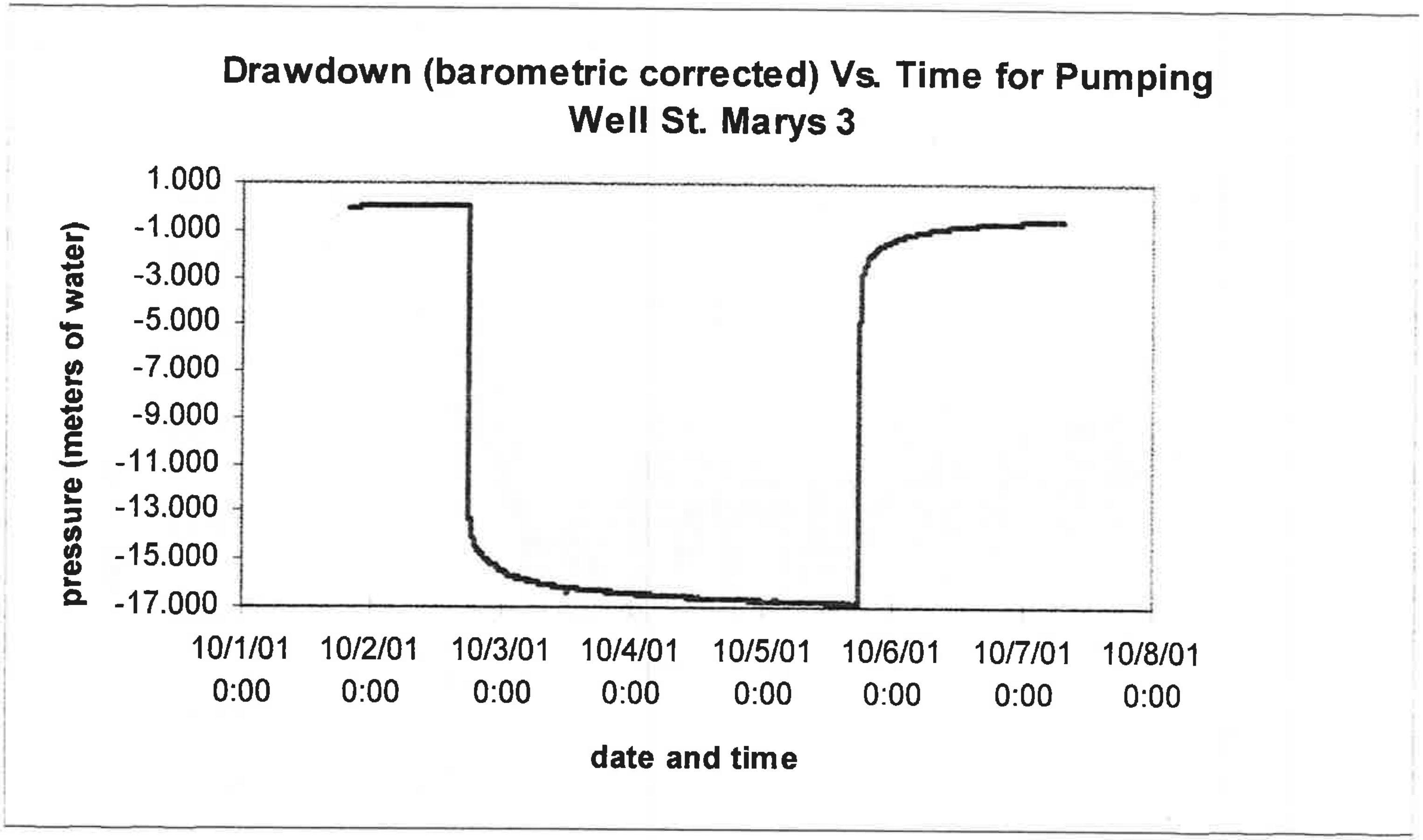

Figure 9. Graph showing barometric corrected drawdown and recovery for pumping well St. Marys 3 (screened in aquifer X).

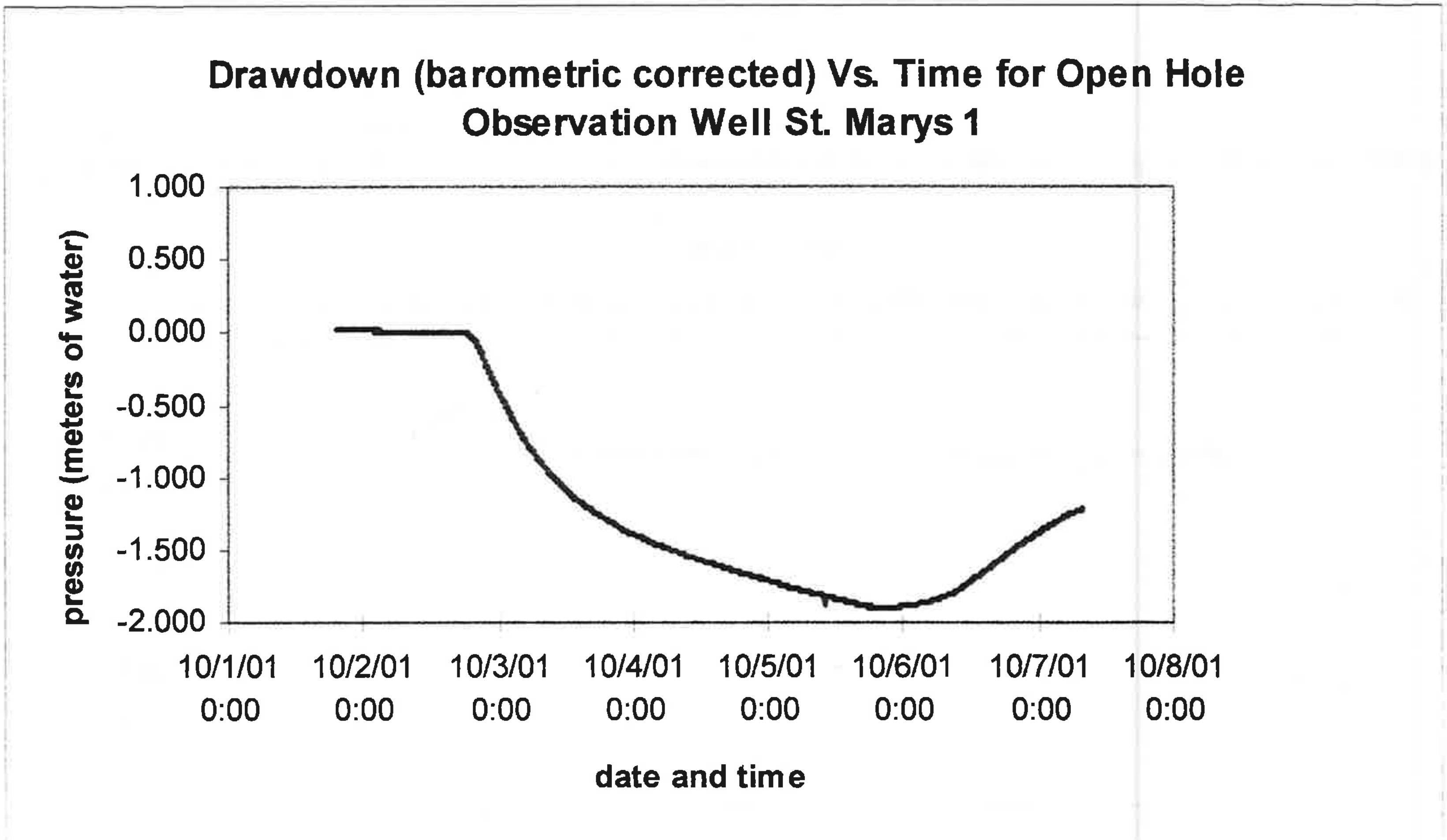

Figure 10. Graph showing barometric corrected drawdown and recovery for observation well St. Marys 1 (unscreened and open hole).

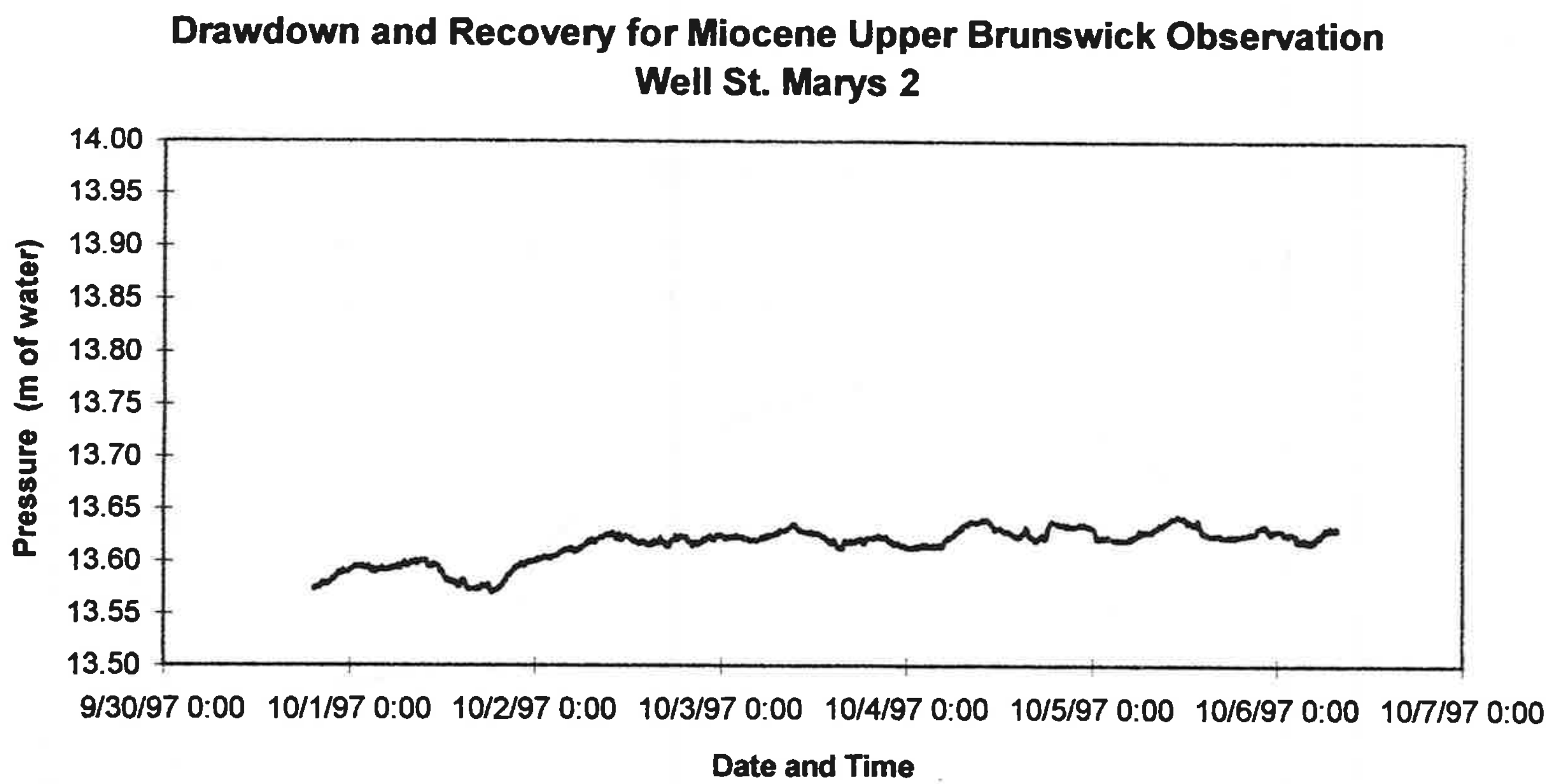

Figure 11. Graph showing barometric corrected drawdown and recovery for observation well St. Marys 2 (screened in the Miocene Upper Brunswick aquifer).

Well	Screened zone	Depth of static WL pror to pumping	Max. depth of static WL due to pumping	Max drawdown
S. M. 3	Aquifer X	7.88ft (2.40 m)	62.80 ft (19.14 m)	54.92 ft (16.74 m)
S. M. 1	Unscreened	16.21 ft (4.94 m)	22.22 ft (6.78 m)	6.04 ft (1.84 m)
S. M. 2	Up. Br. Aquifer	10.70 ft (3.26 m)	10.70 ft (3.26 .m)	0.00 ft (0.00 m)

Table II. Static water levels and maximum drawdown for test wells.

Data Analysis Results

Barometric Corrections

Water level pressure data from the pumping well and monitor wells were corrected for atmospheric pressure changes using the following barometric efficiencies. The barometric efficiencies were calculated using the method described in a previous section (atmospheric pressure corrections). Table III shows calculated barometric efficiencies for aquifer X (St. Marys 3), the Upper Brunswick aquifer (St. Marys 2) and the open hole monitor well St. Marys 1.

Well	Barometric Efficiency
St. Marys 3-Aquifer X	.900
St. Marys 1-Open Hole	.700
St. Marys 2-Up. Br. aquifer	.400

Table III. Calculated barometric efficiencies.

Tidal Corrections

The St. Marys test site was located far enough away from the ocean that the well pressure data showed no response to the tidal fluctuations. Therefore no tidal corrections were necessary for the St. Marys data analysis.

Trend Corrections

Background water-level data was not available due to the malfunction of a down-hole datalogger installed in pumping well St. Marys 3.

Calculated Aquifer Properties

Data from the observation wells was not used to calculate storativity for aquifer X because observation well St. Marys 2 was not screened in the same aquifer as the pumping well and observation well St. Marys 1 was unscreened with an unknown open interval. Pumping well skin factor and transmissivity of aquifer X at the St. Marys test site were calculated using data collected from the pumping well St. Marys 3 during the 72 hour pump test. Figure 12 shows a Theis-Jacob curve match for measured and calculated drawdown vs. time. Early time data (from 1 to 1000 seconds) was not used in the curve match because of well bore storage effects. Calculated drawdown for the aquifer X pumping well St. Marys 3 was based on multiple flow rates with flow rate steps of 71.00 gpm (0-24,500 seconds), 71.40 gpm (24,500-259,200 seconds)(Figure 8), and a well radius of 2 inches. A storativity of 0.0001 was estimated and the well was assumed to be fully screened over the entire thickness of the aquifer. Hydraulic conductivity and permeability calculations are based on the transmissivity and an estimated aquifer thickness of 30 ft (9.14 m) for aquifer X (Figure 4). A curve match for the pumping well St. Marys 3 yielded a skin factor of 3.44, a transmissivity of 538 ft^2/day (50 m^2/day), a hydraulic conductivity of 17.95 ft/day (5.47 m/day), and a permeability of 6.59 darcys.

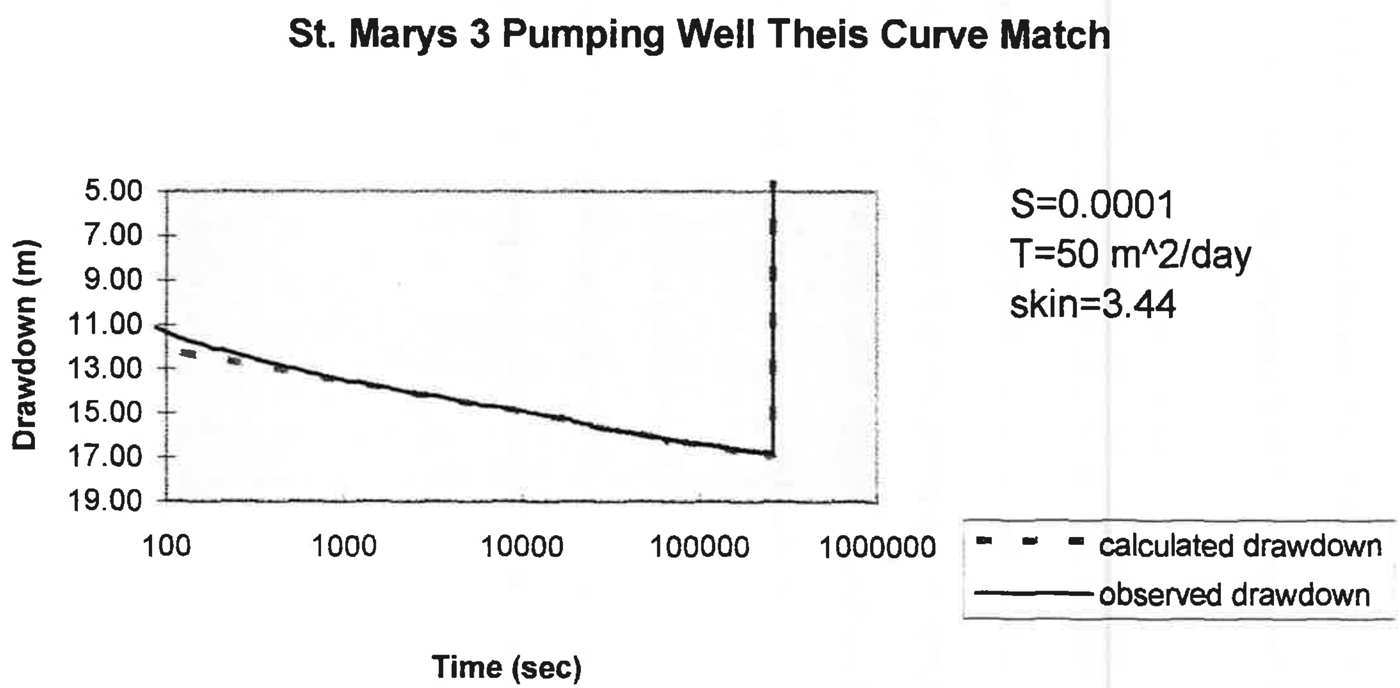

Figure 12. Theis-Jacob analysis (curve match) for pumping well St. Marys 3 using a multiple flow rate.

Calculated Skin Factor

The skin factor is a variable that quantitatively describes the conductive properties of the well itself. A high skin factor would normally indicate a poorly developed well, whereas a skin factor of 0 normally indicates a perfectly developed well. A skin factor of 3.44 was calculated for the pumping well, Mary's 3.

Well Efficiency

The well efficiency is a variable that is directly related to the skin factor of a production well. The well efficiency is calculated by dividing the theoretical drawdown by the measured drawdown in a production well, where the theoretical drawdown is the calculated drawdown assuming the well 100% efficient (skin factor is set to 0). A well efficiency of 73.8% was calculated for the pumping well St. Marys 3 as shown in Figure 13.

Specific Capacity

An average flow rate of 71.40 gpm created a 54.92 ft (16.74 m) drawdown after 72 hours of pumping in pumping well St. Marys 3 (aquifer X). This equates to a specific capacity of 1.30 gpm/ft.

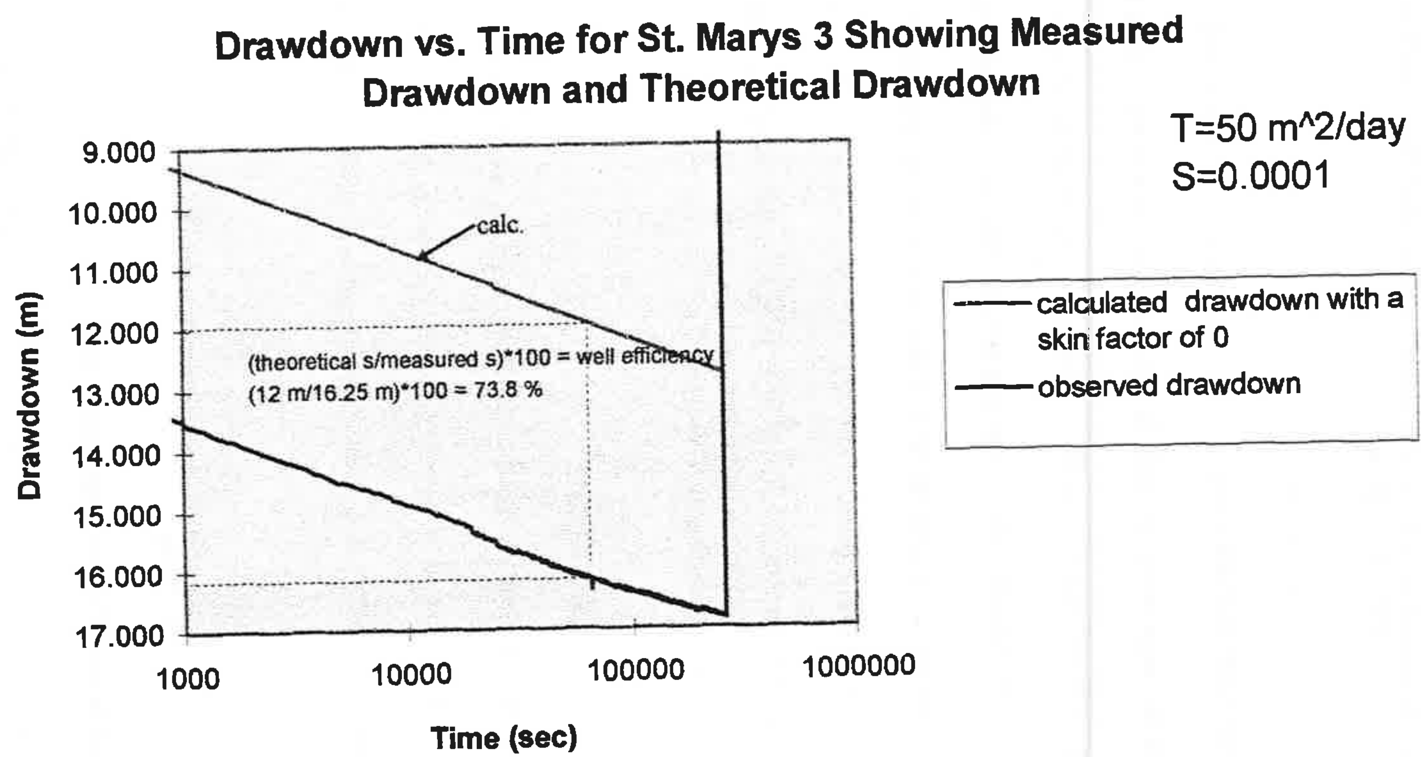

Figure 13. Plots of pumping well St. Marys 3 measured drawdown (all correction factors applied) and theoretical drawdown with skin = 0, T = 2000 m^2/day and S = 0.0001, showing well efficiency calculations. A well efficiency of 73.8% was calculated but may not be realistic due to the storativity (and therefore the pumping well skin factor) not being able to be estimated from the data analysis.

DISCUSSION

Analysis

A complete observation well analysis using the Theis curve matching method was not possible for St. Marys test because monitor well St. Marys 2 was not screened in the same aquifer as the pumping well and monitor well St. Marys 1 was unscreened with an unknown open interval. Since a storativity value from the observation well analysis was not possible, the storativity used in the pumping well analysis had to be estimated. A typical value for storativity for a confined aquifer is 0.0001. The best curve match for the pumping well was achieved using a transmissivity of 538 ft^2/day (50.0 m^2/day), and a skin factor of 3.44. This yielded a permeability of 6.59 darcys.

Ocean Effects

Ocean tidal effects in the St. Marys river caused the surface of the river to fluctuate approximately 7 feet. However, due to being far enough away from the river (approximately 3000 ft) the wells at the test site showed no response to the water level fluctuations in the river.

Leakage

No leakage was detected across the confining layer that separates aquifer X and the underlying Upper Brunswick aquifer at the St. Marys test site. Figure 11 shows a 8 cm overall increase in water level for the Upper Brunswick monitor well St. Marys 2, over the duration of the pump test, indicating an effective confining layer between the two aquifers.

REFERENCES

Clarke, John S., Hacke, Charles, M., and Peck, Michael F., 1990, Geology and ground-water resources of the coastal area of Georgia, Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, Bulletin 113, 106 p.

Cooper, H. H., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history, Transactions of the American Geophysical Union, v. 27., pp. 526-534.

Dawson, Karen J., and Istok, Jonathan D., 1991, Aquifer Testing, Design and Analysis of Pumping and Slug Tests, Lewis Publishers, Inc., Chelsea, Michigan, 344 p.

Earlougher, Robert C., 1977, Advances in Well Test Analysis, Millet the Printer, Inc., Dallas, Texas, 264 p.

Fetter, C. W., 1988, Applied Hydrogeology, Macmillan, Inc., New York, NY, 691 p.

Freeze, Allan R., Cherry, John A., 1979, Groundwater, Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 p.

Hantush, M. S., 1961, Drawdown around a partially penetrating well, Journal of the Hydrualics Division, Proceedings of the American Society of Civil Engineers, pp. 83-98.

Hantush, M. S., 1964, Hydraulics of wells: Advances in hydrosciences, v.1., Academic Press, New York, pp. 281-432.

Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer, American Geophysical Union Transactions, part 2, pp. 574-586.

Jenson, V. G., and Jeffreys, G. V., 1977, Mathematical Methods in Chemical Engineering, Academic Press Inc., New York, NY, 599 p.

Kroening, David E., Snipes, David S., Brame, Scott E., Hodges, Rex A., Price, Van and Temples, Tom J., 1996, The rehabilitation of monitoring wells clogged by calcite precipitation and drilling mud, Ground Water Monitoring and Remediation, v. 16, no. 2, pp. 114-123.

Press, William H., Teukolsky, Saul A., Vetterling, William T., and Flannery, Brian P.,1992, Numerial Recipes, Cambridge University Press, New York, NY, 963 p.

Snipes, David S., Benson, Sally M., and Hodges, Rex H., 1996, Establishment of a field hydrogeology experimental site final report; January 15, 1991 - January 14, 1996, Clemson University Hydrogeology Program, SCUREF Task Order 26 and Cooperative Agreement 29-95, 161 p.

Theis, C.V., 1935. The relation between lowering of the piezometric surface and the rate and duration of the discharge of a well using groundwater storage. Transactions of the American Geophysical Union, Vol. 2., pp. 519-524.

Van Everdingen, A. F., 1953. The skin effect and its influence on the productive capacity of a well. Petroleum Transactions, Vol. 198, pp. 171-176.

Appendix A

Correction Factors in the Analysis of Raw Well Data

Barometric Efficiency

To compute the barometric efficiency of an aquifer, several measurements of the ambient barometric pressure change in time along with the corresponding change in water levels vs. time, for wells only screened in the designated aquifer, are required. Figure A-1 (Dawson and Istok, 1991) is a hypothetical data set consisting of hydraulic head versus atmospheric pressure for a well screened in a confined aquifer. The slope of the fitted line in Figure A-1 is the ratio of the measured rate of change of hyraulic head to the corresponding rate of change of atmospheric pressure (in units of pressure /unit weight of water) over the same time range. This ratio is termed the barometric efficiency and is used as a weighting factor to determine the relative amount of atmospheric change to remove from the well data (Dawson and Isok,1991).

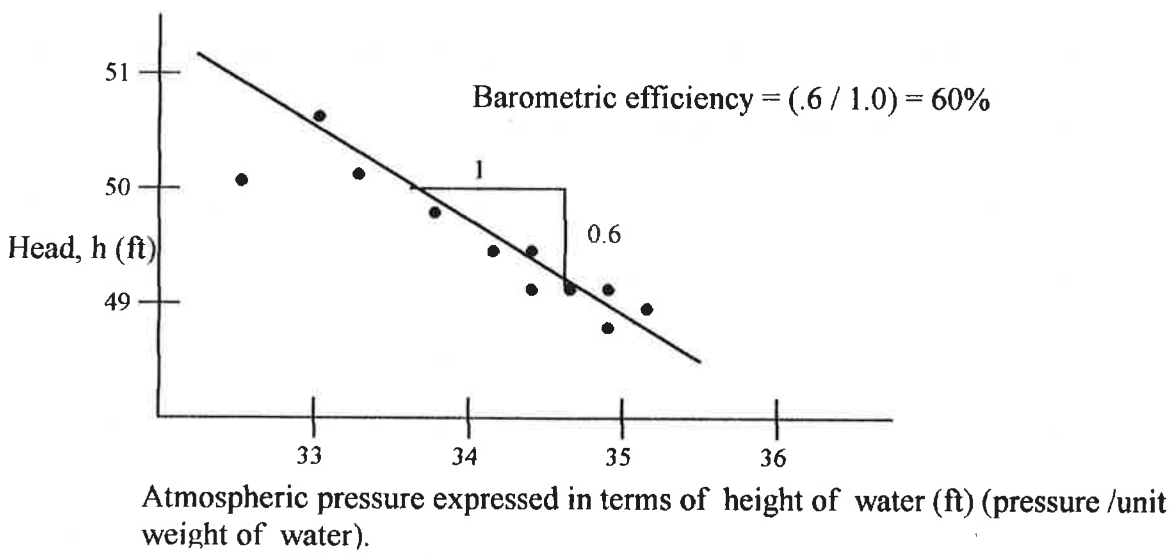

Figure A-1. Plot of hypothetical data set showing change of measured hydraulic head vs. change of atmospheric pressure in the same units (ft) (modified from Dawson and Istok, 1991).

A BE of 1 indicates that 100% of the atmospheric pressure changes have been transmitted to the aquifer (normally confined) and that all of the relative atmospheric changes should be removed from the well data. A BE of 0 indicates that none of the atmospheric pressure changes have been transmitted to the aquifer (normally unconfined) and therefore none of the relative atmospheric pressure changes should be removed from the well data.

Calculating the Barometric Efficiency

Clemson University has adopted a graphical method for determining the BE of a well by visually comparing the atmospheric pressure data to the BE corrected well data. The following step-by-step procedures pertaining to this method are taken from Snipes et al., 1996. Through the use of a spreadsheet, atmospheric pressure data and the BE corrected well data are plotted on the same chart. Changing the BE of a well on the spreadsheet, automatically changes all the BE corrected pressure values for that well on both the spreadsheet (Table A-1, columns J,K and L) and on the chart (Figures A-2 through A-5). The value for BE is repeatedly guessed until no effects of atmospheric pressure change can be seen in the well data. Figures A-2 through A-5 graphically show that a barometric efficiency equal to .700 minimizes the effects of atmospheric pressure change on the pumping well St. Marys 3 pressure data.

The following procedures are followed to correct the raw well data for atmospheric fluctuations:

	A	B	C	D	E	H	J	K	L
1						"initials" = avg of 1 minute prior to pump on			
2							initial Pressure	initial Pressure	initial Pressure
3	Columns A - F from raw data						St. Marys 3-PW	St. Marys 1-OW	St. Marys2-OW
4	1) Plot ¯t/¯atm and ¯t/(BE corr press) varying BE to remove atm effects - for each well						*45.419*	*13.501*	*13.577*
5	2) Positive ¯t's and BE corr pressures - copy to analysis spreadsheet						BE factor	BE factor	BE factor
6							St. Marys 3-PW	St. Marys 1-OW	St. Marys2-OW
7						initial atm	0.700	0.900	0.400
8			PW-raw	OW1-raw	OW2-raw	*10.306*			
9			St. Marys 3	St. Marys 1	St. Marys 2		St. Marys 3-PW	St. Marys 1-OW	St. Marys2-OW
10	dt	atm-raw	Well Pressure	Well Pressure	Well Pressure	Delta P atm.	BE corr press	BE corr Press	BE corr Press
11	(s)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
296	-10	10.31	45.42	13.50	13.58	0.00	0.00	0.00	0.00
297	-7	10.31	45.42	13.50	13.58	0.00	0.00	0.00	0.00
298	-5	10.31	45.42	13.50	13.58	0.00	0.00	0.00	0.00
299	-3	10.31	45.42	13.50	13.58	0.00	0.00	0.00	0.00
300	-1	10.31	45.42	13.50	13.58	0.00	0.00	0.00	0.00
301	1	10.31	43.13	13.50	13.58	0.00	-2.29	0.00	0.00
302	3	10.31	42.85	13.50	13.58	0.00	-2.57	0.00	0.00
303	5	10.31	41.97	13.50	13.58	0.00	-3.44	0.00	0.00
304	8	10.31	41.34	13.50	13.58	0.00	-4.08	0.00	0.00
305	10	10.31	40.64	13.50	13.58	0.00	-4.78	0.00	0.00

Table A-1. Barometric correction speadsheet, showing raw pressure values and BE corrected values for all wells in the St. Marys test (abbreviated from 1608 data points).

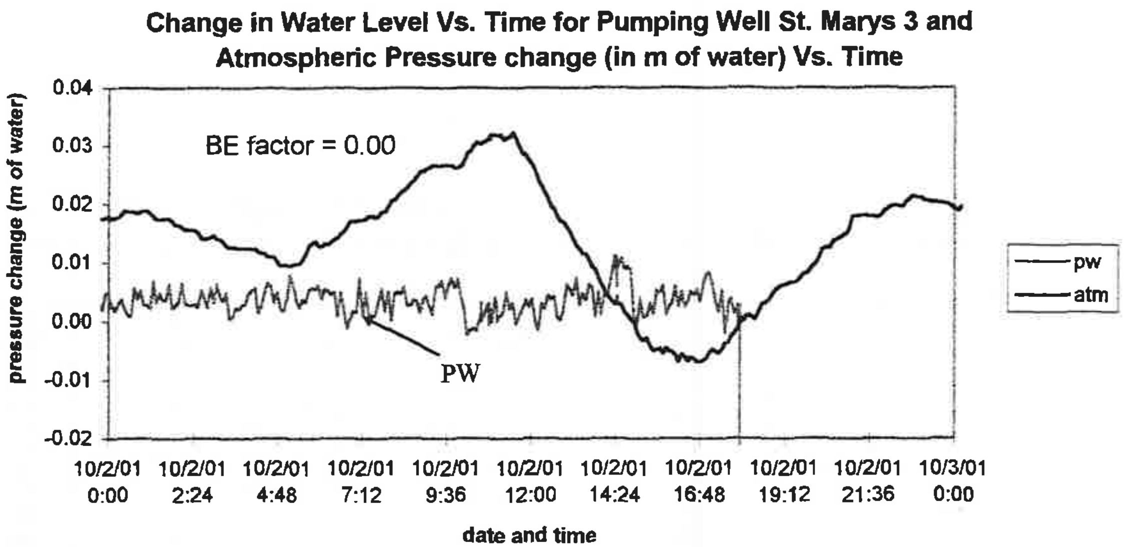

Figure A-2. Pumping well St. Marys 3 background water-level change versus time relative to "pump on" ("BE factor = 0.00) and atmospheric pressure change versus time relative to "pump on" (units in meters of h_2o).

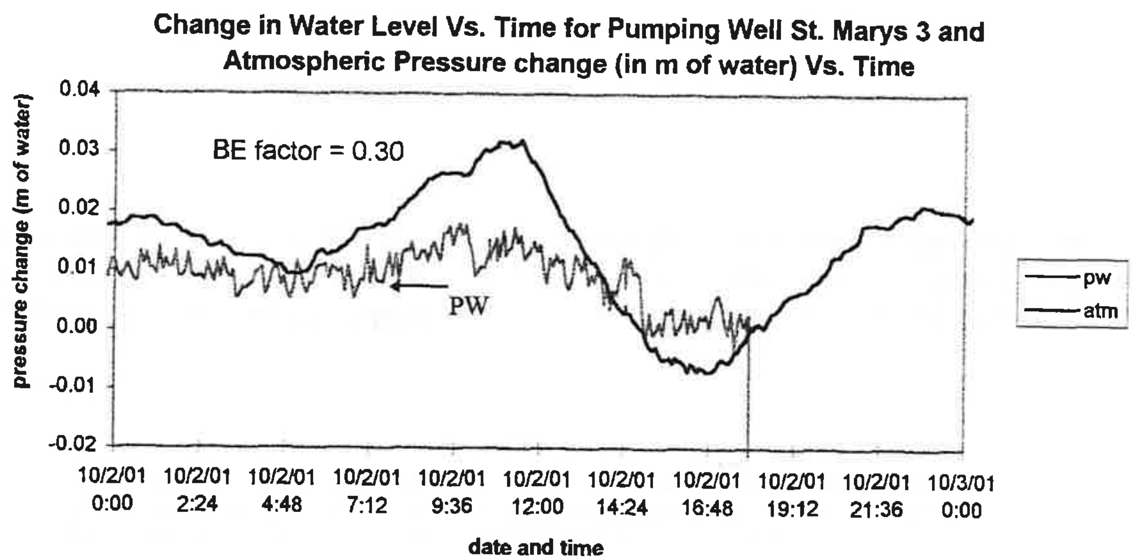

Figure A-3. Pumping well St. Marys 3 background water-level change versus time relative to "pump on" ("BE factor" = 0.30) and atmospheric pressure change versus time relative to "pump on" (units in meters of h_2o).

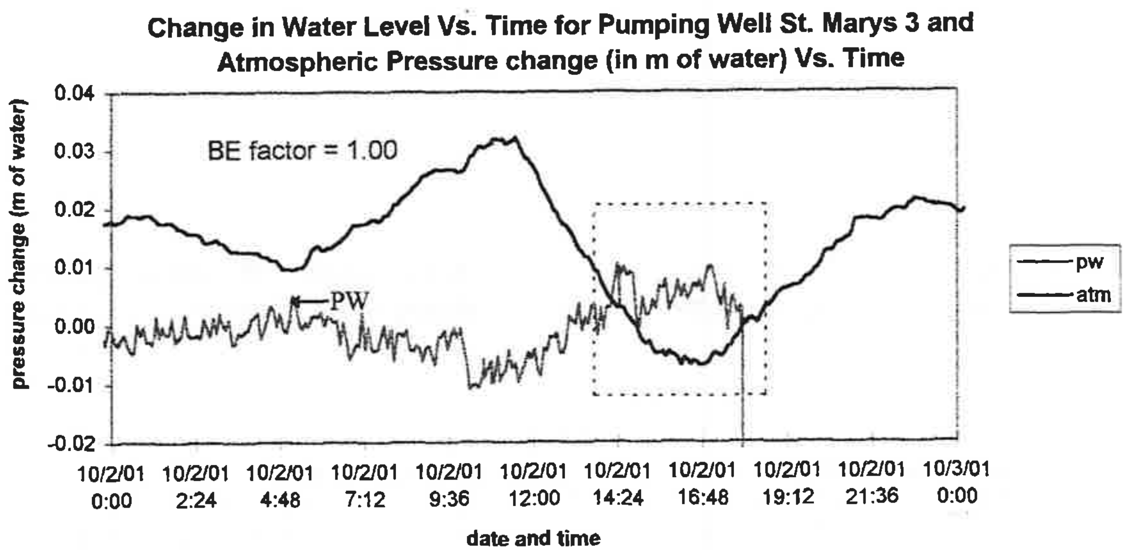

Figure A-4. Pumping well St. Marys 3 background water-level change versus time relative to "pump on" (BE=1.0) and atmospheric pressure change versus time relative to "pump on" (units in meters of h_2o). Note how the well data has been over-corrected. In the dashed box, the water level data spikes down as the atmospheric pressure data spikes up.

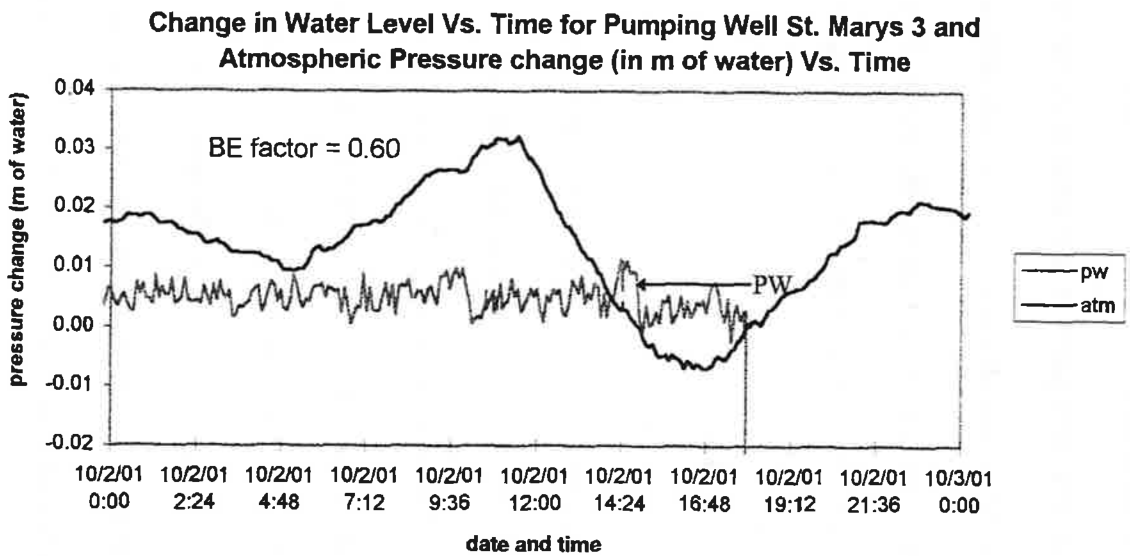

Figure A-5. Pumping well St. Marys 3 background water-level change versus time relative to "pump on" (BE=0.7) and atmospheric pressure change versus time relative to "pump on" (units in meters of h_2o).

(1) The raw well data and the atmospheric data, along with the elapsed time in relation to the time the pump was first turned on (dt) , are entered into the barometric correction spreadsheet (Table A-1, columns A-E).

(2) An initial value for atmospheric pressure (Table A-1, cell H-8) (taken as the average atmospheric pressure data points just prior to pump on) is subtracted from the raw atmospheric pressure data (Table A-1, column B) to calculate the relative change in atmospheric pressure (Delta P atm) (Table A-1, column H) from a set datum.

(3) The relative well pressure (water level) change for a well is calculated by subtracting an ititial well pressure (taken as the average well pressure just prior to pump on) (Table A-1, row 4) from the raw well pressure data. The effects on the raw well pressure due to atmospheric pressure changes are then removed by subtracting the (Delta P atm * BE factor) from the raw relative water level changes to give the BE corrected relative water level changes (Table A-1, columns J, K and L).

Trend Corrections

Trends in well data occur as a response to periodic fluctuations in the combined effects of recharge and discharge to the aquifer. The main factor in causing water level trends, is the seasonal fluctuations in recharge to the aquifer (with periods on the order of months). Trend corrections are necessary if the test occurs at a time when the aquifer pressure is rapidly decreasing or increasing due to seasonal fluctuations or other factors. It becomes more difficult to correct for if the trend is changing during the pump-on phase of the test. With sufficient background and recovery data, most long term linear trends can be recognized and easily removed by a simply subtracting the quantified trend effect from the barometric and tidal corrected data. Due to a malfunction in the data logger used to collect background water level data at the St. Marys test site, no background data was available, therefore there was no trend correction applied to the well data.

Appendix B

The Time Transient Spreadsheet Analysis Method Applied to the St. Marys Well Data

Theis Equation

To analyze pump test data, Clemson University uses a spreadsheet curve matching method based on the Theis equation. Radial flow to a well is mathematically modeled using the Theis equation. The Theis equation for radial flow to a well states that the drawdown (s) in a well is proportional to the flow rate and the well function (W(u)), and is inversely proportional to the transmissivity (Snipes et al., 1996). The Theis equation for radial flow to a well is written:

$$s = \frac{Q}{4\pi T} W(u) \qquad (1)$$

where

$$u = \frac{r^2 S}{4tT} \quad \text{and} \quad W(u) = \int_u^\infty \frac{e^{-z}}{z} \partial z$$

and

s = drawdown from static water level in the pump well or observation well, units in lenth [L],

Q = discharge rate from the pumped well, units in volume per time [L^3/T],

T = transmissivity of the aquifer, units in area per time [L^2/T],

S = coefficient of storage (storativity) of the aquifer, in dimensionless units,

r = radius, the radius of the pumping well or if analyzing the observation well data, the distance from the pumping well to the observation well, units in length [L],

t = time, t = 0 for initial "pump on",

W(u) = infinite series well function, in dimensionless units, u = the lower limit of integration of the infinite series, in dimensionless units.

The well function approximations are given below.

for u < 1 for pumping well or a nearby observation well and/or late pump time

$$W(u) = -\ln(u) + A_0 + A_1(u) + A_2(u^2) + A_3(u^3) + A_4(u^4) + A_5(u^5)$$

where

$A_0 = -0.57721566$,

$A_1 = 0.99999193$,

$A_2 = -0.24991055$,

$A_3 = 0.05519968$,

$A_4 = -0.00976004$,

$A_5 = 0.00107857$.

for u > 1 for a distant observation well and/or early pump time

$$ue^{u}W(u) = \frac{u^4 + a^1(u^3) + a^2(u^2) + a_3(u^3) + a_4}{u^4 + b_1(u^3) + b_2(u^2) + b_3(u^3) + b_4}$$

where

$a_1 = 8.5733287401$ $b_1 = 9.5733223454$

$a_2 = 18.059016973$ $b_2 = 25.6329561486$

$a_3 = 8.6347608925$ $b_3 = 21.0996530827$

$a_4 = 0.267737343$ $b_4 = 3.9584969228$

The Theis equation for radial flow to a well is valid under the following assumptions:

1. The aquifer has a constant thickness and has an infinite horizontal extent.

2. The potentiometric surface of the aquifer is horizontal and not changing with time prior to pumping.

3. All changes in the potentiometric surface of the aquifer are due only to the effect of the pumping well.

4. The pumping well has an infinitesimal diameter and is 100% efficient.

5. There is no source of recharge to the aquifer.

6. Water is released instantaneously from the aquifer as the head is lowered.

7. The well is pumped at a constant rate.

Procedure

The Clemson University Department of Geological Sciences uses a computer spreadsheet algorithm based on the Theis equation which enables the interpreter to curve match a computed drawdown with the measured drawdown to determine an estimate of the hydraulic parameters for a tested aquifer. The time transient spreadsheet analysis method is adapted from the Theis (log-log) type curve overlay method, which also is based on matching a theoretical drawdown curve with the measured drawdown curve. In the Theis method, a type curve is formed by the log-log plot of W(u) vs. 1/u and is matched to the log-log plot of the measured drawdown curve (drawdown vs. time). Whereas in the spreadsheet method, a theoretical semi-log drawdown curve, created by the computer spreadsheet's Theis equation based algorithm, is matched to the measured semi-log drawdown curve. The semi-log plot used in the spreadsheet method is the same configuration used in the Jacob straight-line method of analysis (Cooper and Jacob, 1946). Clemson University has adopted the time transient spreadsheet analysis method as the preferred method of pump test analyzis because it allows for more flexibility in defining the controlling physical parameters of the test. In the spreadsheet method,flow rate changes are accounted for, as well as skin effects due to well development. The spreadsheet can also be modified to account for vertical leakage across an aquitard and well bore storage effects. The time transient spreadsheet analysis method is explained in the following steps (Snipes et al., 1996).

(1) The measured drawdown (all corrections applied) and the elapsed time in relation to the time the pump was first turned on (dt) are entered into the analysis spreadsheet (Table B-1, columns A and B).

(2) The measured drawdown versus time is plotted on a spreadsheet chart (Figure B-1).

(3) A theoretical drawdown for each time step (dt) is calculated (Table B-1, column D). This is based on the Theis equation (1) where $u = \frac{r^2S}{4tT}$. The radius (r) is given as either the radius of the well in the analysis of the pumping well data or is the linear distance from the pumping well to the observation well in the case of observation well data analysis. For observation well data analysis, values for T and S (Table B-1, cells G1 and G2) are guessed by the interpreter until the best curve match is obtained for the theoretical drawdown versus the measured drawdown. In the case of pumping well data analysis, an additional variable (skin factor) (Table B-1, cell G3) is required along with T and S. A full explanation of the skin factor and the inclusion of the skin factor and flow rate changes in the Theis equation are discussed below.

(a) This spreadsheet is designed for 4 flow rate changes (Table B-1, cells A1 through A4), an initial rate for the time the pump was first turned on followed by 2 possible additional flow rate changes and then a recovery period where the flow rate is equal to 0 when the pump is cut off. The time relative to "pump on", when each flow rate change begins, is entered into the cell adjacent to the flow rate (Table B-1, cells B1 through B4). The spreadsheet can be easily modified to account for additional flow rate changes if necessary. The Theis equation in the spreadsheet is modified to account for multiple flow rates in the following manner (Freeze and Cherry, 1979):

$$s = \Delta P = \sum_{n=1}^{n} \frac{Q_n - Q_{n-1}}{4\pi T}\left[W(u_n)\right] \tag{2}$$

where

$$u_n = \frac{r^2S}{4T(dt - t_n)}$$

and

$dt - t_n$ *is the time since the last flow rate changed, units in time,*

$Q_n - Q_{n-1}$ is the change in the flow rate, units in volume per time $[L^3/T]$.

Therefore, for wells with multiple flow rate steps, a u value (Table B-1, columns F through I) and a step drawdown (Table B-1, columns J through M) are calculated for each flow rate change. For the St. Marys pump test, three flow rates where used in the analysis. The flow rates consisted of an initial flow rate of 71.00 gpm continuing from

Q1 [gpm]=	*71.00*	t1 [s]=	*0*		S =	0.0001	L (ft) =	20	full pen.=	0.001			
Q2 [gpm]=	*71.40*	t2 [s]=	*24,491*		T [m^2/day] =	50.0	d (ft) =	15	***d = distance from top of AQ to top of screen***				
Q3 [gpm]=	*0.00*	t3 (s)=	*259,191*		skin factor =	3.44	z (ft) =	17.5	***z = distance from top of AQ to middle of screen***				
Q4 [gpm]=	*0.00*	t4 [s]=	*259,191*		K (m/day) =	5.47	b (ft) =	30	***l = distance from top of AQ to bottom of screen***				
RAH 3-10/95					darcys =	6.59	rad (ft) =	0.1667	***b = AQ thickness***				

					calc u				calc step drawdowns			
dt (pump on) (seconds)	**measured drawdown** (meters)	**time** (mins)	**calculated drawdown** (meters)	**residual** 259.42	dt-t_1 from Q1 u1	dt-t_2 from Q2 u2	dt-t_3 from Q3 u3	dt-t_4 from Q4 u4	pump on Q1 delta h1	flow d1 Q2 delta h2	flow d2 Q3 delta h3	recovery Q4 delta h4
1	2.29	0.0	**9.34**	**109.11**	1.11E-04	not yet	not yet	not yet	**9.34**	0.00	0.00	0.00
3	2.57	0.1	**10.04**	**122.66**	3.49E-05	not yet	not yet	not yet	**10.04**	0.00	0.00	0.00
5	3.44	0.1	**10.36**	**105.13**	2.07E-05	not yet	not yet	not yet	**10.36**	0.00	0.00	0.00
8	4.08	0.1	**10.57**	**92.55**	1.47E-05	not yet	not yet	not yet	**10.57**	0.00	0.00	0.00
10	4.78	0.2	**10.72**	**77.59**	1.14E-05	not yet	not yet	not yet	**10.72**	0.00	0.00	0.00
12	5.36	0.2	**10.84**	**66.20**	9.30E-06	not yet	not yet	not yet	**10.84**	0.00	0.00	0.00
14	5.88	0.2	**10.95**	**56.39**	7.86E-06	not yet	not yet	not yet	**10.95**	0.00	0.00	0.00
16	6.34	0.3	**11.03**	**48.40**	6.80E-06	not yet	not yet	not yet	**11.03**	0.00	0.00	0.00
19	6.74	0.3	**11.11**	**41.88**	6.00E-06	not yet	not yet	not yet	**11.11**	0.00	0.00	0.00

Table B-1. Pump test analysis spreadsheet for pumping well St. Marys 3.

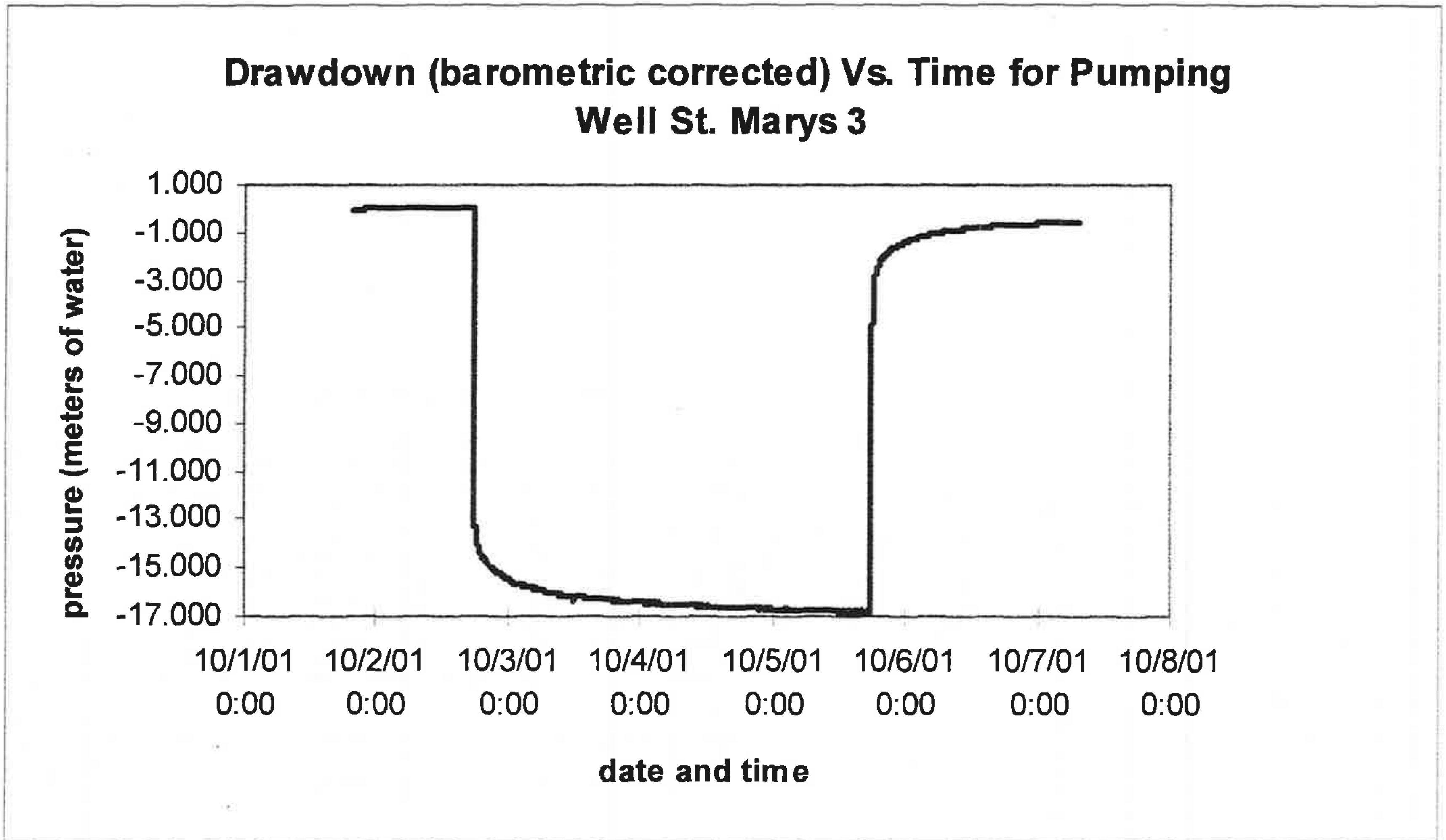

Figure B-1. Measured drawdown versus time for pumping well St. Marys 3 (barometric correction factor applied).

"pump on" (t = 0 seconds) until the relative time to "pump on" was equal to 24,491 seconds, followed by a flow rate of 71.40 gpm and continuing to "pump off" (t = 259,191 seconds, approximately 72 hours) which was then followed by a flow rate of 0 gpm (recovery) which continued for the remainder of the recovery period. Figure B-2 is a plot of flow rate versus time for the duration of the pumping phase of the test, showing flow rate steps used in the analysis.

(b) For pumping well data analysis, a skin factor variable (Table B-1, cell G3) must be considered (in addition to T and S) to produce realistic test results. The skin factor is a numerical representation of the head loss due to the "damage" to the annular region around an installed well. This region, called the skin zone, is a region where the permeability has been altered due to drilling and/or well completion activities (Kroening et al., 1996). The manipulation of three variables (skin, T and S) in the analysis of pumping well data results in unrealistic interpretions, therefore one of the three variables must be held constant. To accomodate for this, it is best to have an observation well screened in the same aquifer whereby the observation well data is analyzed first to determine an estimate of the storativity of the aquifer. This is done by setting the skin factor equal to 0 due to the low groundwater velocity at the observation well. This eliminates the skin factor as a variable in the observation well analysis, thereby allowing an estimate of the storativity of the aquifer to be computed (as well as an estimate of the transmissivity). This estimate of storativity is then entered into the pumping well data analysis as a constant (S is much less sensitive than T) which reduces the number of variables to two (T and skin). For a single well pump test, a storativity value must be estimated from other tests performed in the area. This is a major weakness of a single well pump test. The skin factor (skin), is mathematically defined as (Earlougher, 1977):

$$\text{skin} = \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_s}{r_w}\right) \qquad (3)$$

where

- k is the permeability of the formation, units in area [L^2],
- k_s is the permeability of the skin zone, units in area [L^2],
- r_s is the radial thickness of the skin zone, units in length [L],
- r_w is the radius of the well, units in length [L].

The above equation is based on the following assumptions:

1. If a radial assymetric orientation of the skin zone exists, the effects of differential clogging or improvement will be averaged into a single, symmetric radial representation of the zone.
2. The skin zone and surrounding aquifer are homogenous and isotropic.

The total head loss or drawdown (s) at a pumping well is accounted for by adding the effects of the aquifer and the skin zone (due to different permeabilities), which is expressed in the following equation (Van Everdingen, 1953):

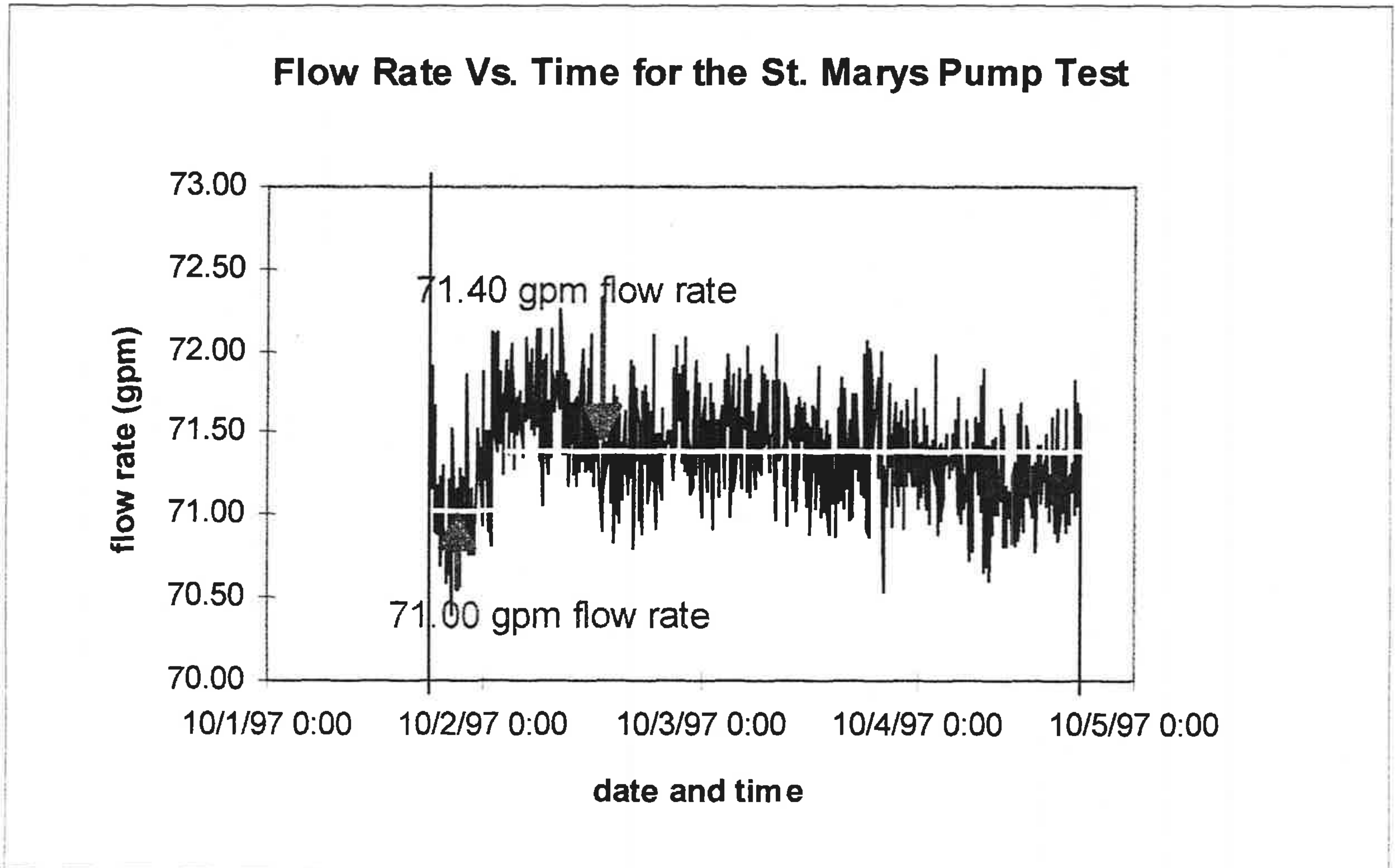

Figure B-2. Graph of flow rate versus time over the duration of the pumping phase of the St. Marys pump test, showing flow rate steps used in the analysis.

$$s = \frac{Q}{2\pi T}\ln\frac{r_e}{r_w} + \frac{skinQ}{2\pi T} \quad (4)$$

where

s	is the total drawdown or head loss, units in length [L],
Q	is the volumetric flow rate, units in volume per time [L^3/T],
T	is the transmissivity of the aquifer, units in area per time [L^2/T],
r_e	is the radius of influence of the pumping well, units in length [L],
r_w	is the radius of the pumping well, units in length [L],
$\frac{Q}{2\pi T}\ln\frac{r_e}{r_w}$	*is the head loss at the pumping well due to the aquifer, units in length* [L],
$\frac{skinQ}{2\pi T}$	is the head loss at the pumping well due to the skin zone, units in length [L].

The Theis equation which is modified to take into account the skin factor for a fully penetrating pumping well then becomes (Van Everdingen, 1953):

$$s = \frac{Q}{4\pi T}\left[W(u) + 2skin\right]. \quad (5)$$

(c) From equations (2) and (5), the modified Theis equation used in the spreadsheet, which takes into account both multiple flow rates and skin factor is (Snipes et al., 1996):

$$s = \Delta P = \sum_{n=1}^{n} \frac{Q_n - Q_{n-1}}{4\pi T}\left[W(u_n) + 2skin\right]. \quad (6)$$

(d) The W(u) for each flow step is calculated by a Fortran program within the spreadsheet based on the previously mentioned approximations.

(e) The step drawdowns are then summed to give the total calculated drawdown (Table B-1, column D).

(4) The theoretical "calculated" data is plotted on the same chart as the measured data. As discussed in step (3), each theoretical data point is calculated based on guesses for T and S for observation well data analysis and guesses for T and skin for pumping well data analysis.

(5) The guesses for T and S (observation well data analysis) or T and skin (pumping well data analysis) are varied by the interpreter and entered into the spreadsheet whereby the plots of the measured and calculated drawdown are compared. By varying the T, the interpeter can change both the slope (T appears in both the equation for u and the equation for drawdown) and the vertical displacement of the calculated curve. Varying the S or skin changes only the vertical displacement of the calculated curve. A time weighted residual value (Table B-1, cell E10) enables the interpreter to produce the best possible curve match. The lowest residual value results in the best curve match. The equation for the residual value in the spreadsheet is:

$$\text{residual}=\sum_{1}^{n-1}(\text{calculated}_n - \text{measured}_n)^2 * (t_n - t_{n+1})$$

where

n	is the number of data points (time steps) in the pumping phase, starting at t~1000 seconds (early time measured data does not follow the theoretical drawdown curve due to well bore storage effects),
calculated_n	is the calculated drawdown at each time step,
measured_n	is the measured drawdown at each time step,
t	is the elapsed time in relation to "pump on" at each time step (n).

In the St. Marys test, data from the observation wells was not used to calculate storativity for the pumped aquifer (aquifer X) because observation well St. Marys 2 was not screened in the same aquifer and St. Marys 1 was unscreened with an unknown open interval. Therefore only the punping well data was analyzed to determine estimates for T and the pumping well skin factor using a typical value for storativity for a confined aquifer of 0.0001. To calculate a more realistic estimate of the storativity for the aquifer would require a step drawdown pump test. Figure B-3 shows the curve match using initial guesses for T and skin, with an estimated storativity of 0.0001, to begin the analysis for the pumping well St. Marys 3. Note that the calculated drawdown curve is well above the measured drawdown curve and therefore is not a match. By increasing the guess for the skin factor, the calculated drawdown curve will increase and move toward the measured drawdown curve as shown in Figure B-4. By increasing the skin factor from 0.00 to 10.00, the vertical position of the theoretical drawdown approximately matches the vertical position of the measured drawdown (Figure B-4). However, the calculated drawdown slope is not steep enough to match the measured drawdown. Decreasing the guess for T will increase the slope as well as the vertical displacement of the theoretical drawdown curve. In Figure B-5, the T is decreased to 50 m^2/day which results in a good match for the slopes of the two drawdown curves, although the theoretical drawdown curve is significantly lower than the measured drawdown curve. By decreasing the skin factor from 10 to 5, as shown in Figure B-6, the theoretical drawdown is increased which moves the theoretical drawdown curve closer to the measured drawdown curve. Decreasing the skin factor from 5 to 3.44 results in the best curve match according to the lowest possible residual value (Figure B-7). The further manipulation of T and/or skin by small increments does not result in a decrease in the residual value. Early time data (0 to 1000 seconds) is not used in the curve match analysis because the measured data is skewed due to well bore storage effects. Late time measured data can also be skewed due to certain hydrologic conditions. The measured drawdown can be less than expected due to a water source (i.e., leakage, constant head source) or it can be more than expected (i.e., impermeable boundary). Recovery analysis is possible if a check valve is installed on the pump which would not allow the water contained in the discharge apparatus to rush back into the well bore. In the St. Marys test, a check valve was installed on the pump, making recovery analysis possible.

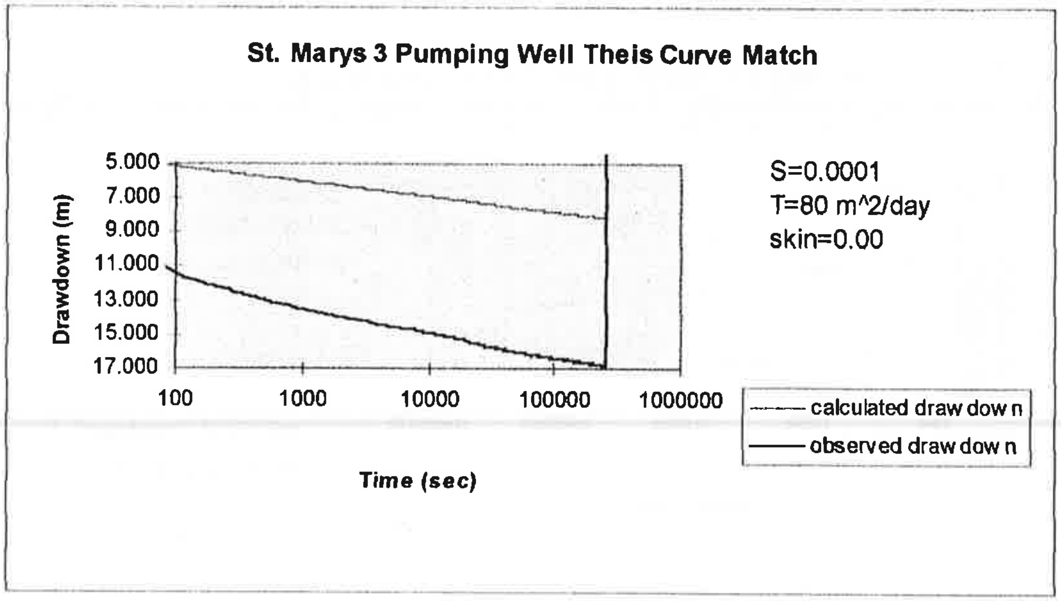

Figure B-3. Semi-log curve match of measured drawdown (all correction factors applied) and Theis equation based calculated drawdown for pumping well St. Marys 3, using a storativity of 0.0001, and intial guesses for T (80 m^2/day) and skin (0.00). The value for S (0.0001) was not able to be estimated from the observation well data analysis and is therefore assumed, based on storativity values from other confined aquifers.

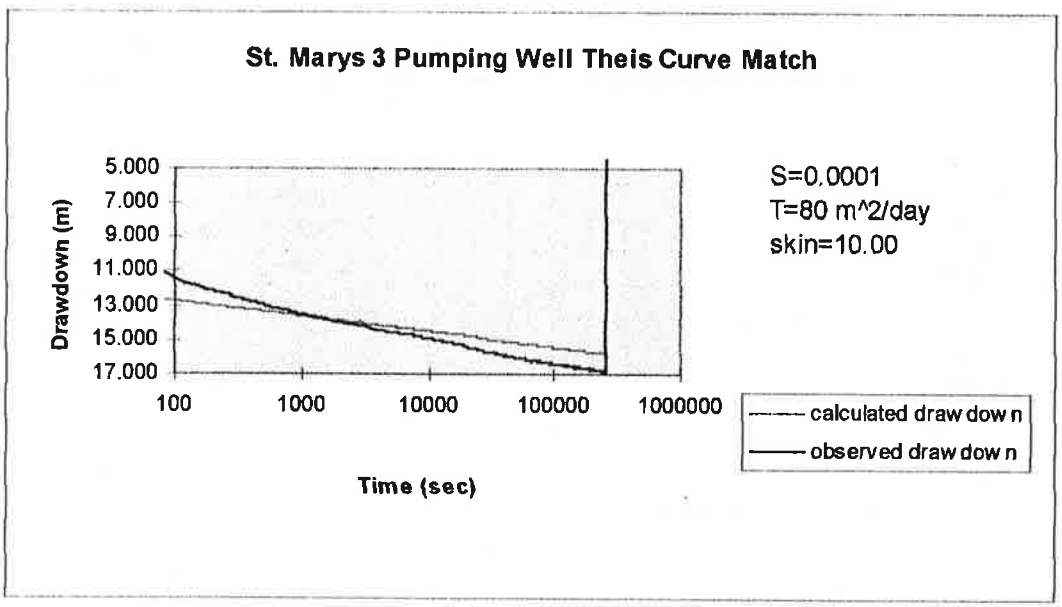

Figure B-4. Semi-log plot of pumping well St. Marys 3 theoretical calculated drawdown and measured drawdown (all correction factors applied), using a value for S of 0.0001 and guesses for T of 80 m^2/day and a skin of 10.00.

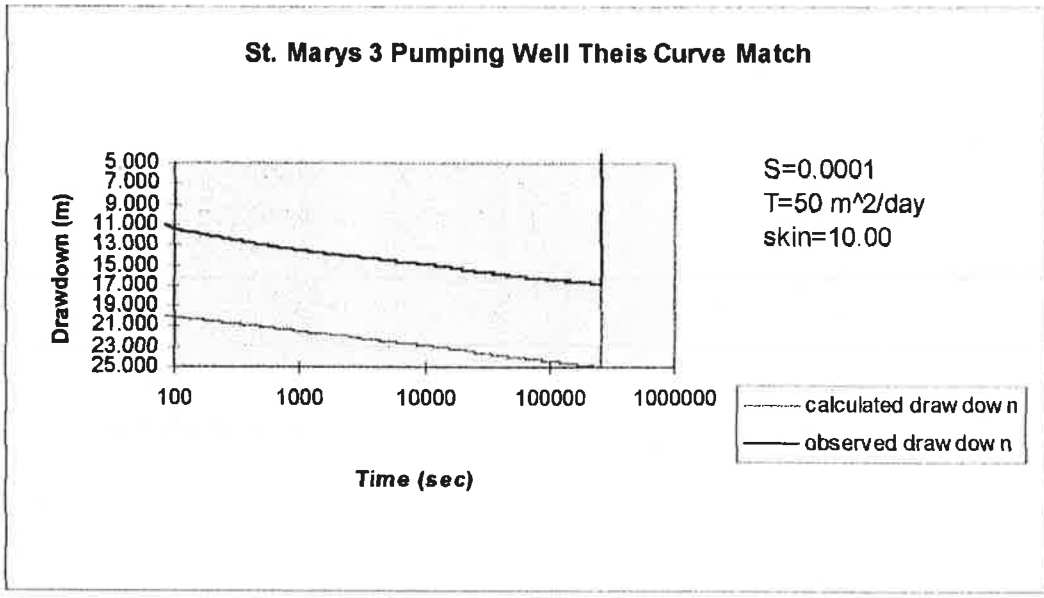

Figure B-5. Semi-log plot of pumping well St. Marys 3 theoretical calculated drawdown and measured drawdown (all correction factors applied), using a value for S of 0.0001 and guesses for T of 50 m^2/day and a skin of 10.00. Notice the slope of the theoretical drawdown approximately matches the slope of the measured drawdown.

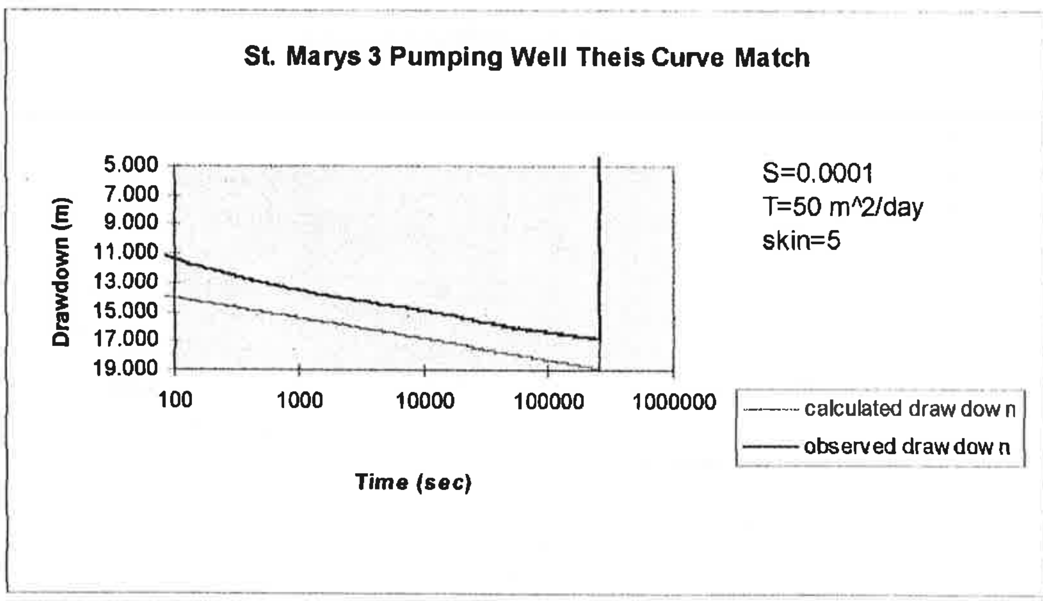

Figure B-6. Plot of pumping well St. Marys 3 theoretical calculated drawdown and measured drawdown (all correction factors applied), using a value for S of 0.0001 and guesses for T of 50 m^2/day and a skin of 5.00.

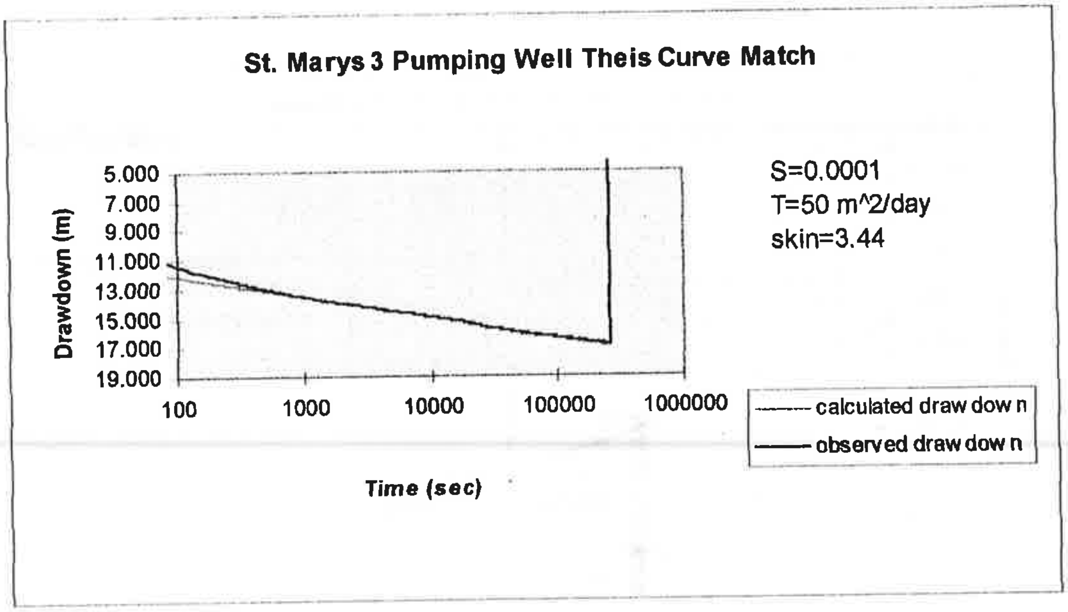

Figure B-7. Plot of pumping well St. Marys 3 theoretical calculated drawdown and measured drawdown (all correction factors applied) using a value for S of 0.0001 and guesses for T of 50 m^2/day and a skin of 3.44. This is the best curve match possible according to the lowest residual value.

(6) The well efficiency of a pumping well is calculated by determining the ratio of the theoretical calculated drawdown with a skin factor of 0 to the actual measured drawdown. A perfectly efficient well would have a well efficiency equal to one. In the case of the St. Marys pump test, a storativity value for the aquifer had to be assumed because it could not be estimated from observation well data analysis. The skin factor in the pumping well data analysis depends on the accuracy of storativity estimate and therefore makes the computation of the well efficiency invalid. To get a more accurate estimate of the skin factor (and therefore storativity) in the pumping well without the application of observation well data analysis, a step drawdown pump test on the pumping well would be neccesary. Assuming the value for storativity is accurate, the well efficiency of the pumping well St. Marys 3 is 73.8% as shown in Figure B-8.

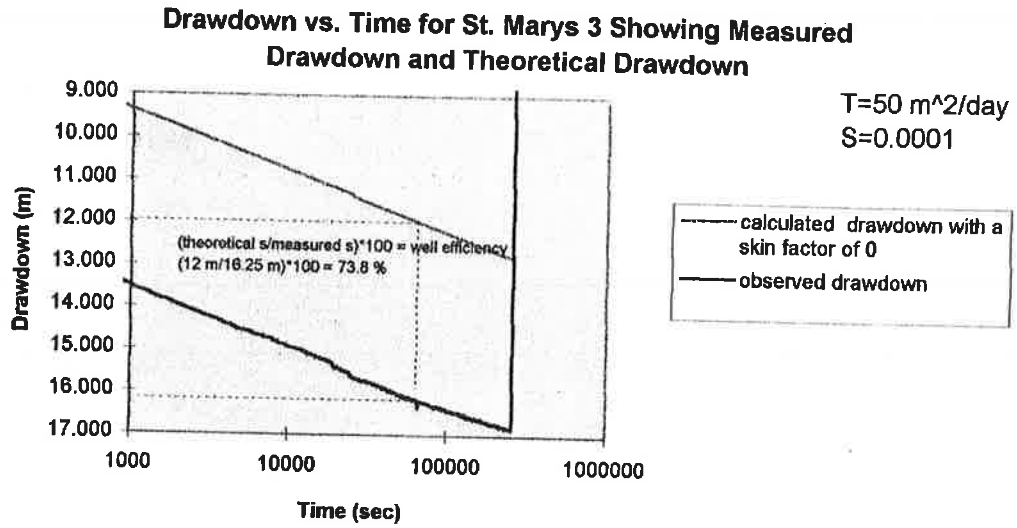

Figure B-8. Plots of pumping well St. Marys 3 measured drawdown (all correction factors applied) and theoretical drawdown with skin = 0, T = 2000 m^2/day and S = 0.0001, showing well efficiency calculations. A well efficiency of 73.8% was calculated but may not be realistic due to the storativity (and therefore the pumping well skin factor) not being able to be estimated from the data analysis.