CITY OF ST. MARYS, OHIO DRINKING WATER SOURCE PROTECTION PLAN

Appendix F

Delineation of Wellhead Protection Area Report

REPORT

DELINEATION OF WELLHEAD PROTECTION AREA

Submitted to the:

City of St. Marys, Ohio

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EXECUTIVE SUMMARY

In a continuing effort to understand and protect its groundwater resources, the City of St. Marys has been actively involved in developing a comprehensive Wellhead Protection Program (WHPP). This report was developed as a result of these efforts, and its objective is to present the results of the activities performed in delineating the Wellhead Protection Areas (WHPAs) for the two existing wellfields.

Diverse activities were performed in the development of this report including: compilation of previous studies/investigations relative to the geology and hydrogeology of the region and of the immediate vicinity of St. Marys; review of over 100 well logs from private, industrial, and municipal wells drilled in the study area; and drilling of a production well in the South Wellfield in which a pump test was performed. Other activities conducted included the interpretation of pump tests, collection of groundwater elevation data from several wells still available in the area, and survey of wells and various points along streams and rivers. The information compiled and generated was fundamental in developing a three-dimensional numerical flow model of the study area and in the delineation of the WHPA's.

1.0 INTRODUCTION

1.1 GENERAL

As a result of the increasing number of groundwater contamination caused by man's activity reported over the last decade, public attention has been drawn to the need for a strategy to manage and protect our groundwater resources. This has led to the development of groundwater protection programs at the federal, state, and local levels. Amendments to the Safe Drinking Water Act (SDWA) passed in June 1986, mandated that each state, through legislation, regulation, and administration policies, develop criteria for protection of groundwater. As a result, the Wellhead Protection Program (WHPP) was created.

The objective of the WHPP is to define an area surrounding a public water supply well or wellfield and to develop management strategies to control potential sources of contamination within the designated area. This area is know as the Wellhead Protection Area (WHPA). The WHPA has been defined as the surface and subsurface area surrounding a public water supply well or wellfield, through which contaminants, if spilled or deposited, will most likely pass and eventually reach the wellfield.

From a practical point of view, the activities to be performed in relation to the development of a local WHPP can be grouped into three main categories:

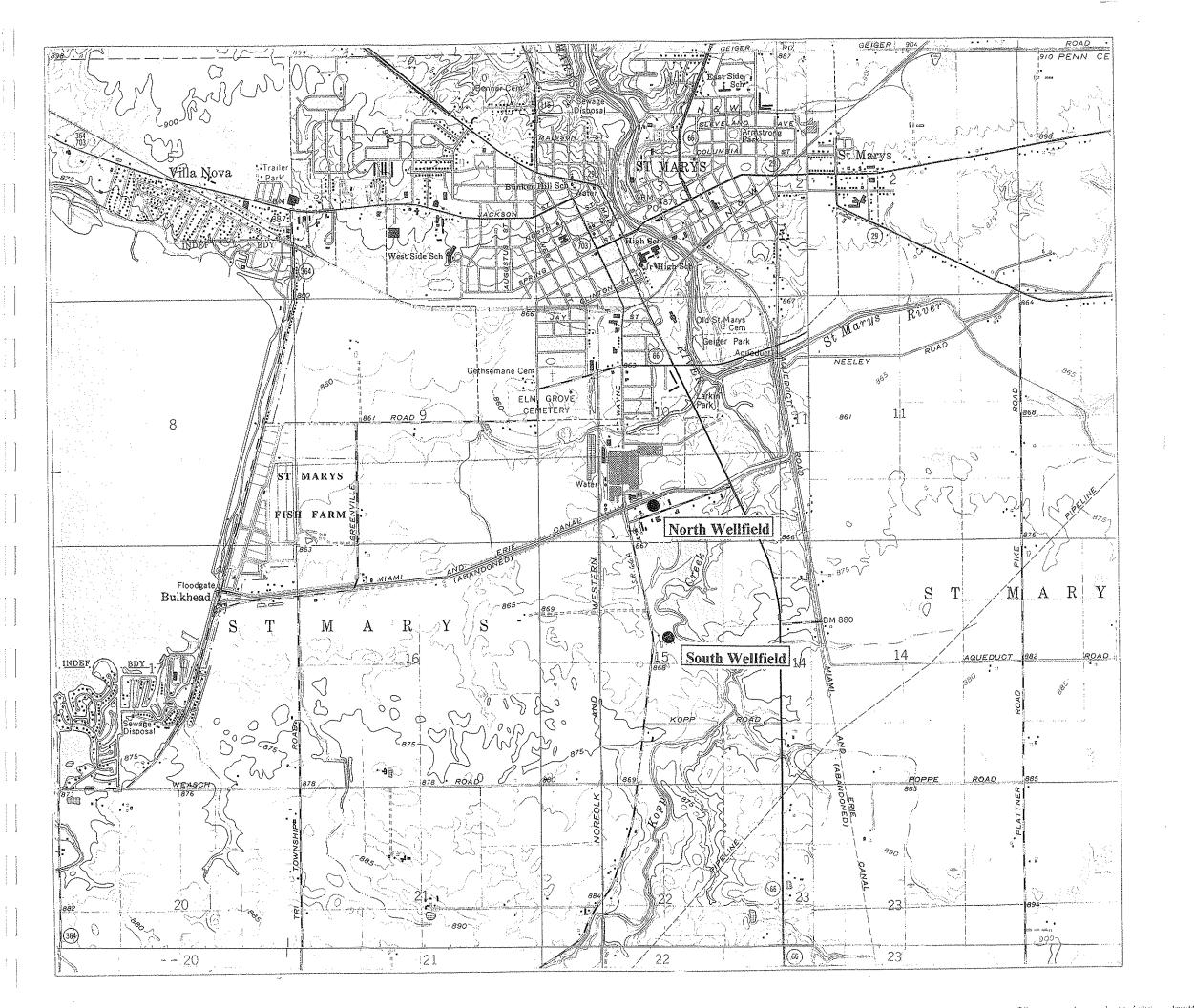
- 1. Delineation of WHPA
- 2. Inventory of Potential Sources of Contamination within the WHPA
- 3. Development of management strategies for efficient management of the WHPA

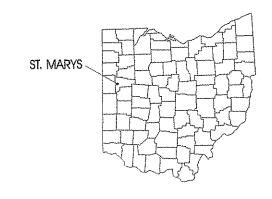
The recommended procedures for developing a WHPP is a phased-approach, beginning with the delineation of the WHPA. This report is a summary of the activities conducted with the objective of delineating the WHPAs for the City of St. Marys' wellfields.

1.2 STUDY AREA

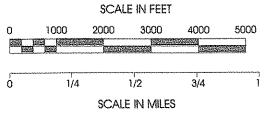
The City of St. Marys is located in the west-central portion of Auglaize County; which itself is located in the west-central portion of Ohio, approximately 20 miles East of the Indiana-Ohio border (Figure 1). The study area is characterized by a relatively-flat topography with ground elevations ranging from approximately 850 to 900 feet above USGS datum for a relief of approximately 50 feet. The ground slopes gently in a northerly direction; therefore, the highest elevations are encountered in the south portion of the study area.

Regionally, the study area is located near a surface water divide in which the area immediately north of the City drains into St. Marys River, eventually reaching the Maumee River and draining into Lake Erie. On the other hand, the area immediately south of the study is drained by the Miami River, which eventually drains into the Ohio River and finally discharges into the Gulf of Mexico. The area of interest, however, is drained by the St. Marys' River which has its origin within study area. It moves northward for a short distance before taking a west-northwesterly direction into the State of Indiana where it joins the Maumee River on the west side of the City of Fort Wayne, before draining into Lake Erie.









ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

STUDY AREA



Jones & Henry Engineers, Ltd.

FIGURE 1

1.3 WATER SUPPLY

The City of St. Marys relies entirely on groundwater for its water supply. Consequently, it is necessary that the wellfields be capable of meeting the current and future "Average-Day" water demand. A previous study conducted by Jones & Henry Engineers in 1991 estimated the "Average-Day" water demand for that year at approximately 1.3 mgd. This demand is expected to increase to 2.8 mgd by the year 2020.

The City currently operates two wellfields to meet the City's water demand. The first wellfield to be developed was the South Wellfield, which is located approximately one-half mile north of State Route 219 on the east side of County Road 66A (See Figure 1). The other wellfield developed, is the North Wellfield, which is located approximately 3/4 miles north of the South Wellfield between State Route 66 and County Road 66A and north of South Park Drive. The following is a brief description of the characteristics of each wellfield.

1.3.1. South Wellfield

Development of the South Wellfield began in 1943 with the construction of an 8-inch well, currently identified as Well No. 3. An additional 12-inch well was constructed in 1946 at approximately 250 feet southeast of Well No. 3 and is currently identified as Well No. 4.

During the course of this study, a new well, identified as Well No. 5, was drilled in the south wellfield and is intended as a replacement to Well No. 3 which is failing.

The aquifer intercepted by the wells located in the South Wellfield consists of sand and gravel deposits from the ancestral Teays valley. This aquifer is overlaid by more than 250 feet of glacial till and moraine. The information available indicates, that the glacial deposits in the South Wellfield area may be over 400 feet thick.

During construction of Well No. 3, it was noted, that the main aquifer is encountered at a depth of approximately 275 feet below ground surface. The well was drilled to a depth of 332 feet and penetrated approximately 57 feet into the aquifer. The aquifer in this area is under high hydrostatic pressure, producing an artesian effect that causes the groundwater to flow above the top of the well casing. At the time of construction of Well No. 3, it was determined, that the rate at which the well overflowed was approximately 990 gpm.

At the site of Well No. 4, the aquifer was intercepted at approximately 311 feet. The well was drilled to a depth of 343 feet and intercepts 32 feet of aquifer. An artesian effect was also noted in this well, causing the groundwater level in the well to rise to within six feet below the ground surface. However, the effect did not produce a flow of water over the top of the casing, probably due to the operation of Well No. 3.

The drilling of Well No. 5 was completed in December 1998. During its construction, it was noted, that the main aquifer was encountered at a depth of approximately 288 feet below ground surface. The well was drilled to a depth of 354 feet, of which the last six was reported to contain a substantial percentage of clay. Based on information derived from the log of Well No. 5, it is estimated, that the main aquifer is approximately 60 feet thick. Overlaying the main aquifer are alternating layers of clay, and clay with sand and/or gravel. Due to the artesian effect described previously, the water level in the well rises to near ground level (approximately 12 feet), depending on the activity in the wellfield. It is estimated, that if

operations in the wellfield should be suspended for a prolonged period of time, the water level would rise above the ground surface.

1.3.2. North Wellfield

Development of the North Wellfield began in November 1967 with the construction of a 12-inch well, currently identified as Well No. 1. Construction of Well No. 2 began in May 1968, immediately after the construction of Well No. 1. Well No. 2 is also a 12 inch well; both wells intercept a bedrock aquifer.

The bedrock aquifer in the vicinity of St. Marys consists of alternating layers of light gray, blue, and yellow consolidated limestone. In certain locations there is some evidence of sandstone. In the area of Well No. 1, the limestone aquifer is approximately 190 feet thick and is overlaid by 75 feet of glacial deposits consisting mainly of clay, clay and gravel, and boulders. In the area of Well No. 2, the limestone aquifer is 171 feet thick and is overlaid by 94 feet of glacial deposits consisting mainly of clay. Underlying the limestone aquifer, is a blue shale formation, which according to the well logs, is over 20 feet thick. Both wells were finished in the shale formation, leading to the conclusion that the wells fully intercepted the limestone aquifer. An artesian effect was also noted in both North Wellfield wells, resulting in groundwater levels at approximately 27 feet below ground surface at the time of construction.

A pump test was conducted in Well No. 1 at the time of construction. During the test, Well No. 1 was pumped at a rate of 800 gpm, for a duration of 14-1/2 hours. The resulting drawdown at the end of the test was 10.75 feet. The initial specific capacity computed for this well is 74.42 gpm/ft. Well No. 2 was tested at 800 gpm during eight hours, resulting in drawdown of 10.33 feet. The specific capacity for this well is 77.44 gpm/ft.

1.3.3. Well Construction Details

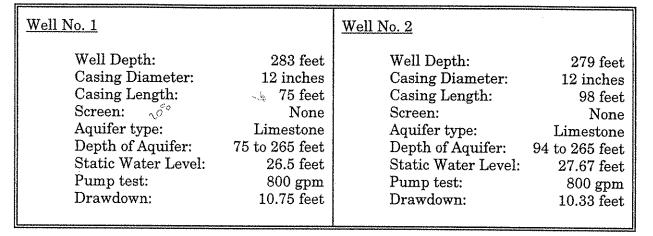
As mentioned previously, Wells No. 1 and No. 2, located in the North Wellfield, were completed in the consolidated aquifer limestone, which is underlaid by a shale formation. Both wells are of the "open-hole" type construction, which means that the bore hole is drilled to the top of the consolidated formation (in this case, the limestone aquifer) into which the casing is set; the construction then proceeds to the desired depth, preferably to the bottom of the aquifer. No screen is required in "open-hole" bedrock well construction, as the aquifer is a stable consolidated formation which does not crumble and, consequently, little or no fines enter into the well during operation.

Following is a summary of construction details for the wells located in the North Wellfield. Additional information is included on the well logs located in Appendix A.

TABLE 1







Wells No. 3 and No. 4, located in the South Wellfield, intercept a sand and gravel aquifer within the glacial deposits and consequently were screened to avoid fine particles entering the wells during operation. As mentioned previously, these wells were constructed in the early 1940s and are approximately 50 years old. It is generally accepted, that the life expectancy of a well is approximately 25 years. This may vary depending on the aggressiveness (corrosiveness) or incrusting (scaling) capacity of the groundwater quality, the operating conditions, and maintenance of the wells. However, as a rule of thumb, 25 years is utilized as the life expectancy of any given well. This is especially true of "screened wells," as typically, the well screen deteriorates faster than the well casing. Consequently, it can be stated, that Wells No. 3 and No. 4 have outlived (in fact doubled) their life expectancy.

Maintenance records indicate, that in 1988, the screen in Well No. 3 was replaced due to the fact that it had "collapsed," allowing large gravel and sand to enter the well, to the extent of damaging the pumping unit. The original construction of this well included 39 feet of screen consisting of a six-inch slotted pipe. Based on typical construction material available at time of well construction, it is estimated, that the design capacity of this well was approximately 420 gpm. This indicates that the well was substantially "over-pumped," which may have accelerated its deterioration.

Well No. 3 was "overdrilled" in 1988 to remove the six-inch screen which was replaced with 43 feet of five-inch stainless steel screen, with a slot size of 0.025 inches. It is estimated, that the replacement screen has an hydraulic capacity of approximately 680 gpm (based on typical screen construction and assuming an entrance velocity of 0.1 ft/sec). The replacement well screen is fairly new and of sturdy and lasting construction, and should provide many years of good service at the estimated capacity. However, there is still a possibility of casing failure.

Well No. 4 was tested at a rate of 1,062 gpm for a period of 24 hours, at the time of well construction, resulting in a drawdown of 34 feet for a specific capacity of 31.2 gpm/ft. Information from the log of this well indicates, that the length of the screen is only 11.5 feet. There is no information available as to size of the screen slot or its diameter (which can be assumed to be 10 inches - based on standard well construction practices). As a result, it is not

possible to make an accurate estimate the design capacity of the screen. However, assuming a best-case scenario of a 12-inch screen with a 22% open area (slotted pipes seldom provided more than 15% open area), the design capacity of the screen would be approximately 350 gpm. These results indicate, that Well No. 4 has been pumped at an excessive rate, greatly exceeding the design capacity of the well. Based on the experience from Well No. 3, it is safe to assume that Well No. 4 is even less reliable than Well No. 3. Well No. 4 should be monitored closely in order to detect any early signs of well deterioration.

As mentioned previously, the construction of Well No. 5 was completed in December 1998. The well was constructed with a 20-inch casing and 45 feet of 18-inch wire-wound, stainless screen. The estimated capacity of the well is 1,800 gpm (2.6 mgd).

Following are construction details of the wells located in the South Wellfield taken from the well logs included in Appendix A. The data for Well No. 3 was modified to incorporate the modifications made during the well rehabilitation conducted in 1988.

TABLE 2

SOUTH WELLFIELD WELL CONSTRUCTION DETAILS

Well No. 3	Well No. 4	Well No. 5
Well Depth: 332 feet Casing Diameter:	Well Depth: 343 feet Casing Diameter: 12 inches	Well Depth: 350 feet Casing Diameter: 20 inches
Casing Length: 8 inches 308 feet	Casing Length: 338 feet Screen Length: 11.5 feet	Screen Length: 45 feet
Screen Length: 43 feet Screen Diameter: 5 inches	Screen Diameter: Unknown Screen type: E.E. Johnson	Screen Diameter: 18 inches Screen type: W.W.S.S.
Screen type: SS No. 0.025	Estimated Capacity: 350 gpm.	Estimated Capacity: 1800 gpm.
Estimated Capacity: 680 gpm.	Aquifer type: Sand & gravel	Aquifer type: Sand & gravel
Aquifer type: Sand & gravel	Depth of Aquifer: 311 feet	Depth of Aquifer: 288 feet
Depth of Aquifer: 275 feet	Aquifer thickness: Unknown	Aquifer thickness: 60 feet
Aquifer thickness: Unknown	Static Water Level: 6 feet	Static Water Level: 12.9 feet
Static-Water Level: Flowing	Pump test: 1,062 gpm	Pump test: 2,463 gpm
Pump test: 990 gpm	Duration: 24 hrs	Duration: 24 hrs
Drawdown: None*	Drawdown: 34 feet	Drawdown: 103 feet
* No drawdown. Overflow volume due to artesian effect.		

1.3.4. Wellfield Operation

The table provided below summarizes the operating conditions of the wells.

TABLE 3
INSTALLED PUMPING CAPACITY

WELL I.D.	PUMPING RATES (1991)	PUMP SETTING (feet)	MAXIMUM OPERATING DYNAMIC LEVELS (feet)
Well No. 1	1166 gpm	60 ft	N/A
Well No. 2	1012 gpm	80 ft	20 feet
Well No. 3	469 gpm	90 ft	N/A
Well No. 4	720 gpm	65 ft	51 feet
Well No. 5	1300 gpm	200 ft	120 feet

Based on the information presented on Table 3, it can be concluded that both wellfields have adequate installed capacity to meet the future water demands of the City.

1.4 CHEMICAL CHARACTERISTICS OF THE GROUNDWATER QUALITY

Table 4 below is a summary of groundwater quality data available for the first four existing wells. It indicates, that in general, the water quality of both aquifers is practically the same. This leads to the conclusion that there may be an intimate contact between the bedrock and sand and gravel aquifers. Therefore, from the standpoint of water quality, there is no preference in selecting any aquifer over the other. Included in Appendix B, is a detailed report of water quality, corresponding to Well No. 5, which was taken at the time of the pump tests, immediately after well construction. The table below is provided for comparison of the two wellfields.

TABLE 4
WATER QUALITY DATA

		NORTH W	ELLFIELD	SOUTH WE	LLFIELD
PARAMETER	UNITS	No. 1	No. 2	Nos. 1 & 3 ¹	No. 4
pH	S.U.	7.4	7.4	7.4	7.6
Total Alkalinity	mg/ℓ	320	252	335	334
Total Hardness	mg/l	530	530	469	451
Carbonate Hardness	mg/ℓ	320	252		

		NORTH W	ELLFIELD	SOUTH WELLFIELD				
PARAMETER	UNITS	No. 1	No. 2	Nos. 1 & 31	No. 4			
Calcium as CaCO ₃	mg/l	340	320					
Calcium as Ca	mg/l	136	128					
Magnesium as CaCO ₃	mg/ℓ	190	210	201	194			
Chloride	mg/ℓ	12	15					
Iron	mg/l	2.1	3.6					
Sulfate	mg/ℓ	220.	290					
Manganese	mg/l	0.0	0.0					
Nitrate	mg/l		0.0					
Total Solids	mg/l	752	810					
Specific Conductance	μ mhos/cm	800	870					

¹ Well No. 3 always operates in conjunction with Well No. 1. Data presented is the result of the mixed flow.

2.0 GEOLOGY/HYDROGEOLOGY

2.1 BRIEF GEOLOGICAL OVERVIEW

Basic understanding of the geology of the study area has been derived from the review of over 100 well logs from private, industrial, and municipal wells drilled in the area. Figure 2 shows the location of approximately 50 wells selected to represent the most predominant features of the geology of the area. These wells were utilized in the development of geological/hydrogeological maps of the area such as contour of bedrock elevation, thickness of the sand and gravel deposits, and various cross sections of the area. The logs of these wells are included in Appendix A along with tables summarizing the most outstanding characteristics of each well.

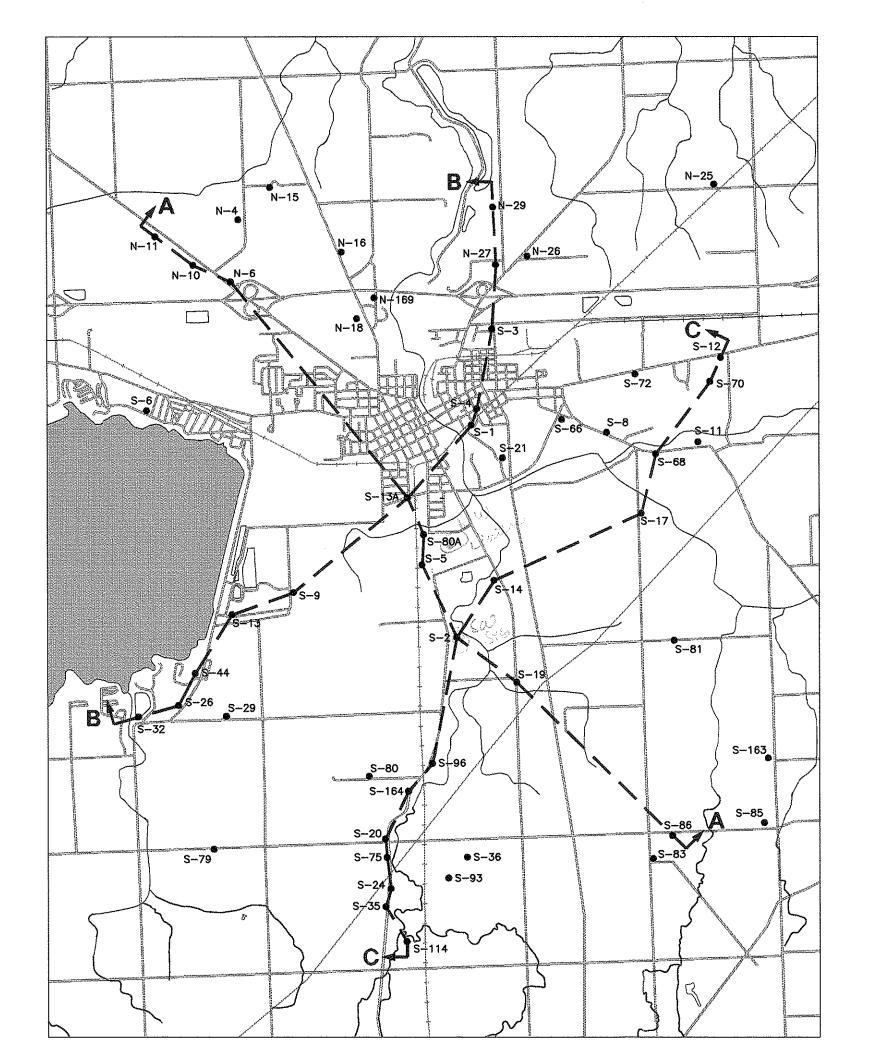
In the vicinity of the City of St. Marys, groundwater can be obtained from two different aquifers. The first, and seldom used, is a surficial aquifer consisting of discontinuous lenses of sand and/or gravel located within the glacial deposits which blanket most of the area. From the standpoint of groundwater resources, the glacial deposits, commonly referred to as drift, can be classified in two main categories, till and outwash.

Till is a predominantly unsorted and unstratified formation with little or no consolidation, deposited directly by glaciers without reworking by meltwater and consists of a heterogeneous mixture of clay, silt, sand, gravel, and boulders. Typically, aquifers located in till formations have very limited capacity as groundwater resources, and in most instances, can only be used for limited domestic water supply.

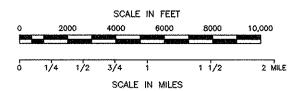
Outwash formations are stratified sand and gravel removed or washed out from a glacier by meltwater streams and deposited in front of (or beyond) the end moraine or on the margin of an active glacier. The coarser material is deposited nearer to the ice, becoming finer as it moves away from the end moraine. Typically, aquifers in outwash and alluvial plains exhibit higher transmissivity than bedrock aquifers and can yield significant quantities of water to meet most industrial and municipal needs. However, outwash aquifers are usually small in extension; therefore, the quantities of water that can be stored will vary depending on the extension and thickness of the coarser material, namely sand and gravel.

It is accepted, that in general, sand and gravel aquifers in the glacial deposits have the best potential for developing high-yield wells. However, in the vicinity of St. Marys, this resource is hardly used, perhaps due to the fact that the bedrock formation has capacity to supply most domestic demands. In addition, bedrock wells are more economical to construct and maintain, and in general, have a longer life span.

The second source of groundwater in the vicinity of St. Marys, and most widely used, is an aquifer located within the bedrock underlying the glacial deposits. The uppermost portion of the bedrock in the study area consists mostly of limestone. However, several wells drilled in the area reported to have encountered some sandstone. Limestone is a sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite, and in general, have little void space for fluid storage. Limestone is generally rigid and cracks easily when unevenly supported. Therefore, almost all limestone formations show extensive joint and fault systems as a result of external stresses. Substantial storage of water can, therefore,

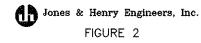






ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREAS

WELL LOCATIONS



take place in the bedrock as a result of secondary permeability from fractures and joints within the formation. However, these occur mostly in the upper portion of the bedrock.

If exposed at or near the land surface, limestone can undergo remarkable changes. Rainwater, in its descent to earth, commonly absorbs carbon dioxide from the air, forming a week acid called carbonic acid. When rainwater enters cracks and crevices in carbonate rocks, the acidic water may dissolve small volumes of rock. Over time, the removal of limestone along the cracks can be extensive, and voids (small reservoirs) can be created. In some cases, the effects of fracturing and dissolution by carbonic acid combine to create extensive high-yield aquifers. This is apparently the case in certain areas in the vicinity of St. Marys.

Underlying the limestone formation in the study area is a shale layer which, based on the well logs available, is at least 20 feet thick. Shale is a fine-grained sedimentary rock formed by the consolidation of clay, silt, or mud and is virtually impermeable. As a result, it is of little or no value as a groundwater resource.

2.2 GENERAL GEOLOGY OF THE AREA

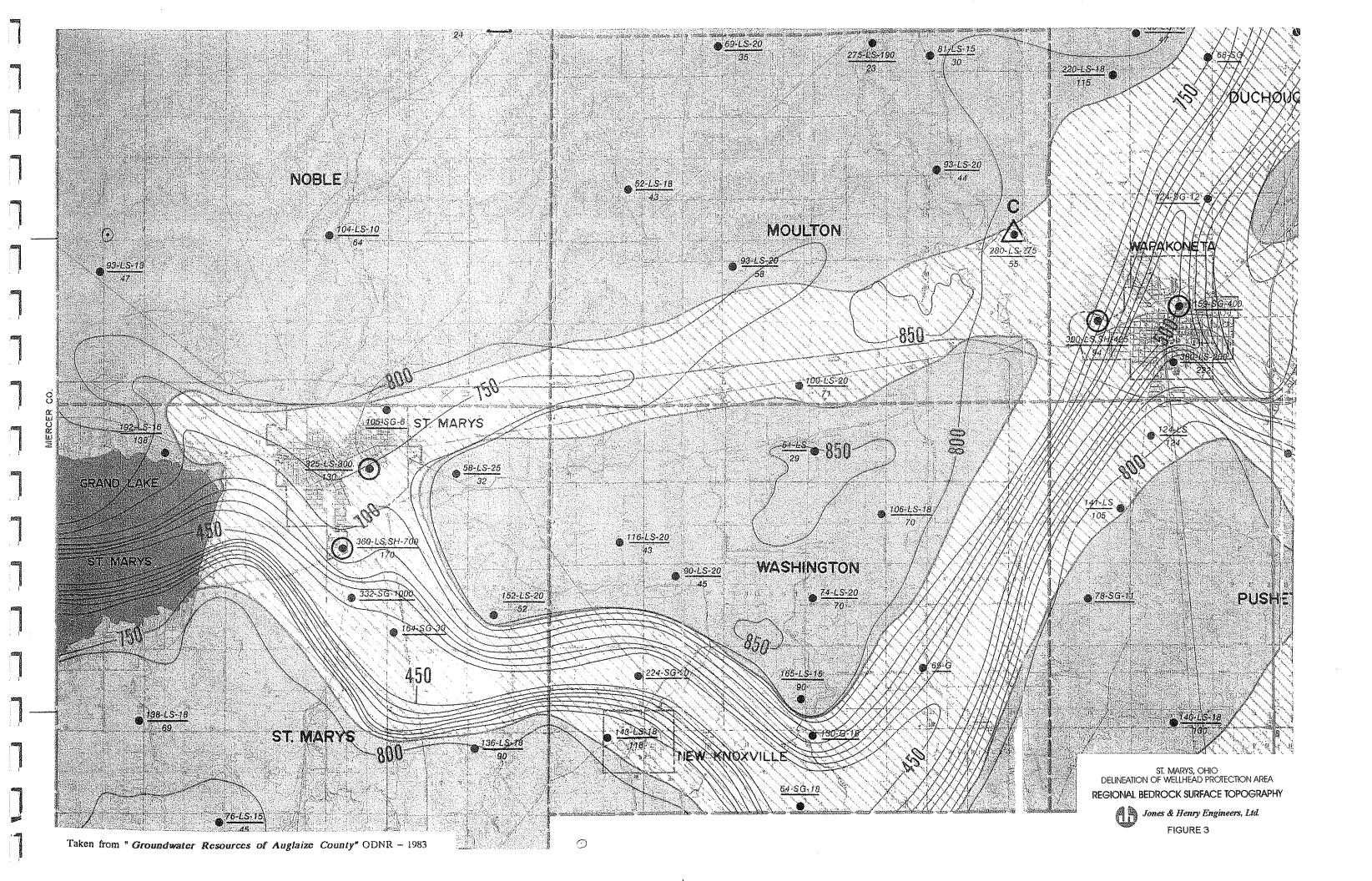
St. Marys lies within the Till Plains region of Ohio, which is characterized by a relatively level to rolling area shaped by the smoothing and depositional action of the Pleistocene Glaciers. The thickness of the glacial deposits in the vicinity of St. Marys vary from approximately 40 to 90 feet in most of the area to over 400 feet in the vicinity of the South Wellfield, and consists mostly of stratified clay lenses alternated with sand and gravel.

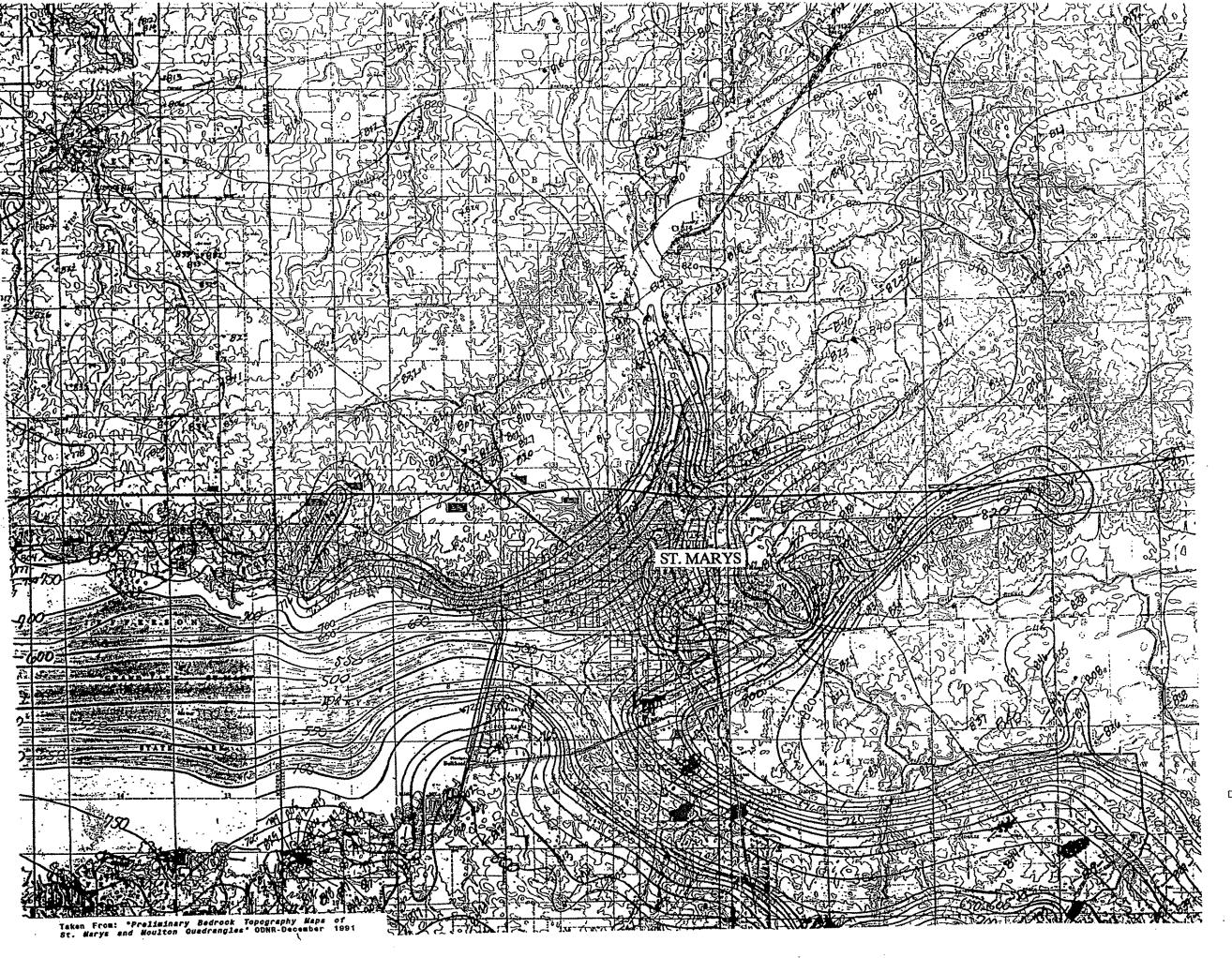
An outstanding geological feature in the area, is a buried bedrock valley associated with the ancient preglacial Teays River which ran across central Ohio into Indiana (Figures 3 and 4). The main body of the Teays flowed just south of the City of St. Marys with a predominantly westerly flow and was joined by tributaries in the general area where the City of St. Marys is now located. The thickness of the glacial deposits in the area is influenced by this occurrence and is what gives the bedrock its current configuration (Figure 5). Throughout the glaciation periods, the valley carved by the Teays has been filled with glacial deposits producing the current surface topography.

Figures 6 through 8 are cross sections developed to better illustrate the geology of the study area and correspond to the lines shown on Figure 2. They indicate the variability in the depth at which the bedrock is encountered and the apparent discontinuous nature of the sand and gravel lenses in the northern portion of the study area. With the exception of the wells drilled in the South Wellfield, no other wells in the area have been drilled in the ancient lakebed of the Teays. However, it is estimated, that the sand and gravel aquifer encountered in this area should be continuous along the course of the ancient river and is limited laterally by the walls of the valley.

2.3 GROUNDWATER FLOW AND RECHARGE

The information gathered from the well logs indicated, that flow in the bedrock formation is confined, evidenced by the fact that after intercepting the bedrock aquifer, the static water level in the wells rises to within a few feet of the ground surface. A similar condition can be noted in the two wells in the South Wellfield which intercept a sand and gravel aquifer deposited in the streambed of the ancient Teays River. Even though the aquifer was intercepted at a depth of more than 280 feet, the static water level in the wells rises to within





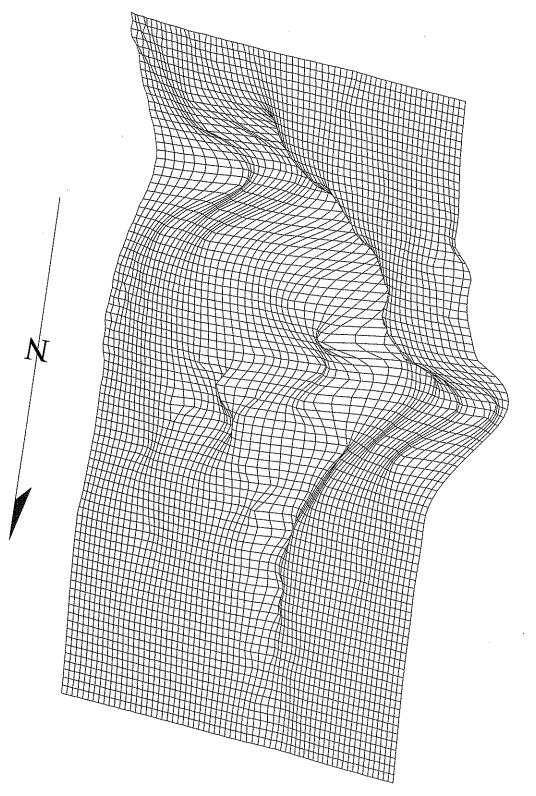


ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

BEDROCK SURFACE TOPOGRAPHY IN THE STUDY AREA



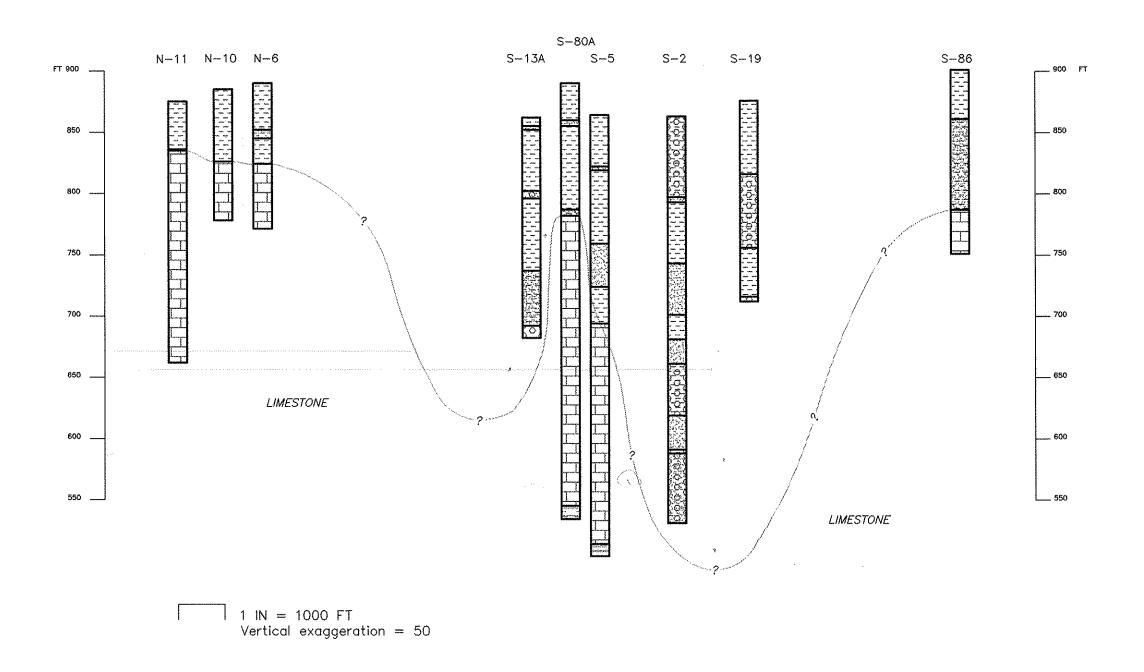
Jones & Henry Engineers, Ltd. FIGURE 4



ST. MARYS, OHIO
DELINEATION OF WELLHEAD PROTECTION AREA

3-DIMENSIONAL VIEW OF
THE BEDROCK SURFACE

1 Jones & Henty Engineers, Ltd.
FIGURE 5

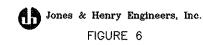


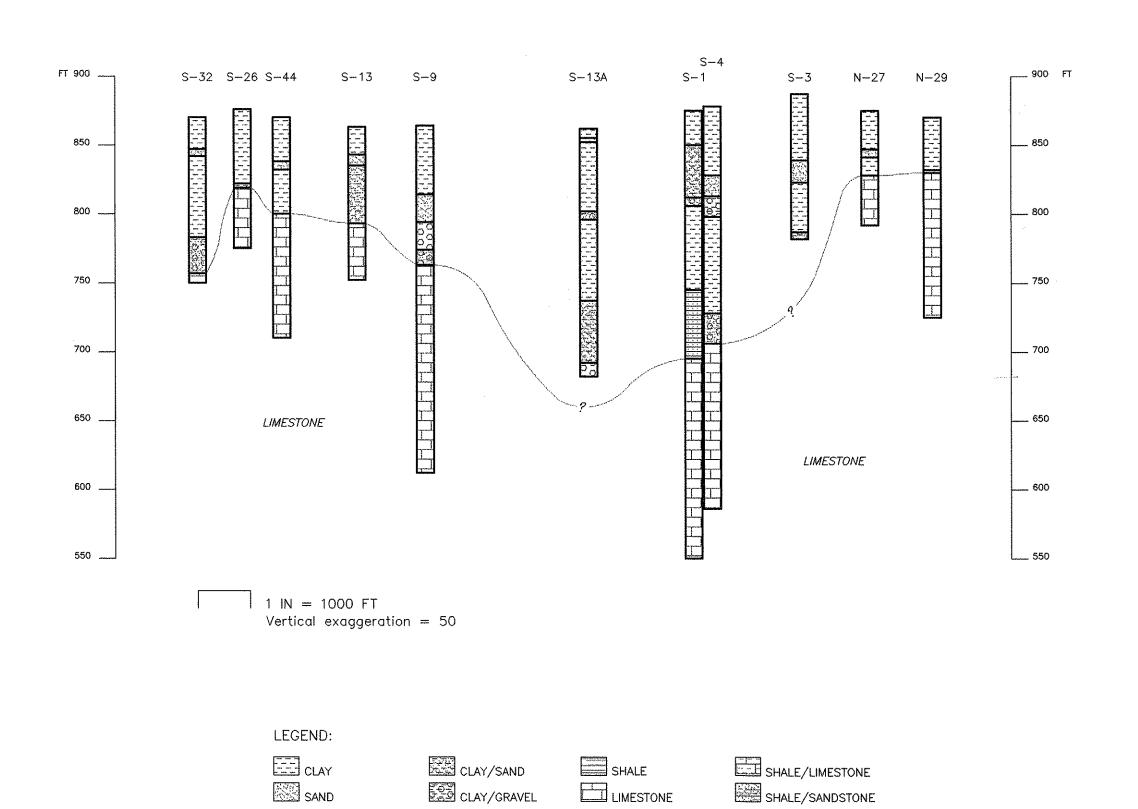
LEGEND:

CLAY
CLAY/SAND
SHALE
SHALE/LIMESTONE
SHALE/SANDSTONE

CLAY/GRAVEL
SAND/GRAVEL
SANDSTONE
TOPSOIL
COAL

ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREAS





ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREAS

CROSS SECTION B-B

Jones & Henry Engineers, Inc. FIGURE 7

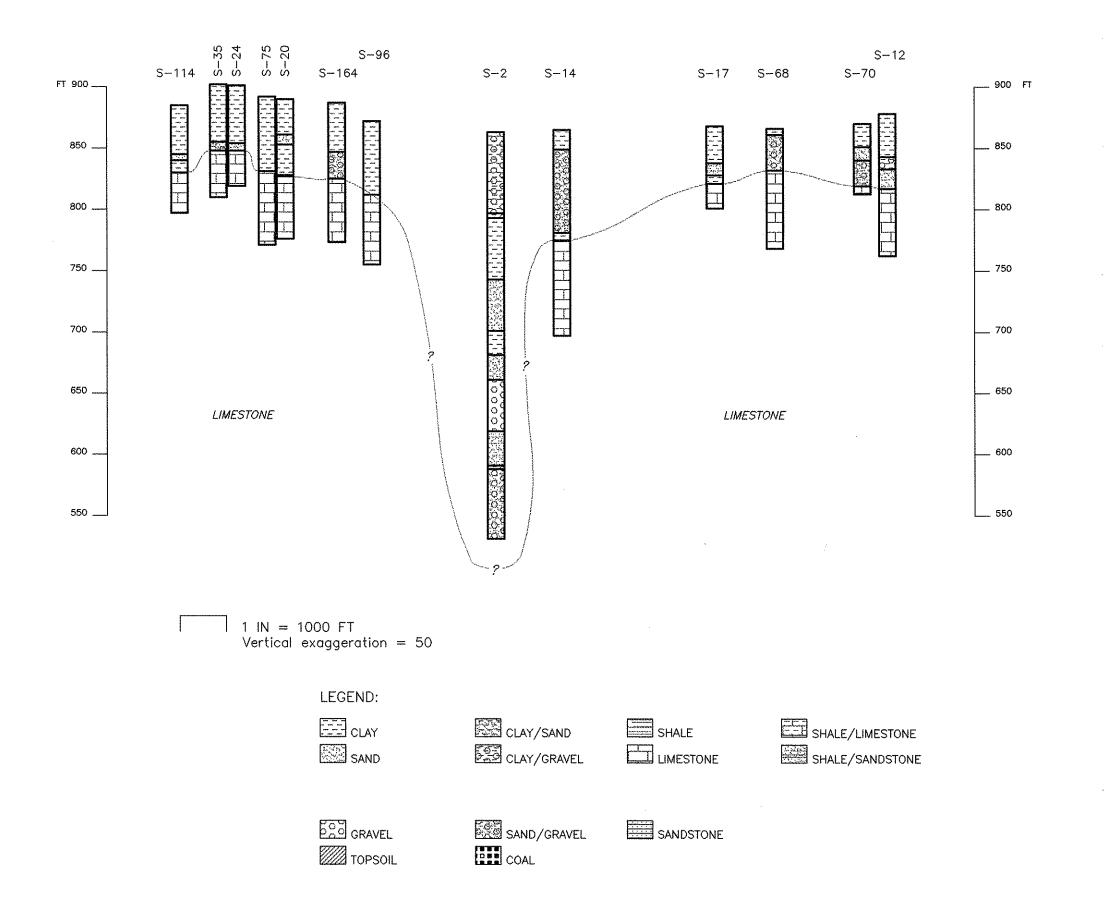
GRAVEL

TOPSOIL

SAND/GRAVEL

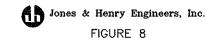
COAL

SANDSTONE



ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREAS

CROSS SECTION C-C



a few feet of the ground surface, and in one well, it was even reported to flow above the ground surface.

One of the most important aspects in evaluating groundwater resources, is to have a clear understanding of the nature of the groundwater flow, its occurrence (source of recharge), and movement. In most geologic environments, groundwater flow at the local scale is toward existing drainage patterns (streams, lakes) with a regional component following the course of the main drainage pattern. Another occurrence frequently noted, is local groundwater flowing under the influence of the bedrock topography.

In order to obtain a preliminary assessment of the direction of groundwater flow, a map depicting the direction of groundwater flow in the bedrock formation was developed. This map was based on static groundwater levels reported on the well logs at the time of well construction and using ground elevations obtained from topographic maps of the area (Figure 9). While the above procedure allows for some error, the objective of defining a preliminary direction of groundwater flow is well served. Figure 9 indicates, that the groundwater flow in the bedrock formation in the vicinity of St. Marys is to the north; apparently, driven by the St. Marys River drainage system. There is no indication that groundwater flow in the bedrock formation is affected by the ancient Teays River.

Based on Figure 9, it can be concluded, that the recharge to the bedrock formation occurs south of the study area, probably in the vicinity of New Bremen and Minster, which corresponds to a surface water divide described previously.

Due to the limited number of wells constructed in the glacial deposits, it was not possible to develop maps depicting the direction of groundwater flow in the sand and gravel formation. However, based on similarities of groundwater levels in glacial wells compared to adjacent bedrock wells, it was estimated, that groundwater flow in the glacial deposits may be similar to the bedrock aquifer. This, in combination with the similarities in groundwater quality, leads to the conclusion that there may be an intimate relationship between the bedrock and glacial aquifers.

2.4 HYDRAULIC PROPERTIES OF THE SAND AND GRAVEL AQUIFER

Two of the most important aquifer hydraulic parameters needed to adequately evaluate a wellfield potential is: a) hydraulic conductivity and b) storativity. Hydraulic conductivity (often referred to as permeability) is a measure of the ease with which groundwater moves through the aquifers. A similar related term, transmissivity, indicates the capacity of the aquifer to transmit water through its entire thickness. Transmissivity is estimated by multiplying the hydraulic conductivity by the thickness of the aquifer. The other parameter is Storativity, which is a measure of the volume of water the aquifer is capable of releasing from or taking into storage.

Aquifer's hydraulic parameters are generally determined from pump tests designed specifically for this purpose. Unfortunately, there is limited information available on the hydraulic properties of the sand and gravel aquifer in the vicinity of the South Wellfield. The only information available pertains to the pump test conducted in December 1998 at the time of the construction of Well 5. Interpretation of the pump test indicates that the Transmissivity is in the order of 32,000 gpd/ft. Considering that the aquifer is approximately 80 feet thick,

the equivalent hydraulic conductivity is 54 ft/day. The storage coefficient was estimated at approximately 2.0×10^{-3} , confirming the confined nature of the aquifer. The transmissivity value is consistent with preliminary estimates performed by Jones & Henry Engineers in a previous study which was reported to be in the order of 40,000 gpd/ft. Those estimates were based on information derived from capacity tests performed in the wellfield.

It is important to note, that during the interpretation of the pump test conducted in Well No. 5, the presence of negative boundaries in the immediate vicinity of the well became evident. These boundaries are assumed to be the walls of the ancient Teays River valley in which the well is drilled. Appendix C contains the results of the pump tests and their interpretation.

2.5 HYDRAULIC PROPERTIES OF THE BEDROCK AQUIFER

Estimates of transmissivity of the bedrock formation in the area of the North Wellfield area was performed based on a pump test conducted in 1967 at the time of well construction. Even though the test was not specifically conducted to determine aquifer hydraulic parameters, it does allow a reasonable estimate. Computations performed indicate, that the transmissivity of the formation is in the order of 150,000 to 200,000 gpd/ft. Considering that the aquifer is approximately 190 feet thick, the equivalent hydraulic conductivity is 105 to 140 ft/day. These values indicated favorable conditions for development of large industrial and municipal water supplies. Preliminary estimates for storage coefficient resulted in values of 1.5×10^{-6} . This value is very low, and apparently is in error.

Additional information on the evaluation of the pump tests is provided in Appendix C. In summary, based on the information available, it can be concluded that both aquifers currently utilized by the City of St. Marys for its water supply are adequate to meet the City's demand.

3.0 FLOW MODEL OF THE STUDY AREA

3.1 DESCRIPTION OF THE MODEL

The selection of a groundwater model is based on the ability of the model to represent, as accurately as possible and within the constraints of the model's objective, the aspects governing the groundwater flow. In the selection of a model for delineation of the WHPA for the City of St. Marys, special consideration was given to the complex nature of the groundwater flow patterns, the existence of relatively-close and complex hydrogeological boundaries, and possible influence of streams (recharge/discharge areas). These variables cannot be accurately represented by analytical or semi-analytical models; consequently, a "simplified" three-dimensional, finite difference numerical model was chosen for delineation of the WHPAs. The term "simplified" is used to describe the fact that a few physical and hydraulic parameters were assumed to be uniform for the pertinent wellfield. For example, an aquifer may have been assumed as having either a uniform thickness, transmissivity, and/or storage coefficient (a homogeneous aquifer). These simplifications, however, are consistent with the nature of the data available, and are acceptable practices within the objective of the model, which is to define the WHPAs for the City of St. Marys.

When constructing a numerical flow model of a given area, the objective is to represent pre-pumping steady state conditions, based on the knowledge of the aquifer's physical characteristics, geology of the area, and hydraulic parameters. Once it is estimated that the initial conditions of the model adequately represent the aquifer, pumping or dynamic conditions are then incorporated into the model. This is known as "stressed" conditions. The results of the model (predicted heads) are then compared to known/measured "stressed" conditions, and the "goodness-of-fit" is determined. The model is then calibrated by varying one or more hydraulic parameters until the best fit is obtained. If the best fit is determined to adequately represent known conditions, it is then concluded that the model is adequate and valid. In the process, a sensitivity analysis is usually performed to determine the variability of the results in relation to each of the parameters in consideration.

Once the model is calibrated, reasonable predictions can be made about the aquifer's performance under hypothetical or projected conditions. In the specific case of delineation of WHPAs, a reverse-particle tracking technique is applied to the flow model to define the wellfield capture zones based on the drawdown predicted by the model for the projected pumping rates.

The model selected for the mathematical simulation of St. Marys' wellfield is the numerical model known as MODFLOW. MODFLOW is the most widely used and accepted groundwater flow modeling program. Particle tracking for delineation of the WHPA was performed with MODPATH. The modeling process was accomplished using the modeling software known as GMS, which is a pre-and post-processor for both MODFLOW and MODPATH.

GMS is considered by many experts in the groundwater modeling industry as the most advanced, powerful, and comprehensive groundwater modeling package available. The program was developed by the Engineering Computer Graphics Laboratory of Brigham Young University under the direction of the U.S. Corps of Engineers with support from the Department of Defense, the Department of Energy, and the Environmental Protection Agency.

In preparing the model of the wellfield, the area was divided into uniformly-spaced segments or grids. Each node of the grid has an assigned X, Y, coordinate. In addition, each note is assigned various elevations, Z, depending on the configuration of the model. These elevations are either aquifer and/or groundwater elevations, river stages, etc.

The calibration of the model was based on a trial and error adjustment of the transmissivity, vertical conductance, or any other relevant factor. Calibration was achieved by determining the Root Mean Square Error (RMSE) for a determined set of parameters based on the following equation:

RMSE =
$$\sqrt{\frac{(e_1)^2 + (e_2)^2 + \dots (e_n)^2}{n}}$$

where:

 $e_i = error$ at node i

n = number of nodes for which an error value was determined

The calculation of the RMSE was obtained by comparing the groundwater elevations measured on a specific date to the elevations predicted by the model for the pumping conditions prevalent for that date.

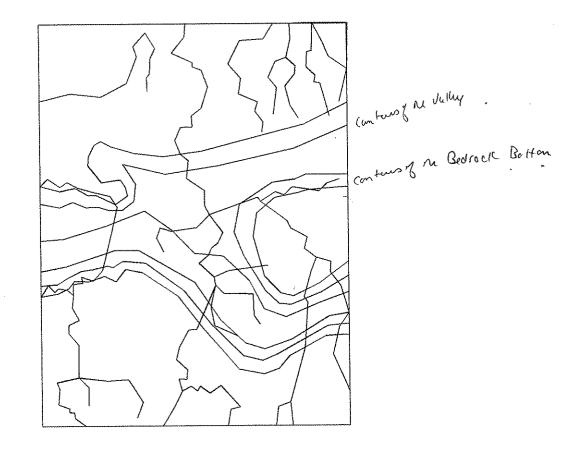
3.2 CONCEPTUAL FLOW MODEL OF THE WELLFIELD

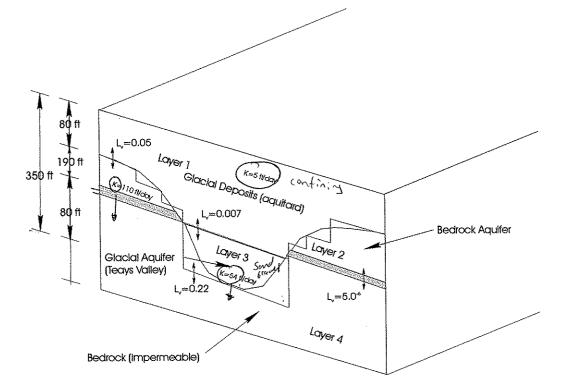
The first step in the modeling process, is to develop the "conceptual model." This involves the definition of the model area or domain, establishing geological/hydrogeological boundaries, defining initial heads, and determining the physical characteristics and hydraulic parameters of the aquifer. This information is usually obtained from geological investigations, well logs review, and evaluation of aquifer pump tests.

The conceptual groundwater model developed for St. Marys consists of four layers, as illustrated by the schematic shown in Figure 10. Layer 1 (the uppermost layer) is an unconfined saturated aquitard and represents the glacial deposits that blankets the area. All surface water entities (rivers and lakes) were assigned to this layer. Vertical permeability of the aquitard was assumed based on the type of soil, using values suggested in literature. The entire area was assumed to be subjected to a uniform recharge value of six inches per year (0.0014 ft/day).

Rivers and streams were assigned specified heads at strategic points, based on measurements (land survey) taken on July 2, 1998. In addition to the land survey, complementary elevations were taken from USGS topographic maps. River-bed conductance was initially based on best engineering judgment. It should be noted, however, that adjustments to river-bed conductance were performed throughout the modeling process to approximate reasonable groundwater flow patterns in the area and to match the heads measured during the land survey.

The bottom elevation of the aquitard, which is the top of the bedrock aquifer (Layer 2), was modeled as variable, based on the information derived from well logs. An assumed uniform "vertical conductance" value was selected, based on best engineering judgment, in order to represent the interaction between the upper glacial deposits and the bedrock aquifer. The





Conceptual Model

ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

SCHEMATIC OF CONCEPTUAL MODEL



Jones & Henry Engineers, Ltd.

FIGURE 10

bedrock aquifer was assumed to have a maximum thickness equivalent to the depth intercepted by the wells located in the City of St. Marys' North Wellfield. The bedrock aquifer was also assumed to be isotropic, that is, no preferential direction was assigned to the hydraulic parameters. The hydraulic conductivity used in the modeling of the bedrock aquifer is 110 ft/day, as determined by pump tests conducted in the North Wellfield.

The third layer represents the sand and gravel aquifer located in the deepest part of the channel of the ancient Teays River Valley, which is the source of groundwater to the wells located in the South Wellfield. The hydraulic conductivity used in the modeling of the Teays aquifer is 54 ft/day, as determined by pump tests conducted in the South Wellfield.

The model includes one additional layer (Layer 4) to represent the base bedrock underlying the area. This layer was assumed to be impermeable.

The model's domain was divided into a uniformly-spaced grid consisting of 66 columns and 85 rows measuring 492.42 ft and 488.23.88 ft each, respectively, for a total area of 32,000 ft x 41,500 ft. The grid is illustrated in Figure 11.

Pre-pumping or unstressed groundwater elevations were not available for the area. As a result, it is difficult to estimate the actual drawdown produced by the operation of the existing production wells. The initial heads used in the model were based on information derived from the numerous well logs reviewed. The results of the model (and its calibration) were compared to the "stressed" conditions measured in the field in July 1998. The pumping rates utilized in the model are also representative of the pumping rates for the same period.

3.3 CALIBRATION AND SENSITIVITY ANALYSIS

Calibration of the model was performed by varying the values of transmissivity/hydraulic conductivity in certain areas of the model domain as necessary. Extreme values of transmissivity used for trial model runs did not have an appreciable effect on the water elevations predicted by the model. Results of the calibration and sensitivity analysis indicated that using a uniform value for transmissivity resulted in different areas exhibiting relatively-high differences in elevation compared to values measured in the field. These results can be expected, as the geological information available indicates, that the aquifer is not homogeneous throughout the entire area. As a result, some difficulties were encountered in calibrating the model. Most significant in constructing and evaluating the model, is the poor information relative to the sand and gravel aquifer within the ancient Teays River Valley. The information available is derived exclusively from the wells drilled in the South Wellfield by the City of St. Marys. Apparently, no other well has been drilled to intercept this aquifer in the vicinity of St. Marys.

The difficulties described previously are further complicated by the possibility of survey error as described below. The measurements of groundwater levels and river stages were performed using GPS systems (See Table 5). While reasonably accurate, in some instances, due to the location and number of satellite vehicles and local preferences, errors in horizontal and vertical position in the order of 10 feet or greater can occur. It should be noted, however, that these occurrences are rare, and an approximate estimate of the error is usually provided.

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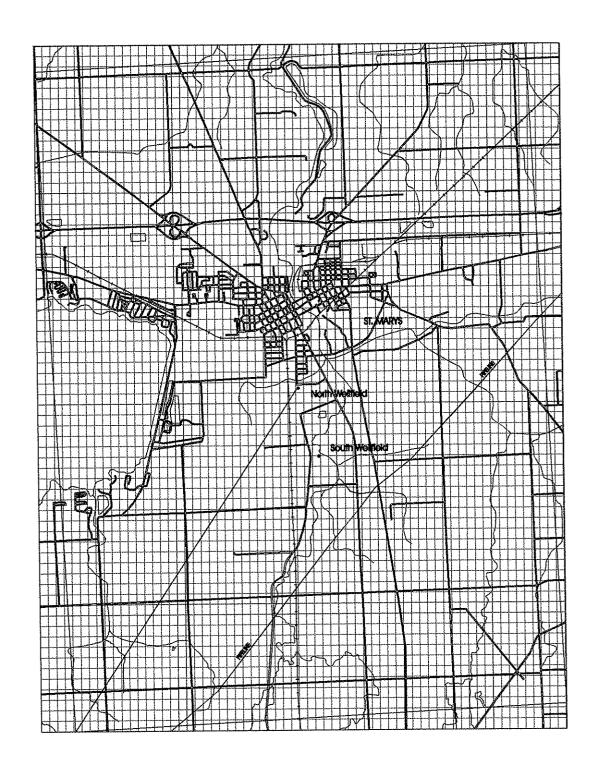
Initial
Initial

CITY OF St. MARYS, OHIO TABLE 5

I ABLE 5 RESULT OF GPS SURVEY

State Plane Coordinate 1983 North American 1983 Geodetic Ref. Sys. 1980 Lambert Conformal Ohio (North) FT 6378137,000 298.2572221 Jul 02 1998 Fillnet Output File TEST1.FOP SPC83 State Plan 3401 PRISM v2.0100 FT NAD83 GRS80 OH N USFT LC83 ASHTECH POINTS FILE INVERSE FLATTENING: SEMI-MAJOR AXIS: CREATED FROM: PROJECTION: ELLIPSOID: PROGRAM: SYSTEM: UNITS: DATUM:

WATER SURVEY	ELEVATION SHEET No.	1000		867.94		868.90		878.11		853.34	852.01	852.85	852.26	839.14	843.00 15						832.59	953.00		889.73	
DEPTH TO	n _Y	N/A	7.15	1.70	7.18	14.79	20.85	23.12	17.06	22.62	13.15	16.58	26.54	30.29	16.90	23.57	19.81	6.64			12-40	Ω		7,20	7.20
	WELL I.D.	BASE	GL	2	S-29	3	S-80	S=83	S-85	님	S-14	S-66	N-25	N-29	St.M-Lndfl	N-16	TH	8-5	Marina	Confr:Pt.1	Stream	Stream		Conf. Pt.2	Cont.Pt.2
	HEIGHT	1027.134	864.004	869.641	875.366	883,689	892.446	901.232	900.277	875.963	865,156	869.434	878.798	869.431	859.897	874.697	872.551	859.428	871.097	883.699	844.992	14 P 23 C		R96 997	896,927
	NORTHING	234604,905	322496.956	317435.802	313083.557	310395.502	310338.267	306205.945	307435,700	318503.351	318533.311	324337.741	333987.953	337024.599	336810.096	332139.489	333169.302	320727.469	324244,449	331548,847	339398.341	125 C+B5C8		12V 175105	307374.437
	FASTING	1504505 887	1437480.951	1435760,416	1434567.292	1441428.621	1440302.175	1451845.293	1456617.230	1451768.025	1446176.033	1449317.566	1456053,565	1445952.264	1442392,811	1440253.930	1436202.826	1444491.578	1438276,522	1773503877	1.000 5.000	C 1 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	1001 00000 TH	8 C C C C C C C C C C C C C C C C C C C	1456975.032



ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

GRID SYSTEM OF MODEL'S DOMAIN



A map illustrating the points that were surveyed is shown on Figure 12. A visual comparison of the elevations measured in the field and the heads predicted by the model is shown on Figure 13. Mathematical comparison of the results obtained is shown on Figure 14. Also shown on Figure 14, is the RMSE computed for the model. It illustrates the differences in elevation for each point surveyed and provides a computation of the RMSE for the entire model. Computation of the RMSE resulted in a value of 3.62 ft which indicates that the flow model developed is an adequate representation of the area.

The results predicted by the model indicate, that there are two areas with a slightly-elevated error compared to the observed values. One area is in the southern part of the model near the St. Marys River, in the vicinity of Well No. 20/OW (See Figure 12). The other is in the vicinity of the North Wellfield (Well S-5). In both cases, the model predicted somewhat lower values that those observed in the field. Considering that the differences noted are not unusually high for a regional model, and that the lower values predicted by the model implies greater hydraulic gradients, making the model more conservative, it was decided not to conduct any additional refinements to the model.

3.4 WATER BUDGET

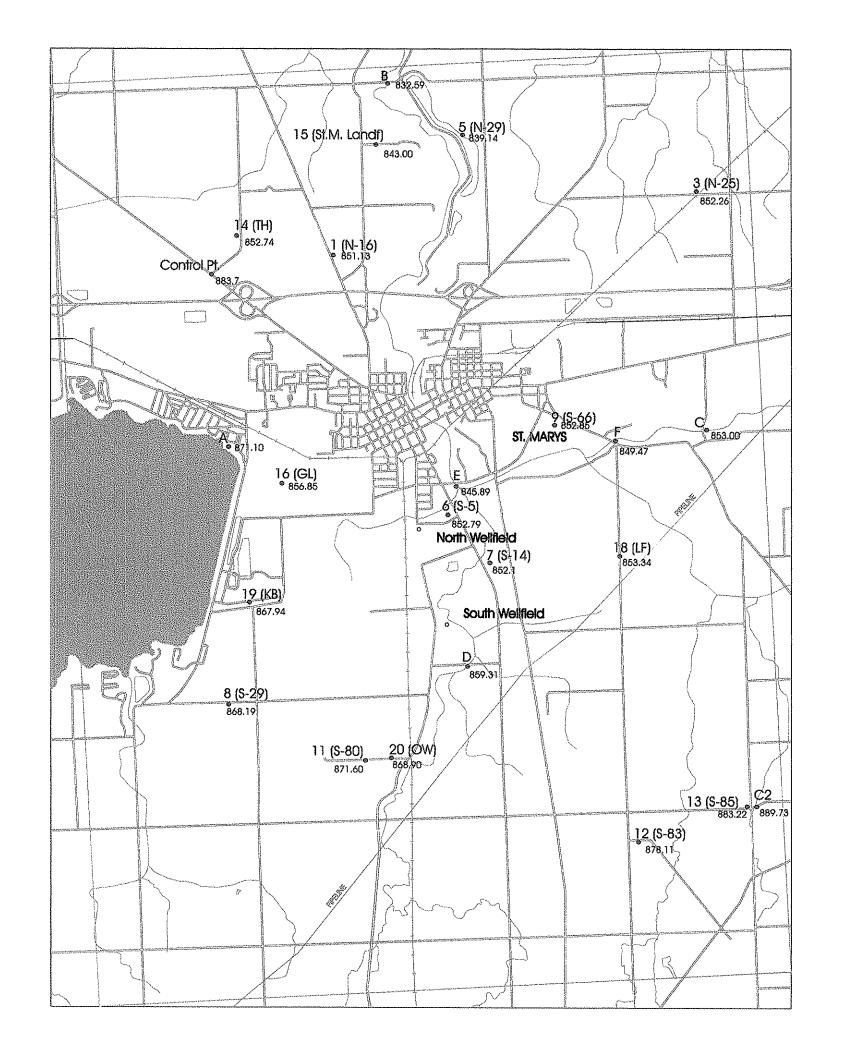
In addition to the calculation of the RMSE, an additional means to evaluate the adequacy of a model is to compute the volumetric water budget of the model (also known as the water balance). Table 6 below is an output from the model which indicates the water budget estimated for the study area.

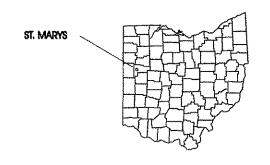
TABLE 6
SUMMARY OF WATER BUDGET

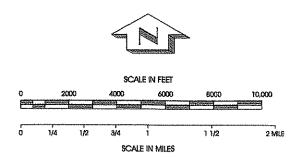
DESCRIPTION	ft³/day	gpd
IN: STORAGE = CONSTANT HEAD = WELLS = RECHARGE= RIVER LEAKAGE =	0.00E+000 2.51E+006 0.00E+000 1.69E+006 1.21E+005	0 18,794,657 0 12,648,363 908,312
TOTAL IN =	4.32E+006	32,351,332
OUT: STORAGE = CONSTANT HEAD = WELLS = RECHARGE = RIVER LEAKAGE =	0.00E+000 3.81E+005 5.01E+005 0.00E+000 3.44E+006	0 2,857,210 3,748,745 0 25,746,126
TOTAL OUT =	4.32E+006	32,352,081
IN - OUT = PERCENT DISCREPANCY	-608 0.00%	(4,554) 0.00%
VOLUMETRIC BUDGET FOR ENTIR CUM LATIVE VOLUMES L**3	E MODEL AT END OF TIME STE	P 1 IN STRESS PERIOD 1

As can be noted from Table 6, the largest components of inflow to the area is from water flowing across the boundaries of the model, and direct recharge from precipitation. The large inflow from groundwater moving across the area is expected, as groundwater moves from the southeast and west toward St. Marys River which serves as drainage to the entire area.

The largest outflow component of the outflow is through the rivers and streams that exit the study area on the northern boundary. The most noticeable of these is St. Marys River which has its origin in the southern part of the model. Also, there are many relatively large tributaries to the St. Marys River that have their origin in the study area, contributing significant amounts of water to the river. A relatively-small component of the outflow is from groundwater flowing across the northern boundary of the model, as a result of the dynamics of the groundwater movement. As expected, the operation of the City's wellfields represent only a minor component of the water budget.





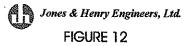


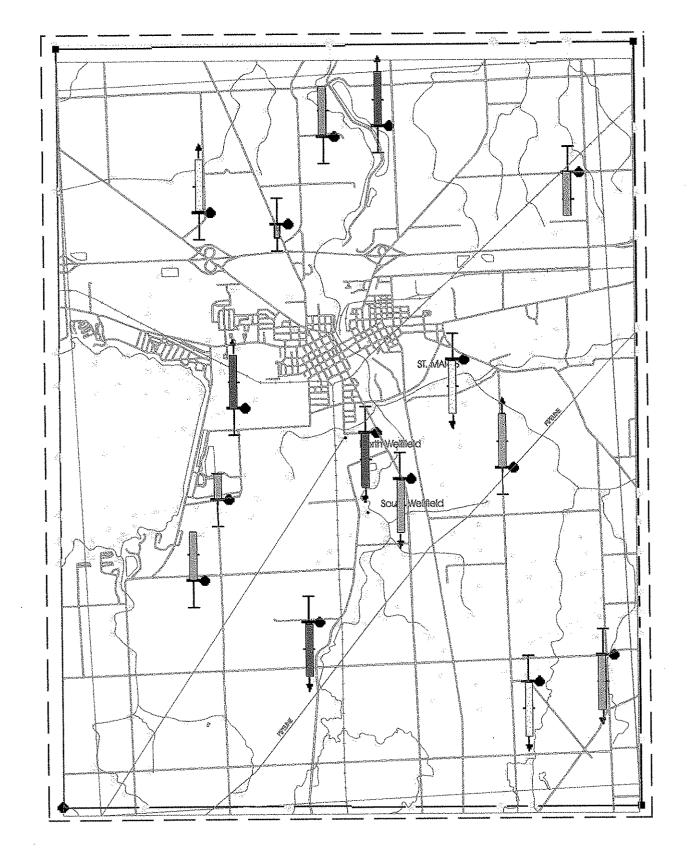
A Surface Water Measurements

19 (KB) Ground Water Measurements

ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

RESULTS OF GPS SURVEY





DELINEATION OF WELLHEAD PROTECTION AREA

CALIBRATION RESULTS



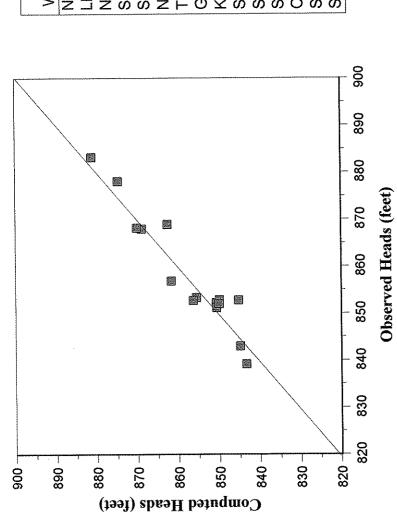
-0.46 3.07 3.62

> Mean Abs. Error. Root Mean Square Error:

Mean Error:

ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

FIGURE 14 (Results of Model Calibration / Computation or RMSE)



Well I.D. Observed Computed (Comp-Obs) N-29 839.14 843.37 4.23 LF 853.34 855.54 2.20 N-25 852.26 850.70 -1.56 St. M. Lnd 843.00 844.89 1.89 S-66 852.85 849.91 -2.94 N-16 851.13 850.64 -0.49 GL 852.74 856.34 3.60 KB 867.94 868.87 0.93 KB 867.94 868.87 0.93 S-5 868.19 870.06 1.87 S-14 868.19 862.79 862.00 -2.01 OW 868.90 862.54 -6.36 S-83 878.11 874.68 -3.43 S-85 883.22 881.12 -2.11		Heads (feet)	(feet)	Difference
839.14 843.37 853.34 855.54 852.26 850.70 844.89 852.85 849.91 851.13 850.64 852.74 856.34 852.74 868.87 867.94 868.87 867.94 868.87 868.19 870.06 852.01 850.00 874.68 883.22 881.12	Well I.D.	Observed	Computed	(Comp-Obs)
852.26 850.70 852.26 850.70 843.00 844.89 852.85 849.91 852.74 856.34 856.74 856.34 867.94 868.87 852.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68	N-29	839.14	843.37	4.23
852.26 850.70 843.00 844.89 852.85 849.91 851.13 850.64 856.85 861.72 867.94 868.87 867.94 868.87 867.94 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68	ഥ	853.34	855.54	2.20
843.00 844.89 852.85 849.91 851.13 850.64 852.74 856.34 867.94 868.87 867.94 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68	N-25	852.26	850.70	-1.56
852.85 849.91 851.13 850.64 852.74 856.34 867.94 868.87 862.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 874.68	St. M. Lnd	843.00	844.89	1.89
852.74 856.34 856.85 861.72 867.94 868.87 867.94 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68	8-66	852.85	849.91	-2.94
852.74 856.34 856.85 861.72 867.94 868.87 852.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 874.68 883.22 881.12	N-16	851.13	850.64	-0.49
856.85 861.72 867.94 868.87 852.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68	Ŧ	852.74	856.34	3.60
867.94 868.87 852.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 874.68 883.22 881.12	GL	856.85	861.72	4.87
862.79 845.23 868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68 883.22 881.12	χ ω	867.94	868.87	0.93
868.19 870.06 852.01 850.00 868.90 862.54 878.11 874.68 883.22 881.12	S-5	852.79	845.23	-7.56
852.01 868.90 862.54 878.11 883.22 881.12	S-29	868.19	870.06	1.87
868.90 862.54 874.68 883.22 881.12	S-14	852.01	850.00	-2.01
874.68 883.22 881.12	<u></u>	868.90	862.54	-6.36
883.22 881.12	S-83	878.11	874.68	-3.43
	S-85	883.22	881.12	-2.10

Jones & Henry Engineers, Ltd.
Toledo, Ohlo

4.0 DELINEATION OF WELLHEAD PROTECTION AREAS

4.1 GENERAL

Delineation of the WHPA for the City of St. Marys was based on the Time of Travel (TOT) criteria. Capture zones based on a 1-year and 5-year TOT were defined for the wellfield as recommended in the WHPP for the State of Ohio. It should be noted, that both the bedrock aquifer and the aquifer located in the sand and gravel deposits within the Teays River Valley are fairly deep. Moreover, they are overlaid by thick layers of clay, and therefore, they are not susceptible to contamination. None-the-less, several conservative assumptions were used in defining the WHPAs as described below.

Delineation of the WHPA was achieved through the use of the particle tracking technique. The term "particle" is a conceptual term and may be viewed as an individual water molecule or a conservative tracer that moves through the aquifer coincident with the bulk movement of the groundwater flow. In the case of a water molecule, its location is assumed not to be affected by dispersion or diffusion.

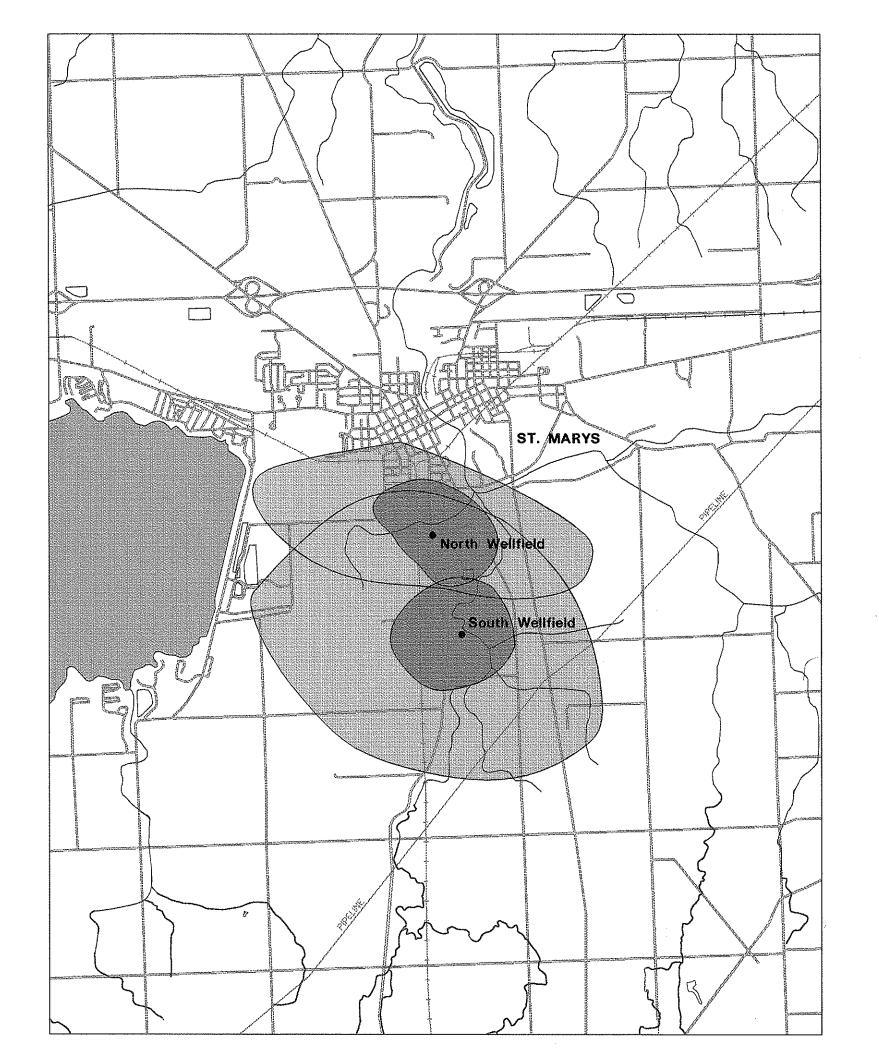
Two types of tracking techniques are recognized in groundwater modeling, forward tracking and reverse-particle tracking. Forward tracking refers to the procedure of tracking water particles in the direction of the groundwater flow, while reverse tracking refers to the procedure of tracking water particles in the direction opposite to the groundwater flow (where the water comes from). Since groundwater flows toward a pumping well, reverse tracking is typically used to define capture zones for WHPA.

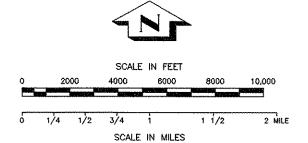
The particle tracking method requires definition of the direction and velocity of the groundwater flow at any point within the aquifer. This implies knowledge of the direction and gradient of the groundwater flow, and the hydraulic conductivity and porosity of the aquifer. This information is usually provided by a flow model developed for the area of interest. Also required, is information relative to the rate at which water is extracted from the wells. The WHPAs defined for the St. Marys' wellfield were based on projected future "average-day" demand for the year 2020 which was estimated at approximately 2.8 mgd (1,944 gpm). As a conservative approach in defining the WHPA, each wellfield was assumed to provide the entire water demand, effectively doubling the estimated rate.

The bedrock aquifer was assumed to have a homogeneous effective porosity of 10%. The sand and gravel deposits were assumed to have an effective porosity of 20%. These values are somewhat low; however, they were selected to provide an additional conservative measure in defining the WHPAs. The resulting WHPAs are illustrated on Figure 15. In addition to Figure 15, a topographic map illustrating the location of the WHPA is also provided and can be used for display and assistance in developing management strategies.

As can be noted on Figure 15, there is some "overlapping" of the WHPAs defined for the two wellfields. This is due to the fact that the two wellfields are located in completely different aquifers, each with its distinct characteristics. Therefore, considering the relative proximity of the wellfields, it is logical and not unusual for the areas to overlap.

Projection Paralle

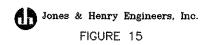






ST. MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREAS

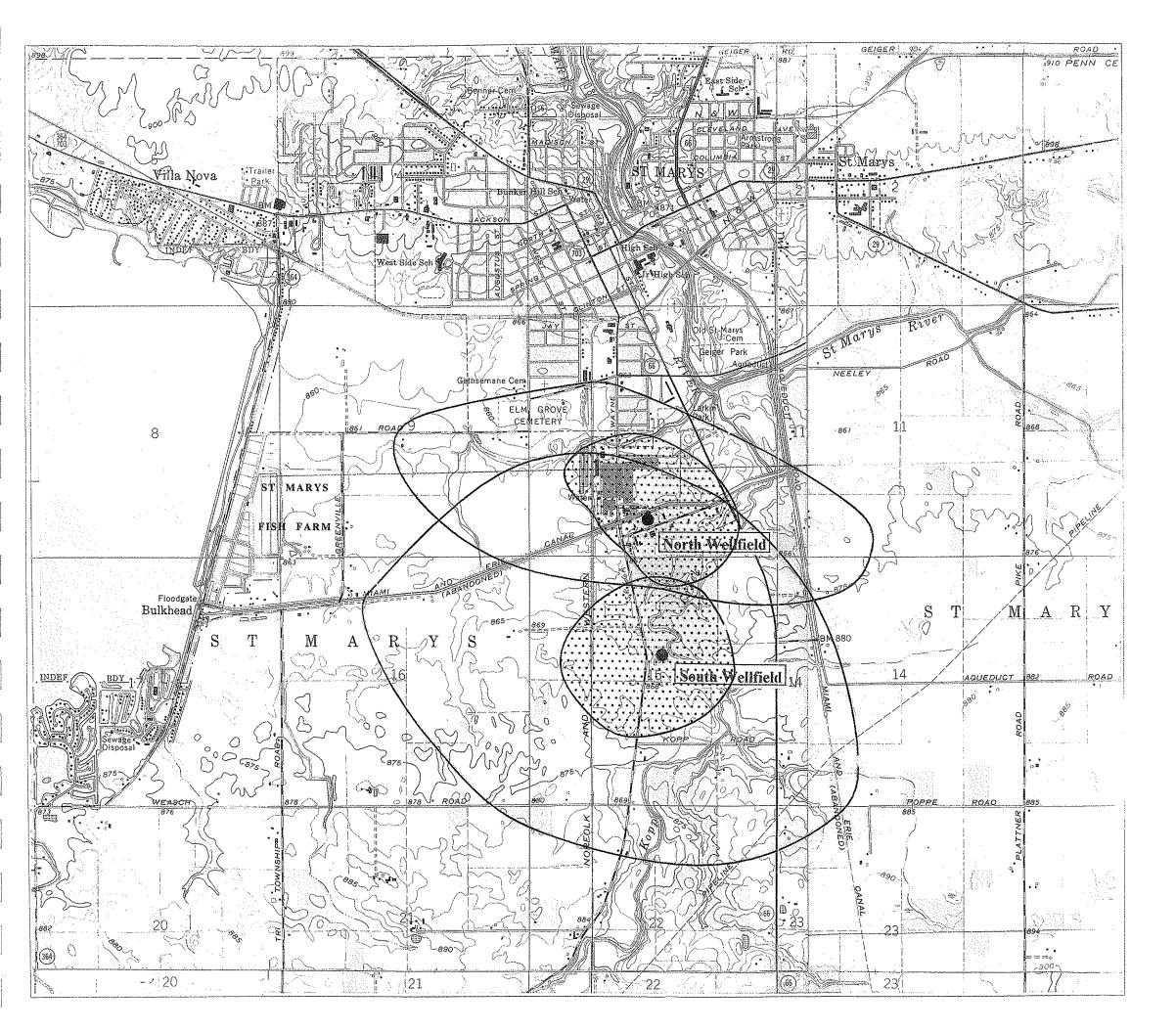
WELLHEAD PROTECTION AREA



To assist the City in the management of the WHPA, an estimate of the areal extension of the wellhead protection area was performed and is included on Table 7. The combined 5-year capture zone for both wellfields was estimated at approximately 1,938 acres. This is less than the sum of the individual capture areas and is due to the "overlapping" of the WHPAs.

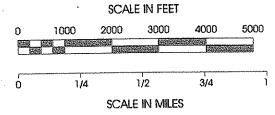
TABLE 7
AREAL EXTENSION OF THE WHPA

	Areal Extension of the 1-Year TOT (acres)	Areal Extension of the Combined 1- and 5-Year TOT (acres)
North Wellfield	186	695
South Wellfield	212	1,546









1-year TOT
5-year TOT

ST, MARYS, OHIO DELINEATION OF WELLHEAD PROTECTION AREA

WELLHEAD PROTECTION AREAS



Jones & Henry Engineers, Ltd.