6792 U-004-307 .13

WELLHEAD PROTECTION AREA DELINEATION REPORT - THE WATER CONSERVATION SUBDISTRICT OF THE MIAMI CONSERVANCY DISTRICT, DAYTON, OH - (USED AS A REFERENCE IN OU 2 RI REPORT)

03/01/92

CH2M HILL
125
REPORT

WELLHEAD PROTECTION AREA DELINEATION REPORT

Prepared for

The Water Conservation Subdistrict of the Miami Conservancy District

Representing a Consortium of Water Users

Champion International
City of Fairfield
Southwestern Ohio Water Company
City of Cincinnati
City of Hamilton
The Water Association
Westinghouse Environmental Management Company of Ohio

Prepared by
CH2M HILL
Dayton, Ohio

March 1992

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The Table of Contents for this report lists the plates (oversized sheets) that were prepared for this project. Each copy of the report contains Plates 1 and 2, which depict the 1-year and 5-year time-of-travel wellhead protection areas for all Consortium members, plotted on a scale of 1 inch equals 2,000 feet. As requested by the Consortium members, each member received additional plates in their copies of the report showing the 1- and 5-year wellhead protection areas delineated for their own well field, plotted on a smaller scale (1 inch equals 400 feet or 1 inch equals 800 feet, depending on the size of the wellhead protection area). Plates showing wellhead protection areas plotted on this smaller scale for Consortium members other than those provided in this copy of the report are available for viewing at the offices of the Miami Conservancy District, 38 East Monument Avenue, Dayton, Ohio.

GLOSSARY

Aquifer—Saturated rock or sediment that is permeable enough to transmit significant quantities of water to wells and/or springs.

Buried Valley Aquifer—An aquifer formed by infilling a pre-existing bedrock valley with water bearing sediments.

Groundwater, Confined—Water within an aquifer that is under greater than atmospheric pressure due to an overlying layer that has a low hydraulic conductivity.

Groundwater Divide—A boundary on a potentiometric surface across which negligible groundwater flow occurs.

Groundwater, Unconfined—Water within an aquifer that has a water table.

Hydraulic Conductivity—A measure of the ease with which an aquifer transmits water.

Hydraulic Gradient—The change in head (groundwater elevation) divided by the change in distance in a given direction.

Leakance (Streambed)—The rate of flow from a stream into an aquifer through the streambed.

Leakance (Till)—The rate of vertical groundwater flow through a till layer.

MODFLOW—A numerical code used to develop 3-D groundwater flow models.

MODPATH/MODPATH-PLOT—Computer codes developed by the U.S. Geological Survey to simulate and plot partical movement in aquifers using output from the MODFLOW computer code.

National Geodetic Vertical Datum of 1929 (NGVD)—a datum maintained by the U.S. Coast and Geodetic Survey. Replaces Mean Sea Level.

Outwash—Generally refers to sediments, in this case sand and gravel with lenses of fine-grained material, deposited by glacial meltwaters.

Porosity—The void portion of an aquifer in which water is stored and through which groundwater flows.

Semi-Confining Low-Permeability Layer—A layer or zone of generally low permeability underlying or overlying more permeable aquifer material whicha retards the movement of groundwater.

Sensitivity Analysis—A qualitative analysis of the impact of changing the value of a hydraulic parameter used in a groundwater flow model.

Till—Generally, an unlayered glacial deposit that consists of a mixture of clay, silt, sand, and gravel and that has a relatively low hydraulic conductivity.

Transmissivity—The product of hydraulic conductivity multiplied by aquifer thickness; a measure of the ability of an aquifer to produce water.

Unsaturated Zone—The zone between the land surface and the water table, where the majority of the pore spaces are occupied by air.

Water Table—The groundwater surface in an unconfined aquifer, the point at which groundwater occurs at atmospheric pressure.

Wellhead Protection Area (WHPA)—The area delineated around a wellhead to be protected from possible sources/causes of groundwater contamination. A zone around drinking water supply wells for the prevention, detection, and remediation of groundwater contamination (Ohio EPA 1991).

Introduction

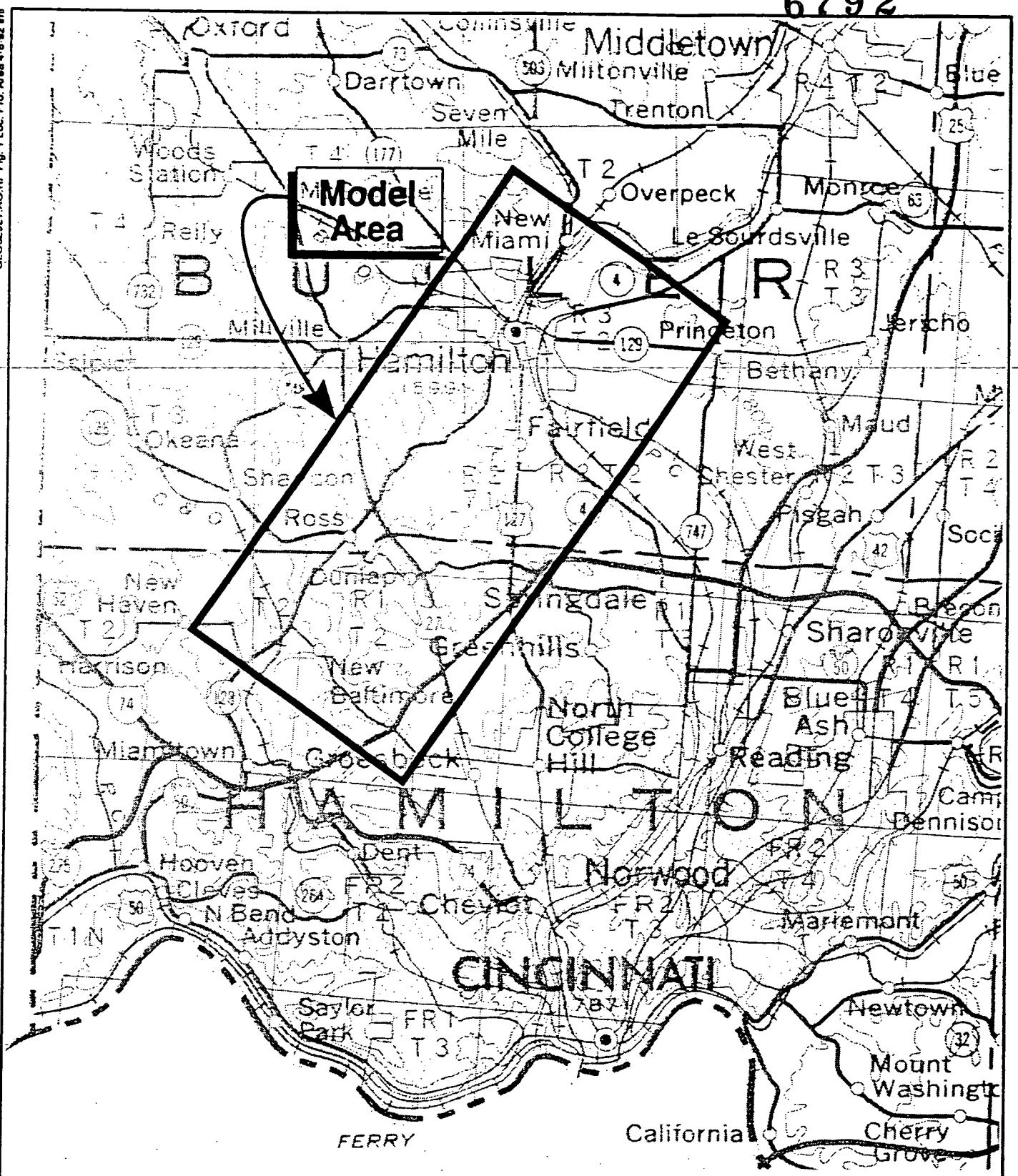
Plentiful groundwater supplies in the area from Hamilton to New Baltimore, Ohio, (Figure 1) have led to the development of several large municipal, commercial, and industrial well fields. The presence of a reliable source of water has spurred considerable industrial development in the area. The same properties that make the aquifer a highly productive, economic source of water (high permeability and shallow depth to water) also make the aquifer highly susceptible to contamination from near surface activities. Groundwater contamination can be caused by a variety of sources, including infiltration of surface chemical spills, underground storage tank leakage, leakage from surface impoundments, landfill leakage, septic tank effluent, and river pollution.

Because of the presence of actual and potential sources of contamination in the area of the well fields, and because of a pending Ohio Environmental Protection Agency (Ohio EPA) policy, the principal users of groundwater in the Hamilton to New Baltimore area have begun a planning process with the goal of protecting the groundwater quality of the aquifer. Seven water purveyors in the area have entered into a cooperative agreement with the Water Conservation Subdistrict of the Miami Conservancy District (MCD) to delineate wellhead protection areas (WHPAs), an initial step in the wellhead protection planning process. The seven members of this Consortium include:

- Champion International (Champion)
- The City of Cincinnati
- The City of Fairfield
- The City of Hamilton
- The Southwestern Ohio Water Company (SWOWC)
- The Water Association
- Westinghouse Environmental Management Company of Ohio, operators of the Fernald Environmental Management Project (FEMP), formerly the Feed Materials Production Center (FMPC)

This report describes the activities undertaken by CH2M HILL to delineate WHPAs for the Consortium members' well fields. This work was completed under the terms of an agreement between the Water Conservation Subdistrict of MCD and CH2M HILL dated October 7, 1991.

GL032927.AO.RP Fig. 1 Loc. Pro. Area 4-8-92 lml



Base Map is USGS 1:500,000 State of Ohio Map, 1971.

NORTH

OHIO

0 4 Miles

Approximate Scale in Miles

FIGURE 1
Location of Project Area
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

CH2M HILL

Project Objective

The project objective is to delineate WHPAs using a three-dimensional groundwater flow model. The model was developed from available hydrogeologic information, and was used to predict groundwater elevations under assumed future pumping conditions. These predicted groundwater elevations were used as a basis for delineating WHPAs for 1-year and 5-year times of travel. The results of the project will be used by the Consortium members to meet part of the general requirements of Ohio EPA's Draft Wellhead Protection Program (WHP Program), which is currently under revision on the basis of comments received from U.S. EPA Region V.

Ohio EPA Draft Wellhead Protection Program

The Ohio EPA's draft WHP Program includes several requirements for water purveyors, including:

- WHPA delineation
- Potential contaminant source inventory
- WHPA management plan including groundwater monitoring
- Contingency planning
- Public participation and education

This study covers only the WHPA delineation component of the WHP Program requirements. The current draft of the program (Ohio EPA 1991) describes criteria and methods to be used for delineating WHPAs.

Criteria

For community water systems using surficial glacial outwash or unconfined aquifers as a water source, such as that occurring in the project area, the Ohio EPA prefers a time-of-travel analysis combined with a flow boundary (aquifer boundary) criterion. The draft policy indicates that successively stricter levels of protection will be associated with WHPAs based on shorter times of travel.

Methods

The Ohio EPA (1991) describes a variety of methods that can be used to delineate WHPAs for purveyors using a time-of-travel criterion for wellhead protection. These include:

- Calculated fixed radius
- Analytical groundwater flow calculation
- Semi-analytical groundwater modeling
- Numerical groundwater modeling

For water systems in complex hydrogeologic settings that have a considerable amount of available hydrogeologic data, the Ohio EPA suggests that numerical groundwater flow models may provide the most appropriate delineation of WHPAs. On the basis of the Ohio EPA's draft policy, because of the substantial amount of hydrogeologic data available from the MCD and because of the anticipated degree of hydraulic interaction caused by closely spaced well fields, the Consortium chose to delineate WHPAs using the U.S. Geological Survey's numerical code MODFLOW (McDonald and Harbaugh 1984).

The version of the MODFLOW code used for this project was the U.S. Geological Survey 1987 revision of MODFLOW. MODPATH (Version 1.2) and MODPATH-PLOT (Version 1.1) (Pollack 1989) were used in conjunction with MODFLOW to compute and display pathlines. MODFLOW, MODPATH, and MODPATH-PLOT were compiled by CH2M HILL in 1991 with Lahey FORTRAN version F77L-EM/32.

Report Organization

This report addresses the WHPA delineation requirements of Ohio EPA's WHP Program. The following sections briefly describe the physical setting of the Hamilton to New Baltimore project area, including the area geology and hydrology, the model used to complete the project, and the wellhead protection area delineation. The report outlines the conceptual model, which is a summary of key components of the hydrologic system used to develop the numerical model, and describes the model setup process. The steps used in model calibration, verification, and sensitivity analysis are outlined, and maps showing measured and simulated groundwater elevations (potentiometric surfaces) are provided. Several maps are presented depicting 1- and 5-year WHPAs.

Physical Setting

Geology

Sources of Geological Data

Table 1 summarizes the sources of information reviewed during data compilation and conceptual model development. The bulk of this information was obtained from the Water Conservation Subdistrict of the MCD and included numerous maps.

General Geology of Project Area

The principal geologic feature of the project is the major buried valley that follows the general trend of the present-day Great Miami River. This buried valley was created when ancient stream valleys, cut into the limestone and shale bedrock, were eroded and enlarged by several cycles of glacial erosion followed by torrential stream erosion. As the glaciers finally retreated, they deposited a heterogeneous mixture of sediments ranging in grain size from clay to gravel in the enlarged valley. After the valley was filled with glacial deposits, surface drainage features formed and the valley was mantled with recent river alluvium. In general, the present-day Great Miami River follows the trend of the buried valley; however, along short reaches, the river may lie outside the edge of the buried valley.

Bedrock Geology

Interbedded shale and limestone comprise the bedrock in the project area. The bedrock surface has been deeply eroded in places by glacial activity, stream erosion, or a combination of both. Within the project area, the main valley trends northeast to southwest and its floor is somewhat less than 350 feet (National Geodetic Vertical Datum, NGVD). The main valley generally ranges from 1 to 2 miles wide and is defined by steeply sloping valley walls.

Near the community of New Baltimore, a smaller buried valley branches off of the main valley stem and trends northwest to southeast. The Great Miami River follows this valley out of the southeastern portion of the project area. In this tributary valley, the valley floor is about 420 feet (NGVD) and ranges from 0.3 to 0.5 mile wide. The walls of the tributary valley slope steeply, similar to the main valley walls.

Surficial Geology

Three general areas of distinctly different surficial deposits occur within the project area. Within the Great Miami River Valley, the surficial deposits consist of discontinuous lenses of clay, silt, sand, gravel, and mixtures of these materials (Figure 2). The sediments may be described as soil, clay, sand and gravel, or mixtures of these materials on driller's logs. The unit ranges in thickness from 5 to 20 feet.

Table 1
Sources of Data For Model Development
Wellhead Protection Area Delineation Project
Water Conservation Subdistrict Consortium

Title	Author	Data Type[1]
A Quantitative Study of the Well Fields of the Mill Creek Valley Water Supply Project, Butler County, Ohio,	Fred H. Klaer, Jr. and Rapheal G. Zasmann, 1943	AHGW
Ground-Water Conditions in Butler and Hamilton Counties, Ohio, 1946	Ralph J. Bernhagen and Edward J. Schaefer, 1947	H
Results of Investigation of the Ground-Water Potential in the New Miami Area	Robert C. Smith and Associates, 1960	AGHW
Results of Investigation Available Well Water Supply at Baldwin-Lima-Hamilton, Hamilton, Ohio	Robert C. Smith and Associates, 1960	AGHW
A Hydrologic Study of the Valley-Fill Deposits in the Venice Area, Ohio	George D. Dove, Geologist, U.S. Geological Survey, 1961	AHR
Summary Evaluation of the Pumping Test at the Proposed Cincinnati Well Field, Butler County, Ohio	Leggette, Brashears and Graham Consulting Ground Water Geologists, 1962	AW
Cincinnati Water Works Ground-Water Development Miami River Area	Robert C. Smith and Associates, 1962	AW
Ground-Water Resources of the Dayton Area, Ohio. Geological Survey Water-Supply Paper 1808. United States Department of Interior Geological Survey	Stanley E. Norris and Andrew M. Spieker, 1966	AHGW
An Investigation of the Potential Yield of the Big Bend Well Field	Robert C. Lewis, C.E. University of Cincinnati 1968	AR
Ground-Water Hydrology and Geology of the Lower Great Miami River Valley Ohio	Andrew M. Spieker, 1968	G
Report of Pumping Test, Well No. 1, Morris Farm Site	Sieco, Inc., 1969	AG
Preliminary Analysis Well S&G-2 Hydrogeologic Survey of Ground Water Potential in Southwestern Ohio	Dames & Moore Consulting Engineers, 1971	AW
Seismic Refraction Survey of Pleistocene Drainage Channels in the Lower Great Miami River Valley, Ohio	Joel S. Watkins and Andrew M. Spieker, 1971	G
The Miami Conservancy District Water Conservation, Subdistrict Phase Two, Observation and Evaluation of Water Resources in the Hamilton to New Baltimore Area	Paul M. Plummer, Michael J. Herbert, Charles J. Moore, 1971	AHR
Ground Water Resources of Selected Buried Valleys in Southwest Ohio	Dames & Moore Consulting Engineers, 1971	GHR
Report of Pumping Test, Well No. 3, Morris Farm Site	Sieco, Inc., 1979	AR
Final Remedial Investigation Report, Chem-Dyne Site, Hamilton, Ohio	1984	AH
Letter to GRW Engineers, Inc. re: Submittal 6 - Well Pumps for the City of Fairfield, Ohio	Leon Simpson, Reynolds Supply Inc., 1985	W

Table 1
Sources of Data For Model Development
Wellhead Protection Area Delineation Project
Water Conservation Subdistrict Consortium

Title	Author	Data Type[1]
Preliminary Characterization of the Groundwater Flow System near the Feed Materials Production Center, Great Miami River Valley-Fill Aquifer, Fernald, Ohio	GeoTrans, Inc., 1985	GW
Hydrogeologic Study of FMPC Discharge to the Great Miami River	IT Corporation, 1987	W
Chem-Dyne Site Trust Fund 1988 Annual Report	Chem-Dyne Corp., 1988	Q
Petition for Sole Source Aquifer Designation of the Great Miami Buried Valley Aquifer System in Butler, Clermont, Hamilton and Warren Counties, Ohio	Ohio-Kentucky-Indiana Regional Council of Governments, 1988	GH
City of Hamilton Ohio Water Supply Improvements	Burgess & Niple, Limited, 1989	AHW
Paddys Run Road Site, Crosby Township, Ohio, Preliminary Activities Report	ENSR Consulting and Engineering, 1989	W
Transport and Fate of Contaminants in the Subsurface	Johnson, Richard L., Joseph F. Keely, Carol D. Plamer, Joseph M. Suflita, and William Fish, 1989	AGHW
Engineering Evaluation/Cost Analysis South Plume, Feed Materials Production Center, Fernald, Ohio	ASI/IT, 1989	AH
Hodapp Landfill, Hamilton, Ohio Hydrogeologic Investigation	Burgess & Niple, Limited, 1990	W
Summary Data Package Phase I Remedial Investigation Paddys Run Road Site, Crosby Township, Ohio	ENSR Consulting and Engineering 1990	WH
Feed Materials Production Center Fernald, Ohio Remedial Investigation and Feasibility Study	U.S. Department of Energy Oak Ridge Operations Office, 1990	GH
The Cincinnati Gas and Electric Company Woodsale Generating Station Butler County, Ohio Groundwater Modeling Report	Westinghouse Environmental and Geotechnical Services, Inc., 1991	AW
Hodapp Landfill, Champion International Groundwater Sampling	Burgess & Niple Limited, 1991	W
Chem-Dyne Site Trust Fund 1990 Annual Report	Chem-Dyne Corp., 1991	HQ
Hydrologic Data for the Hamilton-New Baltimore Area 1990	The Miami Conservancy District, 1991	HR
Final Engineering Report for New Well Field in St. Clair Township	Sieco, Inc., 1991	AGH
Butler County Groundwater File, City of Cincinnati Great Miami Works Well Field Section	The Miami Conservancy District, 1991	AW
Hamilton County Groundwater File, Nease Chemical Section	The Miami Conservancy District, 1991	W

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Table 1
Sources of Data For Model Development
Wellhead Protection Area Delineation Project
Water Conservation Subdistrict Consortium

Title	Author	Data Type[1]
Butler County Groundwater File, Schlicter Landfill Section	The Miami Conservancy District, 1991	W
Memorandum to Ken Shump, CH2M HILL on transmittal of channel cross sections	The Miami Conservancy District, 1991	R

NOTE:

1. The data type is indicated by an alphabetic code which is defined below.

A = aquifer test
G = geological
H = hydrogeological
Q = discharge
R = river
W = well log

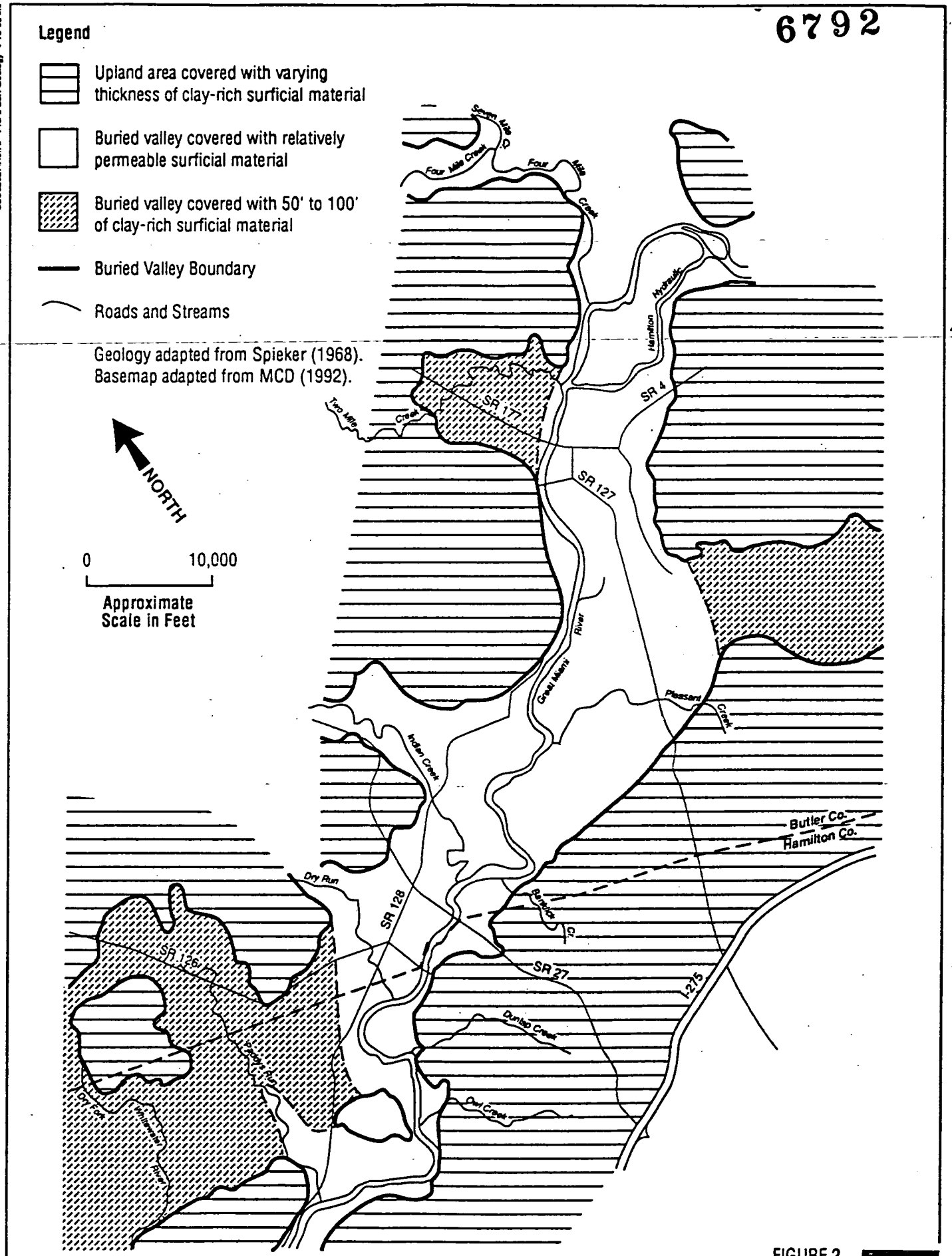

FIGURE 2
Surficial Geology
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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To the east of the City of Fairfield, and also in the vicinity of the FEMP, a layer of clayey sediments occurs at the ground surface. These deposits, which may represent the alluvium of an ancient river system that formerly flowed through part of the project area, are described as dominantly clay and clay with gravel on drilling logs (Spieker 1968). The thickness of this unit ranges from approximately 40 to 140 feet.

The third area is the surrounding uplands, characterized by a layer of clayey sediments directly overlying bedrock. According to drilling logs, this deposit is similar in appearance to surficial deposits near the City of Fairfield and the FEMP. The unit ranges in thickness from less than 20 feet to approximately 100 feet.

Buried Valley Geology

The bedrock valleys were buried by glacial deposits ranging in character from clay-rich sediments (commonly referred to as till) to coarse, well-sorted deposits of sand and gravel (commonly referred to as outwash). The deposits of the main buried valley are described generally as sand and gravel with lenses of fine-grained material (Spieker 1968). The thickness of glacial deposits ranges from about 30 feet near the edge of the valley to greater than 200 feet near the center.

A zone of sediments with a generally finer grain size than typical glacial outwash occurs within the main buried valley between New Miami and the Southwestern Ohio Water Company (SWOWC) well field. In well logs, this zone is described as mixtures of clay, sand and gravel, or as fine-grained sand. This zone, although it is composed of locally discontinuous lenses of finer grained sediments, appears on a regional scale to divide the valley fill deposits into upper and lower layers. The thickness of the zone ranges from approximately 1 foot to 20 feet. The zone appears to dip slightly more steeply than the southward slope of the current valley surface, with the result that it occurs at shallower depths in the northern part of the project area than in the southern part. This trend is depicted by the successively deeper occurrence of the zone from north to south, as shown in the profiles located on Figure 3 and provided in Figure 4. On the basis of geologic boring and well logs reviewed during the study, the lower aquifer appears to thin out in the area of the Cincinnati and SWOWC well fields.

Another fine-grained zone, consisting predominantly of clay, is present in the area east of the City of Fairfield and in the vicinity of the FEMP. This layer, which occurs at depths ranging from approximately 125 feet to 135 feet below ground surface, appears to be relatively flat and ranges in thickness from 2 to approximately 20 feet (Figure 5).

The Four Mile Creek, Indian Creek, and Shandon Buried Valleys constitute the significant tributary buried valleys within the project area. Sediments in the Four Mile Creek and Shandon Buried Valley are nearly as thick as the deposits in the main valley stem and appear similar in composition. The Indian Creek buried valley deposits are similar to the main valley deposits in composition but are generally thinner.

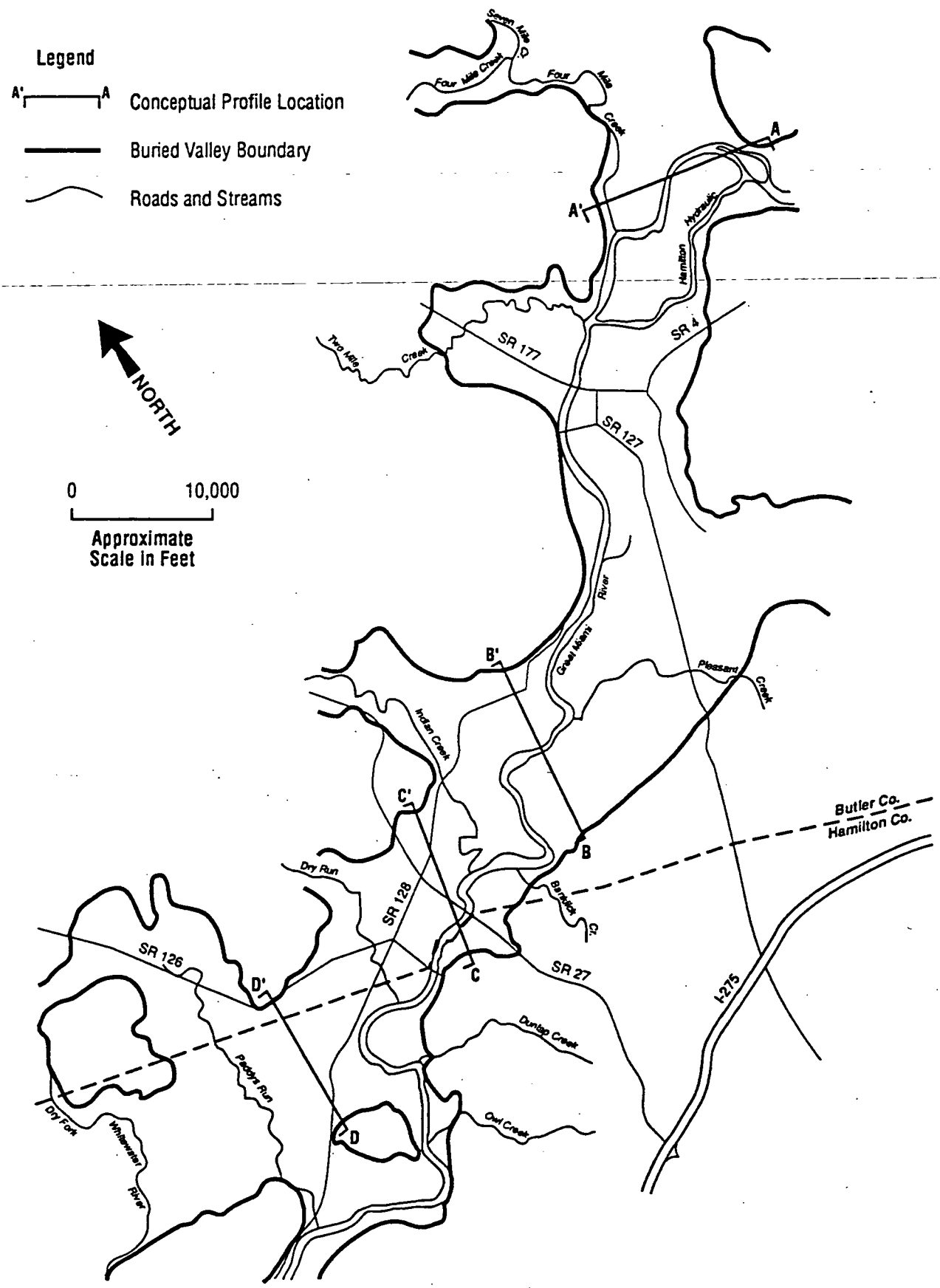

FIGURE 3
Location of Conceptual Profiles
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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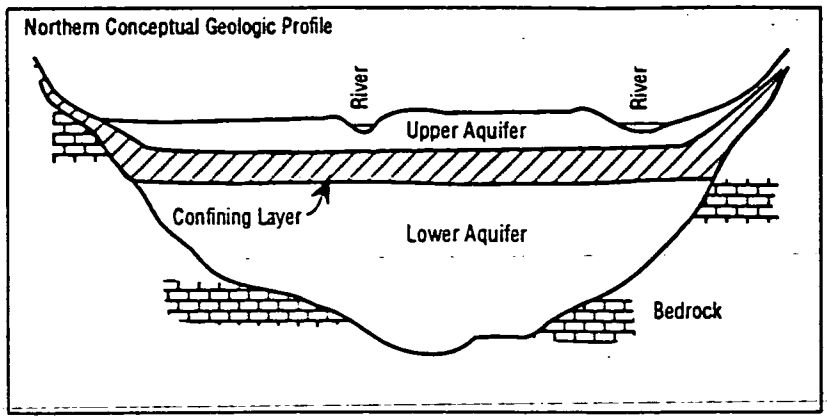
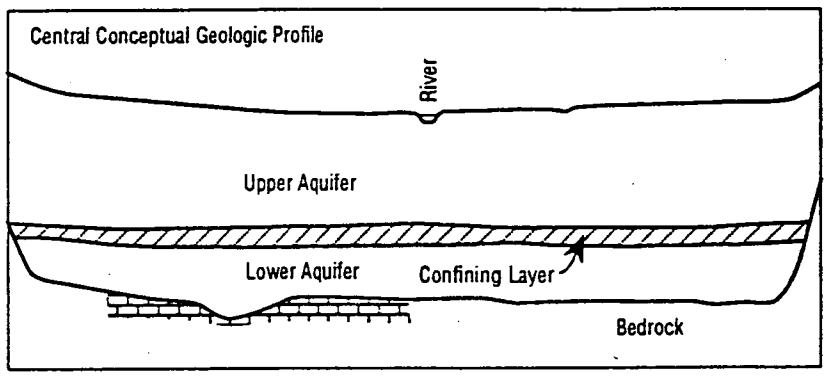
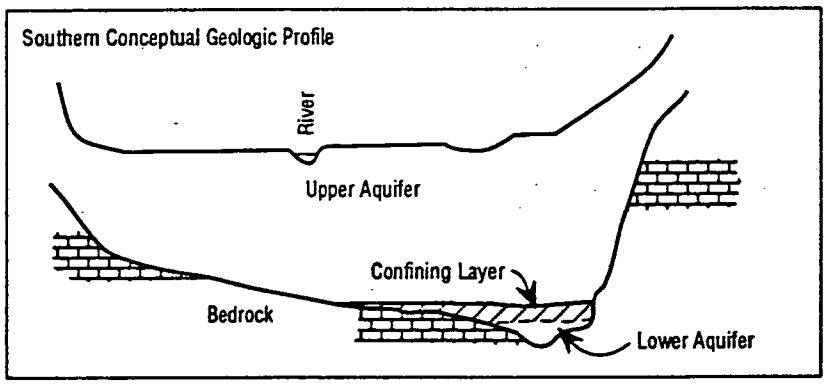
East A — A' West



South B — B' North



South C — C' North



NOTES:

(1) The Upper Aquifer and Lower Aquifer are composed of sand and gravel sized particles interspersed with lenses of clay and/or silt. Well logs indicate that the individual lenses of clay and/or silt are limited in horizontal and vertical extent and generally do not correlate between wells for a significant distance.

(2) The semi-confining layer is composed of clay, silt, and fine sand with some gravel. Although locally the layer may be absent, on a regional basis it can be represented as a semi-confining layer with an approximate dip of 18 to 27 degrees.

(3) The semi-confining layer is composed predominantly of clay and appears to be relatively flat-lying.

(4) The bedrock unit underlying the aquifer system consists of limestone and shale interbedded to various degrees. This unit is generally blanketed by glacial drift in the upland areas.

(5) Refer to Fig. 3 for profile location.

200

Approximate Scale in Feet

0 3200

Vertical Exaggeration = 16x

FIGURE 4

Buried Valley Conceptual Profiles - Main Valley Stem

Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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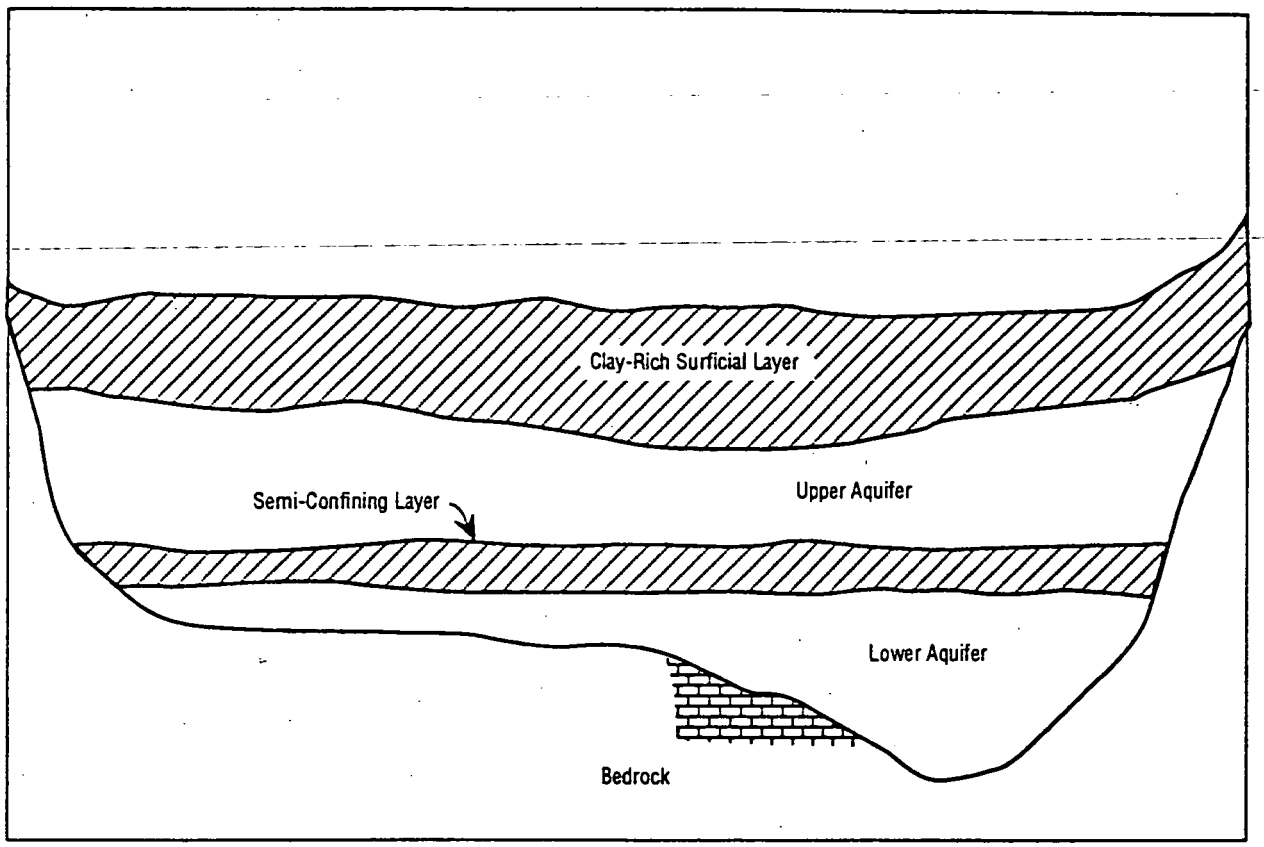
GLC032927.AO.RP Fig 4 Main Valley Stem 3-31-92lml



NOTES:

(1) The clay-rich surficial layer is composed of clay with lenses of coarser grained (silt, sand, and gravel) material. It ranges from 50 feet to approximately 100 feet thick where present.

(2) The Upper Aquifer and Lower Aquifer are composed of sand and gravel interspersed with lenses of clay and/or silt. Well logs indicate that the individual lenses of clay and/or silt are limited in horizontal and vertical extent and generally do not correlate between wells for a significant distance.

(3) The semi-confining layer is composed predominantly of clay and appears to be relatively flat-lying.

(4) The bedrock unit underlying the aquifer system consists of limestone and shale interbedded to various degrees. This unit is generally blanketed by glacial drift in the upland areas.

(5) Refer to Fig. 3 for profile location.

100

Approximate Scale in Feet

0 1500

Vertical Exaggeration = 15x

FIGURE 5
Tributary Buried Valley Conceptual Profile - Continuous Clay-Rich Surficial Layer
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

CH2M HILL

GLO32927.AO.RP Fig 5 Cont Clay Rich Surf 3-31-92lml

Conceptual Model of Area Geology

On the basis of reviewing information collected for this project, the following conceptual model of the project area geology was developed to summarize key geologic characteristics that are important to the project:

- **The bedrock valleys** have wide, relatively flat floors and steeply sloping walls which gives them a U-shaped appearance when viewed in cross section.

- **The surficial deposits** along the Great Miami River consist of laterally discontinuous layers of soil, clay, silt, and sand and gravel. Surficial deposits in the area east of the City of Fairfield, near FMPC, and in the bedrock uplands consist of a relatively thick and continuous layer of clayey sediments.

- **The buried valley deposits** consist predominantly of sand and gravel with lenses of finer-grained material. The glacial outwash deposits are separated into upper and lower layers by a slightly dipping, generally fine-grained zone in the area between New Miami and the SWOWC well field (Figures 3 and 4). Another, relatively flat-lying, zone of fine-grained sediments occurs in the area east of the City of Fairfield and in the vicinity of the FMPC (Figure 5). The valley-fill deposits range in thickness from about 30 to greater than 200 feet.

Hydrology

Surface Water Hydrology

Precipitation within the study area has averaged approximately 40 inches per year for the last 20 years. Precipitation runoff has averaged about 12 inches per year over the same period (MCD 1991a). Runoff is collected by the Great Miami River and its tributaries. Surface water either enters the groundwater flow system as recharge or flows out of the project area in the Great Miami River. Principal tributaries to the Great Miami River in the project area are Four Mile Creek, Twomile Creek, Pleasant Run, Indian Creek, Banklick Creek, Dry Run, Dunlap Run, Owl Creek, and Paddys Run (Figure 6). In addition to these streams, the Hamilton Hydraulic Canal diverts and returns water from the Great Miami River near Hamilton.

MCD (1990) has calculated the annual average discharge for the Great Miami River at Hamilton a 3,400 cubic feet per second (cfs), using data from 1910 to 1990. The discharge for Four Mile Creek north of Hamilton was 5.67 cfs in October 1991 (MCD 1991). The discharge for the Hamilton Hydraulic Canal in October 1991 was 160 cfs, and Twomile Creek was 1.13 cfs (MCD 1991).

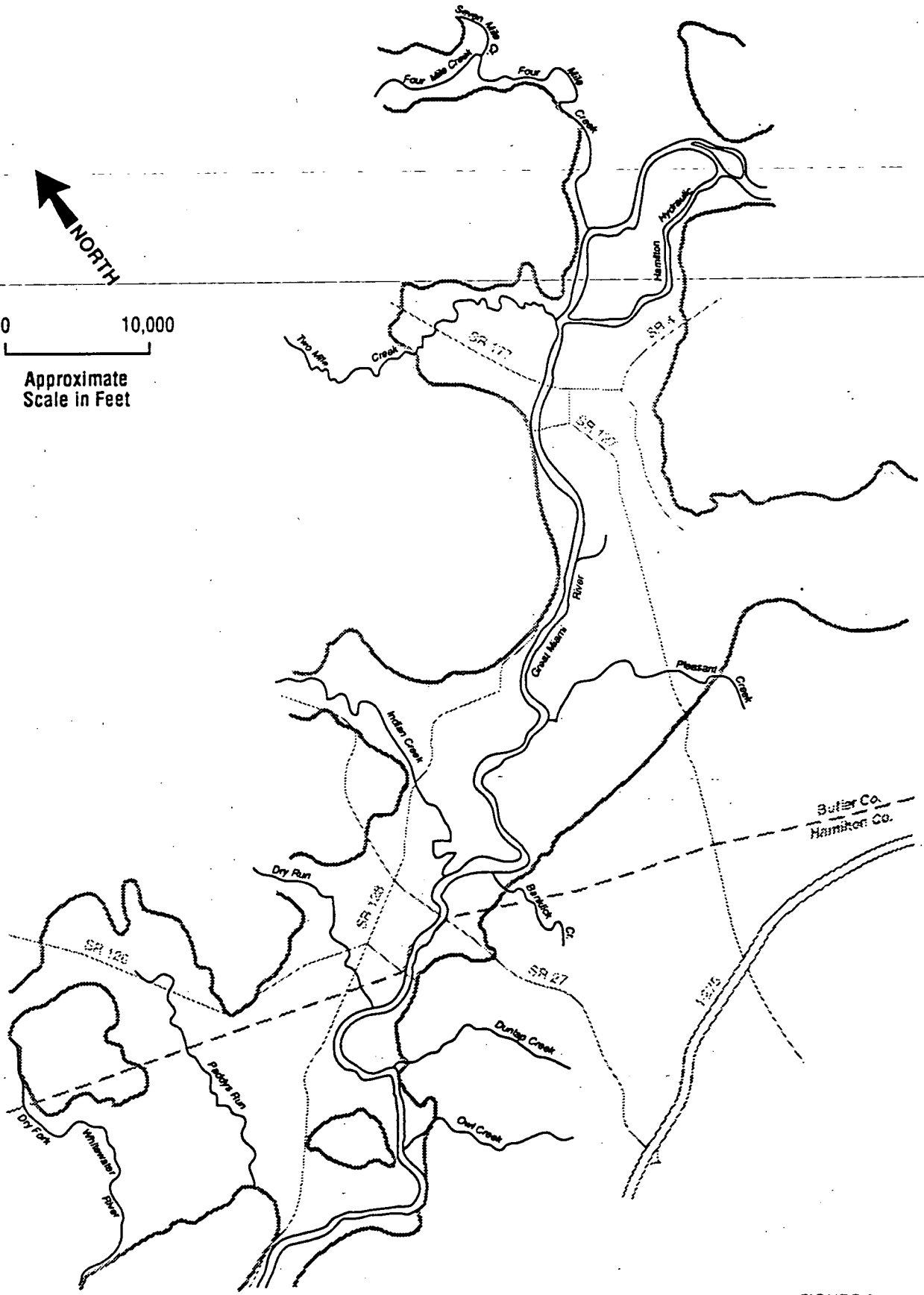


FIGURE 6
Location of Major Streams
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Wellhead Protection Area Delineation Project

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Groundwater Hydrology

Groundwater Occurrence

Groundwater within the project area occurs principally in sand and gravel deposits in the buried valley aquifer. Yields from high-capacity wells completed in sand and gravel outwash deposits can exceed 1,000 gallons per minute (gpm). These deposits are separated into upper and lower aquifers by the relatively low-permeable fine-grained zones described previously. Groundwater also occurs within these low-permeability zones, or confining layers, but these zones yield relatively little water to wells. For the purposes of the project, the lower aquifer is considered to be confined or semi-confined. This means that the water level in a well completed in the lower aquifer would rise above the top of the lower aquifer. The upper aquifer is unconfined, meaning that groundwater levels in wells completed in the upper aquifer generally coincide with the water table, or top of the zone of saturation.

The upper aquifer receives recharge from percolation of precipitation and from infiltration from streams. Stream recharge, also referred to as river leakance, occurs where groundwater levels have been lowered by pumping wells. Recharge to the upper aquifer by precipitation occurs principally where surficial sediments are fairly permeable. This situation exists in much of the main valley stem. Where surficial sediments have relatively low permeability, such as in some of the tributary valleys, recharge by precipitation is assumed to be less than in the main valley stem. Where groundwater levels in the upper aquifer have been lowered by pumping from shallow production wells, the upper aquifer may be recharged by upward vertical leakage across the confining layer from the lower aquifer.

The lower aquifer is principally recharged by groundwater from the upper aquifer flowing vertically downward through the confining layer. In some areas, a relatively good connection has been demonstrated between the upper and lower aquifers (Smith and Associates 1960).

Minor amounts of recharge to the upper and lower buried valley aquifer is supplied by discharge from the bedrock uplands. Although little information is available on the quantity of recharge supplied by the bedrock, it is considered in this study to be insignificant relative to the amount contributed by infiltration of precipitation and surface water.

Groundwater occurs in bedrock primarily in fractures and bedding planes. The bedrock supplies a number of residential wells in localized areas. Yields from bedrock wells reported on well logs from the Ohio DNR are fairly low-generally less than 5 gpm-and are considered insignificant relative to yields in the buried valley aquifer (Speiker 1968).

Groundwater Flow

Groundwater in the buried valley aquifer flows generally southwestward, parallel to the trend of the valley walls. Groundwater flow near pumping centers tends to converge toward production wells. On the basis of groundwater level measurements made by MCD in October 1991 as part of this study the hydraulic gradient in the upper aquifer is approximately 13 feet per mile, and the hydraulic gradient in the lower aquifer ranges from 4 to 10 feet per mile. Near pumping wells, the gradients steepen because of drawdown in the aquifer.

Hydrogeologic Properties

Table 2 summarizes the hydrogeologic properties for the project area that were identified during the data review. The term hydraulic conductivity refers to a measure of the ease with which groundwater will move through a saturated medium. The term transmissivity, which is calculated by multiplying the hydraulic conductivity by aquifer thickness, refers to the water-yielding capability of a confined aquifer.

Table 2
Hydrogeologic Properties

Layer	Property (Reference)	Units	Value
Upper Aquifer	Main Valley Stem Hydraulic Conductivity (Klaer and Zasmann 1943; Dove 1961; MCD 1991d)	ft/d	400 to 600
	Tributary Valley Hydraulic Conductivity (Sieco 1969, 1979)	ft/d	290 to 440
	Aquifer Thickness (Klaer and Zasmann 1943; Dove 1961; MCD 1991d)	ft	31 to 140
Lower Aquifer	Main Valley Stem Transmissivity (Smith and Associates 1960)	ft^2/d	69,500
	Tributary Valley Transmissivity (AS/IT 1989)	ft^2/d	4,700 to 40,100
	Aquifer Thickness (Smith and Associates 1960; AS/IT 1989)	ft	31 to 186
Confining Layer	Layer Thickness (Klaer and Zasmann 1943; Smith and Associate 1960; Smith and Associates 1962; IT Corporation (1987)	ft	1 to 65

Note: Transmissivity is calculated by multiplying the hydraulic conductivity by the aquifer thickness.

Conceptual Model of Area Hydrology

- **Surface water** is a source of recharge to the buried valley aquifer. The Great Miami River generally recharges the aquifer along much of its length, however, it may be gaining flow from discharged groundwater in areas located far from pumping centers. Streambed permeability is assumed to be relatively consistent throughout the project area, except immediately upstream of the Hamilton Low Dam, where the streambed sediments are considered to be thicker and less permeable because of lower river velocity.

- **Groundwater** in the project area occurs primarily in the buried valley aquifer system. This aquifer system is divided into upper and lower aquifers by a low-permeability confining layer. Groundwater flows generally to the southwest under natural hydraulic gradients. Pumping from production wells in the project area causes groundwater to converge near areas of intense pumping.

  The low-permeability layer is leaky and allows groundwater to flow between the aquifers under the influence of vertical hydraulic gradients. The rate of flow across the low permeability layer depends on its hydraulic conductivity, its thickness, and the magnitude of the vertical gradient across the layer. For the purposes of this study, the hydraulic conductivity of the low permeability layer is assumed to be constant. For a given vertical gradient, therefore, the rate of flow across the low permeability layer will depend on the thickness of the layer.

- **Recharge** to the aquifer is primarily from river leakance and infiltration of precipitation falling within the study area. Groundwater is subsequently discharged back to the river and to production wells along the river. The bedrock is considered to be essentially impermeable relative to the buried valley aquifer. Recharge by precipitation is assumed to be greatest in areas with permeable surficial material. In areas where the surface is composed of relatively low-permeability material, recharge by precipitation is considered less significant than in other areas.

Groundwater Flow Model

MODFLOW Code Description

Origin

MODFLOW is an acronym for *Modular Three-Dimensional Finite-Difference Ground-Water Flow Model* (McDonald and Harbaugh 1984). It is a numerical code developed by the U.S. Geological Survey (USGS) as a tool for use in specialized groundwater investigations. The version of the MODFLOW code used for this project was the U.S. Geological Survey 1987 revision of MODFLOW. MODPATH (Version 1.2) and MODPATH-PLOT (version 1.1) (Pollack 1989) were used in conjunction with MODFLOW to compute and display pathlines. MODFLOW, MODPATH, and MODPATH-PLOT were compiled by CH2M HILL in 1991 with Lahey FORTRAN version F77L-EM/32.

General Characteristics

MODFLOW was created to satisfy the need for a groundwater flow model that was:

- In the public domain
- Easily modified
- Simple to use
- Easily maintained
- Compatible with a variety of computer types with few modifications

MODFLOW allows each user to use modules, or packages, that are appropriate for the conditions being simulated. The major packages used in the project were:

- BASIC PACKAGE (identifies the major packages being used; defines model dimensions, specifies the length of time of the simulation, and specifies the initial water levels)

- OUTPUT CONTROL PACKAGE (identifies what water level data and volumetric budget data are to be printed or solved)

- BLOCK-CENTERED FLOW PACKAGE (computes the hydraulic flow associated with three-dimensional flow between cells in the model)

- RIVER PACKAGE (simulates flow interaction between surface water and groundwater)

- RECHARGE PACKAGE (simulates areal distributed groundwater recharge from precipitation entering the groundwater system)

- WELL PACKAGE (simulates wells that extract water from or inject water into the groundwater system)

- PRECONDITIONED CONJUGATE GRADIENT SOLVER PACKAGE (efficiently solves the matrix equations created in the model)

Limitations

As with all groundwater-flow-modeling codes, general assumptions are made about the way aquifer conditions and stresses applied to the aquifer system (i.e. pumping wells) will be represented in the model. Some of the major assumptions inherent to the MODFLOW code are:

- Pumping wells fully penetrate their assigned layer

- Pumping wells are located in the center of the cell

- Pumping wells are assumed to pull water from the entire cell volume with 100 percent efficiency

- Vertical flow between surface water and groundwater obeys the saturated groundwater flow theory

- Water levels in individual cells are averaged over the entire cell area

The above assumptions should have little discernable effect on the development of WHPAs. The full penetration assumption may lead to inaccurate simulation of vertical groundwater gradients near pumping wells, but WHPA delineation considers flows at considerable distances from wells. The assumption that flow between surface water and groundwater follows saturated flow theory is made to simplify flow calculations in the model. It does not assume high potentiometric heads beneath the stream and should therefore not significantly affect groundwater movement or particle tracking near streams represented in the model.

Model Setup

Model Area

The model covers an area that is approximately 100 square miles (Figure 7). The size of the model was chosen by estimating the area in which at least 5 years of groundwater flow travel could be calculated around each Consortium member's well field. The model area was divided into 106 rows and 56 columns for a total of 5,936 cells in each layer. The locations of the active cells, or nodes, in each model layer and the locations of Consortium drinking water supply wells are shown in Figure 8. Model grid cells varied in width and length by a range 400 by 400 feet to 1200 by

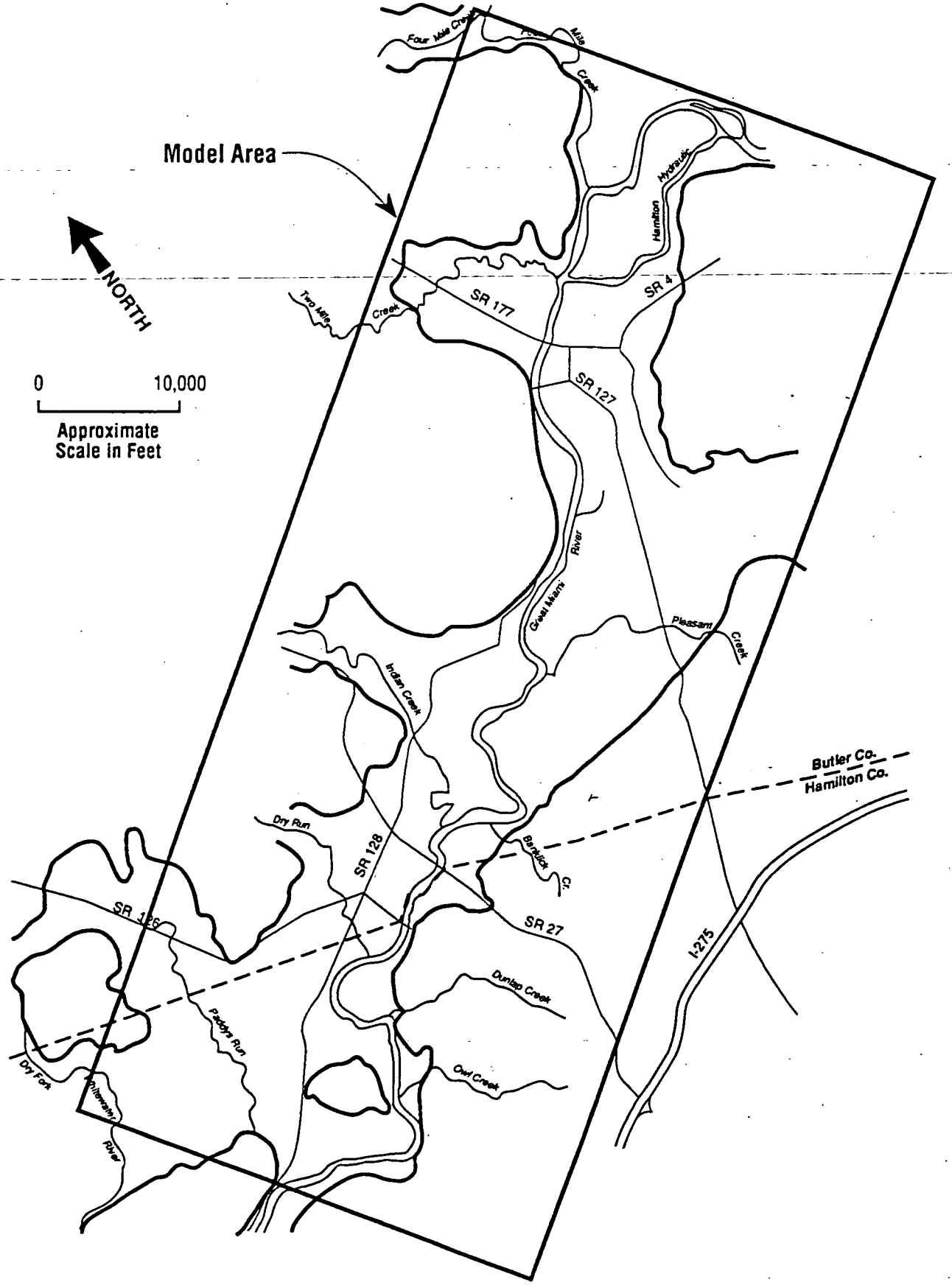

FIGURE 7
Model Area
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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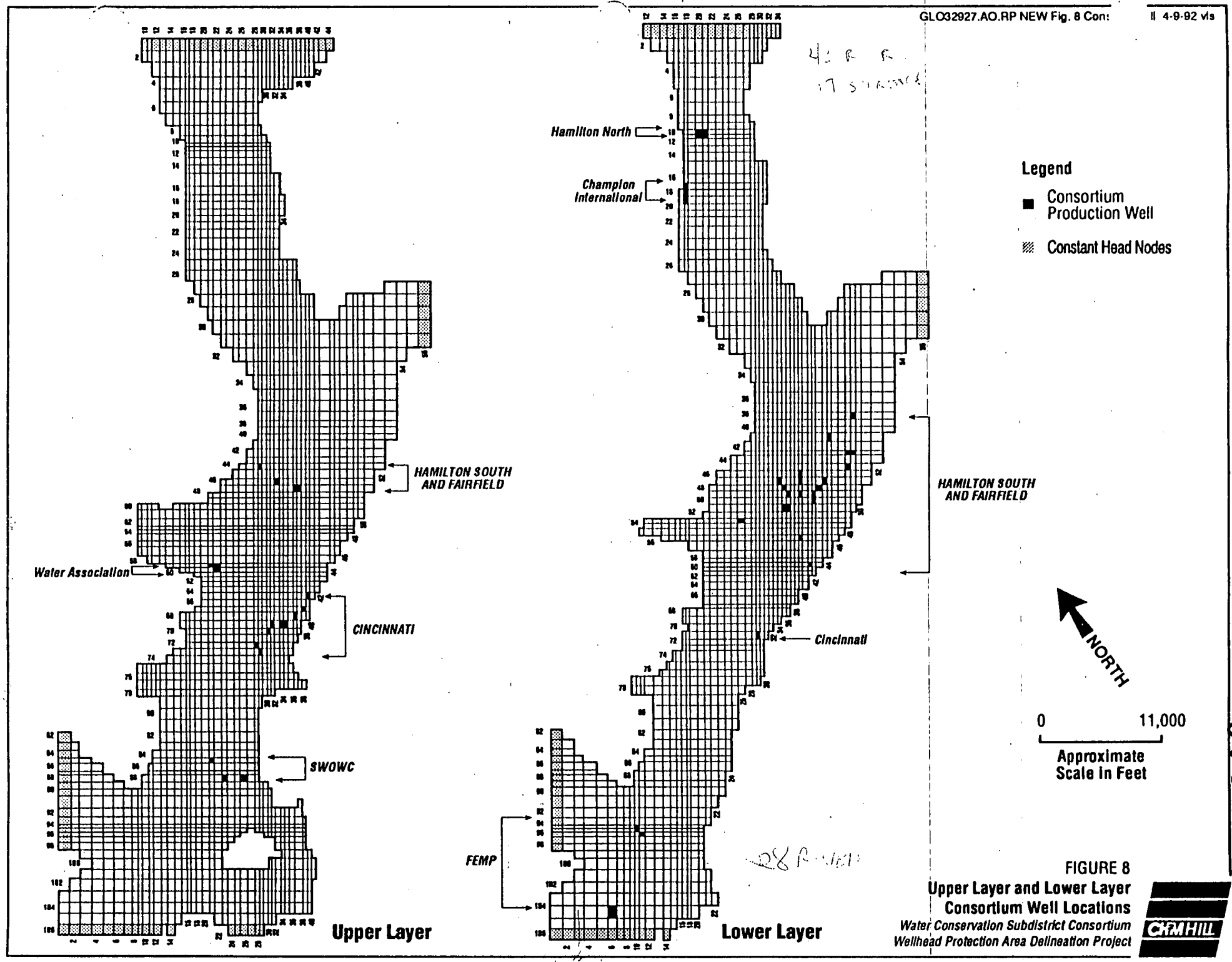

FIGURE 8
Upper Layer and Lower Layer Consortium Well Locations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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1200 feet. Smaller cells (tighter grid spacing) were located around the production wells for each Consortium member to provide a more refined picture of the simulated water levels around the Consortium well fields.

The Great Miami Buried Valley Aquifer enters the model area near New Miami, Ohio, and exits the model near New Baltimore, Ohio. A tributary buried valley aquifer, believed by some to be associated with the ancient Ohio River, is simulated in the model area in the east near Fairfield, Ohio and the southwest toward New Haven, Ohio. In the model, the buried valley aquifer is defined as areas where Speiker (1968) and Speiker and Watkins (1971) defined major buried valley aquifer material as shown in Figure 2. In the locations where the model cells along the boundary of the model intersect the simulated buried valley aquifer, the cell is defined as having a constant head. This means the groundwater level assigned to that cell remains the same during model execution. In locations outside of the buried valley aquifer where the model boundary intersects simulated bedrock areas, the cell is defined as a no-flow or inactive cell. This is defined as an area in the model that contributes no water to the aquifer during the simulation.

Model Layers

The model is divided into two layers to simulate the two-aquifer system previously defined. Within the each layer, groundwater flow is assumed to move horizontally. The groundwater flow within the aquifer system is simulated as having the ability to flow in any direction with equal ease (a condition referred to as isotropy). The hydraulic conductivity in the upper aquifer is assumed to be constant within the main stem of the buried valley aquifer; however, the hydraulic conductivity of the ancient Ohio buried valley aquifer and other tributary valleys is less than that in the Great Miami buried valley aquifer to reflect fine-grained (less permeable) sediments in these areas. The transmissivity in the lower layer is constant in the model.

The discontinuous separating glacial till between the two sand and gravel aquifers was defined as an area of vertical leakance referred to in MODFLOW as VCONT. This means that flow within the VCONT area flows in only the vertical direction, allowing flow to pass from layer to layer much like the till would allow flow from aquifer to aquifer without significant horizontal movement (compared to the sand and gravel aquifers). In simplified terms, the vertical leakance for this model is determined by a fixed vertical hydraulic conductivity of the till (or low-permeability material separating aquifers) divided by the thickness of the till. This allows less vertical flow of groundwater between layers in areas where the till is thick and more vertical flow in areas where the till is thin.

The thickness of the upper aquifer was varied by developing a separating till surface throughout the model area. The till surface was created by determining the till depth from well logs (provided by MCD) and considering the well locations within the model area, contouring the data with the aid of a contouring program (CONTOUR2, CH2M HILL 1991). CONTOUR2 develops a matrix that was transferred to the MODFLOW model. This process was also used to develop a top surface for the

lower aquifer by developing a matrix representing bottom of the separating till. The variable till thickness was considered in the model by developing a matrix of the inverse till thickness that was multiplied by the vertical hydraulic conductivity to create a variable vertical leakance layer.

Simulated River

The Great Miami River, Four Mile Creek, Hamilton Hydraulic Canal, and Paddys Run were considered sources of surface water for the aquifer system. Smaller seasonal tributaries were not included in the model because they were assumed to contribute an insignificant amount of water to the aquifer system on an annual basis. The Great Miami River and its major tributaries were input into the model by overlaying a river location map onto a model grid map. In the locations where the river intersected a model cell, the area of the river in the cell was estimated. The water level measurements made in October 1991 by MCD were input into the model as part of the river stage data. In sections of the river where measured data did not exist, the stage of the river was interpolated from available data. The river bed elevation was included as an estimate in the model after studying a number of MCD-developed river cross sections throughout the model area. The thickness of the river bed sediments is not known, but was estimated for the model. The vertical hydraulic conductivity for flow through the river bed was also estimated to determine the vertical leakance of surface water into the aquifer system. The river and its the tributaries were assumed to be located in the upper layer only.

Simulated Wells

Wells in the model area were input as either extracting or injecting wells within the layers being stressed. Residential wells were not included in the well data because their overall effect on groundwater flow was considered to be negligible compared to the effects of municipal, commercial, and industrial wells. Pumping data were provided by MCD for major pumping activities in October 1991.

Simulated Areal Recharge

Aquifer recharge from precipitation was estimated initially by assuming that one-third of the annual precipitation infiltrated into the aquifer system (equal to 14 inches per year) in agricultural portions of the valley. This value was adjusted slightly during model calibration, but the initial value of 14 inches was used in the final calibrated model.

Few studies are available on infiltration rates in Ohio. In a study conducted by the Ohio State University in the Scioto River Valley, one-fourth of the precipitation was estimated to infiltrate into the aquifer (Ward 1991). This value for the Scioto River Valley was determined through groundwater model calibration. A separate study conducted by the MCD using hydrographs estimated precipitation infiltration rates at 12 inches per year (Rozelle 1992).

Infiltration of precipitation varies depending on several factors such as the slope of the ground surface, the soil type, ambient soil moisture conditions, rainfall intensity, and land use. Because the land surface is assumed to be fairly flat over the valley aquifer areas, topography was not considered as a significant factor affecting recharge in this model. Land use, however, was considered important because a large portion of the aquifer is overlain by heavy industrial or urban development where precipitation is diverted to storm sewers, and a smaller portion of the rainfall is expected to enter the aquifer. Soil type was also considered important in areas of the model where the aquifer is overlain by greater than 20 feet of low-permeability till. For this model, three major recharge zones were mapped for the aquifer area:

- Undeveloped or agricultural areas with fairly permeable surface soil
- Undeveloped or agricultural areas mapped by the USGS as having low-permeability glacial till near the ground surface
- Municipal or industrial areas that are expected to have a high proportion of impermeable surface (pavement and roof tops)

Empirical coefficients from the rational runoff equation (Chow 1964) were used to estimate the relative amount of precipitation recharge in these areas. The rational runoff method was originally developed to predict peak runoff rates given specified rainfall intensities and drainage basin characteristics. Coefficients for the rational method range from 0.05 for flat-lying, sandy soil (representing low potential for runoff and high potential for recharge) to 0.95 for concrete or asphalt pavement (representing a high potential for runoff and a low potential for recharge).

For this analysis, it was assumed that the amount of recharge estimated to occur in agricultural areas represented the maximum amount of available recharge. The ratio of the rational runoff coefficient for undeveloped areas with fairly permeable surficial soils (0.2) and the coefficients for other areas of interest (areas with municipal/industrial development and areas with low-permeability surficial soil) was used to estimate the proportion of the maximum available recharge that is expected to recharge the groundwater in the area being considered:

Type of Surface	Rational Coefficient	Proportion of Available Recharge
Agricultural	0.2	1
Municipal/Industrial	0.8	0.3
Surficial Till	0.3	0.7

Note: The proportion of available recharge is calculated by dividing the coefficient for agricultural areas (0.2) by the coefficient for the area being considered.

Model Calibration

Model calibration is an iterative process where the model is run, its results compared to measured data, small adjustments are made to certain model input parameters, and the model is rerun to observe the change in model results caused by parameter adjustment. Calibration is considered to be complete when certain general criteria (described below) are met.

Limits on the degree to which parameter values should be changed during calibration include:

- The parameter values should vary within ranges of values known to have been measured in the area, or within ranges of values that have been measured in other areas with similar physical conditions

- The parameter values for a particular physical property should be similar throughout the model area unless physical conditions (such as the geologic setting or land surface characteristics) are known to differ

Calibration Procedure

After the model was constructed, it was run using the MODFLOW code. The output from the code includes:

- OUTPUT FILE (written in an ASCII format with information on the input files included, the space allocated for the files, the output of heads and simulated volumetric budget)

- CELL-BY-CELL BUDGET FILE (written in an unformatted file with information on the volumetric budget of the model)

- HEAD FILE (written in an unformatted file with information on the heads in each cell of the model)

The model output was analyzed during model calibration in three ways:

- The head data for each layer were contoured to create a potentiometric surface map that was compared to a contour plot of the water levels measured in the field.

- The difference between the simulated heads and field-measured groundwater levels was calculated at specific target locations within the model area.

- The volumetric budget results for the model were compared against a specific budget goal.

Potentiometric Surface Map Comparison

For this model, the October 1991 water level measurements were contoured for each aquifer using the contouring steps outlined previously, supplemented by inferred contours in areas where data were unavailable (Figures 9 and 10). The resulting potentiometric surface maps were compared to the model output to determine if groundwater gradients, groundwater levels, and overall contoured potentiometric surface shapes were similar. If these criteria were not met, selected model input parameters were adjusted slightly and the model was rerun in order to develop a simulated contour map that more closely matched the measured data contour map.

Calibration Target Location Comparison

This criterion is a less objective method for checking calibration than the potentiometric surface map comparison. For this check, the model results were compared against October 1991 water levels measured at a set of wells distributed throughout the model area in both the shallow and deep model layers (Figure 11 calibration wells). Wells were chosen as calibration targets if the following criteria were met:

- Groundwater level data were available for both October 1991 (calibration data) and May 1988 (validation data, discussed below)
- The depth, and if possible, the geologic log of the well was known
- The well was not located close to an active pumping well or another calibration target well

The WELLDIR database file (MCD 1991b), which contains over 700 well records in the project area, was reviewed using these criteria to identify calibration target locations. A total of 31 wells met most of the criteria and were selected as calibration targets. The criteria were met in most of the selected wells, except for where wells were scarce in an area where a comparison was needed.

After each model run was completed, the October 1991 target well groundwater levels were compared to simulated groundwater levels for the cells in which the target wells were located. The absolute value of the differences between simulated and measured water levels was averaged. The average was compared against a target mean difference of 5 feet, as preliminarily agreed upon by the Consortium before the modeling effort began. If the difference between target groundwater levels and simulated heads differed by an average of more than 5 feet the model was adjusted and rerun.

Volumetric Budget Comparison

At the end of each model run, a list of the modeled inflow and outflow water volumes and volumetric flow rates was printed in the Output File. The difference between

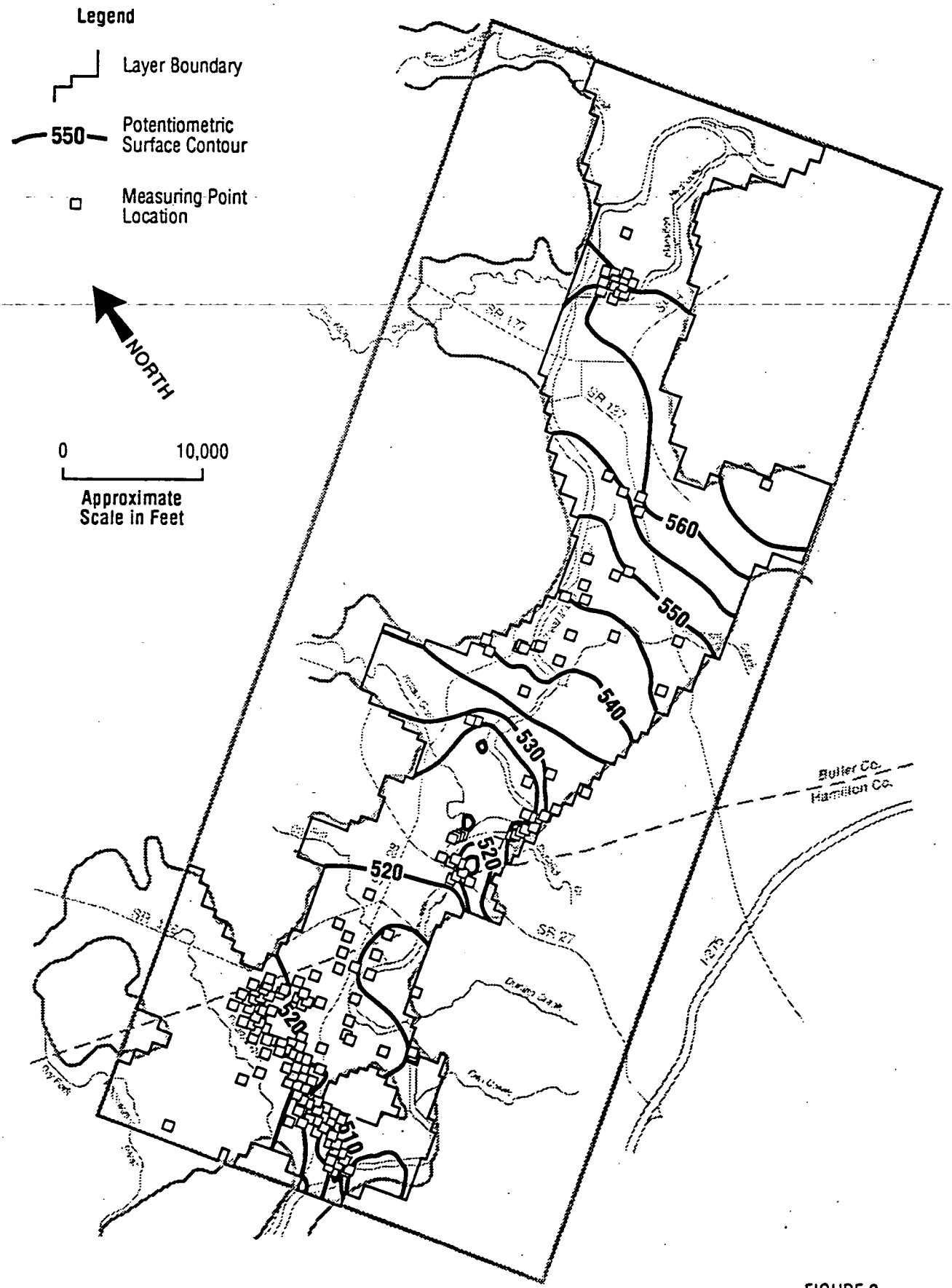

FIGURE 9
Upper Layer Measured Groundwater Elevations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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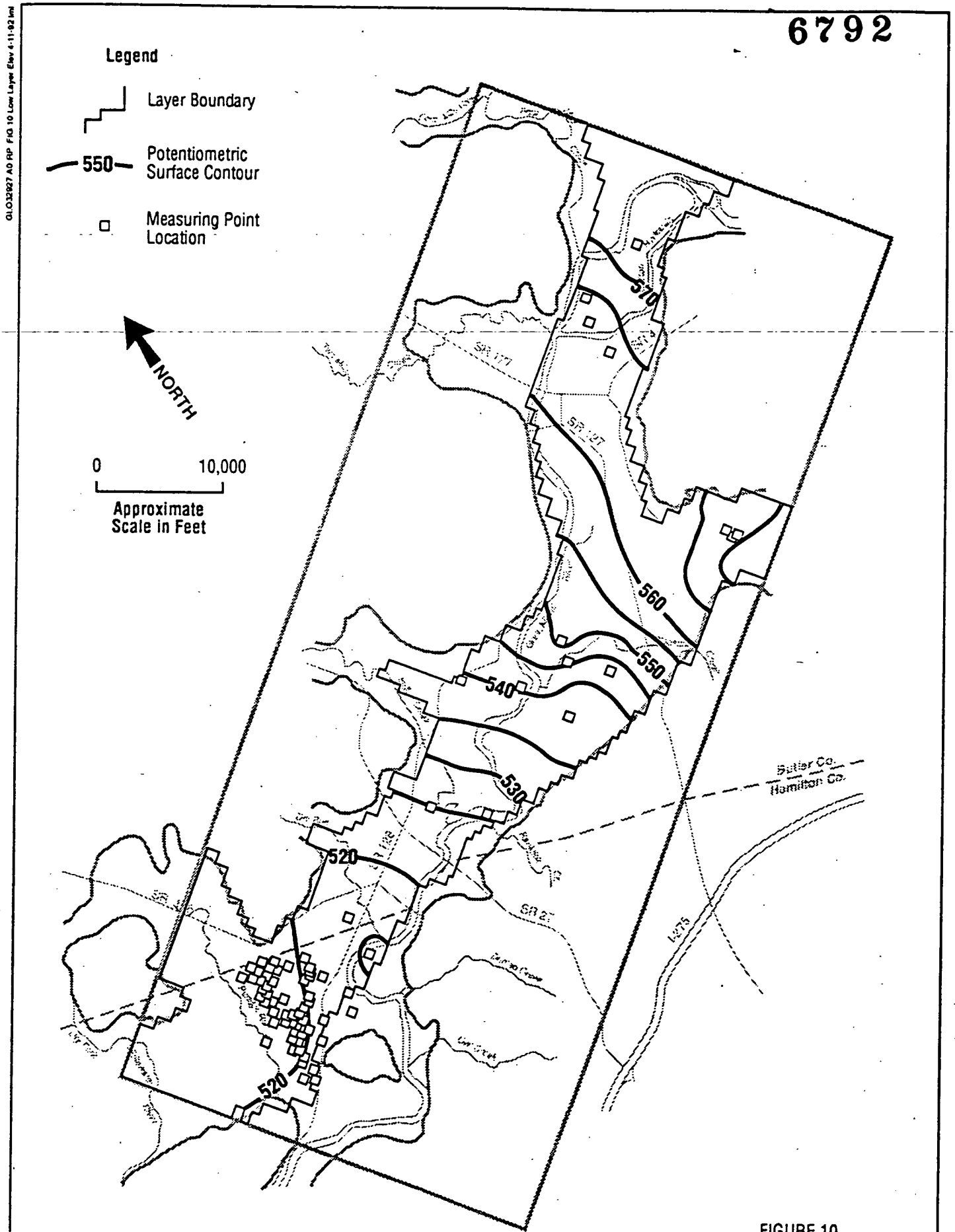

FIGURE 10
Lower Layer Measured Groundwater Elevations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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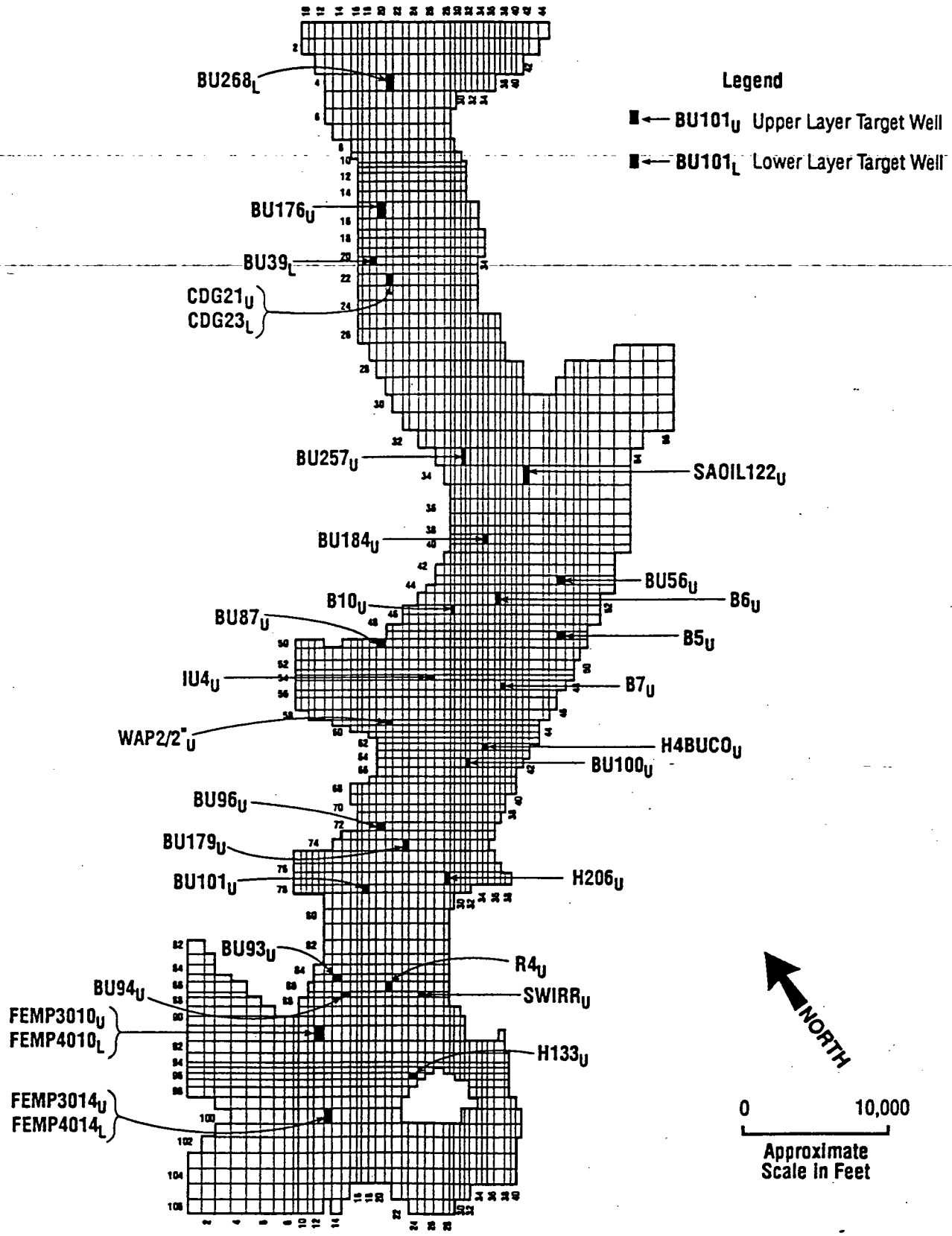

FIGURE 11
Calibration Target Locations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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total inflow and outflow was presented as a percentage. This percentage was compared to an acceptable level of error selected during model setup. For this model, the error level was set at one percent. If the simulated total volumetric inflow and outflow error was greater than one percent, the model was adjusted and rerun.

Calibration Results

Calibration Target Location Comparison

The simulated water levels were compared against a set of 31 field-measured water levels scattered throughout the model area in both the upper and lower aquifer (Figure 12). The average of the absolute values of the differences between simulated and field-measured groundwater levels was 1.9 feet in the upper layer and 1.6 feet in the lower layer, well within the preliminary criterion of 5 feet.

Potentiometric Surface Map Comparison

The groundwater levels simulated by the model (Figures 13 and 14) appear to match well with the potentiometric surface data from October 1991 (Figures 9 and 10). A comparison of these two sets of maps shows that the magnitude and direction of hydraulic gradients for the observed data and the simulated model results are generally similar.

A quantitative method of comparing potentiometric surface maps is to prepare a contour map of the difference between observed and simulated groundwater levels. These maps, which are commonly called residual maps, are created by developing an array of measured water levels, comparing this array to simulated water levels (model output), and creating a new array that contains the differences between the two. This comparison is conducted by computer on a node-by-node basis.

As shown by the small squares on Figures 9 and 10, groundwater level measurements for October 1991 were available from approximately 335 wells in the project area. Despite this large number of measuring points, a measuring point was not located in the area covered by each model node. To make the comparisons required for Figures 15 and 16, it is necessary to specify a "measured" water level value for each model node in the two model layers. Contouring programs (LPLNEW and CONTOUR2) were used to interpolate between points of measurement to prepare the contour maps of measured groundwater levels (Figures 9 and 10). Digital versions of these maps were then compared to digital versions of model output to create Figures 15 and 16.

Three areas in model layer 1 (upper aquifer) and one area in model layer 2 (lower aquifer) can be identified on Figures 15 and 16 as having the greatest difference between simulated and observed groundwater levels. These areas are:

- A northern area, which is apparent in both layers 1 and 2, located east of Hamilton near the Hamilton Airport

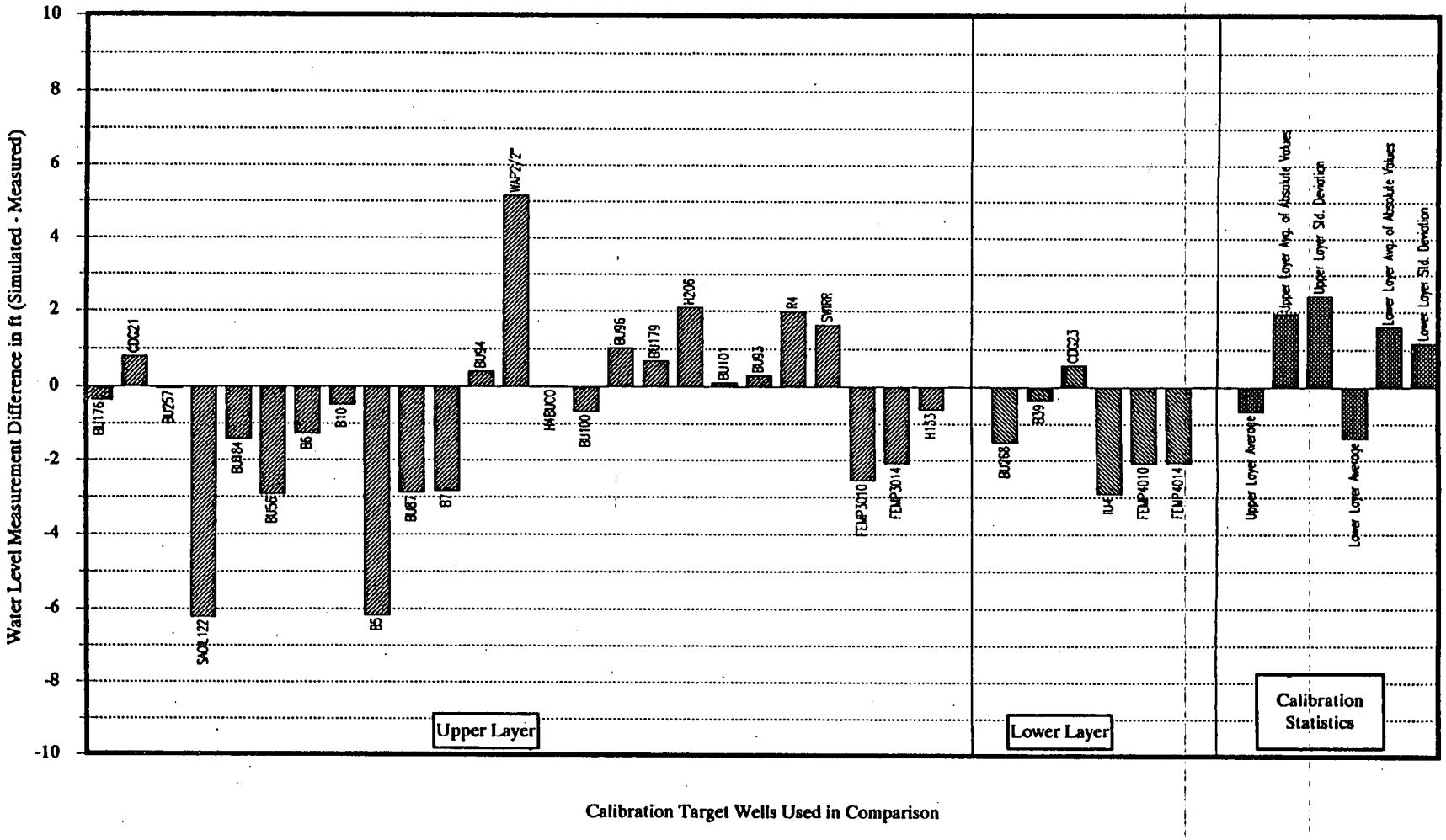

FIGURE 12
Calibration Target Well Comparison
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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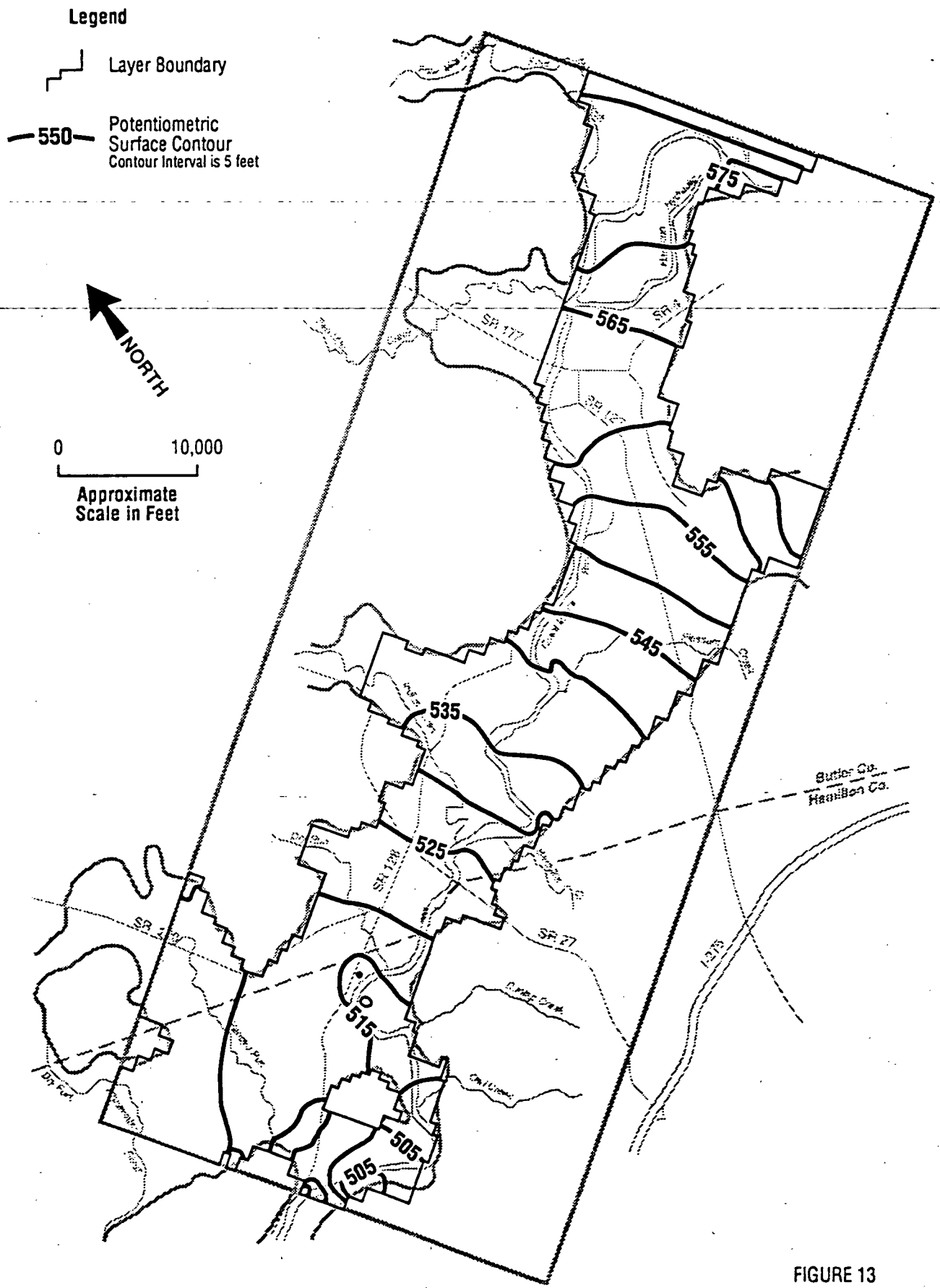

FIGURE 13
Upper Layer Calibrated Groundwater Elevations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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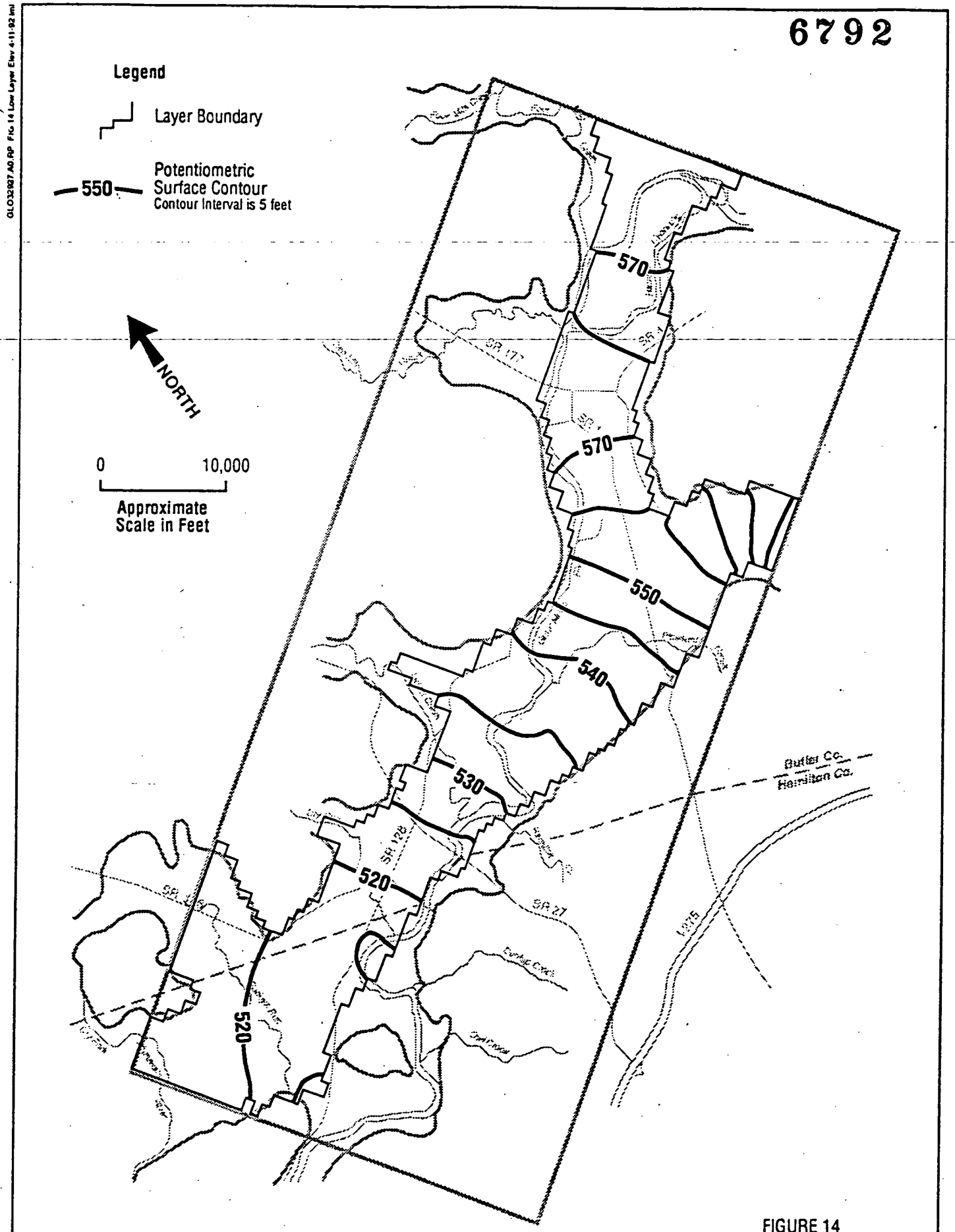

FIGURE 14
Lower Layer Calibrated Groundwater Elevations
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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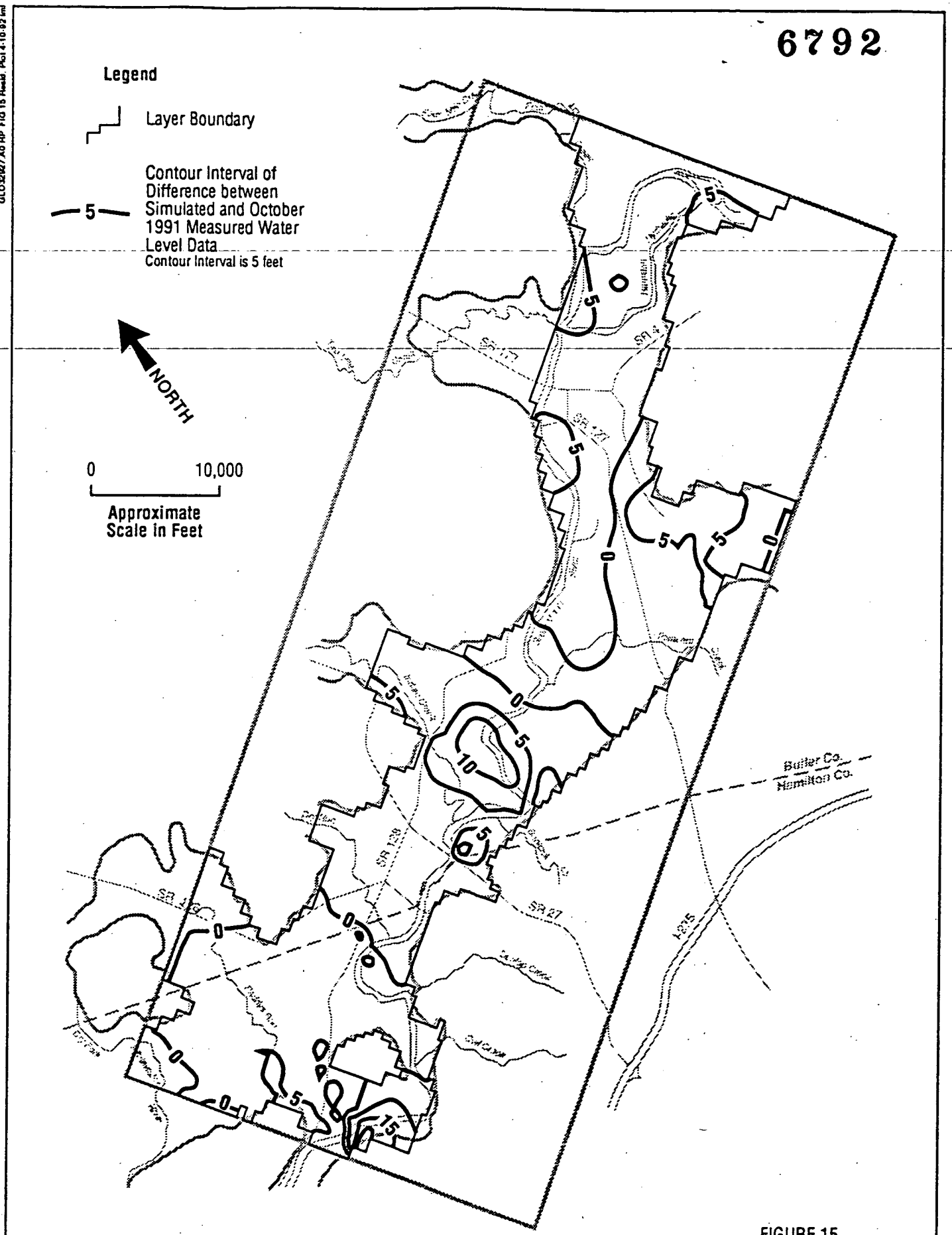

FIGURE 15
Residual Plot for Upper Layer Comparing Simulated and Measured Water Levels
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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Plot Low 4-11-92 Ini
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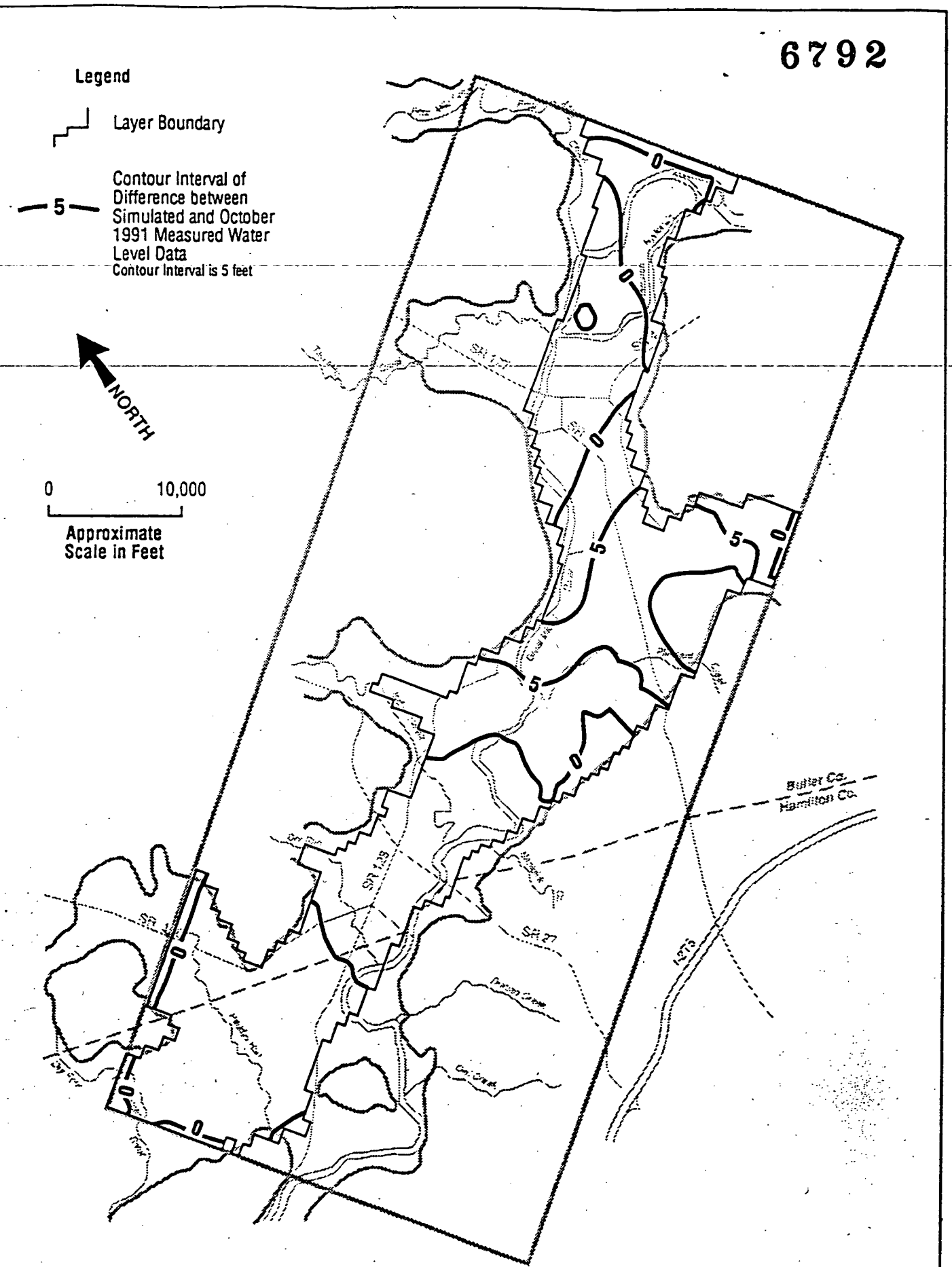

FIGURE 16
Residual Plot for Lower Layer
Comparing Simulated and Measured Water Levels
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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- A central area, which is apparent in model layer 1, located near the Water Association's well field
- A southern area, which is apparent in model layer 1, located south of the Cincinnati well field near Ross

In addition to these three areas, the effect of constant-flux and no flow boundaries along the edges of the model cause model-simulated groundwater levels to differ locally from measured groundwater levels. These differences are related to the model boundaries and reflect uncertainties in the current understanding regarding the position and hydraulics of the glacial outwash/bedrock boundary.

The three areas having the greatest difference between simulated and observed groundwater levels are discussed in more detail below.

Northern Area. The northern area of apparent difference between measured and observed groundwater levels appears to be related to the scarcity of measuring points in this part of the project area. As shown by the measuring point locations plotted on Figures 9 and 10, groundwater levels were measured in a total of four closely-spaced wells in this area during the October 1991 survey. The distance between the wells in this tributary valley and the next closest wells in the main part of the aquifer was more than 10,000 feet in the upper layer and 18,000 feet in the lower layer. Because the water level information available to assess model calibration in this area is interpolated over a long distance, it is not known if the apparent differences shown in the tributary area on Figures 15 and 16 actually exist, or if they are caused by errors in interpolating between widely-spaced measurements.

Moreover, geologic logs for the wells that were measured in this tributary area were unavailable except for American Cyanamide well No. 3, which showed that this well is screened across a thick lens of glacial till. CH2M HILL's experience in the Great Miami Buried Valley Aquifer is that wells screened in till lenses, which generally have low permeability, may have anomalous water levels compared to wells screened entirely in sand and gravel. The lack of available information on the other wells measured in this area makes it difficult to assess the reliability of the measurements.

In summary, the apparent difference between the simulated and observed data in the northern area is impossible to resolve with available data. Additional measuring points, such as new monitoring well installations, would be needed to define groundwater gradients in this area. It would then be possible to compare measurements in this area with simulated groundwater levels.

Central Area. The cause of the water level residual mapped in Figure 15 in the central part of the project area is probably related to the proximity of the measuring points in this area to the Water Association's production wells. A regional model such as that created for this project tends to generalize groundwater gradients to varying degrees. The degree of generalization depends upon the node size, which is dictated by grid spacing. In the central area, the difference between observed and

simulated groundwater levels is probably related to steep gradients created by drawdown at the Water Association's production wells, and by the model's inability to resolve large changes in hydraulic gradient over short distances. Evidence for steep gradients in this area is provided by October 1991 groundwater level measurements showing that groundwater levels in this area differ by more than six feet over a distance of a few hundred feet.

Southern Area. The localized southerly water level residual mapped in Figure 15 appears to be caused by an anomalous water level measurement in a single well, identified as BU121. The measured groundwater elevation in this well was about 511 feet NGVD, yet this well was surrounded by other wells that were determined to have groundwater elevations of greater than 520 feet, NGVD. This unusually low groundwater level could be caused several factors, including:

- Measurement error
- Non-representative water level in BU121 (caused by a plugged well screen or by geologic conditions)
- The presence of an unknown pumping well near BU121 causing drawdown in a localized area.

The presence of other wells near BU121 with substantially higher groundwater levels, which are similar to groundwater levels simulated by the model, indicates that the effect of the low groundwater level in BU121, even if it is accurate, is unlikely to be significant on a regional scale.

Volumetric Budget Comparison

The volumetric budget for the model indicated that the total model inflow originated from:

- The Great Miami River—43 percent
- The model boundaries—40 percent
- Areal recharge—17 percent
- Injection wells (at the Chem Dyne Superfund Site)—less than 1 percent

The total model outflow was comprised of:

- The Great Miami River—15 percent
- Model boundaries—28 percent
- Production wells—57 percent

The volumetric budget error between the inflows and outflows was -0.1 percent. This error level was one-tenth of the preset error criterion of one percent.

Calibrated Hydraulic Values

The calibrated values for hydraulic parameters used in the final calibration run are provided in Table 3 with reported values for the hydraulic parameters provided by references reviewed for this study. In general, values lie within ranges of values reported for the project area. The calibrated upper aquifer hydraulic conductivity value is slightly above the range of hydraulic conductivity values measured in the study area, however, it is well within the range of values reported near the project area for the Great Miami Buried Valley Aquifer (Schaefer and Walton 1957, Norris and Speiker 1966).

Model Validation

After model calibration was completed, the model was run using a different set of data to see how model performance changed under different conditions. This process is referred to as model validation. The data set selected for validation was from May 1988, which represents different seasonal and pumping conditions from the October 1991 calibration data set.

Procedure

During model validation, the model input files were adjusted to include the May 1988 data set, while aquifer hydraulic parameters, such as aquifer properties, river leakance, and separating till hydraulic conductivity remained the same as the values set in the final model calibration run.

Results

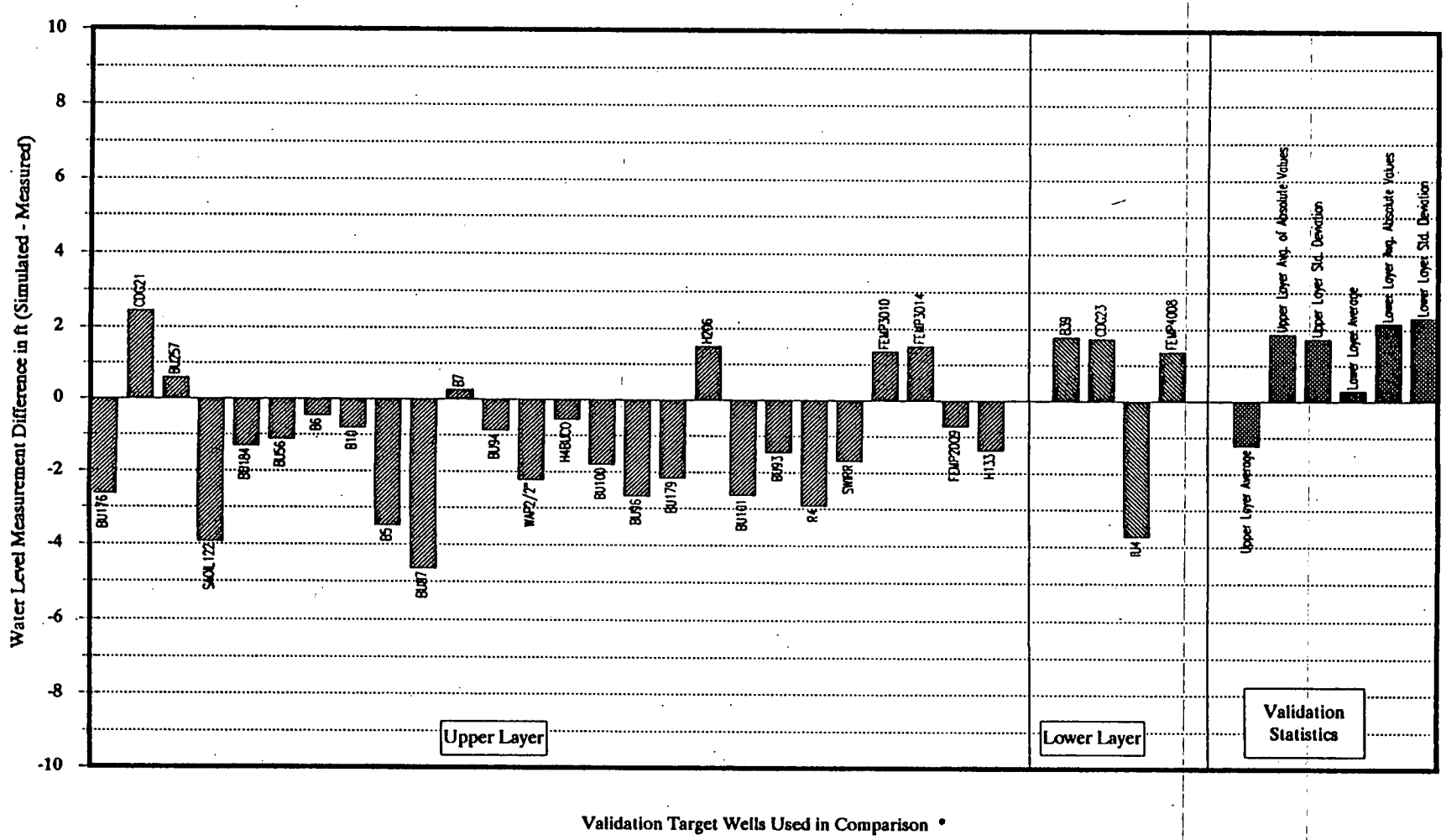
Overall, the model appeared to respond well to changes in aquifer stress parameters. The potentiometric surface interpreted with measured data from May 1988 was compared to the simulated potentiometric surface in the upper and lower model layers. Comparison of the surfaces was difficult because the available field data were unevenly distributed throughout the model area. Available data were concentrated in areas where groundwater contamination investigations or remediation were occurring, such as at the FMPC, the Chem-Dyne Trust Site, and the Paddys Run remedial investigation site. In areas where data were available, the model results appear to match measured data.

The simulated water levels were also checked against the May 1988 groundwater levels measured at target wells used for model calibration. Data from 30 target wells were included in the validation comparison data set. As shown in Figure 17, the averages of absolute values of the difference between simulated groundwater levels and measured groundwater levels from May 1988 were 1.9 feet in the upper model layer and 2.2 feet in the lower model layer. These values fell within the preliminary calibration criterion of 5 feet, and were similar to the differences observed with the October 1991 calibration data set.

Table 3
Comparison Between Reported And Simulated Aquifer Hydraulic Parameters

Parameter	Units	Reported Value	Simulated Value
Layer 1			
Hydraulic Conductivity-Main Valley Stem	ft/d	400 to 600	800
Hydraulic Conductivity-"Ancient Ohio" Tributary	ft/d	-	560
Hyd. Conductivity-Other Tributaries	ft/d	290 to 440	240
Aquifer Thickness	ft	31 to 140	0.27 to 140
Effective Porosity	%	-	25
Separating Low Permeability Zone			
Vertical Hydraulic Conductivity	ft/d	-	0.5
Layer Thickness	ft	1 to 65	9 to 55
Effective Porosity	%	-	10
Layer 2			
Transmissivity-Main Valley Stem	ft^2/d	69,519	69,519
Transmissivity-"Ancient Ohio" Tributary	ft^2/d	4,700 to 40,100	48,663
Transmissivity-Other Tributaries	ft^2/d	-	20,856
Aquifer Thickness	ft	31 to 186	0.15 to 176
Effective Porosity	%	-	25
Areal Recharge			
Agricultural/Light Municipal	inches/yr	-	14
Municipal/Heavy Industrial	inches/yr	-	4.2
More Than 20 ft Surficial Till	inches/yr	-	9.8
Riverbed Vertical Hydraulic Conductivity			
Great Miami River	ft/d	-	0.5
Four Mile Creek	ft/d	-	0.1
Hamilton Hydraulic Canal	ft/d	-	0.1
Paddys Run	ft/d	-	0.5
Bedrock Valley Walls			
Hydraulic Conductivity	ft/d	-	0

Notes:
1. "-" = No readily available information on parameter value.
2. References for reported values listed in Table 2.



* 1991 well identifiers were used

FIGURE 17
Validation Target Well Comparison
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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000047

6792

As a final check on model performance during validation, the volumetric budget's inflows and outflows were analyzed. The volumetric budget error for the validation run was -0.2 percent, or about one-fifth of the error criterion of one percent.

Model Predictions

The goal of this modeling effort was to predict potentiometric surfaces (or groundwater heads) for future pumping scenarios from which 1- and 5-year WHPAs could be produced for each Consortium member's well field. As outlined in the Introduction, the Ohio EPA recommends that maximum pumping rates be used for delineating the WHPAs to take future well field expansions into account.

To address the Ohio EPA's recommendation, maximum pumping rates for each Consortium member's well field were estimated using an approach developed by the MCD. In this approach, the ratio of the well field's maximum month's production rate (expressed as an average daily pumping rate) was divided by the well field's annual average production (expressed as an average daily pumping rate):

$$\text{Ratio} = \frac{\text{Daily Pumping Rate (Averaged for Maximum Month)}}{\text{Daily Pumping Rate (Annual Average)}}$$

This ratio provides a measure of how variable well field production is for a given well field; in other words, it accounts for the difference between extremely high periods of production compared to long-term average production rates. Well fields with a large ratio indicate variable pumping rates. Well fields with a small ratio indicate relatively consistent production rates.

The ratio was multiplied by the predicted average future pumping rates (estimated by each Consortium member) to predict future maximum pumping rates for the years 1996, 2001, 2006, and 2011 (Appendix A). Pumping rates predicted for 1996 were used in the model to create the 1- and 5-year WHPAs.

In the future-condition simulations, the calibrated model conditions for river leakance, areal recharge, and other, nonconsortium pumping wells were assumed to be similar to values used in the calibration data set and were not changed.

Wellhead Protection Area Delineation

MODPATH and MODPATH-PLOT Code Description

A particle tracking postprocessing package consisting of two programs, called MODPATH and MODPATH-PLOT, was developed in 1989 by the USGS to compute three-dimensional groundwater flow pathlines based on the output from MODFLOW steady-state simulations (Pollack 1989). MODPATH calculates pathlines and MODPATH-PLOT plots MODPATH results.

MODPATH Program

MODPATH input files consist of data from both MODFLOW input and output. These data are necessary to compute the velocity of particle movement in the simulated aquifer system. The files consist of:

- MAIN DATA FILE (provides information on location of option packages, grid size and geometry, and porosity)
- RIVER FILE (similar to MODFLOW RIVER PACKAGE with flow direction assignment)
- RECHARGE FILE (similar to MODFLOW RECHARGE PACKAGE with flow direction assignment)
- WELL FILE (similar to MODFLOW WELL PACKAGE with flow direction assignment)
- CELL-BY-CELL BUDGET FILE (same as MODFLOW BUDGET OUTPUT; provides flow rate information for each model cell)
- HEAD FILE (same as MODFLOW HEAD OUTPUT; provides information on water levels in each cell)
- OPENING FLOW SYSTEM FILE (provides the file names and user-assigned unit numbers to MODPATH so appropriate files can be accessed during operation)

While MODPATH is running, a number of questions are presented to the user, such as: where particles should be located, the number of particles requested, and the length of time required for simulated particle movement.

MODPATH-PLOT Program

MODPATH-PLOT graphically represents the particle locations or pathlines simulated by MODPATH for a given length of time at a given map scale. Either planar or

cross-sectional views can be plotted. The input files required by MODPATH-PLOT are the same as for MODPATH, with the addition of the plotting output directions.

Limitations

The program MODPATH has the following limitations:

- Flow can only be simulated for simple linear velocity in the seven directions recognized in three-dimensional finite-difference problems
- Accuracy of particle pathlines is limited by the level of detail (i.e. node size) available from the MODFLOW simulation of hydrogeologic setting
- The level of uncertainty in hydrogeologic parameters being simulated will affect the uncertainty of predicted pathlines

Sensitivity Analysis

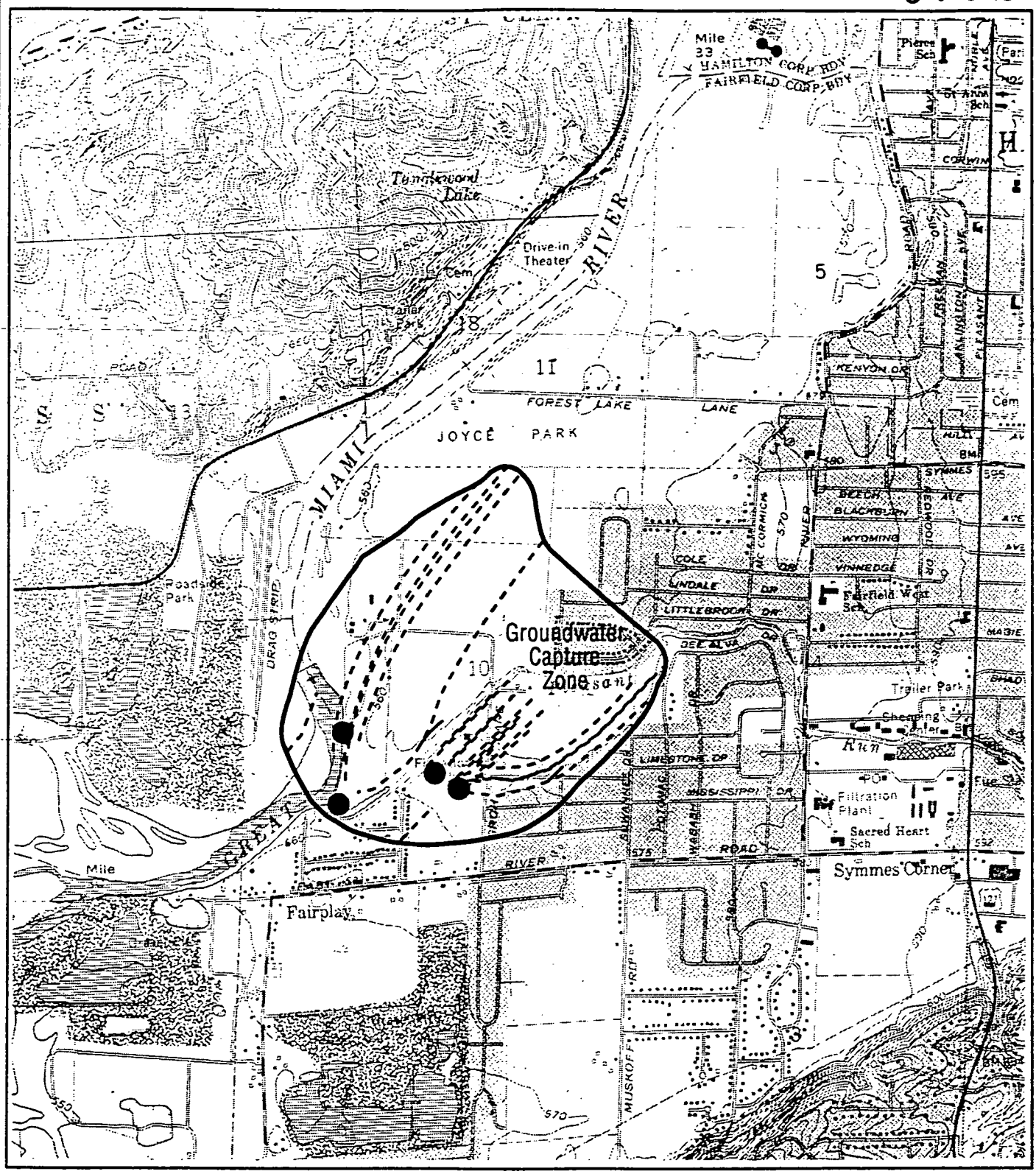
Groundwater flow models are sensitive to various hydraulic parameters. For some of these parameters a range of field-measured values may be available (such as for hydraulic conductivity or transmissivity). For other parameters, few or no known field-measured values are available (such as for river leakance, separating till leakance, and areal recharge). A qualitative measure of the model's sensitivity to these parameters was obtained by varying each parameter individually and comparing the resulting capture zone to the baseline capture zone produced using calibrated parameter values.

Procedure

To simplify the sensitivity analysis, the City of Fairfield's well field was selected as a test case to represent the effect of varying model input parameters because its central location. Output files and selected input files from the MODFLOW simulation of October 1991 conditions were used as input files in the MODPATH program. Using MODPATH, groundwater particles starting from production wells in the City of Fairfield's well field were simulated to flow backwards in time for a period of one year to determine an area of groundwater capture around the well field (Figure 18). A line drawn around the particle flow paths indicates the 1-year capture zone for the well field under October 1991 pumping conditions.

Five parameters were analyzed for this project.

- Horizontal hydraulic conductivity in the upper layer
- Horizontal hydraulic conductivity in the lower layer
- Vertical hydraulic conductivity through the river bed
- Vertical hydraulic conductivity through the separating till
- Rate of areal aquifer recharge from precipitation



Legend

Groundwater Capture Zone

Particle Tracks

Active Production Well

NORTH

0 2,000

Approximate Scale in Feet

FIGURE 18

Particle Tracks and Capture Zone

Water Conservation Subdistrict Consortium

Wellhead Protection Area Delineation Project

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Each parameter was individually varied by dividing its calibrated value by half and by doubling its calibrated value. The ten resulting 1-year capture zones were developed for the Fairfield well field and compared against the 1-year capture zone developed for the calibrated model (Figures 19 and 20).

Results

Pumping in the City of Fairfield's well field was simulated in the lower model layer because the production wells are screened below the depth at which the low-permeability till layer is simulated to occur. This is reflected in the comparison of different horizontal hydraulic conductivity values in the upper and lower layers. The capture zone for Fairfield's well field changed only slightly in response to varying the hydraulic conductivity in the upper layer because most of the groundwater moving into Fairfield's wells is predicted to be supplied by the lower model layer. By comparison, changing the horizontal hydraulic conductivity in the lower aquifer strongly affected the size of the capture zone, indicating that the capture zone for a well field is fairly sensitive to changes in hydraulic conductivity for the layer in which the wells are screened.

Considering the effect on Fairfield's capture zone size, the results of the sensitivity analysis are summarized in Table 4:

Table 4
Sensitivity Analysis Results

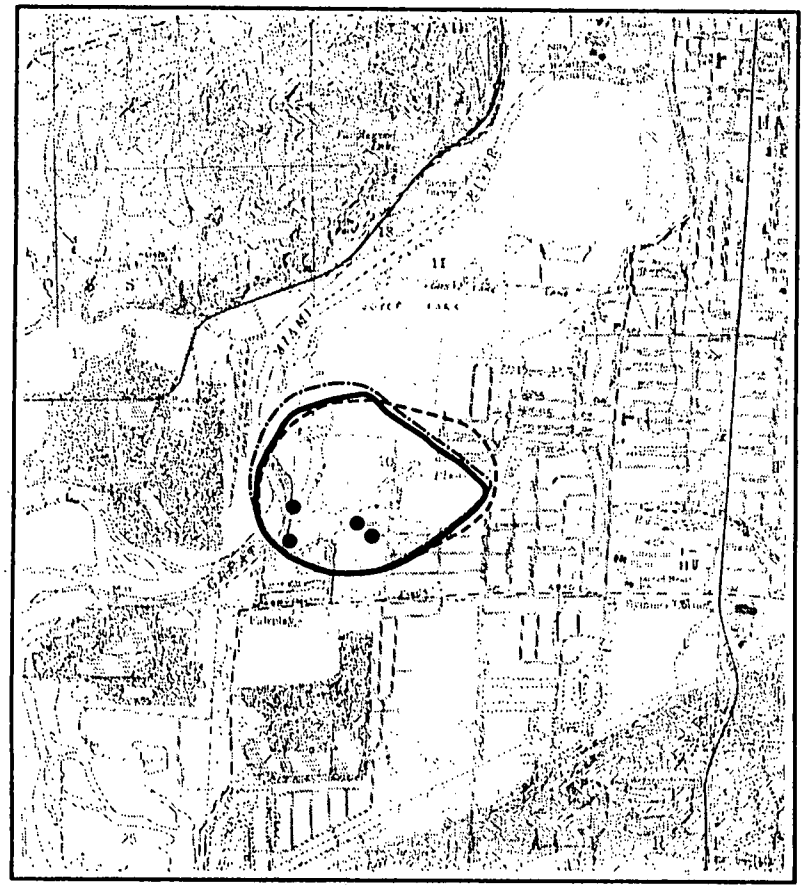
Relatively Sensitive	Relatively Insensitive
Lower Layer Hydraulic Conductivity	Upper Aquifer Hydraulic Conductivity
River Bed Leakance	Till Vertical Hydraulic Conductivity
	Precipitation Recharge

Note: For wells screened in the upper aquifer layer, the upper aquifer hydraulic conductivity is expected to have a greater sensitivity than the lower aquifer hydraulic conductivity.

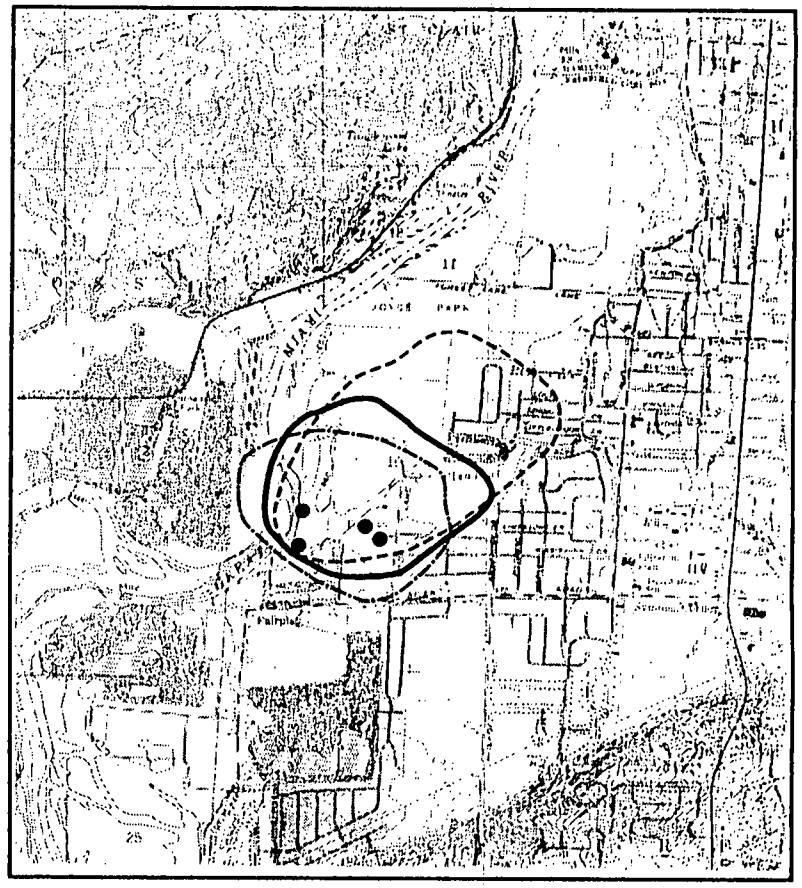
Results of Delineation

The MODPATH and MODPATH-PLOT codes were used to delineate 1- and 5-year WHPAs for each of the eight well fields by:

- Running the MODFLOW calibrated model using 1996 pumping conditions for all Consortium members
- Using the MODFLOW output and selected MODFLOW input files from the 1996 simulation in the MODPATH program



Hydraulic Conductivity in the Upper Layer



Hydraulic Conductivity in Lower Layer

NORTH

0 4,000

Approximate Scale In Feet

Legend

- Double the Calibrated Value
- Calibrated Value
- Half the Calibrated Value
- Active Production Well

FIGURE 19
Capture Zone Sensitivity to Adjusted Model Parameters (First of Two Figures)
Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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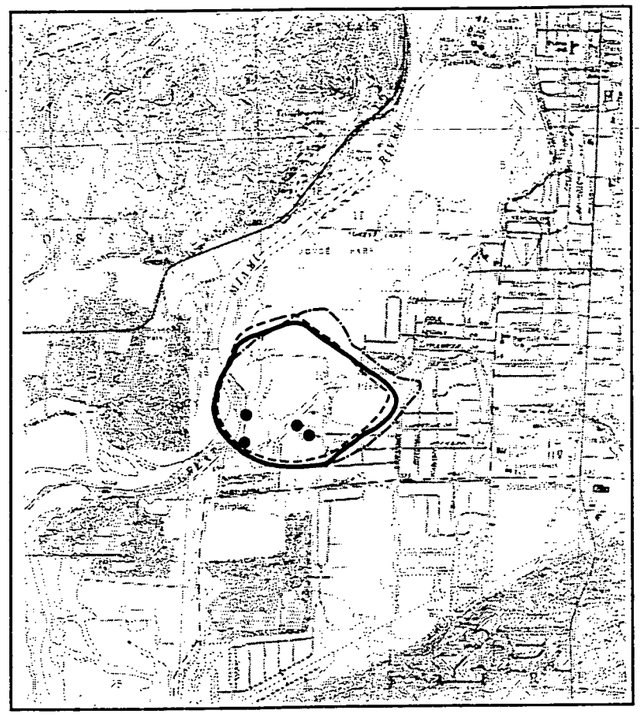
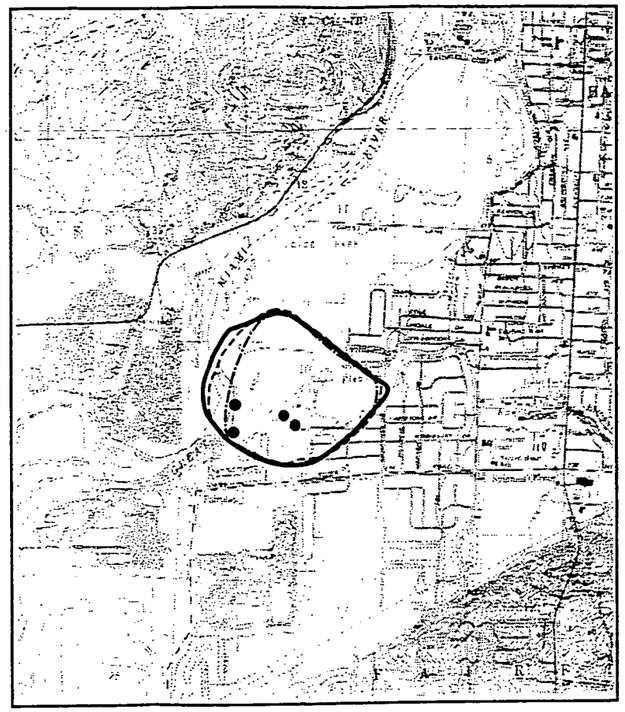
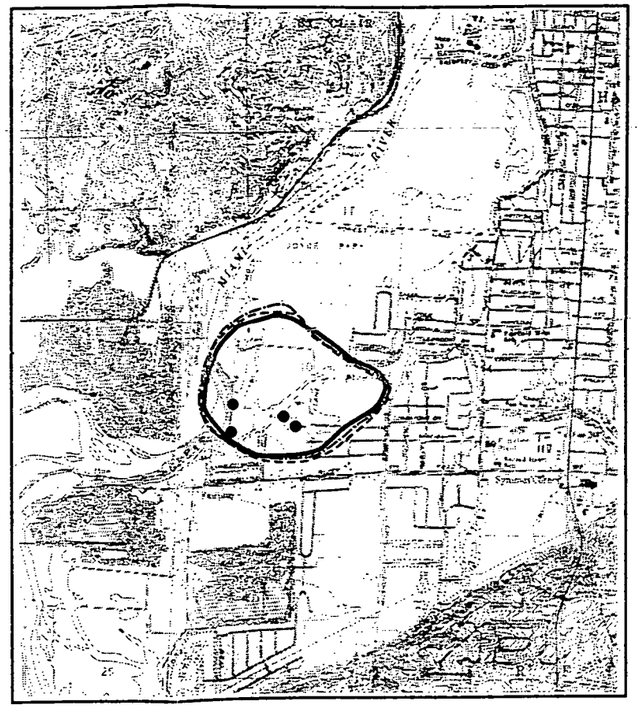
GLO32927.AO.RP Fig. 20 River Leak 4-8-92 lml



Vertical Hydraulic Conductivity Through Riverbed



Vertical Hydraulic Conductivity Through Low-Permeability Layer



Rate of Areal Recharge from Precipitation

NORTH

0 4,000

Approximate Scale In Feet

Legend

- Double the Calibrated Value
- Calibrated Value
- Half the Calibrated Value
- Active Production Well

FIGURE 20

Capture Zone Sensitivity to Adjusted Model Parameters (Second of Two Figures)

Water Conservation Subdistrict Consortium
Wellhead Protection Area Delineation Project

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- Creating individual well field plots of particle paths originating from each production well of the well field and moving backwards (hydraulically upgradient) for periods of one year and 5 years

- Drawing the capture area around the particle flow paths that end in the modeled area of the aquifer

- Including an estimated amount of the bedrock wall (as described below) if the capture area edge intersects the model edge (simulated aquifer valley edge)

- Including a portion of specific tributary valleys (as described below) if the capture area intersects the model edge (simulated aquifer valley edge) at one of the major Great Miami River tributaries

The 1996 groundwater flow was simulated assuming that the October 1991 modeled conditions represent average aquifer conditions with the exception of the eight Consortium well field maximum production rates. The 1- and 5-year WHPAs are depicted in Plates 1 through 18.

Where the capture area intersected the simulated aquifer edge, it was necessary to include part of the area outside the aquifer in the delineated the WHPA to account for uncertainties in the exact position of the aquifer edge and to account for surface runoff from the uplands that may contribute contaminants to the aquifer. Two principal approaches were used in the past to account for the aquifer edge in WHPA delineations:

- Extend the WHPA an arbitrary distance (such as 1,000 feet) away from the simulated aquifer edge

- Extend the WHPA to the surface water drainage divide

As discussed in progress meetings, the Consortium preferred to use a logical approach for extending WHPAs beyond the aquifer edge, however it was recognized that extending the WHPA all the way to a surface water drainage divide could yield an unmanageably large WHPA because of the relatively gentle slopes of the uplands and the resulting large drainage areas. The conclusion reached in a Consortium progress meeting was that the WHPA would include the approximate area where the bedrock valley wall slope changes from steeply ascending out of the valley to more gentle upland area. The break in surface slope would define the WHPA edge.

Where a major Great Miami River tributary that was too small to be included in the model (Dunlap Creek, Paddys Run, Bank Lick, Pleasant Run, and Twomile Creek) intersects a delineated WHPA, an estimate of the distance the WHPA extends up the tributary valley was made. Ideally, this estimate should be made using hydrogeologic data collected from the area. Because this information was not readily available, the groundwater movement in the tributary valleys either under current conditions or

under expected future conditions could not be estimated with confidence. In these areas, a distance of one-half mile from the estimated valley edge upgradient into the tributary valley was included in the WHPA.

As shown in Plates 11 through 18, the estimated 5-year capture zones fit together as pieces of a puzzle. This situation illustrates the interrelationship of the Consortium capture zones. Pumping by Hamilton and Fairfield, for example, appears to block much of the potential groundwater movement into Cincinnati's well field. If pumping rates at Hamilton's or Fairfield's well fields change substantially, or if these well fields are abandoned altogether in the future, the size of Cincinnati's capture zone would probably increase significantly. This degree of interdependence points out the need for Consortium members to keep informed of planned changes in well field production rates near their well fields.

As previously discussed, several delineated WHPAs include tributary streams that feed into the Great Miami River. Although including entire drainage basins for these streams could lead to the creation of unmanageably large WHPAs, as wellhead protection management strategies are developed in the future, Consortium members may want to include a mechanism to track major changes in land use activities in the drainage basins that could eventually effect groundwater quality in the aquifer.

When considering the WHPAs depicted in Plates 1 through 18, it should be remembered that these WHPAs are delineated on the basis of simulated water movement. In reality, contaminants in groundwater generally move at a different rate than the water itself.

Contaminants in groundwater generally fall into two major groups: miscible and immiscible contaminants. Miscible contaminants include inorganic contaminants such as metals, chloride, or nitrate, as well as highly soluble organic compounds such as acetone and benzene. Immiscible, or hydrophobic, contaminants include a variety of organic contaminants such as chlorinated solvents, polychlorinated biphenyls (PCBs), and polynuclear aromatic hydrocarbons (PAHs or PNAs). Despite their classification as immiscible contaminants, some of these compounds have solubilities of more than 1,000 parts per billion, which for a compound such as trichloroethene (a chlorinated solvent), exceeds the drinking water Maximum Contaminant Level (MCL) by a factor of several orders of magnitude.

Immiscible contaminants also can be divided into two major groups: those with a density less than water (approximately 1,000 grams per liter) and those with a density greater than water. When released in sufficient quantities, light immiscible contaminants tend to "float" on the water table, where they spread on the water table surface and migrate laterally with the hydraulic gradient or along high-permeability pathways such gravel-filled utility trenches. Dense contaminants, on the other hand, tend to sink through the aquifer where they may pond on the low-permeability aquifer bottom. When they occur as pools at the bottom of the aquifer, dense contaminants can move in response to the slope of the aquifer bottom or in response to gradients within the dense contaminant pool caused by pumping from the

pool. Groundwater movement over a dense immiscible contaminant pool has little effect on the movement of the pool. A major threat posed by immiscible contaminants in the subsurface is that they can occur as relatively immobile sources of dissolved contaminants that may persist indefinitely unless actively remediated.

Dissolved contaminants migrate in the direction of groundwater flow, except for minor effects caused by molecular diffusion. Depending on aquifer heterogeneities and temporal or spatial variability in groundwater flow directions, dissolved contaminant plumes spread laterally to varying degrees along the predominant flow path. Reactions such as adsorption, precipitation, biotransformation, hydrolysis, and volatilization can cause concentrations of dissolved contaminants to decrease with increased distance from the source area, and can slow the rate of contaminant movement relative to the ambient groundwater flow rate.

Retardation factors for dissolved contaminant migration (the rate of groundwater movement divided by the rate of contaminant movement) are less than 5 for mobile organic contaminants such as benzene, and can exceed 100 for relatively immobile contaminants such as PCBs or lead. This means that a contaminant with a retardation factor of 100 could take 100 years to travel the same distance as water moves within one year, and a contaminant with a retardation factor of 5 takes 5 years to move the same distance as water moves in one year. Conservative ions such as chloride and nitrate, by comparison, are generally considered to migrate at about the same rate as groundwater. WHPAs, because they are based on the movement of water rather than contaminant migration, are generally conservative because most contaminants of concern to water purveyors have a retardation factor greater than one.

The movement of some contaminants, such as chromium and uranium, also depends heavily upon the form of the contaminant that is present. For example, in chemically oxidizing environments (abundant oxygen present) mobile, highly oxidized forms of uranium and chromium may be stable. Under reducing conditions, which can occur in deep groundwater or near sources of oxygen-depleting contamination (such as landfills), the chemically reduced, relatively immobile forms, of these contaminants may occur. For other contaminants, such as iron, the reverse may be true. To accurately predict the mobility of a particular contaminant requires an understanding of the contaminant source, contaminant properties, and the prevailing geochemical conditions in the aquifer.

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APPENDIX A

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TABLE 1

MAXIMUM PUMPAGE

Champion Papers Ground Water

	1987	1988	1989	1990	1991
Month	Jan.	July	Jan.	Aug.	May
Total, Million Gallon	79.230	78.540	67.680	47.870	45.500
Max. Month Ave., MGD	2.556	2.534	2.183	1.544	1.468
Annual Ave., MGD	2.450	2.238	1.911	1.500	1.082
Ratio = Max. Month Ave. / Annual Ave.	1.043	1.132	1.142	1.029	1.357
Average Ratio:	1.141				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	1.541	1.760	2.009	2.295

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	1.758	2.008	2.292	2.618

Maximum pump rate = average ratio * estimated demand

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TABLE 1

MAXIMUM PUMPAGE

Cincinnati Bolton Well Field

	1987	1988	1989	1990	1991
Month	Aug	June	Dec	July	June
Total, Million Gallon	518.932	764.037	546.544	605.179	620.754
Max. Month Ave., MGD	16.740	25.468	17.630	19.522	20.692
Annual Ave., MGD	15.210	17.320	16.000	16.630	17.161
Ratio = Max. Month Ave. / Annual Ave.	1.101	1.470	1.102	1.174	1.206
Average Ratio:	1.211				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	18.000	19.000	20.000	20.000

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	21.789	23.000	24.210	24.210

Maximum pump rate = average ratio * estimated demand

TABLE 1

MAXIMUM PUMPAGE

City of Fairfield

	1987	1988	1989	1990	1991
Month	Aug	June	July	July	July
Total, Million Gallon	160.270	(1)	164.469	167.719	(1)
Max. Month Ave., MGD	5.170	7.500	5.305	5.410	7.200
Annual Ave., MGD	4.010	4.800	4.360	4.490	5.200
Ratio = Max. Month Ave. / Annual Ave.	1.289	1.563	1.217	1.205	1.385
Average Ratio:	1.332				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	6.400	8.100	9.400	10.900

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	8.523	10.786	12.517	14.515

Maximum pump rate = average ratio * estimated demand

(1) Water use restrictions in place. Maximum monthly average estimated as if full demand were satisfied. Actual production in June, 1988 = 6.8 MGD and July, 1991 = 6.5 MGD

TABLE 1

MAXIMUM PUMPAGE

Fernald Environmental Management Project

	1987	1988	1989	1990	1991
Month		Jan.	Nov.	Jan.	July
Total, Million Gallon		16.148	12.635	11.822	12.242
Max. Month Ave., MGD		.521	.421	.381	.395
Annual Ave., MGD	.460	.383	.336	.220	.316
Ratio = Max. Month Ave. / Annual Ave.	.000	1.360	1.253	1.733	1.250
Average Ratio:	1.119				

Table 2

ESTIMATED AVERAGE DAILY PUMPAGE
MILLION GALLONS PER DAY

	1996	2001	2006	2011
Onsite production wells	.284	.298	.313	.328
Alternate water supply	.252	.265	.278	.292
South Plume Remediation	2.880	3.024	3.175	3.330

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
Onsite production wells	.318	.334	.350	.367
Alternate water supply	.282	.297	.311	.327
th Plume Remediation	3.224	3.385	3.554	3.727

Maximum pump rate = average ratio * estimated demand

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TABLE 1

MAXIMUM PUMPAGE

Hamilton North

	1987	1988	1989	1990	1991
Month	May	June	Aug	Sept	July
Total, Million Gallon	40.463	152.182	108.357	97.613	198.643
Max. Month Ave., MGD	1.305	5.073	3.495	3.254	6.408
Annual Ave., MGD	.649	1.830	1.360	1.510	2.623
Ratio = Max. Month Ave. / Annual Ave.	2.011	2.772	2.570	2.155	2.443
Average ratio:	2.390				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	1.900	2.000	2.200	2.400

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	4.541	4.780	5.258	5.737

Maximum pump rate = average ratio * estimated demand

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TABLE 1

MAXIMUM PUMPAGE

Hamilton South

	1987	1988	1989	1990	1991
Month	Aug	June	Oct	July	June
Total, Million Gallon	483.350	485.260	476.805	499.121	504.853
Max. Month Ave., MGD	15.592	16.175	15.381	16.101	16.828
Annual Ave., MGD	13.530	14.510	14.460	14.810	15.339
Ratio = Max. Month Ave. / Annual Ave.	1.152	1.115	1.064	1.087	1.097
Average ratio:	1.103				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	16.700	18.100	19.800	21.500

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	18.420	19.965	21.840	23.715

Maximum pump rate = average ratio * estimated demand

TABLE 1

MAXIMUM PUMPAGE

Southwestern Ohio Water Company Coll #1

	1987	1988	1989	1990	1991
Month	July	July	July	Aug	July
Total, Million Gallon	410.320	365.530	363.970	371.380	403.570
Max. Month Ave., MGD	13.236	11.791	11.741	11.980	13.018
Annual Ave., MGD	9.818	8.950	8.180	8.750	9.882
Ratio = Max. Month Ave. / Annual Ave.	1.348	1.317	1.435	1.369	1.317
Average Ratio:	1.357				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	9.088	9.543	10.019	10.019

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	12.337	12.955	13.601	13.601

Maximum pump rate = average ratio * estimated demand

TABLE 1

MAXIMUM PUMPAGE

Southwestern Ohio Water Company Coll #2

	1987	1988	1989	1990	1991
Month	May	Aug	Sept	June	July
Total, Million Gallon	307.969	310.501	310.042	297.070	296.606
Max. Month Ave., MGD	9.934	10.016	10.335	9.902	9.568
Annual Ave., MGD	9.118	8.980	8.970	8.366	8.625
Ratio = Max. Month Ave. / Annual Ave.	1.090	1.115	1.152	1.184	1.109
Average Ratio:	1.130				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
MGD	9.088	9.543	10.019	10.019

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
MGD	10.270	10.784	11.322	11.322

Maximum pump rate = average ratio * estimated demand

TABLE 1

MAXIMUM PUMPAGE

Water Assaociation

	1987	1988	1989	1990	1991
Month	July	June	Aug	July	July
Total, Million Gallon	70.033	81.283	74.908	76.116	84.855
Max. Month Ave., MGD	2.259	2.709	2.416	2.455	2.737
Annual Ave., MGD	1.980	2.190	2.090	2.050	2.322
Ratio = Max. Month Ave. / Annual Ave.	1.141	1.237	1.156	1.198	1.179
Average Ratio:	1.182				

Table 2

ESTIMATED AVERAGE DAILY DEMAND

	1996	2001	2006	2011
(1) MGD	1.612	1.868	2.166	2.511
(2) MGD	2.686	3.114	3.610	4.186

Table 3

MAXIMUM PUMPING RATE FOR WELLHEAD DELINEATION

	1996	2001	2006	2011
(1) MGD	1.906	2.208	2.561	2.968
(2) MGD	3.175	3.681	4.268	4.949

Maximum pump rate = average ratio * estimated demand

(1) With new well field in place.
(2) Without new well field.