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Final Report

Source Water Protection Delineation Model Update

Prepared for

City of Dayton, Ohio

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CH2MHILL

Executive Summary

This report describes the process by which CH2M HILL updated the City of Dayton's model of the aquifer system in and surrounding its active well fields. It will also provide predictions based on multiple scenarios for groundwater flow to the production wells in those well fields given movement of water over a one-year and a five-year period of time (also referred to as a one-year and five-year groundwater time-of-travel).

The areas defined from the time-of-travel results, presented in this report, will provide the basis for evaluating and if necessary, adjusting the City's current source water protection area boundaries.

A good conceptual understanding of the aquifer system is key to developing a strong predictive model. The Dayton Region in and around the Dayton area has been heavily studied over time. Subsequent to modeling efforts in the 1980s and 1990s, a significant number of wells have been drilled and additional aquifer information has been gathered. This has added refinement to the general conceptual model of the region's aquifer system which, in large part, has remained generally unchanged. Some of the significant characteristics of the aquifer include:

- The Great Miami Buried Valley aquifer is filled with thick deposits of sand and gravel that are divided intermittently into 3 layers by clay tills. These deposits in our region are mostly saturated with groundwater from multiple primary sources:
  - Groundwater flowing from upgradient locations of the buried valley;
  - Rainwater percolating into the top portion of the aquifer; and
  - Surface water systems such as rivers, lakes and lagoons that can act as a source of recharge for groundwater.
- Groundwater is also flowing out of the valley aquifer in the region primarily through means such as:
  - Downgradient locations of the buried valley aquifer as the groundwater continues to flow through the valley and generally toward the south;
  - Pumping wells from which groundwater is extracted as a source of drinking water or water used in industrial processes;
  - Surface water systems;
  - Evaporation of water in the near surface during dry weather; and
  - Transpiration (or uptake of groundwater) by plants.

The groundwater flow model constructed in the early 1990s for the City was used as a starting point for the development of the 2010 groundwater flow model. Refinements were made in the new model when compared to the 1993 model to include current practices for modeling and capture zone analysis.

Calibration of the updated model was, consistent with accepted hydrogeologic analytical practice, an iterative process of manually adjusting model parameters (hydraulic conductivity, recharge, etc.), running the model, and then quantitatively comparing the model output against targets of field measured data. The field measured data used for comparison were 283 measured groundwater elevations collected on May 26 and 27, 2010, from shallow, intermediate and deep wells. A statistical comparison procedure was used to evaluate how closely the model output compares to the field measured data. Model residuals were calculated by subtracting the simulated groundwater elevations from the measured elevations at the target locations and calculating for all targets combined:

- The average of the differences (residual mean) = 0.13 feet;
- The average of the absolute differences (absolute residual mean) = 2.40 feet
- The standard deviation of the differences (residual standard deviation) = 3.10 feet

The statistical comparison indicates a good match between the simulated and measured water levels.

To establish greater confidence in the model's ability to represent different hydrologic conditions, a verification process was conducted for the calibrated model. This consisted of setting up the model with June 1989 hydrologic conditions and pumping rates and then comparing the simulated water levels to a set of water level collected in June 1989. The resulting residual statistics for the verification process indicate a satisfactory match between the simulated and measured water levels.

Any calibrated model is necessarily influenced by uncertainties in the model input values. Therefore, a sensitivity analysis was performed to identify the effect of uncertainty on this calibrated model. Sensitivity analysis was conducted for the model grid spacing, the vertical and horizontal hydraulic conductivity distribution, the areal recharge distribution, and the streambed hydraulic conductivity distribution. Overall, the sensitivity testing results indicate that the calibrated model is effective in representing the region's aquifer conditions.

The calibrated, steady-state model was used to predict 1- and 5-year groundwater time of travel areas (also referred to as capture zones) for the Dayton Miami, Rip Rap Road, Mad River, Eastwood Park, and Huffman Dam Well Fields (Dayton Well Fields) under various hydraulic conditions (scenarios). The analysis was performed using the MODPATH particle tracking model (Pollock 1989).

Three model run scenarios were selected to illustrate a range of 1- and 5-year capture zones:

- Scenario 1: The hydraulic conditions of the region are represented as "average". The Dayton Well Fields are pumping at "safe yield" levels.

- Scenario 2: The hydraulic conditions of the region are represented as "average". The Dayton Well Fields are pumping at the rate suggested in Ohio EPA's Division of Drinking and Ground Waters in the Wellhead Protection Area Delineation Guidance (Ohio EPA 1994; 5-year peak average plus 1% growth factor for 10 years).

- Scenario 3: The hydraulic conditions of the region are represented as "drought". The Dayton Well Fields are pumping at "safe yield" levels.

The model run scenarios were selected after consulting with Ohio EPA's Division of Drinking and Ground Waters.

One year and 5-year Dayton Well Field capture zones under the various scenarios are presented in Figures 8.1 through 8.6.

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SECTION 1

Introduction

1.1 History of Water Supply and Protection

Today, the City of Dayton (City) operates the Mad River Well Field (including Eastwood Park and Huffman Dam Well Fields) and the Miami Well Field (including Rip Rap Road Well Field), which supply water to the residents, businesses, and industry within and in the vicinity of the City of Dayton. Dating back to the initial development of drinking water supply in the Dayton Area in the early 1800s (Drury, 1909), the City has sought to understand the local water resource and to supply that resource to the residents.

1.1.1 Wellhead Protection

Over time the approach to development and protection of the drinking water resource has been refined not only in the City, but across the United States and more specifically in the State of Ohio. As presented in the State of Ohio's 1986 Strategy of Groundwater Protection and Management (State of Ohio, October 1986), "Ground water's unique vulnerability to contamination, and our dependence on it, makes it essential that Ohio take action now to protect and manage this resource." Subsequent guidance documents developed by US EPA and Ohio EPA outline how water suppliers can accomplish this goal of management and protection of our drinking water resource in a program referred to as the Wellhead Protection Program.

In 1992 and then through refinements in 1994, the State of Ohio outlined the *Ohio Wellhead Protection Program's Wellhead Protection Area Delineation Guidance* for the wellhead protection of drinking water resources (Ohio EPA, August 1994). The guidance outlines how to define the area to be protected, referred to as the "wellhead protection area" (WHP area). This WHP area is defined by the area within which groundwater moves during a specified time period to reach the pumping wells (also referred to as wellheads). As captured in Ohio's 1994 guidance and the draft review criteria, *Drinking Water Source Assessment and Protection Plan Review Criteria* (Ohio EPA, October 2009), Ohio's WHP Program outlines that water suppliers delineate a WHP area based on the estimated five-year time-of-travel area for groundwater moving toward wells in the well field and provide for a 1-year inner management zone.

1.1.2 City of Dayton's Wellfield Protection Area Delineation

The City's Environmental Protection Program (CH2M HILL 1986) was developed to plan for the continued water supply protection of the Miami Well Field. The Environmental Protection Plan Program included the creation of a groundwater flow model to facilitate the study of groundwater development options and drinking water source protection in the Miami Well Field vicinity.

The Miami Well Field Groundwater Model was developed to facilitate the study of groundwater development options and environmental protection captures zones for the

Miami Well Field (CH2M HILL 1986). In support of the Miami Well Field Groundwater Model development, a regional model was developed to help establish the boundaries and hydrogeologic conditions for use in the Miami Well Field Groundwater Model.

The City's 1987 Mad River Well Field Assessment (Geraghty & Miller 1987) outlined development potential and protection assessment elements related to the Mad River Well Field. This assessment included groundwater flow modeling to predict the "primary areas of influence" for water supply protection planning.

In 1993, CH2M HILL supported the City's efforts to maintain, expand, and protect its sources of drinking water by revising the regional groundwater model in order to delineate the 1- and 5-year groundwater capture zones for the Huffman Dam and Eastwood Park well fields, and to delineate the 5-year groundwater capture zone for the combined Mad River, Eastwood Park, Miami, future Rip Rap Road, and Huffman Dam Well Fields (Dayton Well Fields; CH2M HILL, Draft February 1, 1993). The inclusion of both of the listed well fields in the evaluation allowed for a comprehensive assessment of the well field capture areas.

In 2010, the City requested that CH2M HILL update the 1993 regional groundwater model in order to incorporate new information collected within the region from boring logs and aquifer tests completed since 1993; to update the groundwater model to current common-use groundwater modeling software; and to provide the basis for evaluating and if necessary, adjusting the City's current wellhead protection area boundaries in accordance with Ohio EPA WHP Program guidance. This report documents these update activities for the regional groundwater model.

1.2 Objectives

The objectives for this groundwater modeling effort were to update the City regional groundwater model developed in 1993 in order to delineate the 1-year and 5-year groundwater time-of-travel capture zones for the combined Miami, Rip Rap Road, Mad River, Eastwood Park, and Huffman Dam Well Fields. This was completed in order to incorporate new information collected within the region from boring logs, monitoring well logs, and an aquifer test completed since 1993. The update was also to incorporate advances in modeling software and computer resources that have been made since 1993. The 2010 modeling also takes into account any post-1993 changes in Ohio EPA's guidelines for groundwater model development and capture zone delineation.

1.3 Scope of Work

To address the objectives listed above, CH2M HILL completed the following activities:

- Updated the 1993 groundwater model files, originally developed using the modeling code MODFLOW (McDonald and Harbaugh 1988), to align with the latest version of MODFLOW-2000 (version 5.43; McDonald, et al 2000).
- Imported the updated groundwater model files into the Groundwater Vistas version 5 (Environmental Simulations, Inc. 2007). Groundwater Vistas is a graphical user interface

used to create and modify the groundwater modeling files used by MODFLOW. Groundwater Vistas was also used to pre- and post-process the data.

- Reviewed the model parameters and identified which needed to be updated with current common modeling practice and latest investigative information.
- Prepared a conceptual site model using historic and latest investigative information.
- Prepared a groundwater model that is representative of the current conceptual site model of the aquifer in the area and used it to delineate the 1-year and 5-year capture zones

1.4 Model Development Process

The goal of the model development process is to produce a tool that will be useful in analyzing the important features of the problem in question and to demonstrate that the site-specific model will produce meaningful results. It is also important to estimate the degree to which uncertainty in input parameters may limit the accuracy of the predictions. Steps used to demonstrate and evaluate the validity of the model include the following:

- Establish a purpose (Section 1 of this document)
- Develop the conceptual site model (Section 2 of this document)
- Select the computer code (Section 3 of this document)
- Design the model (Section 4 of this document)
- Calibrate the model to observed aquifer conditions (Section 5 of this document)
- Verify the model when possible (Section 6 of this document)
- Conduct sensitivity analysis of the model parameters (Section 7 of this document)
- Predict groundwater conditions under specific scenarios using the model (Section 8 of this document)

1.5 Report Organization

The remainder of this report presents detailed information that supports the modeling predictions, and is organized as follows:

- Section 2 – Conceptual Site Model
- Section 3 – Groundwater Model Software
- Section 4 – Groundwater Model Features
- Section 5 – Calibration
- Section 6 - Verification
- Section 7 – Sensitivity Analysis
- Section 8 – Model Prediction – Capture Zones
- Section 9 – References
- Appendix A – Geologic Cross-Sections
- Appendix B – Supporting Documentation

SECTION 2

Conceptual Site Model

The conceptual site model presented below is a site-specific interpretation of the hydrogeology including the surface water and groundwater flow systems of the region encompassing Dayton's Mad River, Huffman Dam, Eastwood Park, Miami, and Rip Rap Road Well Fields based on readily available information. Included are discussions of the general setting, the geology and hydrogeology, aquifer properties, the hydrology and area water users.

2.1 General Setting

The region encompasses the central and northeastern portion of the City and extends past the City boundaries to Taylorsville Dam in the north and Wright-Patterson Air Force Base to the East. This area includes portions of the Great Miami, Mad, Stillwater, and Wolf Creek river valleys and includes the Miami, Rip Rap Road, Mad River, Eastwood Park, and Huffman Dam Well Fields.

The topography of the area is relatively flat with approximately 250 feet of elevation difference from the highest to lowest elevation. The land cover is primarily commercial/industrial and residential with some areas of open forests, shrubbery, and grasslands.

2.2 Geology

The underlying geology consists of portions of the Great Miami Buried Valley Aquifer System (GMBVAS). The GMBVAS is a buried valley system that follows the general trend of the present-day Great Miami, Mad, Stillwater, and Wolf Creek rivers; however, along short reaches, the rivers may lie outside the edge of the buried valley. The GMBVAS is the result of valleys cut into the bedrock (shale and limestone) by river and glacial erosion followed by filling with glacial deposits (clay/silt, sand, and gravel). Cross-sections used as reference for supporting the understanding of the region geology are presented in Appendix A.

2.2.1 Unconsolidated Deposits

The bedrock valleys were filled with glacial deposits of two generalized types differentiated primarily by the principal grain size content: outwash or valley train material was deposited by glacial meltwater and consisting chiefly of gravel and sand sized sediments; and till deposited directly by the glaciers as they advanced over the area and consisting of clay-rich materials. These two primary deposits form a complex and heterogeneous geologic system by varying in thickness and extent throughout the region.

Below is a brief, generalized description of each of the unconsolidated units in descending order:

- **Top soil/surficial clay:** This unit consists of primarily fines (silt or clay). This unit is discontinuous throughout the region. It is generally 10 feet thick with an approximate range of thickness between 5 feet and 40 feet.
- **Shallow sand and gravel:** This unit consists primarily of sand, gravel, or both. It is horizontally continuous throughout the region and has a general thickness of 60 feet with a range of thickness between 10 feet and 100 feet.
- **Shallow subsurface till:** This unit consists primarily of fines (silt or clay). It is horizontally discontinuous throughout the region with a general thickness of 20 feet with an approximate range of thickness between 0 feet and 40 feet.
- **Intermediate sand and gravel:** This unit primarily consists of sand, gravel, or both. It is horizontally discontinuous throughout the region, but varies in thickness with lenses of silt and clay deposits. The general thickness is 50 feet with an approximate range of thickness between 0 feet and 80 feet.
- **Intermediate subsurface till:** This unit consists primarily of fines (silt or clay). It is horizontally discontinuous throughout the region and varies in thickness with lenses of sand and gravel deposits. The general thickness of this unit is 30 feet with a range of thickness between 0 feet and 50 feet.
- **Deep sand and gravel:** This unit consists primarily of sand, gravel, or both. It is horizontally discontinuous throughout the region and is directly overlying basal clays or bedrock. The general thickness of this unit is 70 feet with a range of thickness between 0 feet and 140 feet.

Due to the complex nature of the geologic system as observed in the varying thicknesses and extent of the unconsolidated units, the individual units described above are not consistently observed in all locations within the region. For example, in some areas all the units are observed in other areas only a single unconsolidated unit is observed from the ground surface down to bedrock.

2.2.2 Bedrock

The Richmond Shale underlies the valleys and lowlands in the region while the Brassfield Limestone may be present in the upland areas capping the Richmond Shale. The Richmond Shale is composed of soft, clay-like shale with limestone interbeds ranging from 1 to 5 inches thick. The Brassfield Limestone is composed of light gray to brown limestone ranging up to 30 feet thick.

2.3 Hydrogeology

The hydrogeology of the area is characterized by the partially or fully saturated unconsolidated deposits and bedrock units described above.

2.3.1 Unconsolidated Aquifers

The unconsolidated sand and gravel units (described in Section 2.2) are partially to fully saturated with groundwater and form the three aquifer layers (shallow, intermediate, and deep) for the buried valley aquifer system within the region However, as described in 2.2.1, the hydrogeologic system is complex due to variations in thickness and extent. This buried valley aquifer system is utilized as primary source of groundwater for municipal and private use. The approximate yield for the buried valley sand and gravel aquifers are greater than 500 gallons per minute (gpm) based on *Yields of the Unconsolidated Aquifers of Ohio* map published by the Ohio Department of Natural Resources (Ohio DNR) on June 26, 2000 and up to 2000 gpm based on actual City production well pumping rates.

- **Shallow Aquifer:** The uppermost aquifer in the region is composed of sand and gravel deposits. This aquifer is unconfined. Groundwater is encountered at approximately 15 feet below ground surface (bgs), and elevations range from 840 feet above mean sea level (amsl) in the northeastern and southeastern extent to 720 feet amsl in the southwestern extent of the region. Figure 2-1 depicts the groundwater potentiometric surface for this aquifer.
- **Intermediate Aquifer:** The intermediate aquifer is composed of sand and gravel deposits with some fines. The aquifer is confined to semi-confined by the overlying shallow subsurface clay and silt unit, as described in the geology section above. Groundwater elevations range from 838 feet amsl in the northeastern and southeastern extent to 718 feet amsl in the southwestern extent of the region. Figure 2-2 depicts the groundwater potentiometric surface for this aquifer.
- **Deep Aquifer:** The deep aquifer is composed of sand and gravel deposits and overlays bedrock. Groundwater elevations range from 835 feet amsl in the northeastern and southeastern extent to 717 feet amsl in the southwestern extent of the region. Figure 2-3 depicts the groundwater potentiometric surface for this aquifer.

2.3.2 Bedrock Aquifers

The bedrock aquifer is composed of shale and limestone. The approximate yield 0 to 5 gpm as presented in the *Yields of the Uppermost Bedrock Aquifers of Ohio* map published by the Ohio Department of Natural Resources (Ohio DNR) on June 26, 2000. This yield is significantly less than the yield provided by the unconsolidated sand and gravel aquifers.

2.4 Hydraulic Conductivity

Estimating the hydraulic conductivity is important to understanding the ability of groundwater to flow through an aquifer system and to understanding the well field yield potential. Hydraulic conductivities were compiled from readily available information within the region. The ranges of referenced values are presented in Table 2-1. The hydraulic conductivity values for the shallow unconfined aquifer and for the deeper semi-confined aquifers are summarized below:

- **Shallow Aquifer**: Hydraulic conductivity for the shallow aquifer was reported with a range of values from 2,500 to 14 feet per day (ft/day).

- **Intermediate Aquifer:** A hydraulic conductivity value was reported at 429 ft/day.
- **Deep Aquifer:** Hydraulic conductivity values for the deep aquifer were reported with a range from 8.5 ft/day to 733 ft/day.
- **Bedrock:** There is no readily available information on the hydraulic conductivity for the shale and limestone bedrock aquifer in the region. However, with a reported yield of 0 to 5 gpm, the hydraulic conductivity is expected to be very low relative to the sand and gravel aquifers within the buried valley. Typical hydraulic conductivity values for limestone and shale are 3 to 7 and 6 to 10 orders of magnitude lower than sand and gravel deposits, respectively (Driscoll 1986).

2.5 Porosity

Based on laboratory results from samples collected in the shallow aquifer near the Montgomery County North Incinerator, the effective porosity value in the shallow aquifer is 0.25 (Panterra Group 1993). Literature values for sand and gravel deposits range from 0.10 to 0.40 (Driscoll 1986).

2.6 Surface Water

The major surface water bodies in the region include rivers, lakes, water-filled quarries, golf course ponds, and the well field artificial recharge areas. The rivers were considered significant for the purposes of the modeling effort include the Great Miami, Mad, and Stillwater Rivers and Wolf Creek. River water is diverted from the Great Miami and Mad Rivers in the vicinity of the Miami and the Mad River Well Fields respectively to supply artificial recharge lagoons within both well fields. Other significant surface water features near the Dayton Well Fields being evaluated in this study include Eastwood Lake (adjacent to the Mad River Well Field) and water filled quarries northeast of the Mad River Well Field.

2.6.1 Great Miami River

The Great Miami River flows from the northern extent of the region, past the Miami Well Field to the southwest extent of the region. At distances away from the affects of groundwater pumping, the surface water elevations within Great Miami River appear to be similar to the surrounding groundwater elevations. Therefore, it is reasonable to assume the river is a gaining or losing water from the groundwater based on the localized conditions.

Average stream flow is 1,020ft^3/s according to stream flow data collected by the United States Geological Survey (USGS) in the Great Miami River near Dayton, Ohio (USGS Site ID:03263000), on the right upstream face of Taylorsville Dam.

2.6.2 Mad River

The Mad River flows from the northeastern extent of the region, past the Mad River Well Field to the southwest extent of the region to the confluence with the Great Miami River. The surface water elevations within Mad River appear to be similar to the surrounding groundwater elevations. Therefore, it is reasonable to assume a possible influence of the river on groundwater as a potential source or sink for groundwater depending on the localized conditions.

Average stream flow is 639 ft^3/s according to stream flow data collected by the USGS in the Mad River near Dayton, Ohio (USGS site ID:03270000), on left bank in retarding basin 300 ft upstream from Huffman Dam and approximately 6 miles northeast of Dayton.

2.6.3 Stillwater River

The Stillwater River flows from the western extent of the region to the confluence with the Great Miami River in the southwestern extent of the region. The surface water elevations within Stillwater River appear to be similar to the surrounding groundwater elevations. Therefore, it is reasonable to assume a possible influence of the river on groundwater as a potential source or sink for groundwater depending on the localized conditions.

Average stream flow is 593 ft^3/s, according to stream flow data collected by the USGS in the Stillwater River near Dayton, Ohio (USGS site ID:03266000), on the right bank, 1,000 ft downstream from Englewood Dam, 1 mile southeast of Englewood.

2.6.4 Wolf Creek

The Wolf Creek flows east from the southwestern extent of the region and merges with the Great Miami River. The surface water elevations within Wolf Creek appear to be similar to the surrounding groundwater elevations. Therefore, it is reasonable to assume a possible influence of the creek on groundwater as a potential source or sink for groundwater depending on the localized conditions.

Average stream flow is 65.2 ft^3/s, according to stream flow data collected by the USGS in the Wolf Creek in Dayton, Ohio (USGS site ID:03271000), on the right bank, at West Riverview Avenue Bridge, in Dayton.

2.6.5 Miami Well Field Recharge Lagoons and Pond

The Miami Well Field's recharge lagoons and pond are located adjacent to the Great Miami River within the Miami Well Field and are supplied with diverted water from the Great Miami River. Approximately 13 MGD are diverted from the Great Miami River to the recharge lagoons and ponds as estimated by the City Water Department in 2010 (City of Dayton 2010a).

Prior to entering the recharge lagoons the diverted Great Miami River water enters a settling basin to remove most of the sediments from the water, then approximately 4 MGD of water is piped to two linear recharge lagoons located just south of the City Kittyhawk Golf Course, with the remaining 9 MGD piped to numerous ponds that are integrated into the golf course (City of Dayton 2010b). According to the City Water Department in 2010, the water from Great Miami River is continuously diverted except for when the river water is under low-flow conditions or when the river water is highly turbid. Periodically, the City dredges the sediments from the recharge lagoons.

2.6.6 Mad River Well Field Recharge Lagoons and Lakes

The Mad River Well Field recharge lagoons are a grouping of linear lagoons that are connected by piping, located adjacent to and south of the Mad River in the Mad River Well Field. The recharge lagoons are supplied with diverted water from the Mad River, but the amount of water diverted is not recorded, according to the City Water Department in 2010. In the same area and on the north side of the Mad River, there are two small recharge lakes north of the Mad River that are approximately 80 and 45 acres, respectively. Similar to the recharge lagoons, these lakes are supplied with water from the Mad River, but the amount of water is not recorded.

2.6.7 Rip Rap Road Recharge Lagoons

The Rip Rap Road Well Field's future recharge lagoons are planned to be located adjacent to the Great Miami River within the Rip Rap Road Well Field and will be supplied with diverted water from the Great Miami River. Approximately 12 MGD will be diverted from the Great Miami River to the recharge lagoons. Prior to entering the recharge lagoons the diverted Great Miami River water will enter settling basins to remove most of the sediments from the water, then the water will be piped to two linear recharge lagoons.

2.6.8 Eastwood Lake

The Eastwood Lake is located adjacent to and north of the Mad River Well Field and is approximately 1-mile long and 185acres. Similar to the Mad River Well Field recharge lagoons, Eastwood Lake is supplied with diverted water from the Mad River.

2.7 Precipitation and Infiltration

According to precipitation data collected by Miami Conservancy District (MCD) the average yearly precipitation for the region is 39.05 inches per year. The actual amount of precipitation that infiltrates the subsurface varies depending on factors such as land use, soil type, and slope. However, the land surface in the region is relatively flat; therefore, slope is not considered a significant factor affecting infiltration of precipitation. Considering the land use and the soil type at the ground surface the region has four infiltration zones. These zones are similar to those studied to determine surface runoff (Chow, 1964): 1) undeveloped/agricultural or light residential areas, 2) areas that have low permeability glacial till at the ground surface, 3) Municipal or industrial areas that have a high proportion of impermeable surfaces (i.e. pavement, rooftops, etc.), and 4) Lakes.

2.8 Other Area Water Users

Ohio DNR requires water users to register if they have a capacity to produce surface water or groundwater withdrawal of at least 100,000 gallons per day. There are numerous business and non-City of Dayton municipal water users in the area. Table 2-2 lists these users and their reported water usage for May 2010. Residential water users also are present in the region, but these users withdraw insignificant amounts of groundwater in comparison to City well field pumping.

SECTION 3

Groundwater Model Software

In order to update the previous regional groundwater flow model, three computer software codes were used: MODFLOW-2000, Groundwater Vistas, and MODPATH. A description of these software codes and how they were utilized is provided in the section below.

3.1 Solution Techniques

The computer code to develop this model was the U.S. Geological Survey (USGS) modular groundwater program, known as MODFLOW (McDonald and Harbaugh 1988, 1996), version MODFLOW-2000. MODFLOW is a three-dimensional, finite difference code that can simulate transient and steady-state flow combinations of confined, unconfined, and semi-confined aquifers with a variety of boundary conditions and hydrologic stresses. The code has been in widespread use in the hydrogeologic profession since USGS first introduced it in 1984. It has been thoroughly peer-reviewed and is considered highly reliable as a numerical solver of the basic flow equations of flow in saturated porous media.

MODFLOW (McDonald and Harbaugh 1988, 1996, 2000) uses the finite-difference method to approximate the mathematical equation describing three-dimensional flow of constant-density groundwater in a porous medium. The basic principles underlying the equation are Darcy's Law and the conservation of fluid volume. A combination of the mathematical expressions of these principles results in the governing equation:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t}$$

Where,

- Kxx, Kyy, and Kzz are the values of hydraulic conductivity components along x, y, and z coordinate axes, which are assumed to be parallel to the principle axes of hydraulic conductivity (length/time)
- h is piezometric head (length)
- W is volumetric water influx per unit of aquifer volume representing groundwater sources and sinks (/time)
- Ss is specific storage of the porous medium (/length)
- t is time

MODFLOW can simulate steady or unsteady state flow in an aquifer. It can also handle heterogeneous, anisotropic, confined, and/or unconfined conditions. The code uses several components called "packages" to define the model domain, boundary conditions, sources and sinks, aquifer parameters, solver properties, and input and output control.

3.2 Assumptions

As with all groundwater flow model codes, general assumptions are made about the way aquifer conditions and stresses on the aquifer system will be represented in the model. The following major assumptions are inherent to the MODFLOW code:

- Parameters assigned to a cell such as a storativity, hydraulic conductivity, and recharge is uniform within each grid cell.
- Water levels in individual cells are averaged over the entire cell area.
- Pumping wells fully penetrate their assigned layers, are located in the center of their assigned cell and draw water from the entire cell volume with 100 percent efficiency.

3.3 Limitations

Mathematical models can only approximate processes of physical systems. Models are inherently inexact because the mathematical description of the physical system is imperfect and the understanding of interrelated physical processes is incomplete. The numerical model described in this report is a powerful tool that, when used carefully, can provide useful insights into processes of the physical system.

3.4 Pre- and Post-Processors

3.4.1 Software Interface

Groundwater Vistas (GV) version 5 is a Windows graphical user interface for three-dimensional groundwater flow and transport modeling. GV couples a model design system with graphical analysis tools (Environmental Simulations, Inc. 2007). GV was used to pre- and post-process the data.

3.4.2 Particle Tracking

MODPATH (Pollack 1989) is a particle-tracking code that operates by transporting imaginary fluid particles in a simulated steady-state velocity field derived from the output of a MODFLOW simulation. The imaginary particles to be tracked are added to the simulated flow field at starting locations specified by the modeler. From these starting points, their trajectories can be traced either hydraulically downgradient or upgradient. For this model the particles were traced in the hydraulically upgradient direction.

MODFLOW does not directly produce groundwater flow velocities as part of its output. Rather, it supplies output in the form of piezometric head values at every model cell and volumetric fluxes between adjacent model cells. MODPATH accepts these intercell fluxes and converts them to velocity components in the x, y, and z coordinate directions. The conversion is done by dividing the fluxes by the planar areas of the cell boundaries and the effective porosity of the aquifer. Neither the cell contact area nor the effective porosity is necessarily known by MODFLOW. Therefore, they must be specified as auxiliary input to the MODPATH code.

The particle tracking algorithm is valid for groundwater flow only, and does not track flow in the streams or quarries.

SECTION 4

Model Features

The hydrogeological information from the region is digitized into a modeled study. The model study area measures 44,936 feet from north to south and 64,020 feet from east to west. The horizontal grid has 119 rows and 142 columns. The rows and columns are spaced at 2250 feet and 1650 feet respectively in the peripheral model areas and transition to 300 feet to 250 feet in the area of the well fields (Figure 4-1).

Vertically, the model is divided into five layers. Three of the model layers represent sand and gravel units and two represent the intervening till units. Layer 1 represents the uppermost aquifer, while Layer 3 and Layer 5 represent the intermediate and deep aquifers respectively. Layers 2 and Layer 4 represent the subsurface till layers between the aquifers. All of the model layers have spatially variable thickness, as indicated by the available lithologic boring logs. The uppermost aquifer layer has a bottom elevation averaging 705 ft-amsl and a top elevation corresponding to local topography derived from a monitoring well survey. The intermediate aquifer has an average thickness of 50 ft., located within Layers 2 and 4, which represent the till layers. The bottom aquifer is approximately 70 feet thick, and represents the deep aquifer portion of the flow system. These layers generally conform to specific hydrologeologic units discussed in the Conceptual Site Model Section above.

As discussed in the Conceptual Site Model section, the contribution of water from the bedrock is very low relative to the unconsolidated buried valley aquifer system and it contribution is considered negligible. Therefore, the bedrock aquifer is represented as a boundary to groundwater flow.

4.1 Boundary Conditions

No-flow, constant head, lake, and stream-flow routing boundary conditions were assigned to cells in the model (Figure 4-2).

- **No-flow**: A no-flow boundary condition is a surface across which no flow of groundwater is permitted. These surfaces are defined in the numerical model as the interfaces between active and inactive model cells. Inactive cells are required in some locations because the finite-difference grid occupies the entire model domain, but some parts of that domain may not be occupied by aquifer materials. In addition, the outer edges of the finite-difference grid are automatically no-flow boundaries if the cells adjacent to the edge are active.
- **Constant Head**: A cell assigned as a constant head boundary condition has a groundwater elevation value input that remains constant throughout the model simulation.
- **Lake**: The lake package was used to represent several lakes that are present in the upper aquifer. These lakes are not part of the aquifer, and the equations of groundwater flow are not applicable within them. The MODFLOW lake package represents them as

boundary conditions with flow through the lake bed calculated as a linear function of the difference between the lake stage and the simulated heads in the aquifer cells adjacent to the lake. The lake package also maintains a water budget for each lake and adjusts the lake stages in response to the simulated net lake inflows and outflows at each iterative step of the groundwater flow simulation.

- **Stream-flow Routing**: The stream-flow routing (SFR) package was used to represent streams due to its ability to compute stage elevations and track surface water flow volumes. The SFR package permits water to flow between the stream and the aquifer depending on the hydraulic head differences, and accounts for changes in stream flow volume as the stream gains or loses water.

The assignments of boundary conditions are described below for each layer.

Layer 1

- **No-flow:** The no-flow boundary conditions were assigned to cells identified to represent the till deposits and the bedrock walls bounding the upper aquifer. Boring logs provided by the City and the Groundwater Resources Map of Montgomery County produced by the Ohio Department of Natural Resources were used to determine the extent of the uppermost aquifer in the vertical and horizontal directions. According to this interpretation, no flow boundary conditions were assigned around the periphery of the aquifer except where the aquifer intersects the edges of the model grid, as described below.

- **Constant Head:** The constant head boundary conditions were assigned to cells along the edges of the model grid at the active cells that represent the aquifer. These constant head cells permit groundwater to enter or exit the model as required by the computed hydraulic gradients in these boundary cells. Interpolated surface water elevations of the Great Miami River, Mad River, Stillwater River and Wolf Creek along with measured groundwater elevations were used to estimate the groundwater elevations for the appropriate cells along the model boundary. The upgradient Great Miami River and Mad River boundary cells were input with a groundwater elevation of 795 feet amsl and 856 feet amsl, respectively. Similarly, upgradient Stillwater River and Wolf Creek boundary cells were input with a groundwater elevation of 812 feet amsl and 725 feet amsl, respectively. The downgradient boundary cells of the Great Miami River were input with a groundwater elevation of 721 feet amsl.

- **Stream-flow Routing:** The stream-flow routing (SFR package) boundary condition was assigned to cells identified to represent Great Miami River, Mad River, Stillwater River and Wolf Creek.

  - The Great Miami River was assigned an average width of 385 feet, a streambed thickness of 1 foot, and an average streambed hydraulic conductivity of 0.15 feet per day, a streambed slope of 0.0007 feet/feet, and a Manning streambed roughness coefficient of 0.11. Stream discharge of 1236 cubic feet per second (cfs) at the upstream end of the river was used for the May 2010 calibration condition. Stream discharges were reduced to 1020 cfs for the normal average condition and 75 cfs for the 90-day, 10-year drought condition scenarios (David E. Straub. 2000).

- The Mad River was assigned an average width of 175 feet, a streambed thickness of 1 foot, and an average streambed hydraulic conductivity of 0.38 feet per day, a streambed slope of 0.001 feet/feet, and a Manning streambed roughness coefficient of 0.11. Stream discharge of 756 cfs at the upstream end of the river was used for the May 2010 calibration condition. Stream discharges were reduced to 639 cfs for the normal average condition and 175 cfs for the 90-day, 10-year drought condition scenarios (David E. Straub. 2000).
- The Stillwater River was assigned an average width of 140 feet, a streambed thickness of 1 foot, and an average streambed hydraulic conductivity of 0.15 feet per day, a streambed slope of 0.001 feet/feet, and a Manning streambed roughness coefficient of 0.1. Stream discharge of 777 cfs at the upstream end of the river was used for the May 2010 calibration condition. Stream discharges were reduced to 593 cfs for the normal average condition and 31 cfs for the 90-day, 10-year drought condition scenarios (David E. Straub. 2000).
- The Wolf Creek was assigned an average width of 77 feet, a streambed thickness of 1 foot, and an average streambed hydraulic conductivity of 0.15 feet per day, a streambed slope of 0.002 feet/feet, and a Manning streambed roughness coefficient of 0.1. Stream discharge of 123 cfs at the upstream end of the river was used for the May 2010 calibration condition. Stream discharges were reduced to 65 cfs for the normal average condition and 3.4 cfs for the 90-day, 10-year drought condition scenarios (David E. Straub. 2000).

- **Lake Package:** The lake package boundary condition was assigned to the Eastwood Lake and the 3 other lakes surrounding it, located northwest of the Mad River Well Field. The lake package is designed to serve as a boundary condition for the mathematical description of groundwater flow, in a fashion similar to that of the stream-flow - package, and to calculate the water budget of the lake during simulation, allowing for the stage of the lake to vary in response to budget changes. The Eastwood and surrounding lakes were represented in four model lakes. The model lakes were assigned an average minimum and maximum lakes stages of 730 ft and 760 ft amsl respectively. The bottom of the lakes was represented by a low-permeability material with a uniform vertical hydraulic conductivity of 1 X10^{-8} ft/day.

Layer 2, Layer 3, Layer 4, and Layer 5

No-flow and constant head boundary conditions were assigned to cells in the same manner as Layer 1. No other boundary conditions were assigned.

4.2 Hydraulic Properties

Initial estimates of hydraulic conductivity, stream bed conductance, recharge, and storage coefficient for the three-dimensional groundwater flow models were based on all available geological and hydrological data, as described in the Conceptual Model section. The values of hydraulic conductivity, stream bed conductance and recharge were varied within the range of measured or estimated values, as presented in the conceptual model, until the best match to the measured ground-water level and flow data was obtained. The following is a brief description of these estimates.

4.2.1 Hydraulic Conductivity

Initial estimates of hydraulic conductivities of the hydrogeologic units obtained from aquifer tests were used in the initial model run. Calibrated hydraulic conductivities are estimated as follows:

- **Layer 1 (the top aquifer layer):** The horizontal hydraulic conductivity of Layer 1 was modeled as an array of four zones with values of 0.30, 260, 300, and 600 feet per day (Figure 4-3). For Layer 1, the most widely distributed hydraulic conductivity value is 260 feet per day. To a lesser extent, the recharge lagoons in the Miami Well Field and the lake/aquifer boundaries in the Mad River Well Field are represented by a relatively higher hydraulic conductivity layers, 260 and 300 feet per day, respectively. Also the southern end of layer 1, where finer grain materials were noted as the till layers become more dominant, is represented by a relatively lower hydraulic conductivity of 0.03 feet per day.

- **Layer 2 (the upper till layer):** The horizontal hydraulic conductivity of Layer 2 is modeled as an array of three zones with values of 0.028, 0.3, 260 feet per day (Figure 4-4). The most widely distributed hydraulic conductivity value is 0.028 feet per day. To a lesser extent, areas along the western portion of the model have a relatively higher hydraulic conductivity value of 0.3. Also, several small areas along the central and western portion of the model have hydraulic conductivity values of 260 feet per day where aquifer material extends into this layer.

- **Layer 3 (the intermediate aquifer layer):** The horizontal hydraulic conductivity of Layer 3 was modeled as an array of two zones with values of 120 and 0.3 feet per day (Figure 4-5). The most widely distributed hydraulic conductivity values is 120 feet per day with areas near the edges of the buried valley that have a value of 0.3 feet per day where the aquifer material pinches out and aquitard material extends into this layer.

- **Layer 4 (the lower till):** The horizontal hydraulic conductivity of Layer 4 is modeled as an array of three zones with values of 0.04, 0.3, 260 feet per day (Figure 4-6). The most widely distributed hydraulic conductivity value is 0.04 feet per day. To a lesser extent, areas along the western portion of the model have a relatively higher hydraulic conductivity value of 0.3. Also, two small areas along the western portion of the model have hydraulic conductivity values of 260 feet per day where aquifer material extends into this layer.

- **Layer 5 (the deep aquifer):** The horizontal hydraulic conductivity of Layer 5 was modeled as an array of two zones with values of 0.3 and 300 feet per day (Figure 4-7). The most widely distributed hydraulic conductivity values is 300 feet per day with several areas throughout the layer that have a value of 0.3 feet per day where the aquifer material pinches out and aquitard material extends into the layer.

4.2.2 Areal Recharge

There are four recharge zones: 1) undeveloped/agricultural and/or light residential areas, 2) areas that have low permeability glacial till at the ground surface, 3) municipal or industrial areas that have a high proportion of impermeable surfaces (i.e. pavement, rooftops, etc.), and 4) water bodies. Figure 4-8 presents the areal recharge zone distribution.

Aquifer recharge from precipitation for each zone was estimated by assigning coefficients of runoff to each zone. The coefficients for the rational runoff method range from 0.05 for flat, lying sandy soil to 0.95 for concrete or asphalt pavement (Chow 1964). The undeveloped/agricultural zone was assigned a coefficient of 0.2, the surficial glacial till zone was assigned a coefficient of 0.3, and the municipal or industrial zone was assigned a coefficient of 0.8.

For this analysis, it was assumed that the undeveloped/agricultural zone receives the maximum available recharge, which is estimated to be one-third of the precipitation (Walton and Scudder 1960; Norris and Speaker 1966). To estimate the proportion of recharge assigned to each zone, the ratio of the rational coefficient for the undeveloped/agricultural area and the coefficients of the other areas was calculated. As a result, the proportion of available recharge for the undeveloped agricultural zone is 1, the surficial glacial till zone is 0.7, and the municipal/industrial zone is 0.2. The water bodies receive all available precipitation.

4.2.3 Artificial Recharge

Artificial recharge lagoons and ponds are represented in the model for the existing Miami and Mad River artificial recharge lagoons and ponds, the future Rip Rap Road Well Field. Figure 4-9 represents the artificial recharge distribution.

The Miami Well Field recharge lagoons and pond are represented as injection wells in the model. The simulated injection wells pump a total of about 13 MGD into the upper aquifer. The 13 MGD was diverted from the Great Miami River to the recharge lagoons and ponds as estimated by the City. This diversion amount was subtracted from the stream flow at the point near the recharge lagoons.

The Mad River Well Field recharge lagoons are modeled as part of the stream flow. Mad River flows through these series of dredged lagoons that are designed to serve as efficient conduits for inducing recharge into the upper aquifer.

The future Rip Rap Road Well Field recharge lagoons are represented as injection wells in the model. The simulated injection wells pump a total of about 12 MGD into the upper aquifer. The 12 MGD was diverted from the Great Miami River to the recharge Lagoons as estimated by the City.

4.2.4 Porosity

An effective porosity value of 0.25 was used uniformly for the aquifer layers in all the MODPATH simulations.

SECTION 5

Calibration

Numerical groundwater model calibration is an iterative process of adjusting model parameters (hydraulic conductivity, recharge, etc.), running the model, and then quantitatively comparing the model output against targets of field measured data. Typically for numerical groundwater flow models like this one, the field measured data used for comparison are groundwater elevations. As a rule of thumb, it is good to have this set of measure groundwater elevations meet the following criteria:

- Collected by individual(s) that have familiarity with field measurement processes;
- Distributed across the study area to be modeled vertically and horizontally;
- Obtained ideally within a limited window of time (e.g. within the same week); and
- Representative of conditions that are comparable to those for which the model will be used in predictive simulations.

If these conditions are met, a greater level of confidence in the conceptual model understanding of groundwater flow patterns is achieved. This leads to a greater level of confidence in the numerical model results.

There was one set of groundwater elevation measurements that met all of the above requirements. These data were collected on May 26 and May 27, 2010. Due to the influence on the groundwater water elevations, the pumping rates of the Miami and Mad River Well Field production wells and interceptor wells were also recorded during the same time period.

5.1 Steady-State Condition Calibration

In order to calibrate a groundwater model under steady-state conditions, the groundwater elevation measurements must be collected during relatively steady-state conditions. The May 2010 data set met this criterion. As part of this steady state condition, the simulated pumping wells included: the May 2010 City of Dayton Miami and Mad River Well Field production wells and interceptor wells (Table 5-1) and the May 2010 other area water users (business and non-City of Dayton muinicipal) water users wells (Table 2-2).

5.2 Quantitative Analysis

There were 283 measured water level calibration targets in the aquifer. The targets were groundwater elevations collected on May 26 and 27, 2010, from shallow, intermediate and deep wells (Figures 5-1 through 5-3). The statistical comparison procedure consisted of subtracting the simulated groundwater elevations from the field measured groundwater elevations at the target locations and calculating for all targets combined.

- The average of the differences (residual mean) = 0.13 feet;
- The average of the absolute differences (absolute residual mean)= 2.40 feet

- The standard deviation of the differences (residual standard deviation) = 3.10 feet

While there is no fixed numerical standard for residual statistics that indicates a good model calibration, it is good professional practice to compare the absolute residual mean and the residual standard deviation to the range of values in the target data set. In this calibration, the target values ranged from 720.91 ft amsl to 783.21 ft amsl, a difference of 62.3 ft. The absolute residual mean, at 2.40ft, was 3.9 percent of the range of target values. Standard modeling practice is to consider an absolute residual mean that is 5 percent of the target range or less to indicate good calibration. The residual standard deviation, at 3.10, was 5.0 percent of the target values. Standard modeling practice is to consider a residual standard deviation that is 10 to 15 percent of the target range or less to indicate good calibration.

Figure 5-4 presents these statistical results and presents a graph of the simulated water levels versus the field measured water levels per model layer. The graph illustrates the generally uniform distribution of the comparison values and does not indicate any layers or areas that are estimating too high or too low. The low statistical differences and the uniform distribution illustrated by the graph indicate a generally good match between the simulated and measured water levels.

SECTION 6

Verification

To establish greater confidence in the model's ability to represent different hydrologic conditions, a verification process was conducted for the calibrated model. The verification process consisted of setting up the model with June 1989 hydrologic conditions and then comparing the simulated water levels to a set of water level collected in June 1989.

The hydrologic conditions consisted of the City's monthly pumping for June 1989, the average June 1989 river flow for each of the modeled rivers, and the average precipitation for June 1989. As conducted for the calibrate model, a statistical comparison was completed by subtracting the twenty field measured groundwater elevations from 1989 to the simulated groundwater elevations at the target locations and calculating for all targets combined:

- The average of the differences (residual mean) = -9.2 feet;
- The average of the absolute differences (absolute residual mean) = 5.96 feet
- The standard deviation of the differences (residual standard deviation) = 6.65 feet

In this verification, the target values ranged from 803.75 ft amsl to 725.86 ft amsl, a difference of 77.89 ft. The absolute residual mean, at 5.96 ft, was approximately 6 percent of the range of target values. This is a satisfactory absolute residual mean. The residual standard deviation, at 6.65, was approximately 9 percent of the target values. Standard modeling practice is to consider a residual standard deviation that is 10 to 15 percent of the target range or less to indicate good calibration.

Figure 6-1 presents these statistical results and a graph of the simulated water levels versus the field measured water levels per model layer. Although the residual statistics and graph are not as favorable when compared to the calibration conditions, the residual statistics and the graph for the verification process indicate a reasonable match between the simulated and measured water levels.

SECTION 7

Sensitivity Analysis

The calibrated model is influenced by uncertainties in the model input values. Therefore, a sensitivity analysis was performed in order to establish the effect of uncertainty on the calibrated model. The sensitivity analysis conducted for the model grid spacing, the vertical and horizontal hydraulic conductivity distribution, the areal recharge distribution, and the streambed hydraulic conductivity distribution.

For all inputs except for the grid spacing, the sensitivity analysis was completed by applying a multiplier to the value throughout the model. This was done in a series of model runs in which the multiplier ranged from 0.2 to 1.8. The statistical values used for comparison are the residual mean and the absolute residual mean of groundwater head. The grid spacing sensitivity analysis was conducted by reducing the grid spacing and then comparing residual statistics of the calibrated model grid spacing to the reduced grid spacing to determine which produces the best residual statistics.

7.1 Horizontal Hydraulic Conductivity

The horizontal hydraulic conductivity of the study area was modeled as an array of seven zones with values of 120, 260, 300, and 600 ft/day for the simulated aquifers and three zones with values of 0.028, 0.04, and 0.3 ft/day for the aquitards. Rather than varying the numerical values of each individual zone, the sensitivity analysis was done by applying a multiplier to the array as a whole. This was accomplished in a series of model runs in which the hydraulic conductivity multiplier ranged from 0.4 to 1.8. The statistical value used for comparison is the residual mean and the absolute residual mean of groundwater head. The results are graphed in Figure 7-1.

For multipliers less than 1, the absolute residual mean increased sharply and for multipliers above 1, the absolute residual mean increased slightly. For multipliers less than 1, the residual mean increase sharply and for multipliers above 1, the residual mean decreased moderately. The results illustrate that the model is sensitive to adjustments in horizontal hydraulic conductivity; and that the calibrated hydraulic conductivity values are effective in representing the aquifer conditions –assuming that all other parameters remain unchanged.

7.2 Vertical Hydraulic Conductivity

The vertical hydraulic conductivity of the study area was modeled as an array of six zones with values of 12, 26, and 30 ft/day for the simulated aquifers and three zones with values of 0.028, 0.04, and 0.3 ft/day for the aquitards. Rather than varying the numerical values of each individual zone, the sensitivity analysis was done by applying a multiplier to the array as a whole. This was done in a series of model runs in which the hydraulic conductivity multiplier ranged from 0.2 to 1.8. The statistical value used for comparison is the residual mean and the absolute residual mean of groundwater head. The results are graphed in Figure 7-2.

For multipliers less than 1, the absolute residual mean increased sharply and for multipliers above 1, the absolute residual mean increased slightly. For multipliers less than 1, the residual mean increase sharply and for multipliers above 1, the residual mean decreased moderately. The results illustrate that the model is sensitive to adjustments in horizontal hydraulic conductivity; and that the calibrated hydraulic conductivity values are effective in representing the aquifer conditions assuming all other parameters remain unchanged.

7.3 Recharge

The recharge rate of the study area was modeled as an array of four zones. The sensitivity analysis was done by applying a multiplier to the array as a whole. This was done in a series of model runs in which the recharge rate multiplier ranged from 0.2 to 1.8. The statistical value used for comparison is the absolute residual mean and the residual mean of groundwater head. The results are shown in Figure 7-3. For multipliers less than 1 and above 1, the absolute residual mean increased slightly. For multipliers less than 1, the residual mean increased moderately and for multipliers greater than 1, the residual mean decreased moderately. The results illustrate that the model is moderately sensitive to adjustments in recharge; and that the calibrated recharge values are effective in representing the aquifer conditions assuming that all other parameters remain unchanged.

7.4 Streambed Hydraulic Conductivity

The streambed hydraulic conductivity of the study area was modeled as two zones with values of 0.15 and 0.38 ft/day. The sensitivity analysis was done by applying a multiplier to both zones as a whole. This was done in a series of model runs in which the hydraulic conductivity multiplier ranged from 0.2 to 1.8. The statistical value used for comparison is the residual mean and the absolute residual mean of groundwater head. The results are graphed in Figure 7-4.

For multipliers less than 1, the absolute residual mean increased sharply and for multipliers above 1, the absolute residual mean increased slightly. For multipliers less than 1, the residual mean increase sharply and for multipliers above 1, the residual mean decreased moderately. The results illustrate that the model is moderately sensitive to adjustments in streambed hydraulic conductivity; and that the calibrated streambed hydraulic conductivity values are effective in representing the aquifer conditions assuming that all other parameters remain unchanged.

7.5 Grid

In order to evaluate if the model is sensitive to reduction in grid spacing, the model grid spacing was reduced and the residual statistic compared to the calibrated and verified model residual statistics. The horizontal grid has 119 rows and 142 columns. The rows and columns are spaced at 2250 feet and 1650 feet respectively in the peripheral model areas and transition to 300 feet to 250 feet in the area of the well fields (Figure 4-1). The sensitivity analysis was limited to a single model run in which the grid spacing was halved. The following table presents a comparison between the calibrated model grid spacing and the model grid spacing reduce by half.

Residual Statistic	Calibrated Grid Spacing	Reduced by Half Grid Spacing
Residual mean	0.13 feet	-0.96 feet
Absolute residual mean	2.40 feet	2.37 feet
Residual standard deviation	3.10 feet	2.88 feet

When compared to the calibrated model statistics, the residual mean and the absolute residual mean are slightly worse and the residual standard deviation is slightly better in the model run with the reduced grid spacing. In general a reduction in grid spacing does not improve the model residual statistics and the calibrated model's sensitivity to a reduction in grid spacing is negligible.

SECTION 8

Model Prediction – Capture Zones

The calibrated, steady-state model was used to predict 1- and 5-year groundwater capture zones for the Dayton Miami, Rip Rap Road, Mad River, Eastwood Park, and Huffman Dam Well Fields (Dayton Well Fields) under various hydraulic conditions (scenarios). The analysis was performed using the MODPATH particle tracking model (Pollock 1989).

Simulated groundwater particles were originated at the bottom of the active pumping well screens as represented in the calibrated model, and tracked backward through time to determine the particle's location at one year back in time and 5 years back in time. The area encompassing the termination of the particles for the different time periods is referred to as the time-of-travel area or capture zone.

The scenarios to illustrate a range of 1- and 5-year capture zones under the different potential conditions and were selected after consulting with Ohio EPA's Division of Drinking and Ground Waters:

- Scenario 1: The hydraulic conditions of the study area are represented as "average". The Dayton Well Fields are pumping at "safe yield" levels (Figures 8.1 and 8.2).
  - Miami Well Field including Rip Rap Road Well Field is pumping at 63 MGD as presented in the City Miami Well Field Study Volume II: Development Program Plan (CH2M HILL, 1986). Table 8-1 lists the Miami Well Field pumping rate distribution along with the pumping rates for the Miami Well Field interceptor wells and the Montgomery County Ash Monofill interceptor well. The pumping rate distribution includes the future Rip Rap Road Well Field production wells (RRR3 and RRR4).
  - Mad River Well Field including Huffman Dam and Eastwood Park pumping at 93 MGD as presented in the City of Dayton Mad River Well Field Assessment (Geraghty and Miller, Inc., 1987). Table 8-2 lists the pumping rate distribution.
  - Miami Well Field and Mad River Well Field artificial recharge
  - Rip Rap Road Well Field future artificial recharge
  - Other Area water users pumping at average rates
  - Average stream flow and precipitation
- Scenario 2: The hydraulic conditions of the study area are represented as "average". The Dayton Well Fields are pumping under a condition (5-year peak average plus 1% growth factor for 10 years). Figures 8.3 and 8.4 present the capture zones.
  - Miami Well Field including the Rip Rap Road Well Field pumping at 38 MGD (City of Dayton 2010c). Table 8-3 lists the pumping rate distribution. The pumping rate

distribution includes the future Rip Rap Road Well Field production wells (RRR3 and RRR4).

- Mad River Well Field pumping at 56 MGD (City of Dayton 2010c). Table 8-4 lists the pumping rate distribution.
- Other Area water users pumping at average rates
- Average stream flow, precipitation, and artificial recharge

- Scenario 3: The hydraulic conditions of the study area are represented as "drought" (see below). The Dayton Well Fields are pumping at "safe yield" levels (Figures 8.5 and 8.6).
  - Miami Well Field including the Rip Rap Road Well Field pumping at 63 MGD
  - Mad River Well Field pumping at 93 MGD
  - No artificial recharge
  - Other Area water users pumping at average rates
  - 90 day, 10 year drought for stream-flow and 10 year drought for precipitation

8.1 Conclusion

The Dayton Well field Capture Zones illustrated in this report provide good predictive representations of the local aquifer behavior under steady-state conditions given various scenarios. This confidence is based on generally good input and consideration of the key factors discussed throughout the report including the updated understanding of the aquifer, up-to-date understanding of source water protection delineation expectations form Ohio EPA, and the application of current numerical modeling techniques.

SECTION 9

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Tables

Figures

Appendix A
Geologic Cross-Sections

Appendix B
Supporting Documentation