CITY OF ALLEGAN
WELLHEAD PROTECTION AREA
DELINEATION REPORT

I. PURPOSE AND SCOPE

The purpose of a Wellhead Protection Program for the City of Allegan is to protect the City's public water supply system from contamination. This protection is provided by determining the groundwater areas which contribute to the City's existing wells. This area is called the wellhead protection area (WHPA) and represents that part of the aquifer that will supply water to the City's wells in the future. Once the wellhead protection area is defined, existing and potential sources of groundwater contamination within the area are identified.

Delineation of WHPAs depends not only on the characteristics of the aquifer (i.e., type of media and type of flow), but also on the construction and operation of the wells. This report reviews the data collected for the wellhead protection program to provide estimates of the aquifer type (e.g. confined, unconfined) and hydrogeologic flow conditions (conductivity, gradient, etc.) that are likely to occur within the City's delineated WHPA.

The accuracy, and therefore the validity, of any delineation of a WHPA is a function of several factors, including the amount of information available regarding aquifer and well characteristics, the accuracy of the information, and the delineation methodology selected and applied. Delineations based upon adequate and reliable information will generally be more accurate than delineations where little information, or erroneous information on either aquifer or well characteristics is utilized. Similarly, WHPAs delineated by one of the more sophisticated delineation methodologies (e.g. Numerical Models) will generally be more accurate and defensible than those delineated by one of the simpler methods (e.g. Arbitrary Fixed Radius).

Since one of the fundamental purposes of delineating a WHPA is to define the "true" area which supplies drinking water to the City, the accuracy of the delineated wellhead protection area is important for three primary reasons:

- To avoid developing a WHP plan for areas which *would not have* been included within the WHPA if a more sophisticated delineation method had been applied (i.e. "overly-protective"),
- To avoid developing a WHP plan for areas which *would have* been included within the WHPA if a more sophisticated delineation method had been applied (i.e. "under-protective"),
- In the event that management approaches (especially those which are regulatory in nature) recommended by the local Wellhead Protection Task Committee are challenged, the delineation should be defensible in order to justify the area protected by those approaches.

This report is organized based on current MDEQ guidance for completing WHPA delineation reports. Completion of this report included addressing items discussed at a MDEQ WHPA Delineation Work Plan meeting.

The report also details the hydrogeologic conceptualization for Allegan that was used in a model to delineate the City's 10 year time of travel WHPA. Additionally, some aspects of this work may be used in the future if the City expands their current water system. Specifically, the developed model may be used to characterize the effects on the existing aquifer if an additional production well is installed. There are no other additional considerations or planned uses for this groundwater modeling work (e.g. site specific contamination migration analysis).

Specifically, this report has been divided into sections that review the following items:

- Sources of information
- Description of the area
- Historical aquifer test results
- Wellhead protection area delineation

II. SOURCES OF INFORMATION

Various types of information from several sources have been used in compiling the hydrogeologic model used to delineate the wellhead protection area. Information was gathered for use in evaluating the following items:

- Existing municipal wells
- Regional subsurface lithology
- Regional groundwater flow characteristics
- Other sources of information

A. INFORMATION FOR EXISTING MUNICIPAL WELLS

Information on the City's existing municipal wells was obtained from several sources including the City of Allegan and the Allegan County Health Department.

Attachments A through D contain copies of the municipal wells logs and Figure 1 illustrates the location of the municipal wellfields. The spacing of wells PW-1, PW-2 and PW-3 is illustrated in Figure 9.

B. REGIONAL SUBSURFACE LITHOLOGY

The regional geology for the area is based on a review of several sources including the Quaternary Geology of Michigan Map (W.R. Farrand, 1982), Bedrock Geology of Allegan County (MDNR, 1982), Drift Thickness of Allegan County (MDNR 1982), Bedrock Geology of Michigan (1987), Bedrock Topography of Allegan County (Western Illinois University, 1982), Soil Survey of Allegan County, Surficial Geology of Allegan county (Michigan State University, 1982), Flowing Wells in Michigan (USGS 1977), United States Geological Survey Map (1967), Soil Survey of Allegan County (United States Department of Agriculture, 1987) oil and gas well records, water well records and a recently completed aquifer pump test. A copy of the Quaternary Geology of Michigan Map depicting the Allegan area is shown on Figure 4.

C. REGIONAL GROUNDWATER FLOW CHARACTERISTICS

Information on the regional groundwater flow characteristics was originally presented in the MDEQ Wellhead Protection Program Work Plan report (February, 2000) and illustrated the estimated potentiometric surface based on an analysis of all available depth to water measurements recorded on well drilling logs. The initial MDEQ Wellhead Protection Program Work Plan also included a review of regional boring logs.

This initial, unconfirmed regional groundwater flow is presented on Figure 5A. The Phase II work included confirming the potentiometric surface by measuring depth to groundwater in select wells. The measured wells were then surveyed to existing National Geodetic Vertical Datum benchmarks using Global Positioning Satellite (GPS) professional survey grade equipment the potentiometric head at each well was calculated. The location and spatial distribution of measured wells were selected to provide an appropriate regional distribution of potentiometric heads at locations throughout the study area.

Attachment F contains copies of available well logs for each well in which the depth to groundwater was measured. Attachment F also contains well logs for wells that were not surveyed, but were used in determining the confirmed groundwater potentiometric head. Figures 5B and 5C illustrate the location of each groundwater elevation data point and the resulting confirmed potentiometric surface. All measurements reported in Table 1 (Attachment F) were used in calculating the potentiometric surface with the exception of well 31-1 (well log not available) which appeared to be an outlier based on the surrounding potentiometric surface measurements. The development of the potentiometric surface map is further reviewed in Section III.C of this report.

III. DESCRIPTION OF THE AREA

Review and analysis of the information sources detailed in Section II provide the following the general description of the area. The area description is divided into three main areas as follows:

- General description of the area
- Municipal wells
- Regional groundwater flow direction

A. GENERAL DESCRIPTION OF THE AREA

The general geology for central Allegan County is characterized by 100 to 300 feet of glacial drift which overlies the Marshall and Coldwater upper bedrock formations. The bedrock in Allegan County consists of Mississippian Sandstone and Shale, which are part of the Michigan Basin. Bedrock in Allegan County is overlain by about 50 to 400 feet of drift deposited during the Wisconsin Glaciation. The present surface features generally are the result of this glacial deposition, which occurred when the glacial ice receded about 10,000 years ago (Soil Survey, Allegan County).

The City of Allegan is located within a glacial outwash valley located above the Coldwater Bedrock formation. The majority of material within the valley is described as the Dorr Channel Outwash deposits of fine to coarse sand, pebbles and cobbles. Cutting through this glacial material is the Kalamazoo River Floodplain deposits of bedded sand and silt. Bordering the glacial outwash to the west are Eolian Sand and Glacial Lake deposits of wind deposited sand and pebbles. The lake deposits contain small isolated areas of clay, silt and muck. Area's to the

east are predominantly glacial till of massive to poorly bedded clay rich till. The local surface features are illustrated in Figure 1, Area Topographic Map.

Area lithology, based on selected well logs, is presented in cross section Figures 6, 7 and 8. These cross sections illustrate outwash materials inter-bedded with clay lenses in the lowlands near the river and confining lithology in the highlands east and northeast of the river. The cross sections also illustrate the position of the production well screens relative to the lithology identified at the wellfield.

The aquifer that the City's wells produce from is best described as unconfined based on the lithology presented in the available well logs, comparison of the groundwater breakout elevations reported on the area's USGS map to reported well static water levels, and the recent aquifer tests completed at PW-2. The thickness of the aquifer at PW-2 is approximately 75 feet extending from 3 feet to 80 feet below grade surface (BGS).

B. MUNICIPAL WELLS

The City maintains two wellfields and four active production wells (PW-1, PW-2, PW-3 and PW-4). The wells are all located in Allegan County, Section 28, T02N, R13W. A population of approximately 4,500 is served by the municipal wells. The state plane coordinates for each well were measured in 2000 and are as follows:

PW-1	1,592,389,	378,749
PW-2	1,592,380;	378,729
PW-3	1,592,397;	378,769
PW-4	1,590,431;	378,011

The City currently operates four municipal wells (PW-1, PW-2 and PW-3, PW-4). PW-4 is located near the intersection of M-89 and Hubbard Street and is used only for fire and other water emergencies. PW-1, PW-2 and PW-3 are located on Park Street in the central area of the City. The location of the wells are illustrated in several figures including Figures 1, 2 and 3.

Municipal Well PW-1, installed in 1971, is an 16-inch diameter well screened from 60 to 80 feet below grade surface (BGS) in a sand and gravel formation. The capacity of PW-1 is 1,000 GPM. Static water levels are reported at approximately 7 feet BGS. Available data for PW-1 is included in Attachment A.

Municipal Well PW-2, installed in 1972, is an 16-inch diameter well screened from 65 to 85 feet BGS in a sand and gravel formation. The capacity of PW-2 is 1000 GPM. Static water levels are reported at approximately 7 feet BGS. Available data for PW-2 is included in Attachment B.

Municipal Well PW-3, installed in 1935, is an 18-inch diameter well screened from 64 to 79 feet BGS in a sand and gravel formation. The capacity of PW-3 is 1050 GPM. Static water levels are reported at approximately 7 feet BGS. Available data for PW-3 is included in Attachment C.

Municipal Well PW-4, installed in 1948, is an 16-inch diameter well screened from 45 to 60 feet BGS in a sand and gravel formation. The capacity of PW-3 is 1000 GPM. Static water levels are reported at approximately 13 feet BGS. Available data for PW-3 is included in Attachment D.

The maximum recorded monthly total-pumpage at the City's main wellfield (PW-1, PW-2, PW-3) is 1,681 gpm in July of 1996. This total is based on the City's standard wellfield operation of pumping two (2) of the three (3) wells at any given time. As such, the maximum pumping rate for an individual well would be approximately 840 gpm.

C. REGIONAL GROUNDWATER FLOW DIRECTION

The City of Allegan Wellhead Protection Program Workplan included a calculation of the regional groundwater flow direction based on available well logs. The Workplan included an Initial review of available regional potentiometric surface data which indicated that a confined aquifer may be present. The review also considered the lithology presented in the well logs for PW-1, PW-2 and PW-3 which indicated clay located above the screened sand/gravel aquifer. The Workplan concluded, however, that enough data was not available to determine the vertical extent of the clay or the degree of confinement, if any. Accordingly, an aquifer pump test was completed which indicated an unconfined aquifer response to high volume pumping over an extended period of time.

The initial regional groundwater flow map (Figure 5.A) was based on confined aquifer conditions. Subsequent field work, including the aquifer test, indicated that the aquifer supplying the City's production wells is best described as unconfined. Accordingly, surface water elevations at locations on the Kalamazoo River and Little John Lake were surveyed and used during the development of the confirmed potentiometric map. The data indicated the groundwater potentiometric surface closely matched surveyed surface water elevations. The data also indicated that a groundwater flow divide is located near Miner Creek to the East, the northern portion of Cheshire and Trowbridge Townships to the south.

As illustrated in Figure 5.B and 5.C, the confirmed regional groundwater potentiometric surface maintained the same general contouring determined in the initial field potentiometric surface. The Figures also indicate regional groundwater recharge is occurring predominately from the east and southwest, and discharge is occurring along the Kalamazoo River.

IV. AQUIFER TEST

A. AQUIFER TEST DESIGN AND SETUP

As part of the Wellhead Protection work, a 25 hour aquifer pump test was completed in April, 2000. Graphs, Data (including digital format) and calculations used in the aquifer test are included in Attachments E and G. The aquifer test was completed to determine the aquifer type, transmissivity, storativity and boundary conditions. Well logs, static water elevations and surface water elevation data indicated all four of the City's production wells are located in the same aquifer.

The pumping well for the test was PW-2 which is screened from 64 - 84 feet below grade surface (bgs). The reported lithology at PW-1, PW-2, PW-3, OB-2 and OB-3 identified primarily fine to coarse gravel and cobbles with thin layers of clay located above the screened well depths. The lithology indicated the aquifer may be unconfined. The aquifer thickness was estimated to be 75 feet and located between approximately 5 - 80 feet bgs.

MDEQ guidelines state two observation wells are minimally required to measure water levels during an aquifer test. For Allegan's test, a nearby production well (PW-3) was readily assessable and used as an observation well (OB-1, screened at 30 to 45 feet bgs and located 39 feet north of PW-2). An additional observation well (OB-2, screened at 58 – 78 feet bgs and located 90 feet east of PW-2) was installed for

the test. Water levels were also recorded in an available shallow observation well (OW-3, screened at 27 – 38 feet bgs and located 6 feet east of PW-2). The aquifer test site plan in illustrated in Figure 9.

Setup for the pump test included installing pressure transducers (In-Situ model PXD-261, 15 psi) in the three observations wells (OW-1, OW-2, OW-3) and connecting the transducers to a central data-recorder (Hermit 3000). Prior to the drawdown test, all of the municipal wells were shut down for the maximum allowable time of approximately 1,000 minutes (18 hours) during which time the aquifer was allowed to recover. During this time, water levels were electronically recorded and post-test review of the data indicated a trend of water levels slowly returning to normal static elevations. Also during this time, and during the pumping and recovery tests, no significant changes in barometric pressure were observed and no precipitation was recorded.

The pumping test was conducted with PW-2 continuously pumping the maximum sustainable rate of 810 gpm for the duration of the test (1,500 minutes, or 25 hours). Throughout the entire test, production well discharge was treated and distributed through the City's water system.

B. AQUIFER TEST ANALYSIS

Attachment C, Graphs C-1, C-2 and C-3 illustrate the linear, logarithmic and semi-logarithmic time-drawdown patterns produced from the response to the stress caused by pumping PW-2. As the plots indicate, the observations wells responded instantly.

The observed aquifer response is indicative of an unconfined aquifer system. As illustrated in Graph C-2, the slope of the drawdown for OW-1 changes between t=100 and t=200 minutes.

Sieve analysis of the aquifer material was not found, but review of the driller's logs describe the aquifer material as sand and gravel, sand and gravel and cobbles. Additionally, geophysical logging completed after the aquifer test to confirm lithology at OB-2 indicated no confining layers (Attachment E).

Although the test was completed based on a confined aquifer system, subsequent analysis of the data suggests the aquifer response is more accurately described as unconfined.

All aquifer test data was analyzed using the Earthware software package Pump Test and was based on the following key assumptions:

1. The initial water table is horizontal and extends to infinity radially.
2. The aquifer is bounded below by an aquiclude.
3. The diameter of the well is small and well storage can be neglected.
4. The aquifer is pumped at a constant discharge rate.
5. The aquifer is infinite in extent.
6. The aquifer is uniform in thickness, anisotropic and homogeneous.
7. The aquifer is compressible and completely elastic.
8. Groundwater density and viscosity are constant.
9. Groundwater flow can be described by Darcy's law.
10. Drawdown is small compared with the saturated thickness of the aquifer.

Analysis of the Allegan aquifer pump test data was competed to characterize the aquifer's transmissivity (T) and storage (S). The aquifer characteristics are summarized in Table 2. Table 3 reviews estimated aquifer transmissivity based on the measured specific capacity at certain production wells.

Graphs C-4 and C-5 illustrate the analysis of the early test data for OB-1 and OB-2 using the Theis curve. The Theis curve was used since only the drawdown data prior to any river or delayed yield influence was used in the analysis. The intent of graphs C-4 and C-5 was to characterize the aquifer prior to the introduction of river influence.

Following the aquifer pumping test, recharge was recorded as illustrated in Graphs C-7 and C-8. Recovery data was obtained for approximately 300 min. (5 hours) until the demand for water became crucial. Due to an obstruction in PW-4, water levels were not recorded during the pump test from the pumping well.

The recorded specific capacity for each of Allegan's four production wells were used to estimate aquifer transmissivity. Using the empirical equation Q/s = T/1,500, the estimated aquifer transitivity value was calculated to be 1,050,000 gpd/ft.

Table 2
Estimated Aquifer Transmissivity (T)
and Storativity (S) Values
City of Allegan
Aquifer Pump Test Analysis, PW-2
April, 2000

	OB-1 (r = 40', PW-3)		OB-2 (r = 90')	
	T	S	T	S
Method	(GPD/ft)	(Unitless)	(GPD/ft)	(Unitless)
Theis	859,000	0.20	891,000	0.04

Table 3
Estimated Aquifer Transmissivity (T)
Based on Original Well Capacity
City of Allegan

	PW-1	PW-2	PW-3	PW-4
	(GPD/ft)	(GPD/ft)	(GPD/ft)	(GPD/ft)
Transmissivity	970,000	Not	880,000	1,300,000
(Test Year)	(1971)	Recorded	(1966)	(1948)

T=1,500 * Specific Capacity

The aquifer pump test and the specific capacity data both indicate similar aquifer characteristics. Both methods produce extremely high transmissivity values. These values are high, in part, because of the coarse sediment the wells are screened in, but more likely because of the influence of the Kalamazoo River which likely limits drawdown in these wells.

Well logs indicate the aquifer at the wellfield consists of sand and gravel with scattered deposits of clay. The most productive part of this aquifer is likely the coarse gravel deposit identified on the well logs as being located between approximately 50 and 80 feet bgs. Cross-sections illustrated in Figures 7 and 8 indicate the coarse gravel deposit is located primarily in the immediate vicinity of the Kalamazoo River.

While the lithology data indicates that aquifer transmissivity may decrease significantly at locations outside of the river's coarse gravel deposits, a Transmissivity value of 850,000 gpd/ft. (hydraulic conductivity of 1,500 ft/day) and a Storativity (S) value of 0.25 were used throughout the entire conceptual model.

Additionally, as a part of the WHP delineation work, an aquifer response test was completed to confirm that the main wellfield (WP-1, PW-2, PW-3) is hydraulically connected to PW-4. Since the aquifer response test observed drawdown in PW-2 when pumping was being conducted at PW-4, the two wellfields are hydraulically connected.

V. WHPA DELINEATION

A. SELECTION OF MODEL TO DELINEATE THE WELLHEAD PROTECTION AREA

Numerous groundwater models ranging from simple analytical to complex numerical models are available to delineate a WHPA. The City of Allegan WHPA delineation was completed using a numerical groundwater model. Numerical models are based on algebraic equations that define hydraulic head at specific points and are solved using matrix algebra techniques. Several different numerical methods are available to solve the matrix equations. For this work, the finite difference model MODFLOW (developed by the U.S. Geological Survey) was used. Particle tracking was completed using the MODPATH package. MODFLOW and MODPATH were operated using Visual MODFLOW (developed by Waterloo Hydrogeologic, Inc.). Equations were solved in the steady state mode using the SIP solution technique with a head criterion for convergence of 0.1 feet. Digital output is provided in Attachment G.

B. MODEL BOUNDARIES AND ASSUMPTIONS

An important step in delineating the WHPA is the recognition of the effects to groundwater flow of hydrogeologic boundaries. These boundaries are generally considered to be combinations of the two limiting cases of constant head and no-flow boundaries.

The most common example of a constant head boundary is a stream. In the case of a perennial stream, largely supported by surface flow through a drainage basin, the water level in the stream may show only minor variations over short time intervals. If the WHPA of a pumping well intersects the stream, a hydraulic connection may be established whereby a portion of the water being derived from the well originates within the stream. The net effect is to reduce the size of the WHPA (i.e., less water is being derived directly from the aquifer). Conversely, a perennial stream may act as a source of aquifer discharge. The actual impact of a stream in a model will depend on the hydraulic location of the stream.

No-flow boundaries are those across which groundwater movement is either prevented or reduced to negligible flows. No-flow boundaries are generally associated with groundwater divides, changes in local permeability or along groundwater flow direction streamlines. A groundwater divide is analogous to a topographic divide that separates surface water drainage basins. A groundwater divide is often identified as an elevation high on the water table or potentiometric surface where groundwater moves away from the divide in both directions. Since groundwater cannot flow across the divide, the divide represents a no-flow boundary.

For the City of Allegan, the following aquifer conceptual model boundary conditions have been assumed. The upper boundary of the conceptual model is represented by the potentiometric surface of the unconfined aquifer. The lower boundary of the conceptual model is represented by clay and assumed to be impermeable. Laterally, groundwater flows into the model from the east and south, as indicated by the confirmed groundwater potentiometric map. Water discharges from the model along the Kalamazoo River and also discharges through the municipal wells. Boundary conditions and locations were chosen to replicate the potentiometric surface illustrated in Figures 5B and 5C.

The Kalamazoo River, located downgradient of the wellfield, represents the model discharge area. This was replicated in the groundwater flow model by using the MODFLOW River package and varying the river bed conductance to match the confirmed groundwater potentiometric surface.

While it is likely that the thickness of the aquifer naturally varies across the study area, supporting data was not identified during the wellhead protection work to provide meaningful aquifer thickness contouring. As a result, no changes in aquifer thickness were implemented into the model. Based on review of the recorded lithology from the driller's logs for the production wells and exploratory borings in the municipal wellfield, the aquifer thickness has been conservatively estimated to be 80 feet for the conceptual model.

Recharge within the conceptual model is occurring from the southwest and northeast based on the confirmed potentiometric surface completed as part of the WHPP. Recharge to the model is provided by assigning constant head values along the eastern, western and western portion of the southern border of the conceptual model. Additionally, surface recharge from rainwater, snow melt, etc. was based on estimated values provided by U.S. Geological Survey.

The development of the conceptual model for the Allegan WHPA delineation included the use of certain surface water information. This information was obtained from both available topographic maps and from field surveyed surface water elevations. The collected data indicated several groundwater divides including divides located east and west to southwest of the City. The location of the groundwater divides are illustrated on Figure 5b and 5c. These particular groundwater divides effectively limit the centerline distance of both the wellfield's delineated WHPAs.

C. MODEL INPUT PARAMETERS

The shape of the WHPA is primarily affected by the hydraulic properties of the aquifer, specifically hydraulic gradient, conductivity (transmissivity) and porosity. These properties are intrinsic to the aquifer material and do not vary significantly with time, but may vary significantly across the aquifer region. The flow gradient and flow direction parameters have the most significant effect on the size, shape and orientation of the WHPA.

Key input parameters that have a significant effect on the WHPA delineation have been varied to determine model sensitivity as detailed later in this report. The key modeling input parameters are detailed in Table 4.

Figure 9 illustrates the delineated 1, 5 and 10 year wellhead protection area based on the results of reverse particle tracking on a groundwater flow gradient produced by the model MODFLOW, and based on advection and dispersion of dissolved constituents in the groundwater system. The accuracy of the model was primarily based on two calibration standards; Zone Budget (Visual MODFLOW term for traditional water balance calculations) analysis and the root mean squared (RMS) error between the calculated and observed heads (Attachment G).

The Zone Budget compares inflow and outflow of the model and calculates the percent discrepancy. An error of less than 1% is considered acceptable (Anderson 1992) and an error of 0.1% or less is considered ideal (Konikow 1978). The calculated error for the Allegan baseline model is 0.0%.

Table 4.
Modeling Input Parameters

Parameter Type	Parameter Value Used in Model
Aquifer type	Unconfined
Aquifer Effective Porosity	0.2 (dimensionless)
Number of Pumping Wells	4
Pumping Rate PW-1[1] PW-2[1] PW-3[1] PW-4[2]	 840 gpm 840 gpm 840 gpm 1,000 gpm
Aquifer Thickness	60 feet
Aquifer Transmissivity	850,000 GPD/ft (1,500 ft/day Hydraulic Conductivity)
MODFLOW Specific Storage (Storativity/Thickness)	0.25 ft^{-1}

[1]Pumping rate based on the average day pumping rate for the maximum pumping month over the past 4 years.
[2]Rated capacity. Well is not typically utilized.

The model calibration included wells PW-3, OB-1, OB-2, 13-1, 15-1, 16-1, 23-1, 23-3, 27-1, 31-1, 36-1, RIVER 1, RIVER 2, and Little John Lake. The target base model RMS acceptable error between calculated and observed heads is less than 10 feet. The observed base model RMS is 10 feet. The errors may be the effect of transient effects that are not represented in the model, scaling effects (model requires point measurements of heads not measurements from screened intervals), or measurement error in determining the heads.

D. MODEL SENSITIVITY ANALYSIS

The key to a quality WHPA delineation is the use of data that is representative of the system being modeled. The numerical model MODFLOW used for this project assumes uniform characteristics for the

river area and the inland area. In order to identify what parameters have a significant impact on the particle tracking used to delineate the WHPA, and to quantify the effect, the modeling work included a sensitivity analysis. The sensitivity analysis focused on how changes in key parameters altered the 10 year WHPA. Results of the sensitivity analysis are reported in Table 5.

Table 5.
MODFLOW Particle Tracking Sensitivity Analysis

Condition Varied7	Range Tested	Observed Results
Aquifer Conductivity	500 – 1,500 ft/day	No significant effect on the length or width of the WHPA.
Porosity	0.15 – 0.25	No significant effect on the length or width of the WHPA.
Recharge	4 – 9 inches/year	No significant effect on the length or width of the WHPA.

Based on the sensitivity analysis in the modeled WHPA, it can be determined that the presence of the divides to the east and southwest negates the sensitivity of the model to hydraulic conductivity, porosity , and recharge. The greatest influence in for the Allegan WHPA is the location of the groundwater divides including those which are located east and west to southwest of the City.

VI. MODELING SUMMARY

The WHPA delineation completed for the City of Allegan has been based on the information presented in this report. The results of the modeling work provide an estimated delineated WHPA that will be used throughout the remaining wellhead protection program implementation.

The modeling work recognizes that several factors may influence the delineated WHPA in the future. The WHPA has been delineated based on a set of hydraulic properties, including groundwater flow into and out of the system and stresses applied to the aquifer. Although it may seem unlikely that the hydraulic properties of the aquifer could change appreciably, it is possible that surface-related activities could lead to a significant change from conditions assumed to exist during the development of the initial conceptual model.

Prolonged drought and/or over-drafting of an unconfined aquifer could result in a decrease in the thickness of the saturated zone or variations in gradient. Both parameters could cause a change in the size and orientation of the WHPA.

Any addition of high-volume wells in the WHPA or in proximity to its boundary may also alter the shape of the WHPA. Significant changes in pumping rates would also have an impact on the size of the well's capture zone.

While the delineated WHPA, as indicated by the collected field data and subsequent computer modeling, is not designed to eliminate all uncertainties, it is conservatively designed to increase the likelihood that the ten year groundwater supply to the municipal wells is completely included by the WHPA identified in this report.

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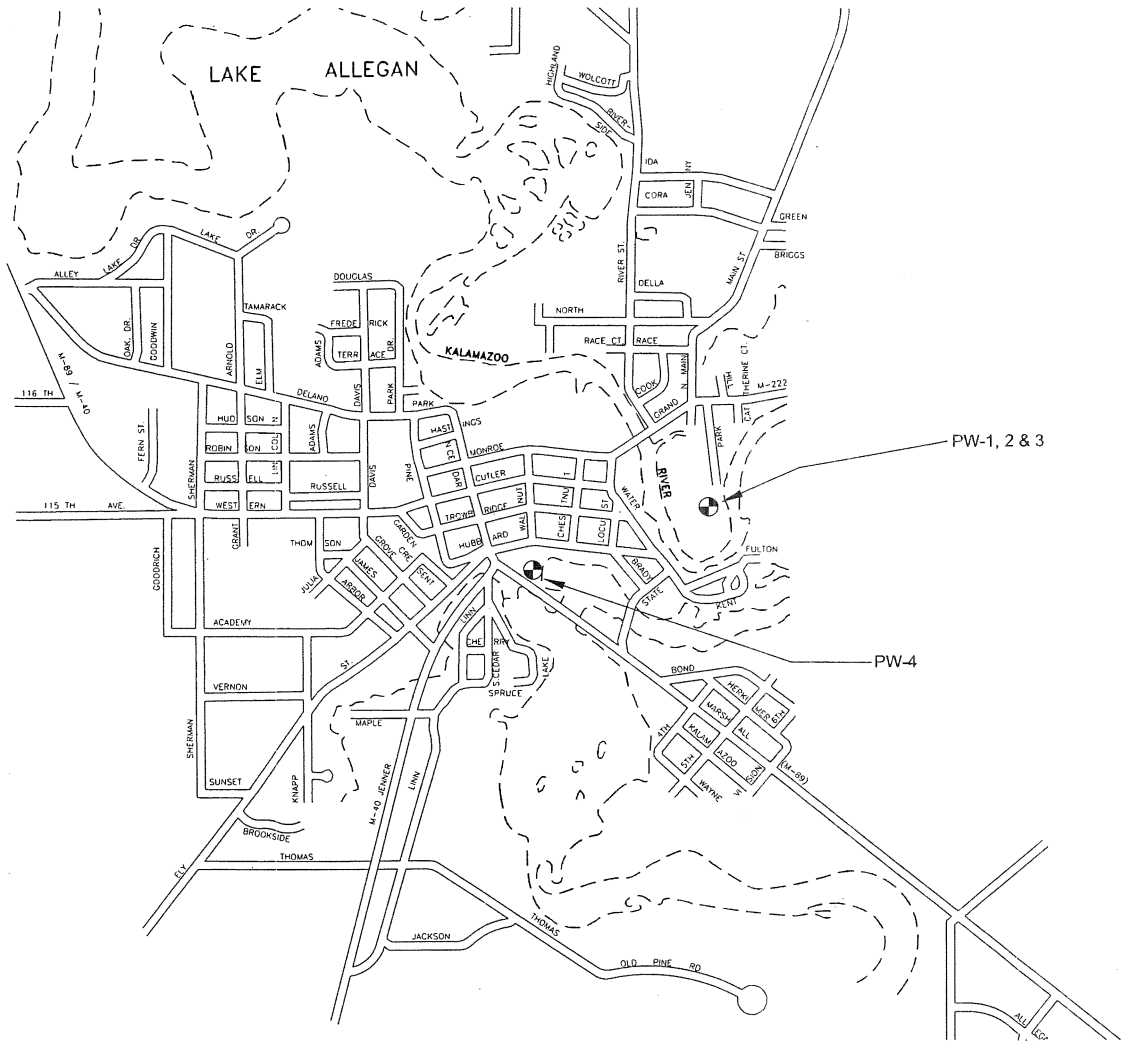

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CITY OF ALLEGAN
ALLEGAN COUNTY, MICHIGAN

CITY MAP
FIGURE 2

2000 3433

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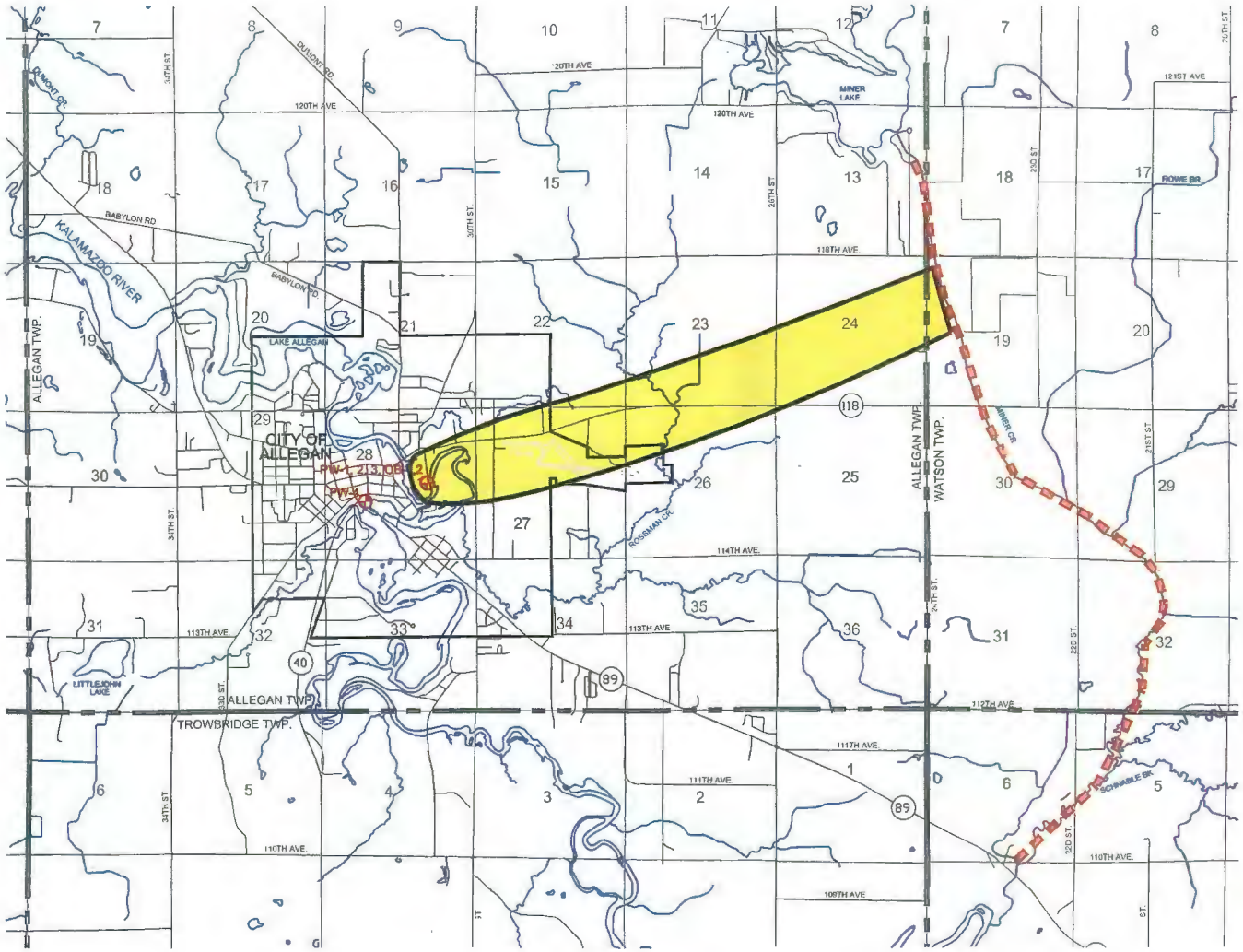

CITY OF ALLEGAN
ALLEGAN COUNTY, MICHIGAN

WELLHEAD PROTECTION AREA - EAST
FIGURE 10.A

2000 3433

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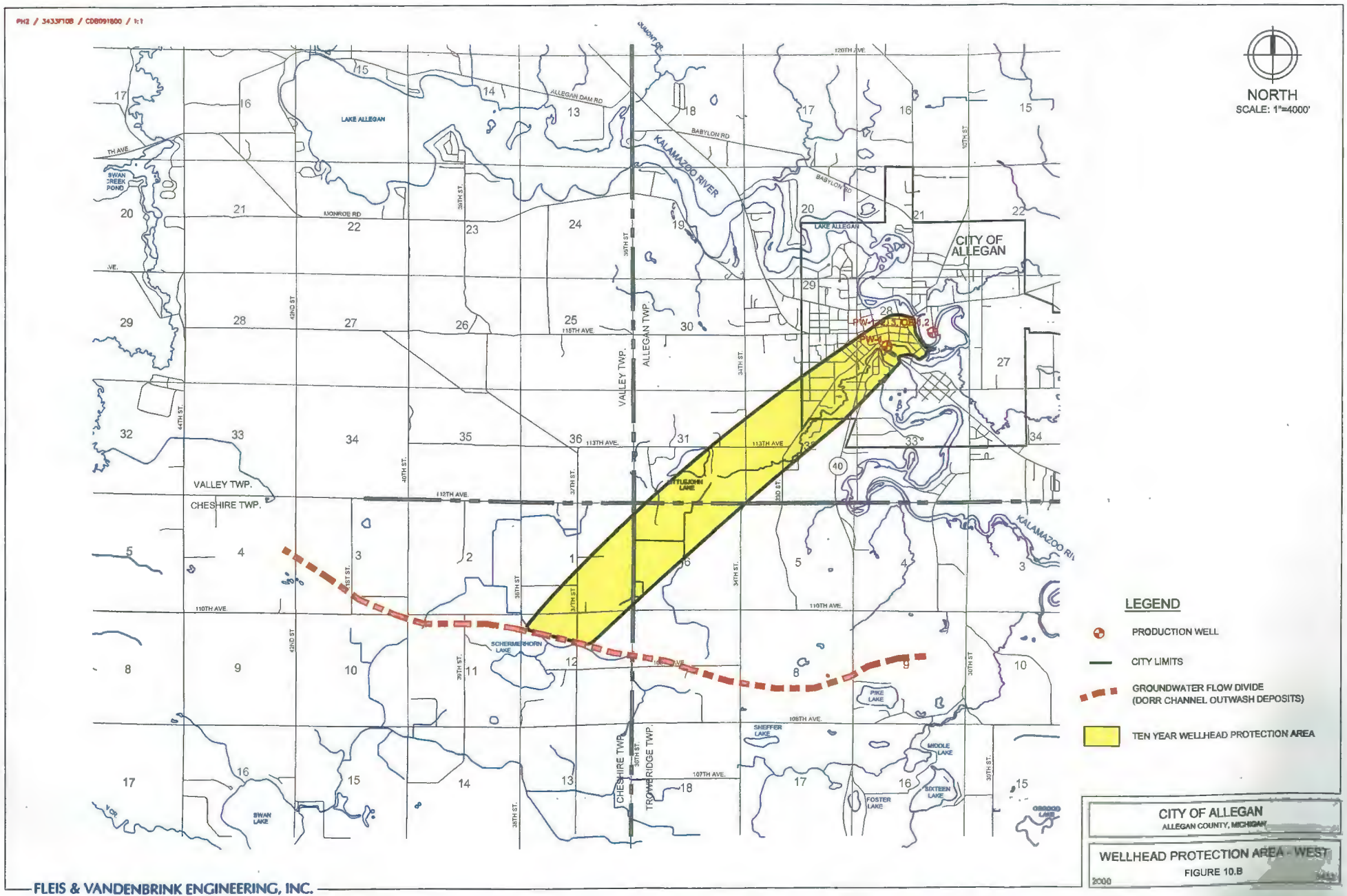

CITY OF ALLEGAN
ALLEGAN COUNTY, MICHIGAN

WELLHEAD PROTECTION AREA - WEST
FIGURE 10.B
2000

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