Simulation of Solute Movement At a Chromium-Contaminated Site

N.W. Mauthe Property
725 S. Outagamie St.
Appleton, WI

for

Ms. Jennifer Borski
Wisconsin Department of Natural Resources
625 E. County Road Y, Suite 700
Oshkosh, WI 54901-9731

March 16, 2007

N1866A05

ENGINEERING • ARCHITECTURE • ENVIRONMENTAL

OMNNI ASSOCIATES

Forward

The intent of this modeling effort is to broadly estimate the behavior of groundwater contamination at the Mauthe site. The audience for this modeling effort is intended to be the decision-makers responsible for the remedial efforts at the site, as well as neighboring parties potentially at risk from the contamination at the Mauthe site. The intent of the effort is to generally estimate how far chromium contamination might move, how long it might take to achieve closure standards, and how significantly the groundwater collection efforts presently underway bear on these issues.

A time period of 500 years was selected for the model. The timeframe was chosen to provide enough time to begin to see attenuation at the front edge of the contaminant plume, given the low hydraulic conductivities at the site. We recognize that any model loses accuracy as the modeling period increases. It is not our intent to present the results as dispositive of exact plume behavior at distant times in the future.

Models are only as good as their inputs. We feel that the inputs used in the present model adequately represent site conditions. Exhaustive additional site testing would further refine the model, enhancing its predictive value. It is our opinion that the model presented herein will assist decision-makers in determining future action necessary to manage risk arising from contaminant conditions at the site.

Questions can be addressed to Don Brittnacher, OMNNI Associates, One Systems Dr., Appleton, WI 54914; tel.: (920)735-6900; email: don.brittnacher@omnni.com.

Simulation of Solute Movement at a Chromium-Contaminated Site

Don Brittnacher, OMNNI Associates, don.brittnacher@omnni.com

ABSTRACT

A groundwater flow and transport model simulating contaminant movement was developed for a chromium-contaminated site in Appleton, Wisconsin. The site has undergone investigation and partial remediation. A groundwater collection system has operated at the site since 1997. Chromium contamination conditions were simulated under two scenarios: one assuming continued groundwater collection, and one assuming system shutdown and natural attenuation. Under each scenario, contaminant movement was modeled over a 500-year timeframe. Estimates were made of the extent of plume migration and reduction in contaminant mass over that time period.

The groundwater flow and transport model was constructed using Visual Modflow (v. 4.1, Waterloo Hydrogeologic).

Neither scenario achieved cleanup goals within the modeled period. The model predicted that under both scenarios, the contaminant plume would expand to approximately the same degree, due to the low hydraulic conductivities of the soils at the site. The plume is expected to remain on the subject property and properties immediately southeast of the subject property.

Continued operation of the groundwater collection system is expected to reduce the cleanup timeframe from that required if the system were shut down. Under both modeled scenarios, however, the present chromium closure level of 5 ug/L will not be achieved in 500 years.

INTRODUCTION

The N.W. Mauthe site is a former electroplating facility, located at 725 S. Outagamie St. in Appleton, Wisconsin. The facility operated from 1960 to 1987, conducting electroplating operations from two buildings at the site. Primary chemicals used included chromium, cadmium, zinc, and copper. Plating solutions leaked from processing areas into surrounding soils, and were also allegedly directly discharged to the ground outside the buildings by a sump pump.

Cleanup efforts at the site have included the removal of over 10,800 tons of contaminated soil, and the construction of three groundwater collection trenches. The trenches are designed to provide hydraulic containment of contaminated groundwater. Groundwater is currently collected and pumped to a large storage tank in a building on-site, and then discharged to the City of Appleton wastewater treatment facility.

Groundwater monitoring wells have been installed at the site to monitor post-excavation groundwater conditions. Chromium concentrations remain elevated in the groundwater. Chromium will be the limiting factor in achieving environmental compliance at the site.

The majority of chromium at the subject property is in the form of hexavalent chromium. Hexavalent chromium is relatively mobile, and does not readily adsorb to soil particles. The EPA has selected the 1992 preventive action limit of 5 ug/L as the closure level for chromium in groundwater at the site.

The present modeling study is being undertaken to provide an indication of length of time before cleanup, and the possible extent of plume migration, under the present scenario and under a scenario where the groundwater collection system is shut off.

DESCRIPTION OF STUDY AREA

Physical Description

The former electroplating facility is a two-acre site located in a mixed residential, commercial, and light industrial area in the City of Appleton, Wisconsin. (See Figure 1 – View of Site and Surrounding Area, Appendix 1.) Railroad tracks bound the subject property on the southeast, and separate the site from a residential/commercial neighborhood further to the southeast. The study area includes the subject property, as well as the area to the southeast, which is bounded by the railroad tracks, Outagamie Street to the east, and Second Street to the south.

Surface soils at the site consist primarily of silty clays, and are found to a depth of approximately 72 feet below the ground surface. The area contains thick sequences of clays laid down when Glacial Lake Oshkosh formed during the last period of glacial recessions.

Site topography slopes slightly to the southeast. Ravines to the Fox River are located southeast of the subject property. (See Figure 2 – Topography of Area, Appendix 1.) Some ravine areas have been filled in for development purposes.

Groundwater flow is to the southeast to the ravine system, located approximately 1/5 mile away, and to the Fox River beyond, located approximately 1/2 mile away.

Three collection trenches have been installed at the site. (See Figure 3 – Site Detail Map, Appendix 1.) One is on-site, one is between the railroad tracks and the properties further southeast, and one is south and east of the majority of the buildings on the properties immediately southeast of the subject property. These collection trenches have altered the groundwater flow direction in the area immediately adjacent to the trenches. Because of the low hydraulic conductivity of the clay soils in the area, the zones of depression around these trenches are limited.

Groundwater Monitoring System

A number of groundwater observation wells and piezometers exist at the site. Groundwater monitoring is conducted on a quarterly basis.

Location of Plume

The contaminant of interest at the site is hexavalent chromium. The original contaminated plume extended from the former buildings on the subject property in a southeasterly direction across the railroad tracks to the neighboring residential/commercial neighborhood. Contaminated soil was excavated from a large area extending across the railroad tracks to the southeast. The excavation was primarily aimed at diminishing the risk due to contact with surface soils, rather than groundwater contact, and its depth was accordingly limited.

Recent groundwater modeling has revealed that the remaining chromium contamination is centered near the former electroplating buildings at the site. (See Figure 4 – Diagram of Chromium Plume, Appendix 1.)

Potential Receptors

The buildings downgradient of the subject property are considered potential receptors of chromium contamination. They have basements and basement sumps, and have water and sanitary lateral connections. In areas of tight clays, such as the present case, any granular material, such as found in utility trenches or in basement wall backfill, acts as a preferential pathway for groundwater flow.

As part of the earlier remedial efforts, the basement sumps in these buildings were piped to one of the project's collection trenches, so that any contaminated groundwater that might enter the building sumps would be drawn away from the buildings. As long as the groundwater in the collection trenches is being pumped, the system of piping to the building sumps will reduce the potential environmental impact to the downgradient buildings. However, if the groundwater collection system is turned off in the future, the trenches holding the piping could act as preferential pathways for contaminant movement.

GROUNDWATER MODEL

Model Geometry

The Visual Modflow model was used to simulate flow and transport in the study area. The model area is divided into a grid of 30 rows and 30 columns. (See Figure 5 – Model Setup, Appendix 2.) Grid refinements were made in the area where the chromium plume presently is found.

According to the site investigation report, the soils in the area can be divided into an upper till and a lower till unit. The upper till unit consists of fill from 1 – 7 feet below ground surface, and is underlain by silty clay to a total depth of 12 feet below ground surface. Certain areas within the upper till unit were excavated during remedial activities, and backfilled and compacted with clay materials. The upper till unit was modeled as a 12-foot thick, homogeneous layer. (See Figure 6 – Typical Cross-Sectional View of Model Layers, Appendix 2.) Fill characteristics were neglected in constructing the model, since the majority of fill is present only in the vadose zone at the site. Areas that were excavated, backfilled, and compacted as part of remedial efforts were assumed to have the same characteristics as the silty clay identified during the site investigation.

The lower till unit is also a silty clay, is about 60 feet thick, and extends to bedrock. The unit was modeled as a 40-foot thick, homogeneous layer. The overall depth of the bottom of the layer from the ground surface was chosen to be 52 feet, so that the layer bottom is well below the bottom of the collection trenches at the site, the deepest of which is 26 feet below the ground surface.

Boundary Conditions, Recharge, and Drainage

Lateral inflows to and outflows from the model area are represented with Modflow's constant head boundary package. Due to the absence of surface water features within the model area, the model could not be constrained by observable surface water heads. Rather, historical groundwater data was used to establish constant head boundaries. There are a number of leaking underground storage tank projects in the area, which provide a body of historical groundwater elevation data from the area. For modeling purposes, constant head boundaries were established upgradient and downgradient of the area of interest, based on average historical groundwater elevation data.

Recharge was assumed to be negligible in the model area, due to the tightness of the clays.

Modflow's drain package was used to model the effects of the three collection trenches at the site. The trenches are used to intercept and move groundwater to the City of Appleton wastewater treatment facility, and are installed to depths ranging from 17 – 26 feet below the ground surface. In the drain package, groundwater is removed when it is present in the drain. The drain package assumes the drain has no effect if the elevation in the aquifer falls below the fixed head of the drain.

In order to model conservatively, the drains were set up in a way that allowed some "leakage" across the drain. This was accomplished by assigning cells to the drain package in a way that at certain locations the drain cells only shared corners, rather than complete sides. (See Figure 3 – Site Detail Map, Appendix 1.)

Physical and Hydraulic Parameters

The porosity and bulk density of the soils in the model domain were established by on-site testing. Slug tests were performed at various well locations to characterize the hydraulic conductivity of the soils at the site. The investigation determined the presence of upper and lower till units. Slug testing identified relatively consistent findings within each till unit.

The upper till unit contains the groundwater table within the model area. Its average horizontal hydraulic conductivity at the site is 7.6×10^{-6} cm/sec, and its average vertical hydraulic conductivity is 1.5×10^{-8} cm/sec. The lower till unit's average horizontal hydraulic conductivity was determined to be 3.9×10^{-7} cm/sec, approximately 20 times less than the conductivity in the upper unit. The average vertical hydraulic conductivity in the lower till unit was determined to be 3.3×10^{-8} cm/sec.

Groundwater Chemistry

The contaminant of interest at the site is hexavalent chromium. Recent groundwater monitoring for both total chromium and hexavalent chromium has revealed that most of the chromium in groundwater at the site is in the hexavalent form. (See Table 1 – Recent Groundwater Analytical Results, Appendix 2.) To be conservative for modeling purposes, all the chromium at the site was considered to be in the hexavalent form.

The heart of the remaining plume is located near the original electroplating buildings at the site, and the majority of chromium contamination is confined to the area between the discharge area and the collection trenches. (See Figure 4 – Diagram of Chromium Plume, Appendix 1.)

Model Calibration

Model calibration consists of changing values of model input parameters in an attempt to match field conditions, using inputs that are within the range of measured or estimated values. In the flow modeling portion of the present study, the calibration targets consisted of averaged groundwater elevations measured at area monitoring wells. Since there was not a single set of wells that had undergone monitoring both while the groundwater collection system has been operating and also under native conditions, two sets of monitoring wells were used for calibration purposes:

- For simulations involving active operation of the groundwater collection system, monitoring wells were used from the subject property and nearby properties, which have been monitoring groundwater conditions during periods when the system has been operating. (See Figure 7 – Location of Observation Wells Used to Calibrate Continued Pumping Option, Appendix 2.) Data from wells W2, W8, W15, MW-101, and MW-103 – MW-108 over the time period 1997 – 2006 was used. Elevations over this time period were averaged, and average elevations were used as calibration targets during modeling runs simulating continued system operation.
- For simulations involving shutdown of the groundwater collection system, model calibration required elevation data from monitoring wells unaffected by system operation. (See Figure 8 – Location of Observation Wells Used to Calibrate System Shutdown Option, Appendix 2.) Data from upgradient wells W2 and MW-108 was used, as well as data from two leaking underground storage tank sites downgradient of the subject property. Since monitoring periods at the three sites overlapped, data was only used

from the 1998 – 1999 time period, during which all three sites were being monitored on a quarterly basis. Average values were used in calibrating the model.

Input parameters were selected based either on site-specific observations or reasonable data from the literature. (See Table 2 – Model Parameters, Appendix 2.) For proper calibration, the input parameters needed to reasonably predict actual field conditions under scenarios of both continued system operation and system shutdown. Therefore, model calibration involved selecting parameters, running the model under both scenarios, and obtaining the best overall fit between predicted and actual heads under both scenarios.

The conductance factor, used in Modflow's drain package, is a lumped coefficient describing the head loss between the drain and the groundwater system, and is caused by a number of factors, including siltation and other forms of blockage. A conductance parameter was selected which produced the highest correlation between predicted and actual heads.

MODEL RESULTS AND SENSITIVITY ANALYSIS

Model Results:

The model was run using observed or reasonably calculated inputs. Due to the relative impermeability of the clay soils at the site, exceedances of the 5 ug/l closure standard for chromium will continue to occur for many hundreds of years. (See Plot 1 – Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Conditions Presently Observed Continue to Exist, Appendix 3.) The chromium plume will likely attenuate prior to reaching residential neighborhoods east of Outagamie Street, or south of Second Street. It is estimated that the plume will extend into the area in the triangle southeast of the subject property, bordered by the railroad tracks and Outagamie and Second Streets. That neighborhood will remain at risk for hundreds of years.

The groundwater collection system will accelerate the reduction in contaminant mass at the site, but will not produce closeable chromium levels within the 500-year timeframe.

Sensitivity Analysis:

A sensitivity analysis was performed to identify parameters, which significantly influence model results. Various parameters were altered in the model to determine the sensitivity of plume migration to the changes. Parameters found to have a significant influence on plume migration were then altered in the direction of producing accelerated contaminant movement, to identify potential risk areas downgradient of the present known plume area.

Two input parameters were identified, which significantly influenced the estimates of chromium movement at the site – the hydraulic conductivity of the soils and the partition coefficient of chromium. The former is an indicator of how easily groundwater moves through the soil matrix, while the latter is an indicator of the ability of a compound to adsorb to soil. Increasing the hydraulic conductivity of a soil matrix and/or decreasing the partition coefficient of a compound will promote movement of the compound through the soil.

The hydraulic conductivities of the soils at the site were well-characterized by field data obtained at multiple locations. The majority of hydraulic conductivity values at the site were found to be similar, within the same order of magnitude, within each till unit. For modeling purposes, each till unit was therefore assigned a single hydraulic conductivity value, based on the averaged field data for that unit.

During sensitivity analysis, the assigned hydraulic conductivity values were multiplied by factors of two and ten, to estimate flow behavior under conditions twice as conductive and ten times as conductive as typically observed at the subject property.

The model predicts that a two-fold increase in hydraulic conductivity results in a plume footprint similar to that estimated under the observed hydraulic conductivity conditions – extending in 500 years no further than to Outagamie Street and Second Street. (See Plot 2 – Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Two-Fold Increase in Hydraulic Conductivity, Appendix 4.)

However, a ten-fold increase in hydraulic conductivity results in plume migration extending southeast of the intersection of Outagamie and Second Streets. (See Plot 3 – Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-fold Increase in Hydraulic Conductivity, Appendix 4.) The continued operation of the groundwater collection system will accelerate the reduction in contaminant mass at the site, and will also significantly reduce the off-site footprint of the plume.

The partition coefficient (K_d), as used in Modflow, is an indicator of adsorption of contaminants to soil. A low partition coefficient means the compound does not readily adsorb, and is relatively mobile. Adsorption of chromium to soil is a function of pH. As pH increases, chromium adsorbs less readily, becoming more mobile.

The pH of groundwater at the subject property has been observed to range from 7.9 to 8.9. Laboratory testing of hexavalent chromium adsorption in various soil matrices under pH conditions in this range indicates that K_d values can range between 0 and 2 ml/g. (A K_d of 0 ml/g means that a compound does not adsorb to soil.) A value of 0.5 ml/g was used in the Modflow simulations representing actual conditions.

During sensitivity analysis, the K_d parameter for chromium was reduced to 0.05 ml/g, which essentially assumes no adsorption. Under this circumstance, assuming shutdown of the groundwater collection system, the model produces a plume after 500 years extending across Outagamie Street. (See Plot 4 – Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-fold Decrease in Partition Coefficient, Appendix 4.) The increase in assumed mobility of chromium, as modeled in this simulation, still results in a relatively restricted plume, due to the low hydraulic conductivity and resultant groundwater movement at the site.

A simulation was run using the extreme cases of both of the above parameters – a ten-fold increase in hydraulic conductivity and a ten-fold decrease in the partition coefficient for chromium. The model produces a plume after 500 years extending to the ravine southeast of Outagamie Street and Prospect Street. (See Plot 5 – Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-fold Increase in Hydraulic Conductivity and Ten-fold Decrease in Partition Coefficient, Appendix 4.) Under this extreme scenario, the groundwater collection system would produce a smaller plume and help to reduce overall contaminant mass at the site, but would not successfully prevent contaminant mass from moving off-site. These extreme conditions are not likely, but the modeling effort gives an indication of the sensitivity of the model to these two criteria.

CONCLUSIONS

The remedial work performed to date at the subject property, in particular the excavation of contaminated soils, has significantly reduced the mass of chromium contamination at the site. The potential to encounter chromium-contaminated soil through contact with surface soils has been minimized. Groundwater concentrations, however, remain in exceedance of the EPA-established closure standard of 5 ug/L for chromium. Recent groundwater testing has revealed the continued presence of high levels of chromium contamination in the original discharge zone.

The clay soils at the site are relatively impermeable. The tightness of the clay soils found in the primary discharge area has positive and negative impacts on remediation. The soils, in combination with the site's clay cap, are in essence "entombing" the remaining contamination, limiting the extent of migration in horizontal and vertical directions. However, the impermeability of the soils also impedes active extraction efforts. The present groundwater collection system, in particular, while capable of minimizing downgradient migration of chromium contamination, will nevertheless operate poorly as an extraction system.

Modeling efforts indicate the following:

- Exceedances of the 5 ug/l closure standard for chromium will continue to occur for many hundreds of years at the site, whether or not the present groundwater collection system continues to operate.
- The plume of chromium-contaminated groundwater will likely migrate to the neighborhood southeast of the railroad tracks from the subject property, whether or not the present groundwater collection system continues to operate. The neighborhood southeast of the subject property will remain at risk for hundreds of years.
- The plume of chromium-contaminated groundwater will likely attenuate before reaching Outagamie Street or Second Street, whether or not the present groundwater collection system continues to operate. Due to the relative impermeability of the clay soils at the site, the footprint of the plume is predicted to remain within the subject property and triangular area to the southeast bordered by the railroad tracks, Outagamie Street, and Second Street. The continued running of the groundwater collection system will not significantly reduce the extent of plume migration.
- The achievement of the closure standard for chromium will occur faster if the groundwater collection system continues to operate, than if it is discontinued. The collection trenches are slowly removing contaminant mass from the groundwater. In either case, achievement of closure standards will not occur for many hundreds of years.

The cost of continued operation of the present system until the present closure criteria is met will be large. Significant chromium concentrations remain at the site. New information from the recent monitoring well installations and subsequent modeling effort should prompt a re-evaluation of the present remediation plan for the site.

In order to more effectively reduce contaminant mass at the site, OMNNI recommends that other remedial options be evaluated. The original remedial choices – a limited excavation and groundwater collection system – were made at a time when experience with soil and groundwater treatment options was limited. The performance of reactive permeable barriers, for instance, was largely unstudied. That technology has now developed a successful track record of altering chromium-contaminated groundwater flowing through the barrier, changing chromium from its mobile hexavalent mode to the largely benign trivalent mode. Other remedial options, such as phytoremediation, are also proving effective in removing or rendering benign metal contamination.

The costs and benefits of further excavation at the site should also be re-evaluated. The area of significant mass of chromium contamination is relatively limited at present. Physical removal of contaminated materials may achieve significant cost savings and reduction in the cleanup timeframe, as opposed to centuries of active system operation.

The purchase of the properties within the triangle to the southeast of the subject property should be evaluated. Modeling indicates that the users of those properties will remain at some risk to exposure from the remaining contaminant plume, under either scenario of continued system operation or system shutdown. The purchase of those properties would significantly minimize the risk of the remaining contamination reaching any potential receptors under any remedial scenario.

The EPA-mandated closure level for chromium at the site, 5 ug/L, should be reviewed. A risk-based approach should be taken at the site, to determine whether alternative closure criteria are available, which are still protective of potential receptors in the area, yet do not require the significant level of effort and cost presently necessitated by the site's closure criteria. Any risk-based approach must be protective of any users of the triangular property to the southeast of the subject property, and would therefore probably require the purchase and vacating of that area.

Prepared by,

Don Brittnacher

Don Brittnacher

OMNNI Associates

Appendix 1

Figures

Figure 1
Aerial View of Site and Surrounding Area

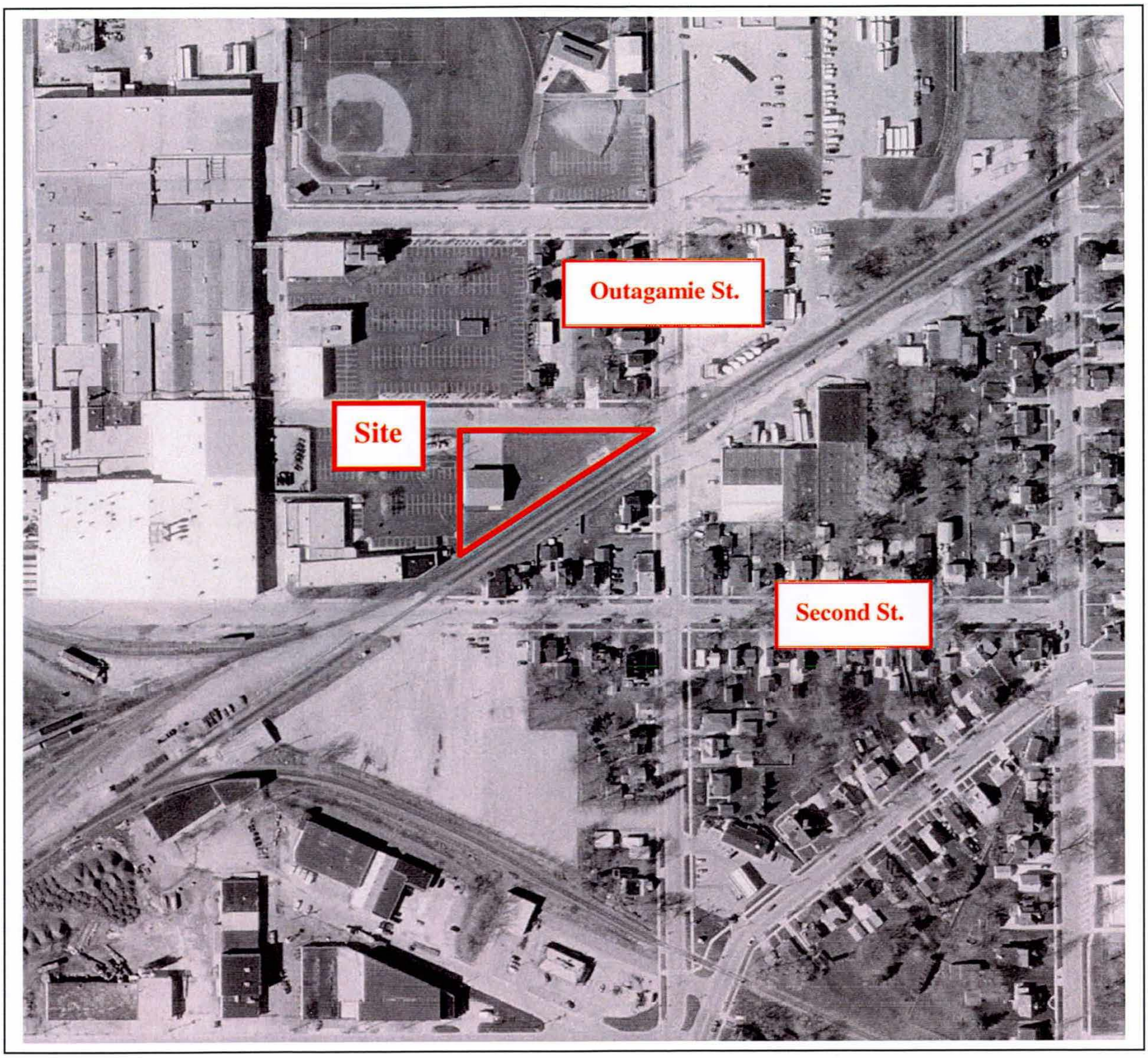


Figure 2
Topography of Area,
Showing Historical Ravine System Downgradient of Site

Figure 3
Site Detail Map

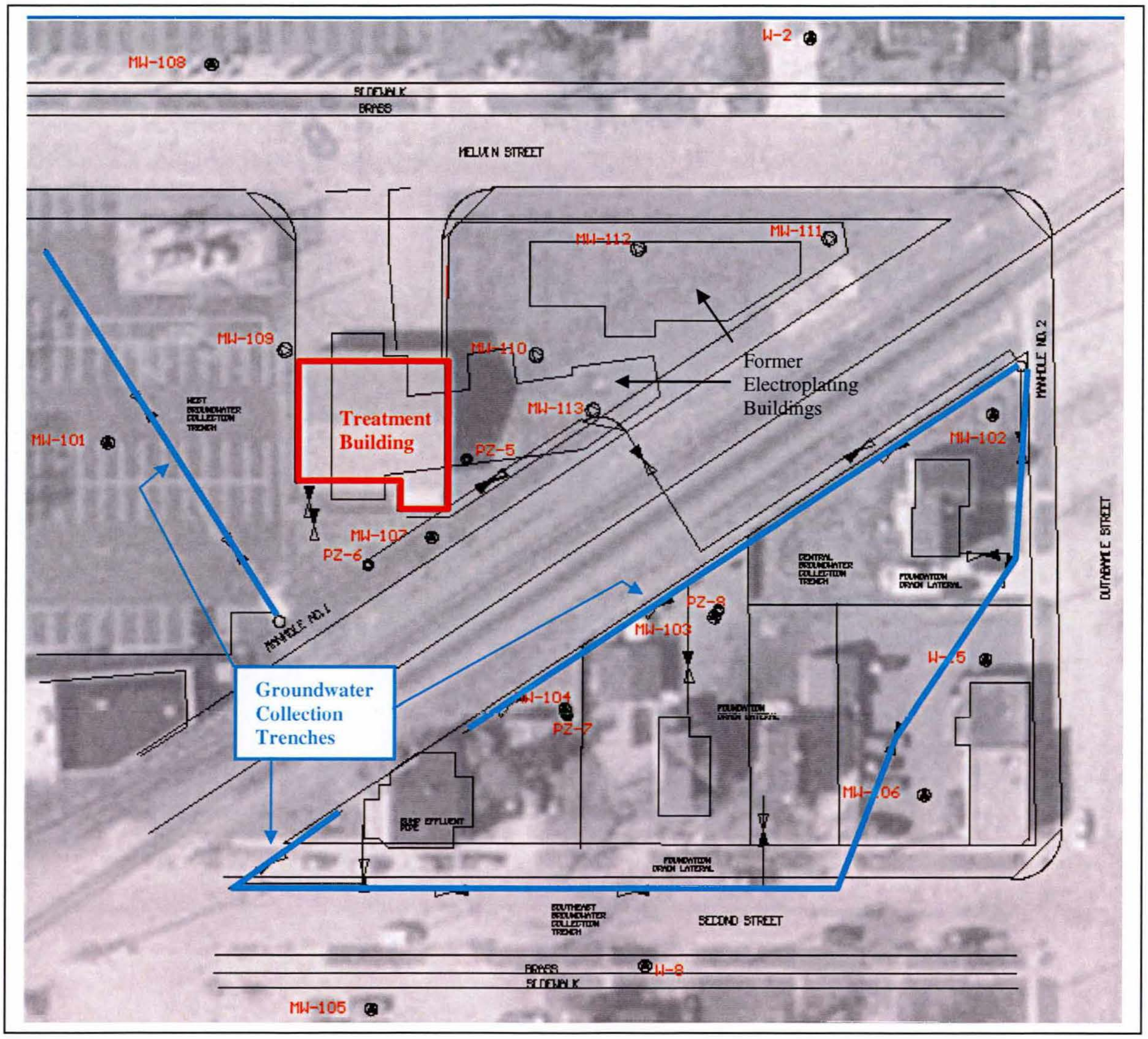
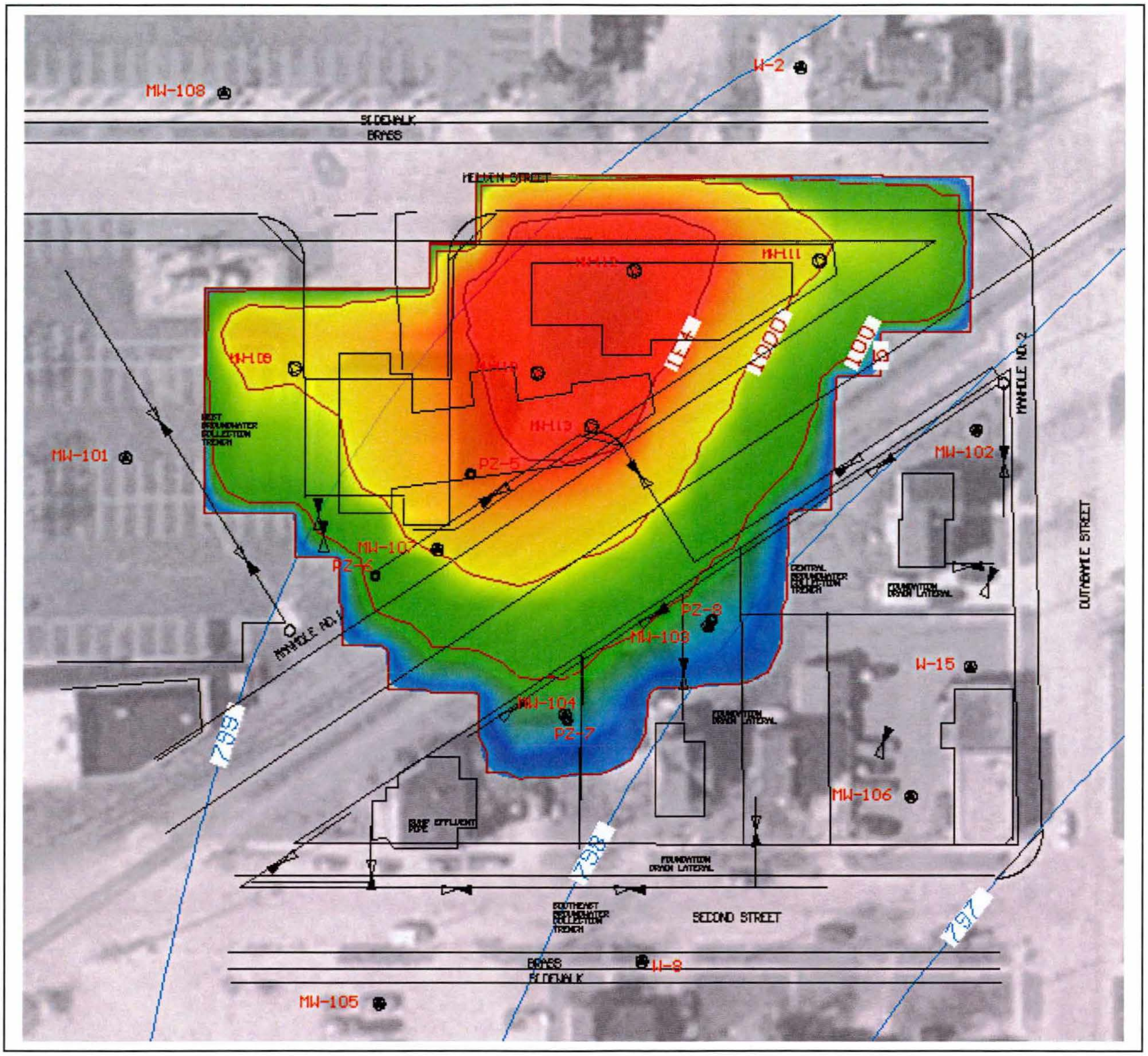


Figure 4
Diagram of Chromium Plume



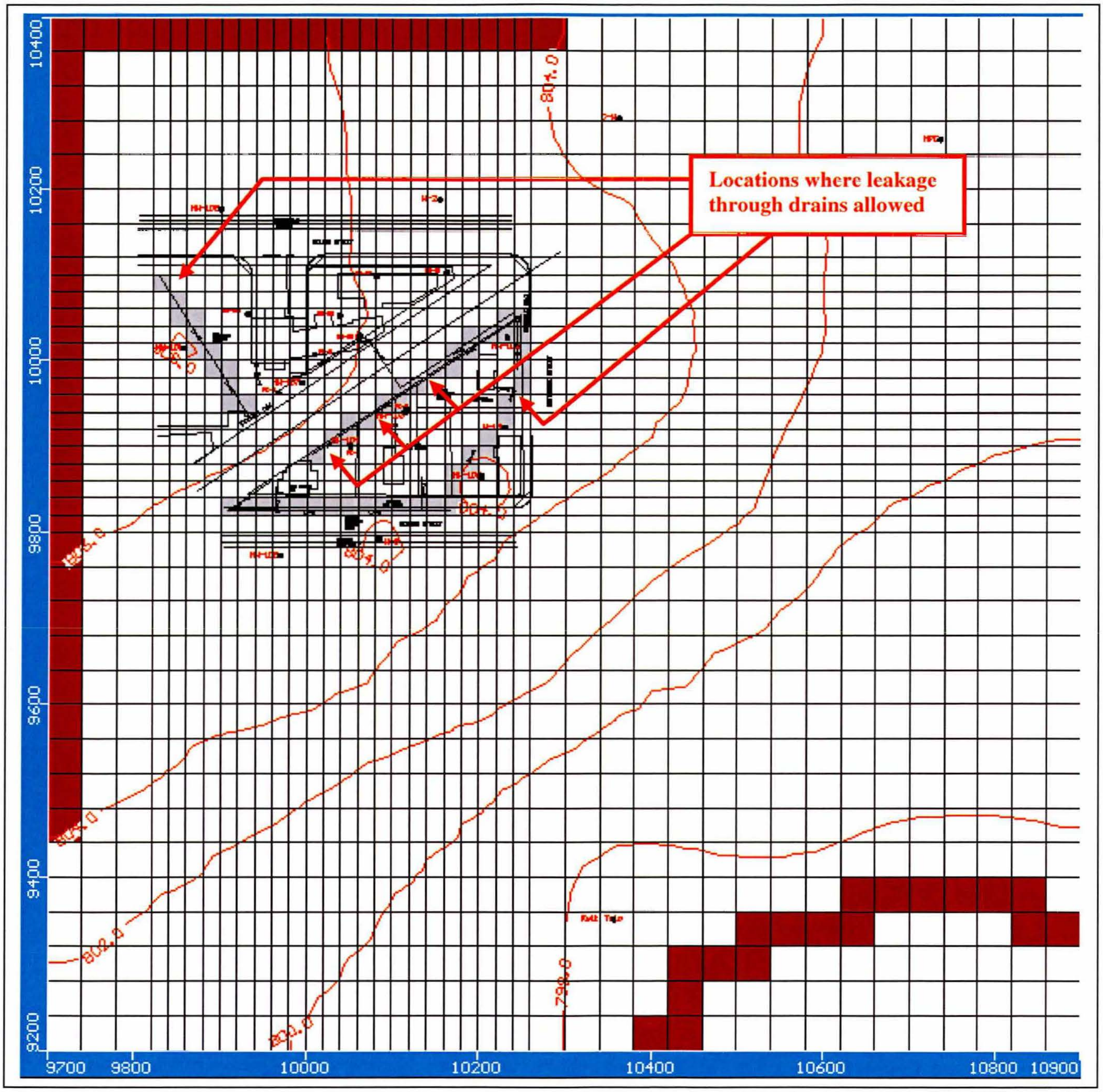
Note: Units are ug/L. The closure standard for chromium at the site is the 1992 preventive action limit of 5 ug/L.

Most of the chromium in groundwater at the site is in the hexavalent form. To be conservative for modeling purposes, all the chromium at the site was considered to be in the hexavalent form. The initial mass of hexavalent chromium inputted into the model was calculated using the average total chromium concentrations observed at each of the 16 observation wells during the March, June, and September 2006 monitoring events. The averaged values at the monitoring points were then run through an interpolation routine to estimate contaminant levels between the points of observation, and to approximate the degree and extent of the initial plume.

Appendix 2

Model Setup

Figure 5
Model Setup



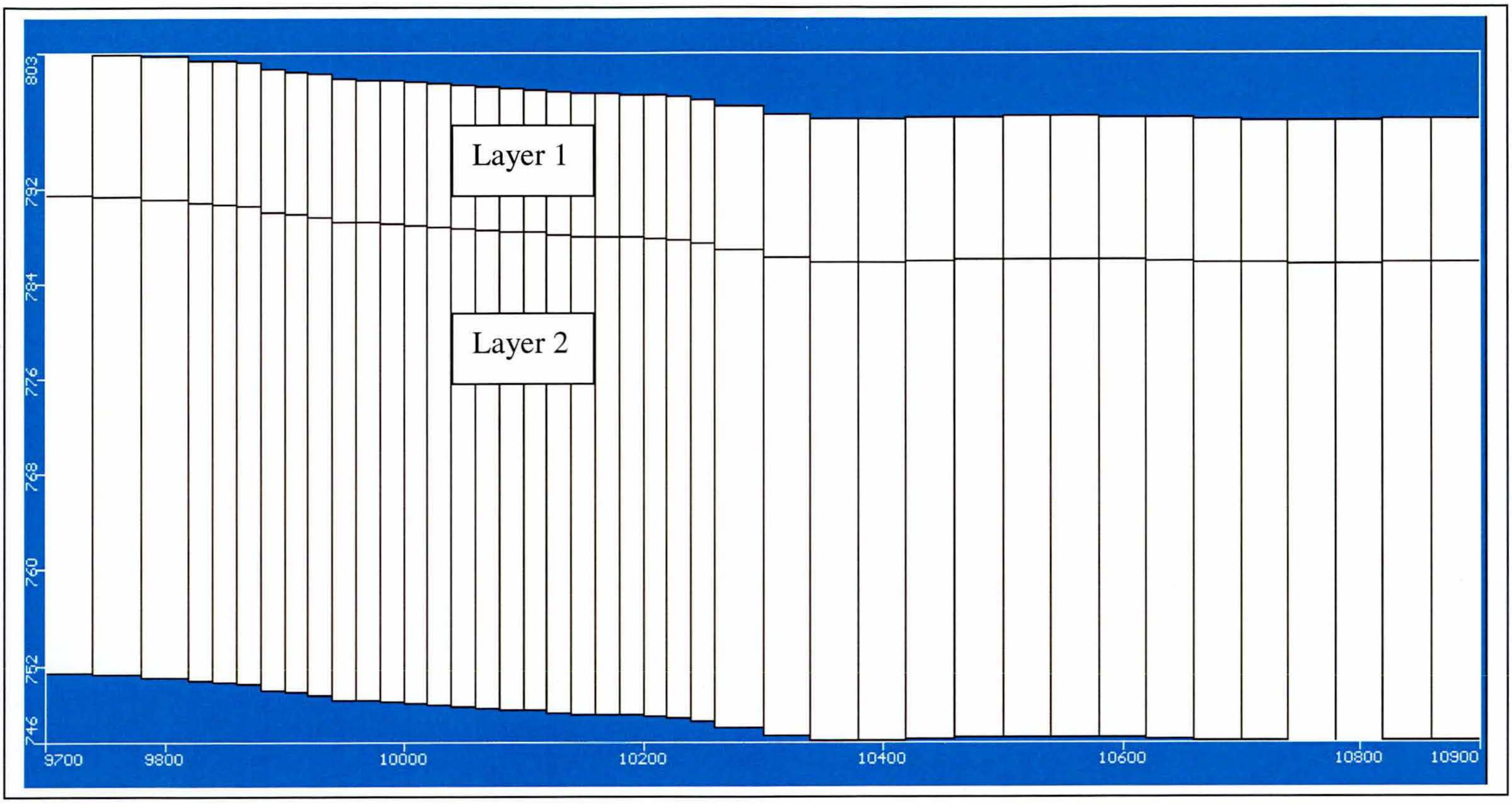
Key:

= constant head boundaries

= drains (groundwater collection trenches)

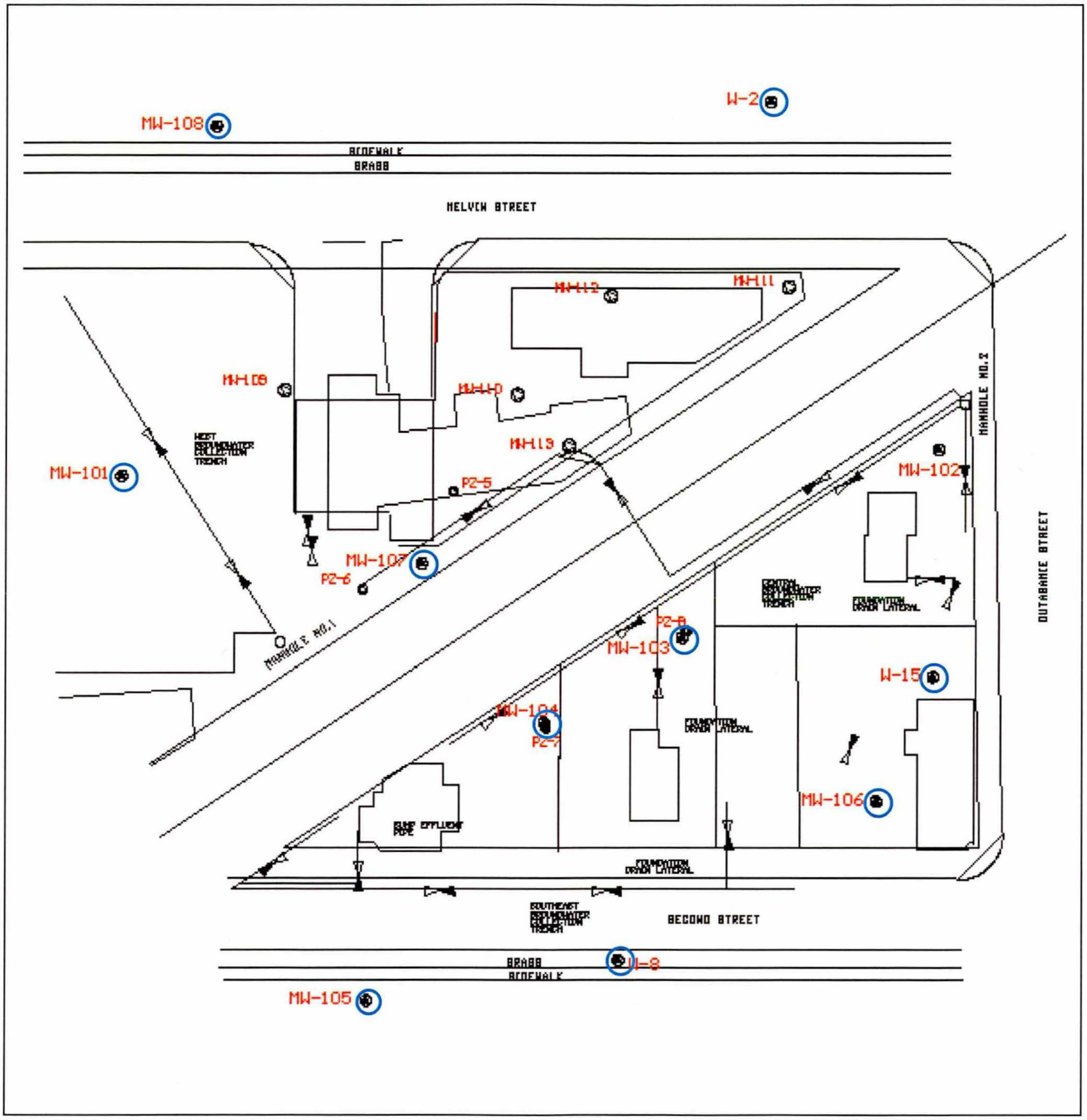
- 802.0 - = surface elevation

Figure 6
Typical Cross-Sectional View of Model Layers



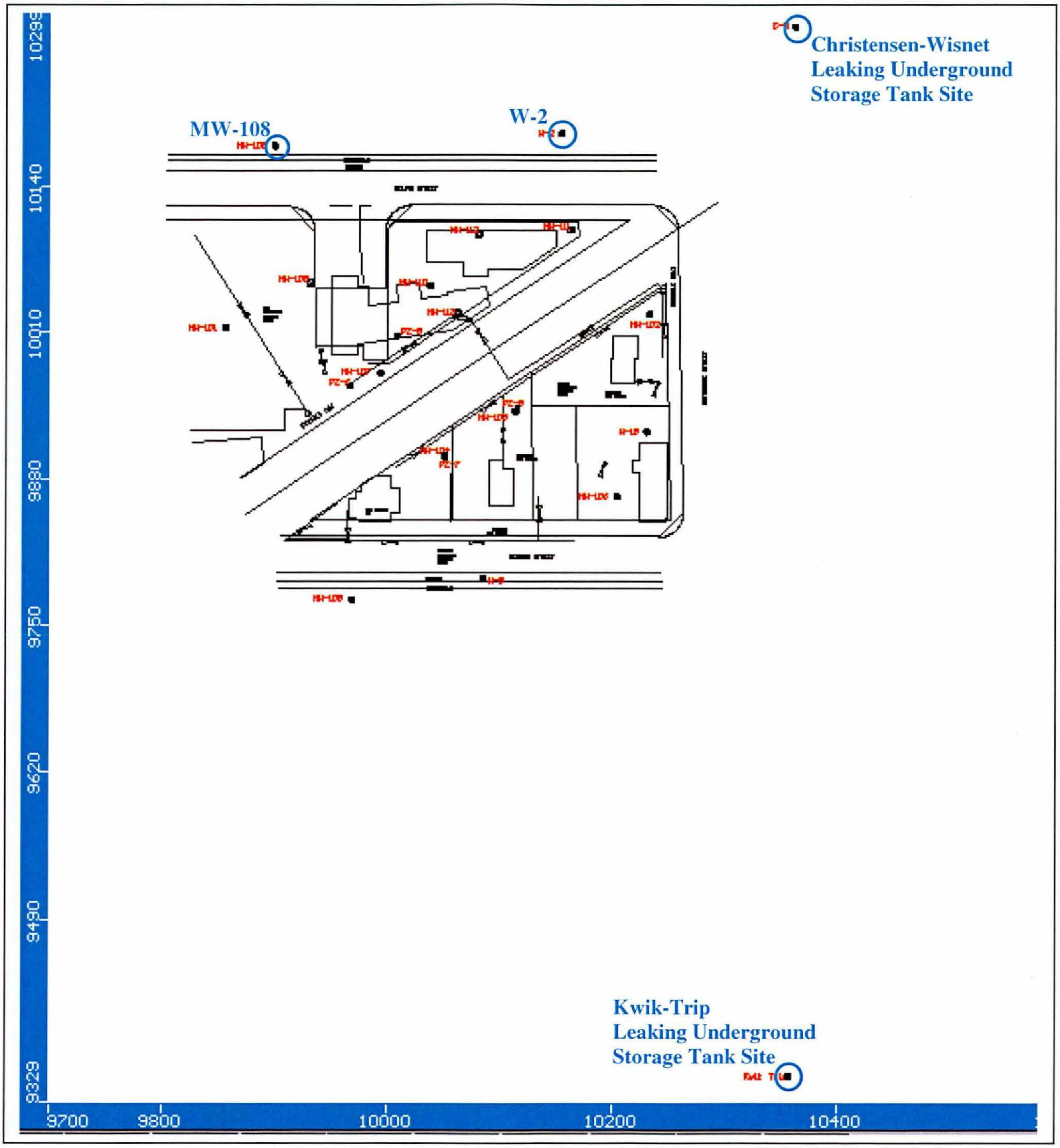
Note: Vertical exaggeration = 10X.

Figure 7
Location of Observation Wells
Used to Calibrate Continued Groundwater Collection Option



◯ = observation well used to calibrate model under scenario of continued groundwater collection

Figure 8
Location of Observation Wells
Used to Calibrate System Shutdown Option



◯ = observation well used to calibrate model under scenario of system shutdown

Table 1
Recent Groundwater Analytical Results

Well Name	Sample Date	Chromium (ug/l)	Hexavalent Chromium (ug/l)
W-2	3/23/06	0.52	<5.0
W-8	3/23/06	<0.4	<5.0
W-15	3/23/06	1.60	<5.0
MW-101	3/23/06	0.55	<5.0
MW-102	3/23/06	<0.40	<5.0
MW-103	3/23/06	***16.0***	**270.0**
	6/28/06	***40.0***	**29.0**
	9/20/06	***45.0***	***35.0***
MW-104	3/23/06	**66.0**	**200.0**
	6/28/06	**76.0**	**58.0**
	9/20/06	2.8	<6.8
MW-105	3/23/06	0.42	<5.0
MW-106	3/23/06	0.45	<5.0
MW-107	3/23/06	**3,200**	**3,600**
	6/28/06	**3,600**	**3,000**
	9/20/06	**4,100**	**4,200**
MW-108	3/27/06	<0.40	<5.0
MW-109	6/21/06	**1,300**	**1,400**
	9/20/06	**450**	NA
MW-110	6/21/06	**24,000**	**26,000**
	9/20/06	**15,000**	NA
MW-111	6/21/06	**1,400**	**1,400**
	9/20/06	***22***	NA
MW-112	6/21/06	**130,000**	**140,000**
	9/20/06	**69,000**	NA
MW-113	6/21/06	**25,000**	**26,000**
	9/20/06	**31,000**	NA
Maximum Contaminant Level (MCL)		100	100*
1992 Enforcement Standard Chapter NR 140.10		50	50
1992 Preventive Action Limit Chapter NR 140.10		5	5*

EXPLANATION:

* = standard is for total chromium.
NA = not analyzed
ug/L = microgram/liter
270 = exceedance of the 1992 NR 140 groundwater quality enforcement standard (ES)
16 = exceedance of the 1992 NR 140 groundwater preventive action limit (PAL)

Note: The EPA Record of Decision establishes the 1992 PAL as the cleanup goal for the site.

Table 2
Model Parameters

west drain	781	ft above MSL	
central drain	779	ft above MSL	
southeast drain	788	ft above MSL	
drain conductance	0.004	sq ft/day	K = 7.6E-6 (layer 1; observed K)
	0.008	sq ft/day	K = 1.52E-5 (layer 1; 2x faster)
	0.025	sq ft/day	K = 7.6E-5 (layer 1; 10x faster)
constant head upper	802	ft	
constant head lower	792	ft	
recharge	0	in/yr	various studies finding negligible recharge in areas of glacial till, especially urban areas
hydraulic conductivity horizontal (layer 1)	7.60E-06	cm/s	site study
hydraulic conductivity horizontal (layer 2)	3.90E-07	cm/s	site study
hydraulic conductivity vertical (layer 1)	1.50E-08	cm/s	site study
hydraulic conductivity vertical (layer 2)	3.30E-08	cm/s	site study
uniform thickness of upper till layer	12	ft	site study
uniform thickness of lower till layer	40	ft	chosen
dispersivity (longitudinal, Dx)	10.5	ft	middle value of 6 ft from Gelhar plot, 9 ft from EPA calculator, and 15 ft from EnviroBrowser Online.
dispersivity (transverse horizontal, Dy)	1.05	ft	0.1 * Dx; Gelhar article, 1992.
dispersivity (transverse vertical, Dz)	0.1	ft	0.01 * Dx; Gelhar article, 1992.
partition coefficient, Kd	5.00E-07	L/mg	Table E2, *Partition Coefficients for Chromium (VI)*, pH > 8.0, Ocala soil: 0 - 1 ml/g. Used 0.5 ml/g = 5.00E-07 L/mg. Chromium appears mobile at site.
bulk density	50.97	kg/cu ft	calculated from site tests. Equivalent to 1.80 g/cm3. Typical silty clay value from literature is 1.5 g/cm3 = 42.4 kg/ft3.
porosity, total	0.3167		calculated from site tests.
porosity, effective	0.2		

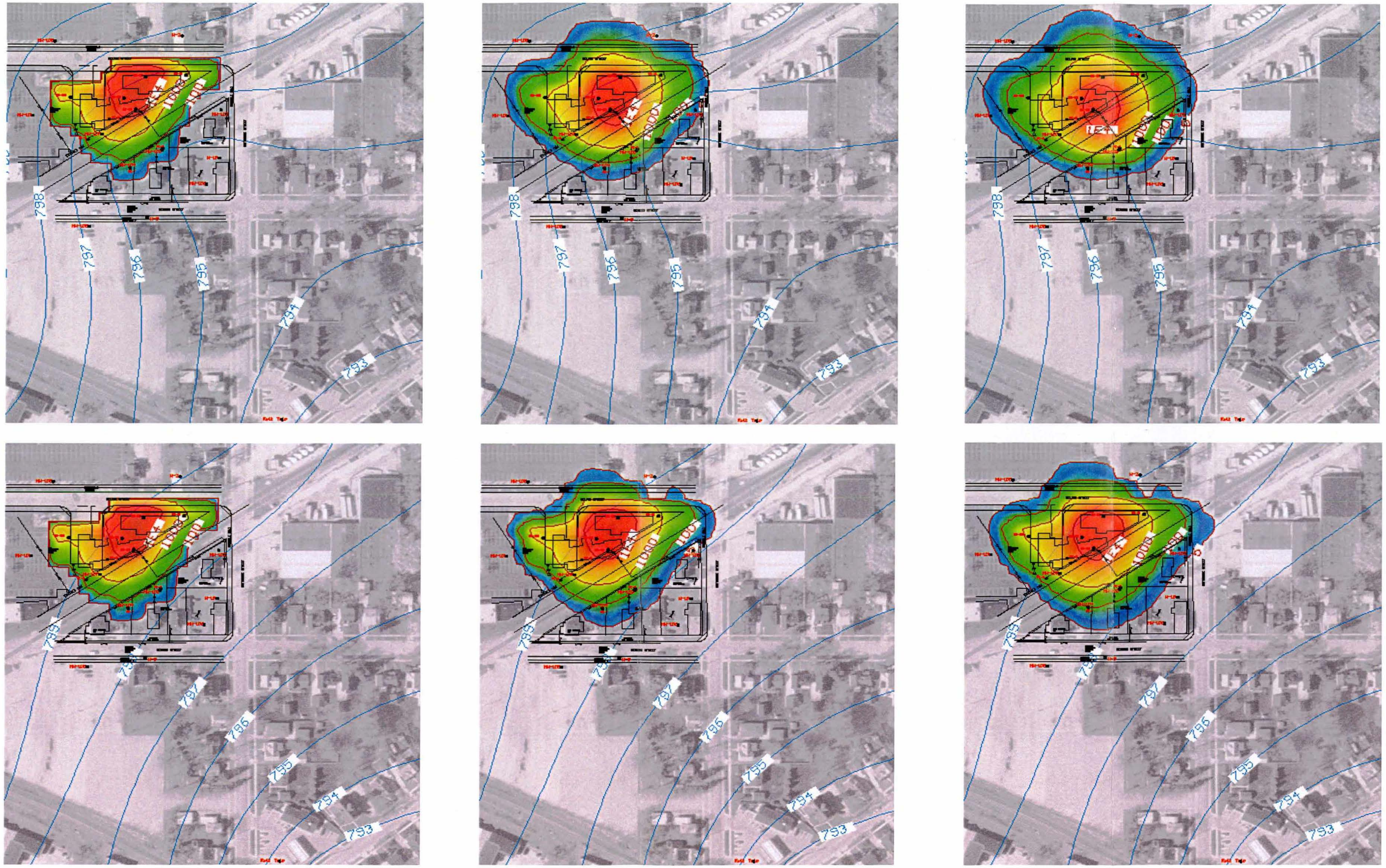
Appendix 3

Model Results

Plot 1 - Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Conditions Presently Observed Continue to Exist

Continued Operation of Groundwater Collection System

No System Operating, ie, Natural Groundwater Flow Conditions



Initial Chromium Plume | Chromium Plume After 250 Years | Chromium Plume After 500 Years

Key:

Hydraulic Conductivity:
Kx, Layer 1 = 7.6E-6 cm/sec
Ky, Layer 1 = 7.6E-6 cm/sec
Kz, Layer 1 = 1.5E-8 cm/sec
Kx, Layer 2 = 3.9E-7 cm/sec
Ky, Layer 2 = 3.9E-7 cm/sec
Kz, Layer 2 = 3.3E-8 cm/sec

Partition Coefficient:
Kd = 0.5 ml/g

Note: Units are ug/L. Maximum extent of plume (shaded blue) is 5 ug/L, the site's closure standard for chromium.

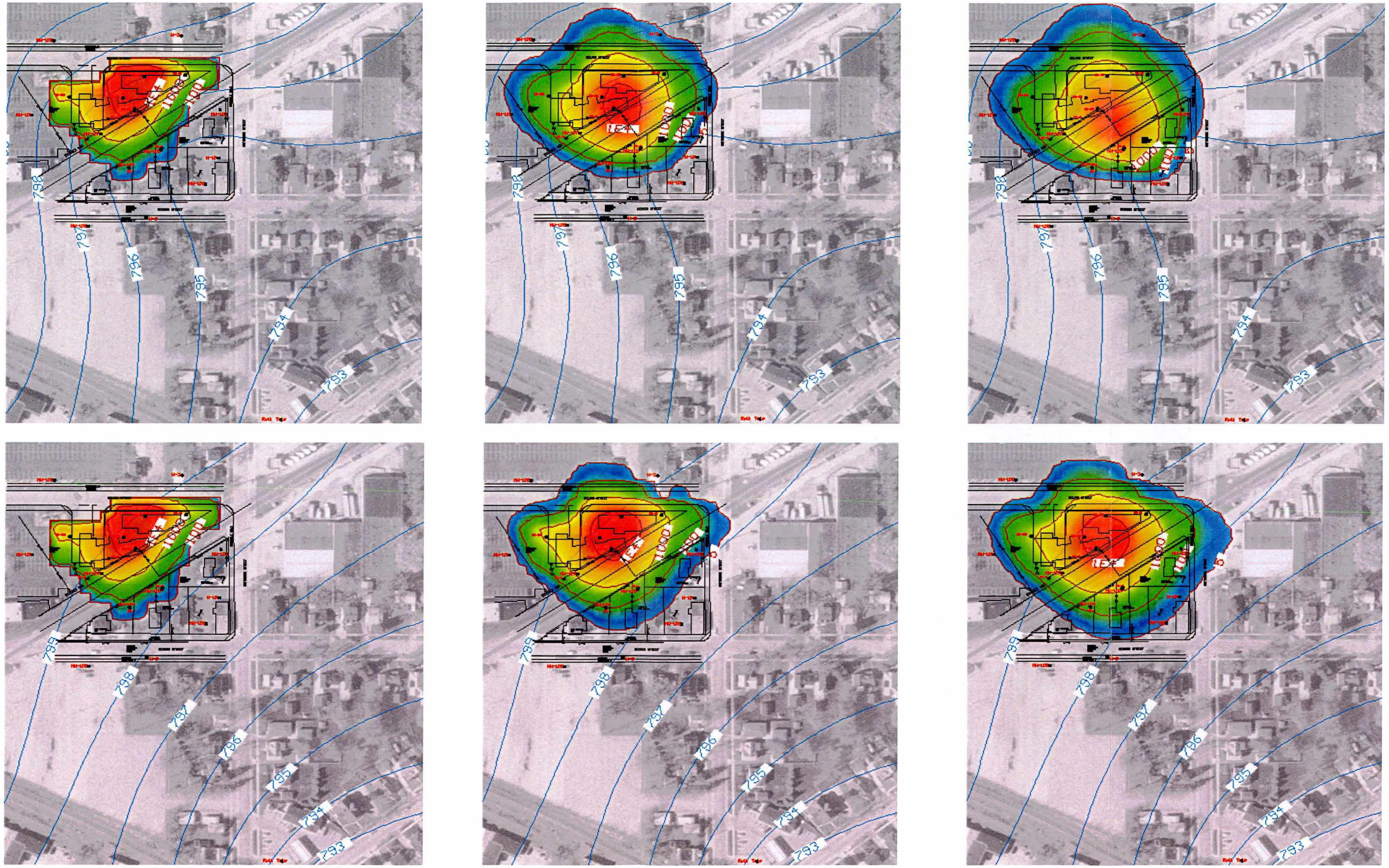
Appendix 4

Sensitivity Analysis

Plot 2 - Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Two-Fold Increase in Hydraulic Conductivity

Continued Operation of Groundwater Collection System

No System Operating, ie, Natural Groundwater Flow Conditions



Initial Chromium Plume

Chromium Plume After 250 Years

Chromium Plume After 500 Years

Key:

Hydraulic Conductivity:

Kx, Layer 1 = 1.52E-5 cm/sec

Ky, Layer 1 = 1.52E-5 cm/sec

Kz, Layer 1 = 3E-8 cm/sec

Kx, Layer 2 = 7.8E-7 cm/sec

Ky, Layer 2 = 7.8E-7 cm/sec

Kz, Layer 2 = 6.6E-8 cm/sec

Partition Coefficient:

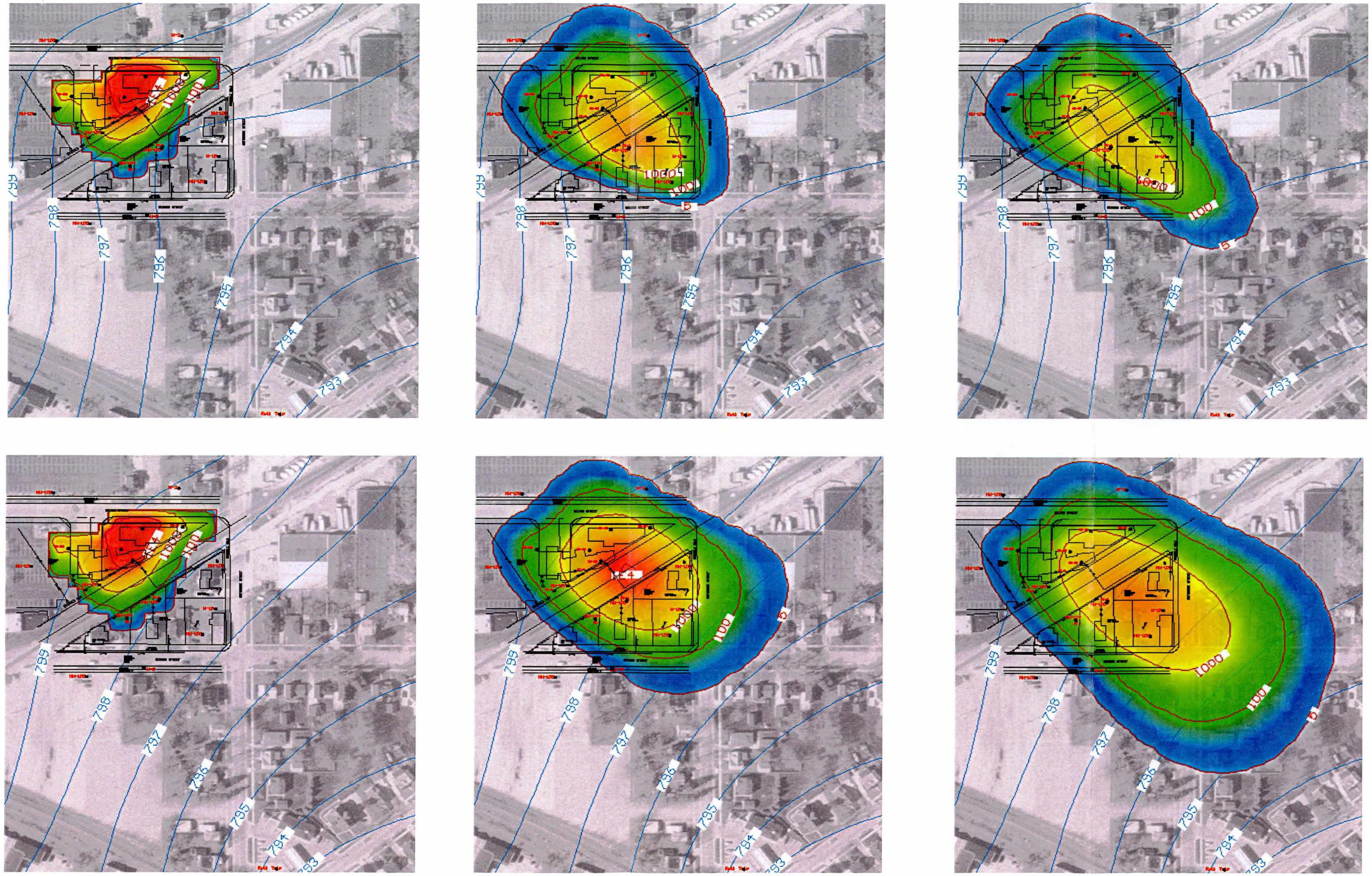
Kd = 0.5 ml/g

Note: Units are ug/L. Maximum extent of plume (shaded blue) is 5 ug/L, the site's closure standard for chromium.

Plot 3 - Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-Fold Increase in Hydraulic Conductivity

Continued Operation of Groundwater Collection System

No System Operating, ie, Natural Groundwater Flow Conditions



Initial Chromium Plume | Chromium Plume After 250 Years | Chromium Plume After 500 Years

Key:

Hydraulic Conductivity:

Kx, Layer 1 = 7.6E-5 cm/sec

Ky, Layer 1 = 7.6E-5 cm/sec

Kz, Layer 1 = 1.5E-7 cm/sec

Kx, Layer 2 = 3.9E-6 cm/sec

Ky, Layer 2 = 3.9E-6 cm/sec

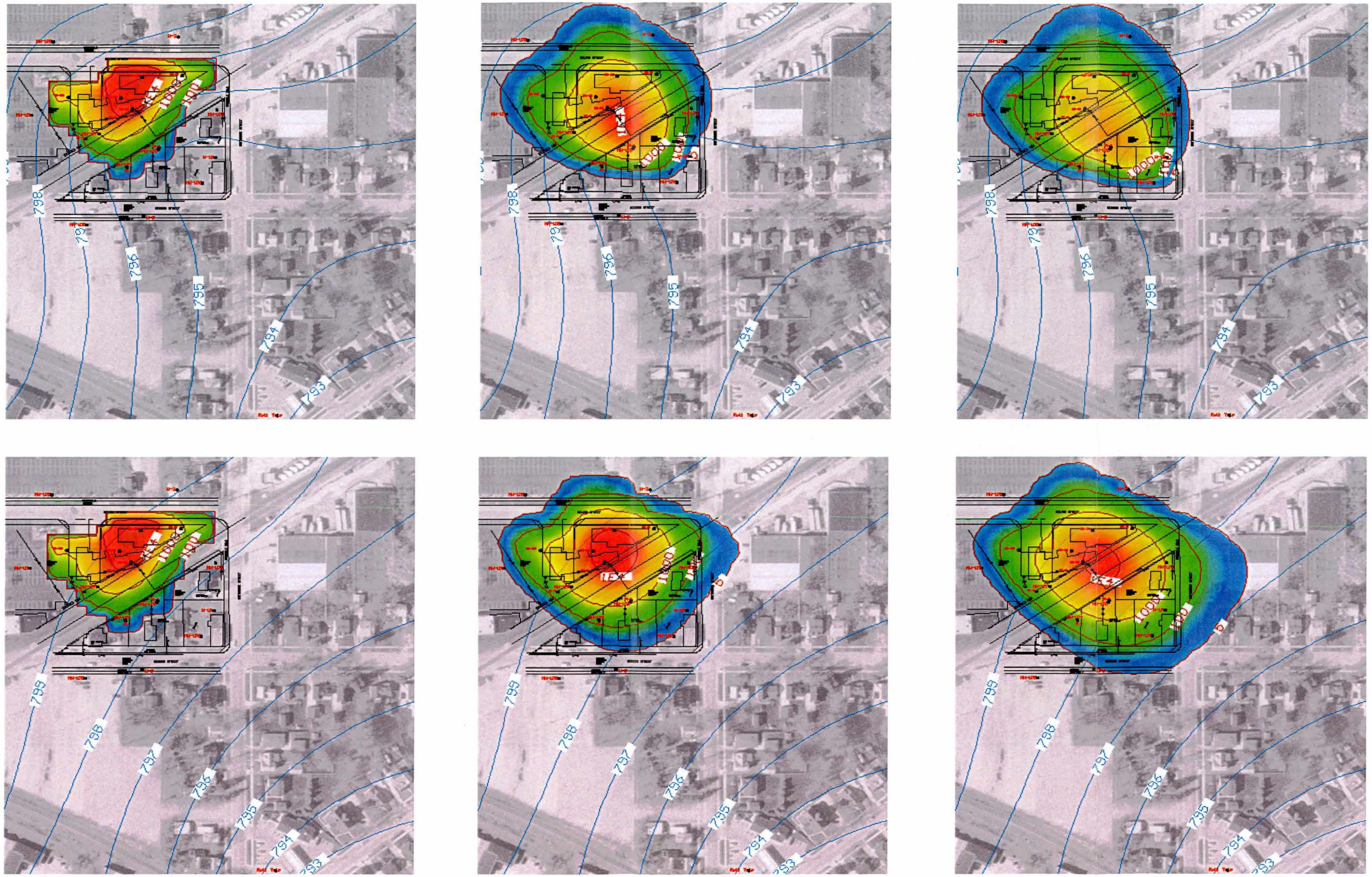
Kz, Layer 2 = 3.3E-7 cm/sec

Partition Coefficient:

Kd = 0.5 ml/g

Note: Units are ug/L. Maximum extent of plume (shaded blue) is 5 ug/L, the site's closure standard for chromium.

Plot 4 - Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-fold Decrease in Partition Coefficient



Continued Operation of Groundwater Collection System

No System Operating, ie, Natural Groundwater Flow Conditions

Initial Chromium Plume

Chromium Plume After 250 Years

Chromium Plume After 500 Years

Key:

Hydraulic Conductivity:
Kx, Layer 1 = 7.6E-6 cm/sec
Ky, Layer 1 = 7.6E-6 cm/sec
Kz, Layer 1 = 1.5E-8 cm/sec
Kx, Layer 2 = 3.9E-7 cm/sec
Ky, Layer 2 = 3.9E-7 cm/sec
Kz, Layer 2 = 3.3E-8 cm/sec

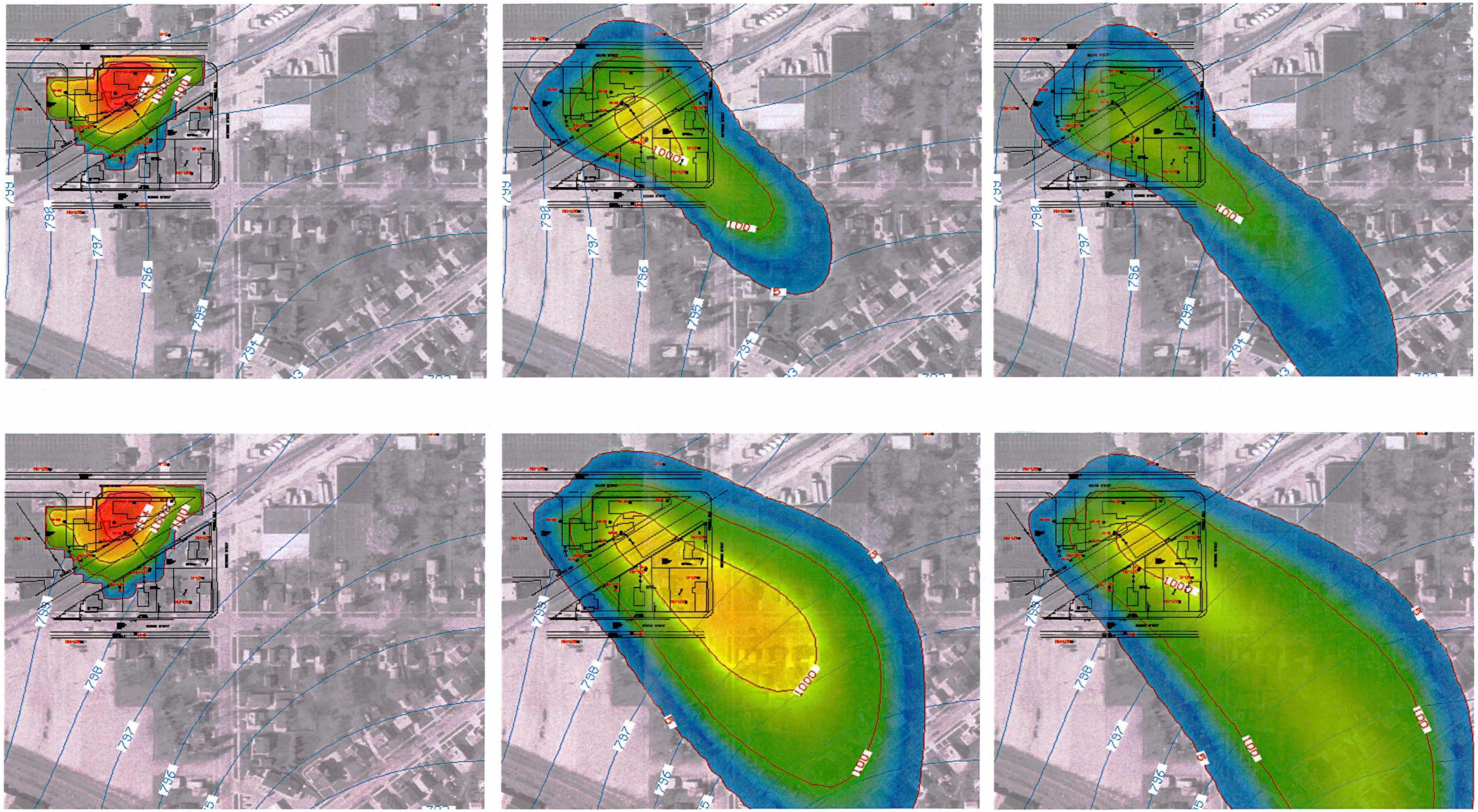
Partition Coefficient:
Kd = 0.05 ml/g

Note: Units are ug/L. Maximum extent of plume (shaded blue) is 5 ug/L, the site's closure standard for chromium.

Plot 5 - Estimated Degree and Extent of Chromium Plume in Groundwater, Assuming Ten-fold Increase in Hydraulic Conductivity and Ten-fold Decrease in Partition Coefficient

Continued Operation of Groundwater Collection System

No System Operating, ie, Natural Groundwater Flow Conditions



Initial Chromium Plume | Chromium Plume After 250 Years | Chromium Plume After 500 Years

Key:
Hydraulic Conductivity:
Kx, Layer 1 = 7.6E-5 cm/sec
Ky, Layer 1 = 7.6E-5 cm/sec
Kz, Layer 1 = 1.5E-7 cm/sec
Kx, Layer 2 = 3.9E-6 cm/sec
Ky, Layer 2 = 3.9E-6 cm/sec
Kz, Layer 2 = 3.3E-7 cm/sec

Partition Coefficient:
Kd = 0.05 ml/g

Note: Units are ug/L. Maximum extent of plume (shaded blue) is 5 ug/L, the site's closure standard for chromium.

ENGINEERING • ARCHITECTURE • ENVIRONMENTAL

OMNNI ASSOCIATES

One Systems Drive
Appleton, WI 54914
1-800-571-6677
www.omnni.com