

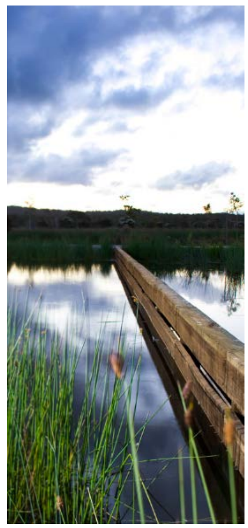

Permeable Reactive Gate Evaluation

Model Development and Application
For the RACER Delco Chassis Industrial Land
13000 Eckles Road Site
Livonia, Michigan

RACER Trust

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1. Introduction

On behalf of Revitalizing Auto Communities Environmental Response Trust (RACER), GHD has prepared this report to document the application of the Groundwater Flow Model to aid in evaluating alternatives to the existing groundwater collection/treatment operation with a permeable reactive gate (PRG) to treat groundwater with elevated concentrations of nickel and hexavalent chromium at Area 1. The report "Groundwater Flow Model for the RACER Delco Chassis Industrial Land" (GHD, 2017) (Groundwater Flow Model Report) documents the Groundwater Flow Model development and calibration.

GHD developed the Groundwater Flow Model to represent the existing hydrologic, geologic, and hydrogeologic conditions observed at the RACER Eckles Road Site located at 13000 Eckles Road, in the City of Livonia (Site). Figure 1.1 illustrates the Site location and Figure 1.2 illustrates historical process and building locations. The Groundwater Flow Model included a 4,700-foot barrier wall, 2.5 feet wide that is installed surrounding Area 1, a zone consisting of 6 Areas of Interest (AOI).[1] with similar environmental conditions. The location of the barrier wall is presented on Figure 1.3.

RACER is currently implementing performance-based Resource Conservation and Recovery Act (RCRA) Correction Actions at the Site pursuant to a September 29, 2011, Performance-based Administrative Order on Consent, Docket Number RCRA 05 2011 0025 between the United States Environmental Protection Agency (USEPA) and RACER.

The French Drain Collection System (FDCS) is a groundwater collection/treatment operation that is located in the southwest corner of the Site and collects groundwater impacted by the historical chrome plating operations through a French drain system. Groundwater is collected and treated by pH adjustment, addition of sodium bisulfate, lime, a polymer flocculent, followed by a gravity settling, and then batch discharged to the Great Lakes Water Authority (GLWA) formerly known as the Detroit Water and Sewerage Department (DWSD). In addition to groundwater extraction through the FDCS, RACER has also been injecting sodium dithionite and sodium sulfide to reduce groundwater nickel and hexavalent chromium concentrations through mineralization and precipitation. The January 2017 plume extents following injections are presented on Figure 1.4. The plume extents on Figure 1.4 are designated as the groundwater target levels of 0.1 milligrams per liter (mg/L) and 0.1 mg/L for nickel and hexavalent chromium, respectively.

RACER is currently considering alternatives to the existing interim measures operating at the Site to reduce operational costs. Specifically, RACER is considering replacing the operation of the FDCS with a PRG that would be installed on the downgradient side of the barrier wall to intercept and treat groundwater with elevated concentrations of nickel and hexavalent chromium. The proposed PRG construction involves excavating a section of the barrier wall and infilling it with PRG media composed of a mixture of granular zero valent iron (ZVI) and background sands. GHD completed a treatability study for ZVI media to be used for the PRG that was presented in the memorandum "Zero Valent Iron Permeable Reactive Barrier Treatability Study, Area 1 – Former Plating Area" (Conestoga-Rovers & Associates [CRA, 2013]). The treatability study indicated that the most

1 These AOIs are listed in the Groundwater Flow Model Report (GHD, 2017).

metals-contaminated groundwater prior to full-scale injections required 30 hours of contact with ZVI media to reduce nickel and hexavalent chromium concentrations to below target levels of 0.1 mg/L.

The Groundwater Flow Model developed for the Site and documented in the Groundwater Flow Model Report (GHD, 2017) consists of a single model layer. Following model development and calibration RACER and GHD began considering a PRG design that did not extend the gates to the full depth of the existing barrier wall but instead extend to a limited depth of approximately 15 feet below ground surface (bgs)[2], which is approximately 9.2 feet below the average depth to groundwater in Area 1.

The PRG evaluations documented in this Report consider the following design criteria:

1. Groundwater will need to have at least a 30-hour hydraulic residence time (HRT)[3] in the 2.5 feet width of PRG
2. After shut-down of the FDCS, contaminated groundwater does not daylight above the ground surface/flood in Area 1

These criteria, the 30-hour HRT and the daylighting avoidance, required evaluation across a range of recharge conditions to ensure that the remedial design does not fail under current or future conditions that are reasonable for the Site.

In addition to these criteria, GHD also evaluated whether groundwater nickel concentrations currently outside of Area 1 would be displaced by the proposed remedial activities.

1.1 Purpose

On behalf of RACER, GHD has prepared this Report to document the application of the groundwater flow model to evaluate sizes and locations for a proposed PRG.

1.2 Report Organization

This Report is organized as follows:

- **Section 1 – Introduction:** Presents the introduction and purpose of the modeling tasks.
- **Section 2 – Permeable Reactive Gate Conceptual Model:** Presents the PRG Conceptual Model developed for the Site based on the Conceptual Hydrogeologic Model and key design features that form the basis for the construction of the numerical PRG Model
- **Section 3 – Simulation Program Selection:** Presents a description of the simulation programs selected to conduct particle pathline and contaminant migration modeling.
- **Section 4 – Permeable Reactive Gate Model Construction:** Presents the model re-discretization including a comparison to August 21, 2003 steady-state conditions followed by a description of the implementation of the PRG design in the PRG Model

[2] This design reconsideration is anticipated to simplify construction, improve delivery of ZVI media throughout the full depth of the PRG, and reduce associated costs.

[3] The HRT is the duration that a particle of water transporting the dissolved metals will reside within the PRG and be exposed to the ZVI media.

- **Section 5 – Evaluation of Proposed Permeable Reactive Gate System:** Presents the simulation results for predicting depth to groundwater in Area 1 (i.e., potential daylighting) and the HRT.
- **Section 6 – Nickel Migration Model Construction and Simulation:** Presents the details for the nickel/chromium migration model construction and the selection of the migration model input parameters. A nickel/chromium migration simulation is presented to investigate nickel concentrations following PRG installation.
- **Section 7 – Summary and Conclusions:** Presents a summary of the hydrogeologic modeling conducted for the Site and the conclusions obtained.
- **Section 8 - References:** Lists the references cited in this Report.

2. Permeable Reactive Gate Conceptual Model

The PRG Conceptual Model is an expansion of the existing Conceptual Hydrogeologic Model for the Site. The existing Conceptual Hydrogeologic Model is described in Section 3 of GHD (2017). Key features of the proposed PRG design and design considerations including subsurface structures and the range of future precipitation conditions that could be reasonably expected at the Site were incorporated into the existing Conceptual Hydrogeologic Model to develop the PRG Conceptual Model[4].

This section provides a description of the range of future precipitation conditions that could be reasonably expected at the Site, subsurface structures and key PRG remedial design features which were incorporated into the existing Conceptual Hydrogeologic Model to develop the PRG Conceptual Model. The PRG Conceptual Model forms the basis for the construction of the numerical PRG Model for the Site.

2.1 Recharge

As described in Section 2.3 of the Groundwater Flow Model Report (GHD, 2017), the Site area primarily receives recharge from precipitation. The average annual precipitation rate is 31 inches per year (in/yr) based on 1981-2010 climatic normal (National Centers for Environmental Information [NCEI], 2013). The amount of precipitation that reaches the groundwater table is typically considered to range from approximately 10 to 40 percent of the average annual precipitation (Arnold et al., 2000; and Rushton and Ward, 1979). A recharge rate of 12 in/yr or 37 percent of average annual precipitation was assigned in the Groundwater Flow Model based on the recession curve method described by Domenico and Schwartz (1990) and as documented in GHD (2017). The assigned recharge rate provides a reasonable match to observed conditions.

[4] For conservative purposes the groundwater flow model did not account for reduced recharge attributable to impervious land surface structures and various potential land covers. By assuming that groundwater is recharged evenly throughout Area 1 at the area average recharge rate the model exaggerates the amount of mounding and potential for daylighting that would occur following shut-down of the FDCS. The exaggerated mounding simulated in the model compared to expected physical conditions would also provide an underestimate of the HRT. These conservative features provide additional levels of safety to the PRG design evaluation.

Annual precipitation rates will vary during the operation of the PRG. Therefore, the PRG design is tested to confirm that design criteria are met under a range of future precipitation conditions that could be reasonably expected at the Site. In the 30 years between 1987 and 2016 the minimum and maximum precipitation rates were 27 in/yr and 47 in/yr, respectively (NCEI, 2017). It is assumed that the proportion of precipitation which reaches the water table and becomes recharge is consistent with that applied in the calibrated Groundwater Flow Model (i.e., 37 percent of precipitation becomes recharge) presented in GHD (2017). Assuming that 37 percent of precipitation becomes recharge yields a minimum and maximum recharge rate of 10 in/yr and 18 in/yr, respectively.

2.2 Subsurface Structures

The Groundwater Flow Model (GHD, 2017) did not incorporate any of the existing subsurface structures because hydraulic conductivity at the Site is sufficiently high that there is little resistance to flow around them. The proposed PRG evaluated as part of the current Report is expected to be installed to a depth of 15 feet bgs, which corresponds approximately with the depth of the Press-Pit Basement and some of the other subsurface structures. The subsurface structures are flow barriers that are located near the proposed PRG and are incorporated explicitly in the PRG Conceptual Model. Figure 1.3 that shows the barrier wall alignment includes green back-slashing indicating the locations of these subsurface structures.

2.3 Key Permeable Reactive Gate Remedial Design Features

Understanding the key remedial design features is fundamental to developing a representative PRG Conceptual Model and guides the development of the numerical PRG Model. The key remedial design features are summarized as follows:

- The PRG will be installed within the existing 2.5-foot thick barrier wall along the eastern section
- The PRG will be installed to a depth of 15 feet bgs
- The PRG will be constructed of granular ZVI mixed with sands of similar composition and hydraulic conductivity of native Site area sands
- Following construction of the PRG operation of the FDCS will be discontinued[5]
- Groundwater moving through the PRG will need to have a HRT of at least 30 hours for treatment to be effective
- Groundwater does not daylight/flood in Area 1 or create any undesirable downgradient impacts following FDCS shut-down

[5] Discontinuation of pumping from the FDCS will occur following a period of monitoring groundwater quality and elevations after PRG construction.

3. Simulation Program Selection

The simulation program selection for the PRG modeling was based on the following considerations:

- The ability of the program to represent the key components of the PRG conceptual model
- The demonstrated verification that the program correctly represents the hydrogeologic processes being considered
- The proven acceptance of the program by regulatory agencies and the scientific/engineering community
- The ability of the program to represent the groundwater flow and migration nature of nickel and hexavalent chromium

3.1 Groundwater Flow Model

As described in the Groundwater Flow Model Report (GHD, 2017) the groundwater flow model was developed using MODFLOW-2005 (Harbaugh, 2005). Details of the groundwater flow model code are described in detail in the Groundwater Flow Model Report (GHD, 2017).

3.2 Parameter Iteration

SENSAN is a utility distributed with the parameter estimation program PEST, which is an acronym for Parameter Estimation (Watermark Numerical Computing, 2016). SENSAN is a model-independent sensitivity analysis application that has become a groundwater industry standard for groundwater high throughput model automation. SENSAN serves to convey input parameters at variable values within their bounds collectively to MODFLOW-2005 for the purpose of automating parameter adjustments. Model observation wells record groundwater at each iteration of the parameter adjustments.

3.3 Contaminant Migration

Contaminant migration was simulated using MT3DMS (Zheng and Wang, 1999). MT3DMS is a reactive transport model that, when integrated with MODFLOW-2005, can simulate multispecies chemical migration in one, two, or three dimensions and is able to simulate all the migration processes in the groundwater flow system that are applicable to the nickel/hexavalent chromium migration modeling study including advection, dispersion, and loss of mass from the aqueous phase (i.e., precipitation). MT3DMS is commonly used by the industry and accepted by the regulatory agencies, and therefore was selected for this study to evaluate the effectiveness of the proposed PRB gate(s) system based on determinations of the estimated nickel and hexavalent chromium HRT in the PRG.

3.4 Graphical User Interface

The graphical user interface (GUI) Groundwater Vistas (Rumbaugh, 2011) was employed as the interface between the assembled hydrogeologic data and the required MODFLOW-2005/SENSAN/MODPATH/MT3DMS input files.

3.5 Post-Processing

The statistical programming language R (R Core Team, 2017) was applied to reading and evaluating the MODFLOW/SENSAN model input and output files. The R programming language is an open-sourced script-based language that permits reproducible analysis of the model files.

4. Permeable Reactive Gate Model Construction

The construction of the numerical PRG Model is the process of developing the horizontal and vertical discretization of the selected model domain, the specification of hydraulic properties, and implementation of boundary conditions consistent with the PRG Conceptual Model. The PRG Model was developed based on the horizontal discretization, hydraulic properties, and boundary conditions specified in Sections 5 and 6 of the Groundwater Flow Model Report (GHD, 2017).

The following sections describe the re-discretization of the Groundwater Flow Model in the vertical direction to facilitate the representation of the PRG (i.e., the PRG only extends to 15 feet bgs, which is only partially through the saturated thickness of the upper saturated zone). Following model re-discretization, the re-discretized model is compared to the August 21, 2003 calibration results for the Groundwater Flow Model. The subsurface structures, range of future precipitation conditions that could be reasonably expected at the Site and key PRG design features are then incorporated to complete construction of the PRG Model.

4.1 Finite-Difference Grid

As described in Section 5.1 of the Groundwater Flow Model Report (GHD, 2017) a rectangular finite-difference grid is extended over the Groundwater Flow Model domain. The PRG Model uses the same horizontal discretization that was presented in Section 5.1 of the Groundwater Flow Model Report (GHD, 2017). Figure 4.1 shows the finite-difference grid in the horizontal direction. The proposed PRG will extend to a depth of 15 feet BGS[6]. The Groundwater Flow Model presented in the Groundwater Flow Model Report (GHD, 2017) is a single layer model and does not have the vertical discretization necessary to evaluate the PRG. The Groundwater Flow Model was re-discretized into an eight layer model (8 Layer Model) so that it could be applied to evaluate PRG design effectiveness. During the model re-discretization minimum model layer thicknesses of 1 foot and 0.5 foot were applied inside and outside the Site Area, respectively, to ensure model stability. Figure 4.2 shows model layer thicknesses in Model Layers 1 and 7. These are the two model layers that were assigned variable thicknesses. Darker colors on Figure 4.2 represent thinner zones in the model layer and lighter colors represent thicker areas. Following re-discretization Model Layer 1 ranges in thickness from 14 feet to 15 feet. Along the eastern section of the barrier wall, where the proposed PRG will be installed, the minimum layer thickness is 15 feet thick.

Model Layers 2 through 6 were assigned uniform thicknesses of 1 foot. The purpose of these model layers was to permit the formation of a concentration gradient between deep nickel and chromium concentrations and shallow treated concentrations during metals migration simulations. Model

6 This design consideration is anticipated to simplify construction, improve delivery of ZVI media throughout the full depth of the PRG, and reduce associated costs.

Layer 7 varies from 0.5 foot (i.e., outside of the Site Area) to 12.7 feet thick southeast of the Site. Model Layer 8 was assigned a uniform thickness of 1 foot.

Figure 4.3 shows the vertical re-discretization along north-south and east-west cross-sections. Following model re-discretization the model is composed of 2,058,868 finite-difference model cells.

4.2 Comparison with August 21, 2003 Steady-State Model Results

The 8 Layer Model was compared to the Groundwater Flow Model to ensure that the increased vertical discretization did not adversely affect the model's ability to represent Site conditions.

The model comparison between the 8 Layer Model and the Groundwater Flow Model was assessed quantitatively. The FDCS, which was active for the steady-state calibration was assigned to Model Layer 7 of the 8 Layer Model using pumping rates that were described in Section 5.2 of the Groundwater Flow Model Report (GHD, 2017). The quantitative comparison was conducted by examining cell by cell groundwater elevations obtained from running the 8 Layer Model in steady-state. GHD then calculated model differences by subtracting maximum cell by cell groundwater elevations (i.e., water table elevations) at target locations in the 8 Layer Model from the Groundwater Flow Model.

The mean model difference, absolute mean model difference, and model difference sum of square statistic, standard deviation, etc., were calculated to quantify the discrepancy between the 8 Layer Model and the Groundwater Flow Model. The model difference statistics are listed in Table 4.1 below.

Table 4.1 Model Difference Statistics

Model Difference Statistics	Groundwater Flow Model – 8 Layer Model Cell by Cell Difference Statistic Values
Mean Difference	-0.02 feet
Absolute Difference Mean	0.02 feet
Number of Active Model Cells in 1 Layer Model	247,781
Difference Sum of Square	18.1 $feet^2$
Difference Sum of Squares per Model Cell	7.3×10^{-5} $feet^2$/Model Cell
Model Difference Standard Deviation	0.01 feet
Minimum Difference	-0.13 feet
Maximum Difference	0.02 feet

The distribution of these groundwater elevation differences between the Groundwater Flow Model and the 8 Layer Model are illustrated on Figure 4.4. The small differences observed between the 8 Layer Model and 1 Layer Model are expected because the 8 Layer Model increases the resolution of the model solution through the application of additional model layers.

As illustrated on Figure 4.4 the biggest cell by cell groundwater elevation differences are near the FDCS where the increased vertical resolution in the 8 Layer Model provides a refinement to the solution of this stressed condition. A histogram showing the distribution of cell by cell groundwater elevation difference frequency counts as a percentage is included as an inset on Figure 4.4. From the histogram 99 percent of the model cells have head differences between -0.05 foot and 0 foot.

These differences are sufficiently small that the 8 Layer Model reasonably can provide results that are representative of the calibrated Groundwater Flow Model results.

A second quantitative measure of the ability of the 8 Layer Model to represent Site conditions was provided by the simulated volumetric water budget reported by MODFLOW-2005 indicating the quantities of flow into and out of the model domain via the groundwater flow components specified in the model. The volumetric budget was reviewed to ensure that the total inflows and outflows were consistent with the Conceptual Hydrogeologic Model. The volumetric budget also provided a percent discrepancy between the total simulated inflows and outflows. A discrepancy of less than 0.1 percent indicates a satisfactory numerical convergence.

GHD examined the volumetric water budget for the 8 Layer Model. A discrepancy of less than 0.005 percent occurs in the budget between the simulated inflows and outflows, demonstrating that a good numerical convergence was achieved throughout the model domain.

4.3 Proposed Permeable Reactive Gate Design Implementation in the Permeable Reactive Gate Model

An acceptable PRG design will satisfy the PRG requirements laid out in Section 1 and will incorporate the key PRG remedial design features described in Section 2.3. To develop the PRG Model, the range of future precipitation conditions that would be expected at the Site, subsurface structures and key PRG design features were incorporated into the 8 Layer Model. Several PRG gate design scenarios were developed and each was simulated to predict potential daylighting/flooding and PRG HRT.

The simulated potential daylighting/flooding was evaluated through the use of model observation locations. For each model simulation SENSAN records groundwater elevations at these selected model observation locations. GHD then compares these groundwater elevations to ground surface elevations to calculate the simulated groundwater depth below ground surface. Figure 4.5 presents the simulated groundwater depth observation locations as blue symbols.

The simulated PRG HRT was also estimated through the use of paired model observation locations. These paired HRT model observations are located along the eastern section of the slurry wall (barrier wall), as presented on Figure 4.5. The HRT is the duration that a particle of water transporting the dissolved metals will reside within the PRG and be exposed to the ZVI media. The HRT for the PRG is calculated using the following equation:

$$HRT = \frac{d_{PRG}}{V_g} \times \frac{24\,\text{hours}}{1\,\text{day}} \qquad \text{Equation 4.1}$$

Where:

HRT = Hydraulic Residence Time (hours)

d_{PRG} = linear distance across PRG (i.e., 2.5 feet)

V_g = mean pore water velocity through PRG (feet/day)

The mean pore water velocities were calculated for each paired HRT model observation locations across the PRG. The mean pore water velocities were calculated by determining the hydraulic gradient based on groundwater elevations at each of the paired HRT model observation locations across the PRG. The paired HRT model observation well locations were spaced 10 feet apart to ensure that permissible model error (i.e., the 0.001 foot head change criterion for model convergence described in Section 5.4 of GHD [2017]) did not adversely affect estimates of HRT. The mean pore water velocities are calculated using the following equation:

$$V_g = \frac{K \times i}{\eta_e} \qquad \text{Equation 4.2}$$

Where:

K	=	hydraulic conductivity (feet/day)
i	=	hydraulic gradient across paired HRT model observation well locations (feet/foot)
η_e	=	the soil effective porosity ($feet^3$ of drainable pore space/$feet^3$ of bulk aquifer matrix)

SENSAN records groundwater elevations for each model simulation at the paired HRT model observation well locations. Figure 4.5 shows the locations of the paired HRT model observation well locations. HRT was calculated at paired HRT model observation wells near the simulated PRG.

Two PRG locations along the eastern section of the barrier wall were considered for the evaluation: 1) a PRG situated near the southeast corner of the barrier wall close to the dissolved metal plumes (Southeast PRG) and 2) a PRG situated 50 feet north of the southeast corner of the barrier wall (Offset Southeast PRG). The northeast corner was not considered as a potential location for the PRG evaluation due to the presence of numerous subsurface obstructions within the barrier wall along the northeastern corner of the barrier wall that might interfere with safe construction of the PRG. Figure 4.6 presents the locations of the simulated PRGs. GHD developed 15 alternatives and 14 alternatives representing various PRG lengths for the Southeast PRG and Offset Southeast PRG scenarios, respectively. These include PRGs that are 100 feet, 140 feet, 180 feet, 220 feet, 260 feet, 300 feet, 340 feet, 380 feet, 420 feet, 460 feet, 500 feet, 540 feet, and 580 feet in length. The Southeast PRG scenarios include PRGs that are 620 feet and 636.5 feet in length and the Offset Southeast PRG scenarios include a PRG that is 586.5 feet in length. Each of these scenarios evaluate ranges of PRG lengths that span from 100 feet long to the full remainder of the barrier wall in a maximum of 40-foot increments. Each of these alternatives represents installing the PRG into the barrier wall to a depth of 15 feet bgs. The barrier wall is represented as fully intact below 15 feet bgs. The PRG was assumed to have hydraulic conductivity that is consistent with the surrounding fine and medium-grained sands of the shallow water-bearing unit.

Each of the simulated PRG alternatives, representing different barrier wall location and length, were evaluated across a range of recharge rates ranging from 10 in/yr to 18 in/yr in increments of 0.44 in/yr (i.e., 0.0001 feet/day) to correspond with annual recharge rates that are reasonably expected to occur within a 30 year timespan. SENSAN served to convey these 21 recharge rates automatically to each of the two groups (i.e., Southeastern PRG and Offset Southeastern PRG configurations) of 15 and 14 PRG alternatives (i.e., PRG gate lengths ranging from 100 feet to 636.5 feet or 586.5 feet for the Southeastern PRG or Offset Southeastern PRG, respectively).

For each scenario, the FDCS was assigned a pumping rate of 0 gallons per minute (GPM) to represent the cessation of operations following the installation of the PRG.

4.4 Time Discretization

Steady-state models assume that conditions are persistent, however the minimum and maximum recharge rates are only expected to be continuous over a single year and not span multiple years. Therefore, the PRG Model was developed to represent transient conditions (i.e., recharge occurring over the span of a year) rather than assuming the minimum or maximum recharge rates are representative of steady-state. The transient model represents a duration of 1 year of recharge using the calibrated conditions (i.e., August 21, 2003) as initial conditions. August 21, 2003 conditions are considered to be appropriate initial conditions as they represent a period prior to installation of the barrier wall, similar to that which would be expected once the PRG is constructed, creating a hydraulic connection between regional groundwater flow and groundwater flow within Area 1. Each of the transient PRG models were simulated using 365 daily time steps.

4.5 Subsurface Structure Representation

Some of the subsurface structures are located near the proposed PRG. The PRG model was developed to consider the affect these structures have on flow through the PRG by assigning zones of no-flow in Model Layer 1 at these subsurface structure locations. Figures 1.3, 4.5, and 4.6 show the locations of the subsurface structures that are represented as no-flow zones in the PRG Model.

5. Evaluation of Proposed Permeable Reactive Gate System

GHD applied SENSAN to convey 21 recharge rates spanning the 30 year minimum and maximum estimated recharge rates to PRG Models representing 15 or 14 PRG gate lengths for the two PRG location orientations, respectively: 1) along the southeast of the barrier wall (Southeast PRG) and 2) offset 50 feet north from the southeast corner (Offset Southeast PRG). The models were evaluated transiently for a 1 year duration. For each of these models, GHD evaluated the minimum simulated depth to groundwater and the HRT. The depth to groundwater was recorded at the simulated groundwater depth observation locations. The HRT was calculated based on paired hydraulic gradient wells separated by the simulated PRG[7].

Tables 5.1 and 5.2 summarize the Southeastern PRG and Offset Southeastern PRG model results, respectively. These tables are organized with the minimum depth to groundwater measured at the groundwater depth observation locations on the leftmost panel and the calculated HRTs in the rightmost panel. Groundwater elevations within 2 feet of ground surface are color-coded red (this situation did not occur in any of the model scenarios) and green if groundwater elevations are deeper than 2 feet bgs. HRT values are specified in red if they are less than 30 hours and in green if they are equal to or greater than 30 hours.

[7] The HRT is not measured for paired wells that are separated by the slurry wall (barrier wall).

As indicated in Table 5.1 a HRT of 30 hours or more is not achieved when the PRG is situated along the southeast barrier wall. In comparison, the Offset Southeast PRG achieves a HRT of 30 hours or more for PGR configurations that are equal to or greater than 180 feet long.

The barrier wall provides a barrier to groundwater flow that depresses groundwater elevations on the southern side of the wall. This groundwater depression results in a relatively high hydraulic gradient as groundwater flows around the southern wall from inside locations to outside locations. This is the reason that each PRG configuration in the southeast corner is unable to achieve a HRT of 30 hours. Based on these results the PRG should be situated away from the southeastern corner of the barrier wall. A PRG that is situated 50 feet from the southeastern corner of the barrier wall that is 180 feet or longer provides sufficient HRT to treat dissolved hexavalent chromium and nickel. GHD therefore recommends a 180-foot long PRG gate located along 50 feet north of the southeast corner of the eastern barrier wall.

6. Nickel Migration Model Construction and Simulation

GHD developed a contaminant migration model to simulate nickel migration for the 180-foot Offset Southeastern PRG scenario. The migration simulation was conducted to evaluate potential displacement of nickel currently outside of the barrier wall by groundwater exiting the PRG. The transport model simulations represent the following migration mechanisms:

- Advection
- Dispersion
- Adsorption, or retardation
- Precipitation through mineralization

Section 6.1 provides a description of these migration mechanisms.

6.1 Migration Mechanisms

6.1.1 Advection

Advection (the bulk movement of a fluid through a geologic medium) is the primary migration mechanism of the dissolved-phase through the porous media at the Site. The advection mechanism is governed by Darcy's Law, which determines the groundwater flow velocity, accounting for hydrogeologic characteristics (hydraulic gradient, hydraulic conductivity, permeability, and effective porosity) of the aquifer. MODFLOW-2005 models advection over the entire model domain. MT3DMS then uses the simulated groundwater flow field, determined by the PRG model, as input for solving the advective component of the transport (migration) equation.

6.1.2 Dispersion

Dispersion is a migration mechanism by which dissolved phase constituents spread along the groundwater flow path. Dispersion results from two basic processes, molecular diffusion and mechanical mixing. Molecular diffusion is a process where solutes move from zones of higher concentrations to zones of lower concentrations. The driving force of this movement is kinetic activity at the molecular level. Mechanical dispersion is derived from the variability (heterogeneity) of the microscopic velocities in soil pore spaces that act to spread or mix a solute in an aquifer. The primary aquifer characteristics that cause this mixing are variable frictional forces in pore channels, variations in pore channel geometry, and pore channel branching.

Dispersion/spreading of solutes during groundwater flow results in dilution of solute pulses and attenuation of concentration peaks. This dilution/attenuation effect is typically taken into account in the transport (migration) equation by applying longitudinal and transverse dispersivity coefficients in a 3D model domain.

Selection of dispersivity values is a difficult process, given the impracticability of measuring dispersion in the field. However, simple estimation techniques, based on the length of the plume or distance to measurement point ("scale"), are available by compiling field test data. It is noted that researchers indicate that dispersivity values can range over 2 to 3 orders of magnitude for a given value of plume length or distance to a measurement point (Gelhar et al., 1992). Typical relationships of dispersivity and plume length (L_P) are provided by a few researchers (i.e., Xu and Eckstein, 1995; Gelhar et al., 1992).

For this study the longitudinal dispersivity was estimated using the approach developed by Xu and Eckstein (1995) as described below:

$$\alpha_L = 0.83 \times [\log_{10}(L_P)]^{2.414} \qquad \text{Equation 6.1}$$

Where:

α_L = is the longitudinal dispersivity in feet

L_P = is the estimated plume length (feet)

Based on the observed 2017 nickel plume length of approximately 880 feet the longitudinal dispersivity was calculated to be 23 feet using Equation 6.1. The horizontal transverse dispersivity was specified to be 1/10 of the longitudinal dispersivity and the vertical dispersivity was assumed to be 1/100 of the longitudinal dispersivity, as suggested by Bear and Cheng (2010).

6.1.3 Sorption/Retardation

Sorption describes the interaction of contaminants with a solid through partitioning between the solution and the solid phase. Sorption causes the contaminant to move at a velocity (V_c) that is slower than the mean pore water velocity (V_g) by a factor of R_d (known as the retardation factor) expressed as:

$$R_d = 1 + \frac{\rho}{\eta_e}\left[\frac{K_{ads}C_{ads,max}}{(1+K_{ads}C)^2}\right] \qquad \text{Equation 6.2}$$

Thus,

$$V_c = \frac{V_g}{R_d}$$ Equation 6.3

Where:

ρ = is the dry bulk density of the soil [kilograms per liter (kg/L)]

K_{ads} = is the Langmuir distribution coefficient [liters per kilogram (L/kg)]

$C_{ads,max}$ = is the total concentration of sorption sites available [milligram per kilogram (mg/kg)]

Langmuir isotherms describe adsorption of inorganic constituents to a finite number of adsorption sites in a manner that is proportional to the constituent concentrations in groundwater. A Langmuir isotherm is expressed as:

$$C_{ads} = \frac{K_{ads} C_{ads,max} C}{1 + K_{ads} C}$$ Equation 6.4

Where:

C = is the dissolved phase inorganic constituent in milligrams per liter (mg/L)

A linear relationship between C and $\frac{C}{C_{ads}}$ is obtained when Equation 6.4 is inversed and the parameters are rearranged (Stumm and Morgan, 1996), as expressed by:

$$\frac{C}{C_{ads}} = \frac{1}{C_{ads,max}} C + \frac{1}{K_{ads} C_{ads,max}}$$ Equation 6.5

GHD applied this methodology to obtain the parameters of the Langmuir isotherm from Site-specific information. Table **Error! Reference source not found.** present the nickel Langmuir parameters based on soil concentrations ((i.e., C_{ads}) and groundwater concentrations (i.e., C) presented in the "Field Pilot Test and Full Scale Implementation Work Plan – Area 1 (Chrome Plating Area)" (CRA, 2010) and the "Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) Report" (CRA, 2005).

For this modeling study, the following parameter values were used for the estimation of retardation factors:

- Langmuir distribution coefficients (K_{ads}) of 5 L/mg was calculated for nickel in the shallow water-bearing unit. An estimated K_{ads} of 0.03 L/mg was applied to the PRG to represent a value for adsorption to the reactive media (i.e., zero valent iron) that would not artificially simulate breakthrough. Site-specific investigations of the $\frac{C}{C_{ads}}$ value in the PRG would need to be conducted to provide an estimate for potential nickel and hexavalent chromium barrier wall breakthrough.

- The total concentrations of sorption sites available ($C_{ads,max}$) of 14 mg/kg was calculated for nickel in the shallow water-bearing unit. An estimated $C_{ads,max}$ of 2,000 mg/kg was applied to the PRG gate to represent a value for the number of sites available on the reactive media (i.e., ZVI) that would not artificially simulate breakthrough.
- A dry bulk density (ρ) of 1.9 kg/L was selected for the shallow water-bearing unit based on geotechnical laboratory testing performed on soils through the Site as describe in Section 2.2 of GHD (2017).
- Effective porosity values were adjusted during the transient secondary check ?OF THE? model that matched simulated and observed groundwater rebound following the March 2014 FDCS shut-off event described in Section 6 of GHD (2017). A value of 14 percent was applied to the metals migration model described in the current Report.

The estimated non-linear cell by cell retardation factors for nickel in the shallow water-bearing unit are calculated for each time-step within each finite-difference model cell based on simulated concentrations by MT3DMS.

6.1.4 Precipitation through Mineralization

Precipitation through mineralization describes the process through which dissolved nickel changes from the aqueous phase into stable mineral compounds that fall out of solution and are no longer transported along the groundwater flow path. It is difficult to describe the rate of mineralization in a rigorous mathematical manner. However, in simplified terms, mineralization and precipitation can be described using a first-order rate expressed as:

$$\frac{\partial C}{\partial t} = -\lambda C \qquad \text{Equation 6.6}$$

Where:

C = is the aqueous concentration (mg/L)

t = is time in days

λ = is the first-order mineralization rate in $days^{-1}$

The mineralization rate is related to a half-life by:

$$t_{1/2} = \frac{\ln(2)}{\lambda} \qquad \text{Equation 6.7}$$

Where:

$t_{1/2}$ = is the half-life in days

GHD assumes that no mineralization would occur in the native shallow water-bearing unit and a λ value of 0 was assigned. A λ value representing mineralization was assigned to the proposed PRG to represent nickel through contact with the ZVI PRG media. Table 4 from CRA (2013) lists initial and measured concentrations obtained during the ZVI treatability studies for high initial chromium concentrations. Table 4 from CRA (2013) is reproduced in this Report as Table **Error! Reference source not found.**[8]. As seen in Table **Error! Reference source not found.** initial nickel concentrations also were elevated during the treatability testing. Two samplings (measurements) reported in Table **Error! Reference source not found.** represent 30 HRTs: the third sampling, which consisted of a 10% ZVI treatment, and the fourth sampling, which consisted of a 20% ZVI treatment[9]. The observed concentration reductions can be applied to estimate λ values by solving the differential equation from Equation 6.6 using the following solution:

$$C = C_0 e^{\left(-\lambda t \times \frac{1\,\text{day}}{24\,\text{hours}}\right)} \qquad \text{Equation 6.8}$$

Thus by rearranging Equation 6.8,

$$\lambda = \frac{1}{t} \times \frac{24\,\text{hours}}{1\,\text{day}} \times \ln\left(\frac{C_0}{C}\right) \qquad \text{Equation 6.9}$$

Where:

t = is the HRT of 30 hours

C_0 = is the initial concentration of 30,600 micrograms per liter (µg/L) for nickel

C = is the measured dissolved metal concentration following 30 hours of exposure to 10% and 20% ZVI, respectively

Measured dissolved metal concentrations following 30 hours of exposure are as follows: 1,094 µg/L in 10% ZVI and 3.78 µg/L in 20% ZVI. Application of Equation 6.9 yields first-order mineralization rates of 2.66 days^{-1} and 7.2 days^{-1} for nickel in 10% and 20% ZVI media, respectively. These mineralization rates correspond with half-lives of 0.26 days and 0.1 days in 10% and 20% ZVI media, respectively.

The migration simulations were conducted to predict potential nickel displacement from treated groundwater discharging from the PRG. The HRT evaluation presented in Section 5 demonstrates that the 180-foot PRG located 50 feet north of the southeast corner of the barrier wall meets the minimum 30-hour HRT.

6.2 Initial Nickel Conditions

The January 2017 nickel plume conditions, estimated for concentrations exceeding 0.1 mg/L and presented on Figure 1.4 were implemented in the migration model as initial conditions.

6.3 Nickel Migration Simulations

The contaminant migration model was used to predict nickel migration under the 180-foot Offset Southeastern PRG scenario over a 30-year time period. GHD applied a model representing

8 For more information on the treatability study referenced on Table **Error! Reference source not found.** refer to the text of CRA (2013).

9 The 1st, 2nd, 3rd, and 5th samplings listed on Table **Error! Reference source not found.** represent metals exposed to 10% ZVI media. Only the 4th sampling represents metals exposed to 20% ZVI media.

20% ZVI to simulate metal migration. Simulated nickel concentrations were evaluated following 5 years, 10 years, 20 years, and 30 years of migration for the 20% ZVI design scenario. The results of the nickel migration simulations are discussed in the following sections.

6.4 Nickel Migration Simulation Results

As described in Sections 1 and 6 the purpose of the migration simulations was to evaluate if permitting groundwater to flow through the PRG would result in displacement of the nickel plume currently located outside of the barrier wall within the next 30 years.

Figures **Error! Reference source not found.** presents the simulated nickel concentrations in plan view in the shallow (i.e., Model Layer 1) water-bearing unit and in cross-sections across the PRG. Figure **Error! Reference source not found.** illustrates that over 30 years of migration nickel currently situated outside of the barrier wall is not substantially displaced by water exiting the PRG. The peak nickel concentrations outside of the barrier wall contract within the 30 year prediction period through mechanisms such as dilution and dispersion.

7. Summary and Conclusions

- In 2017 GHD developed a Groundwater Flow Model as a tool to represent the existing hydrologic, geologic, and hydrogeologic conditions observed at the Site and surrounding area.
- That Groundwater Flow Model was a single layer model that represented existing hydrologic, geologic, and hydrogeologic conditions observed at the Site and surrounding area.
- Development of the construction and calibration of that Groundwater Flow Model was documented in the Groundwater Flow Model Report (GHD, 2017).
- RACER has investigated alternatives to the existing remedial measures operating at the Site and with USEPA approval has moved forward with evaluation of a PRG.
- The proposed alternative remedial measures include ISCR, installation of a PRG system, and cessation of operations of the FDCS and installation of a PRG system.
- Subsequent to development of the Groundwater Flow Model it was determined that a PRG that extends to 15 feet bgs rather than a PRG that extends the full depth of the water-bearing unit to the underlying clay was preferable because it simplifies construction, improves delivery of ZVI media throughout the full depth of the PRG, and reduces associated costs.
- Key design features of a successful PRG system include the following:
  - The PRG will be installed within the existing 2.5-foot thick barrier wall along the eastern section
  - The PRG will be installed to a depth of 15 feet bgs
  - The PRG will be constructed of granular ZVI mixed with sands similar to native sands
  - Following construction of the PRG the FDCS will be shut-down
  - Groundwater moving through the PRG will need to have a HRT of at least 30 hours for treatment to be effective

- Groundwater does not daylight/flood in Area 1 or downgradient property following FDCS shut-down
  - Groundwater exiting the PRG does not displace the nickel plume currently located outside of the barrier wall
- GHD re-discretized the groundwater flow model by adding seven additional model layers for a total of eight model layers.
- The re-discretized 8-Layer Model was compared to the Groundwater Flow Model and provided comparable model results.
- The 8-Layer Model then was applied to develop the PRG Model, which incorporated additional subsurface structures that might impede groundwater migration through the PRG.
- GHD investigated two locations for situating the PRGs along the eastern side of the barrier wall: 1) near the southeast corner of the barrier wall and 2) offset 50 feet north of the southeast corner of the barrier wall.
- For these two scenarios, GHD investigated 15 and 14 alternatives for the Southeastern PRG and Offset Southeastern PRG, respectively, to represent different gate lengths.
- Each of these 29 models were evaluated against 21 recharge rates that span the 30-year minimum and maximum estimated recharge rates.
- Each of the Southeastern PRG alternatives result in HRTs that are less than 30 hours.
- The Offset Southeastern PRG alternatives satisfy the criteria for successful gate designs when the PRG length is equal to or greater than 180 feet long.
- Under the 180-foot long Offset Southeastern PRG alternative the existing nickel plume currently located outside of the barrier wall is not displaced by groundwater discharging through the PRG.
- GHD recommends a 180-foot long Offset Southeastern PRG design located 50 feet north of the southeastern corner of the barrier wall.

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All of Which is Respectfully Submitted,

GHD

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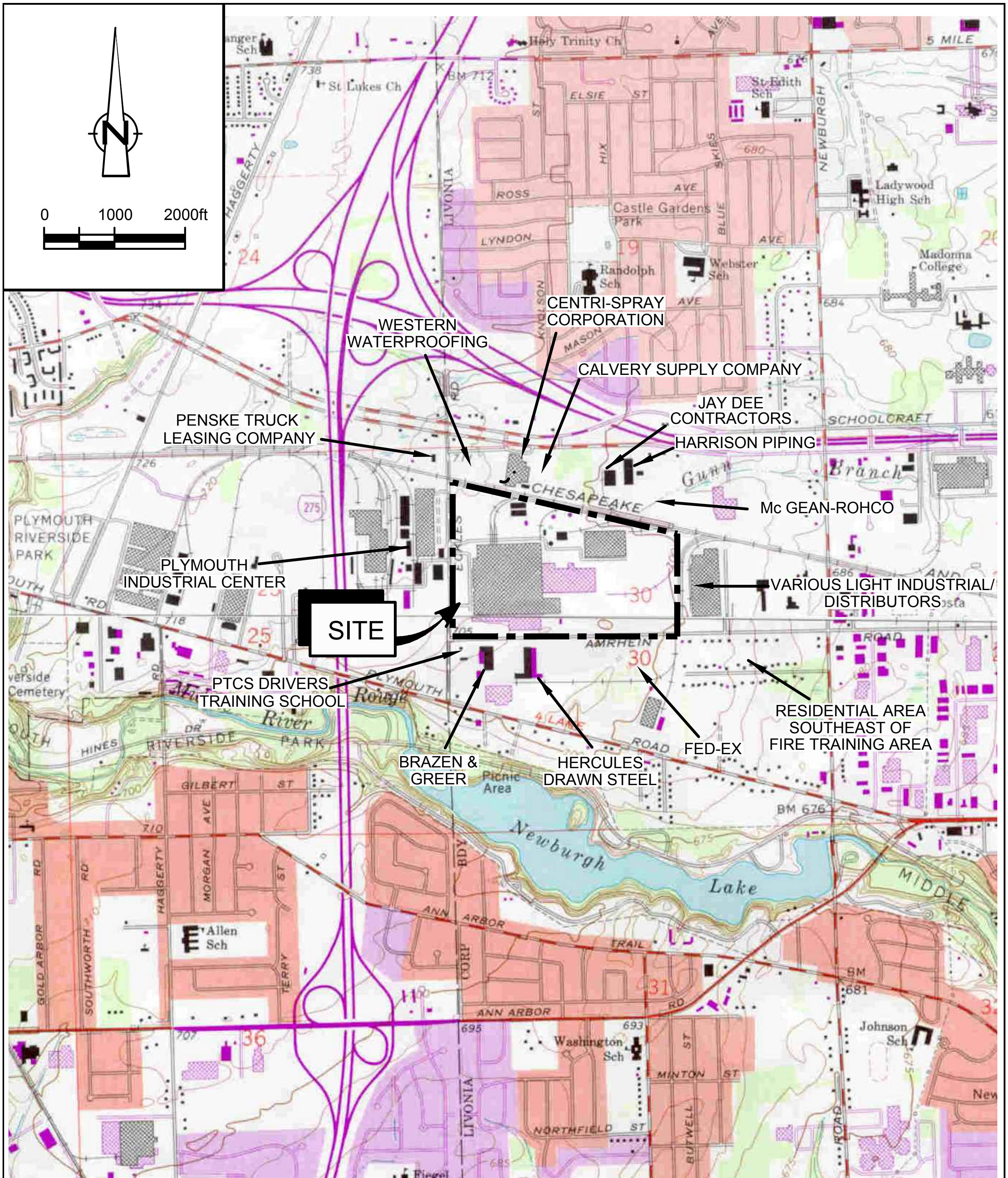
Chris Meincke



SOURCE: USGS QUADRANGLE MAPS;
NORTHVILLE AND WAYNE, MICHIGAN

figure 1.1

SITE LOCATION
13000 ECKLES ROAD SITE
Livonia, Michigan

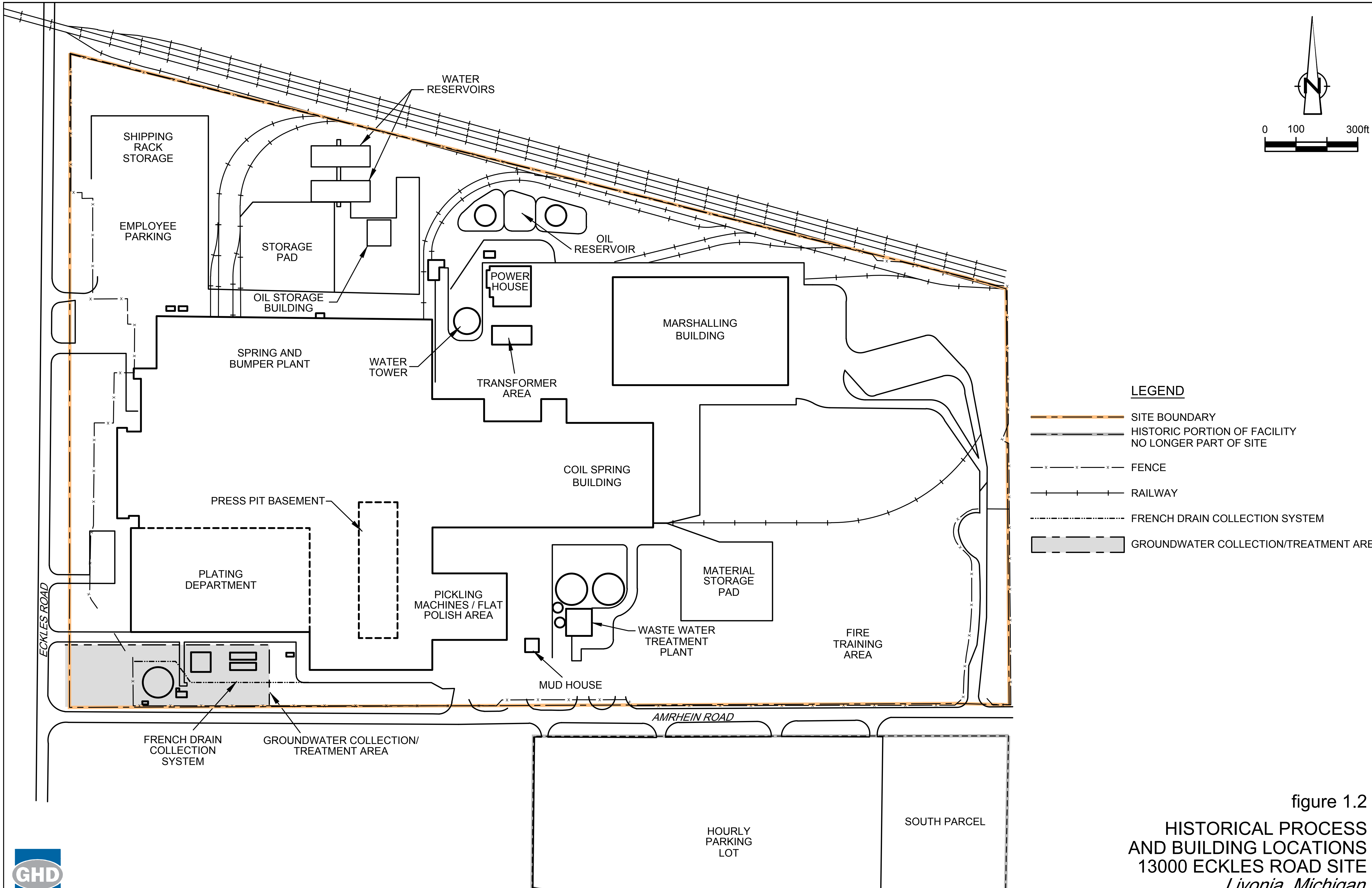
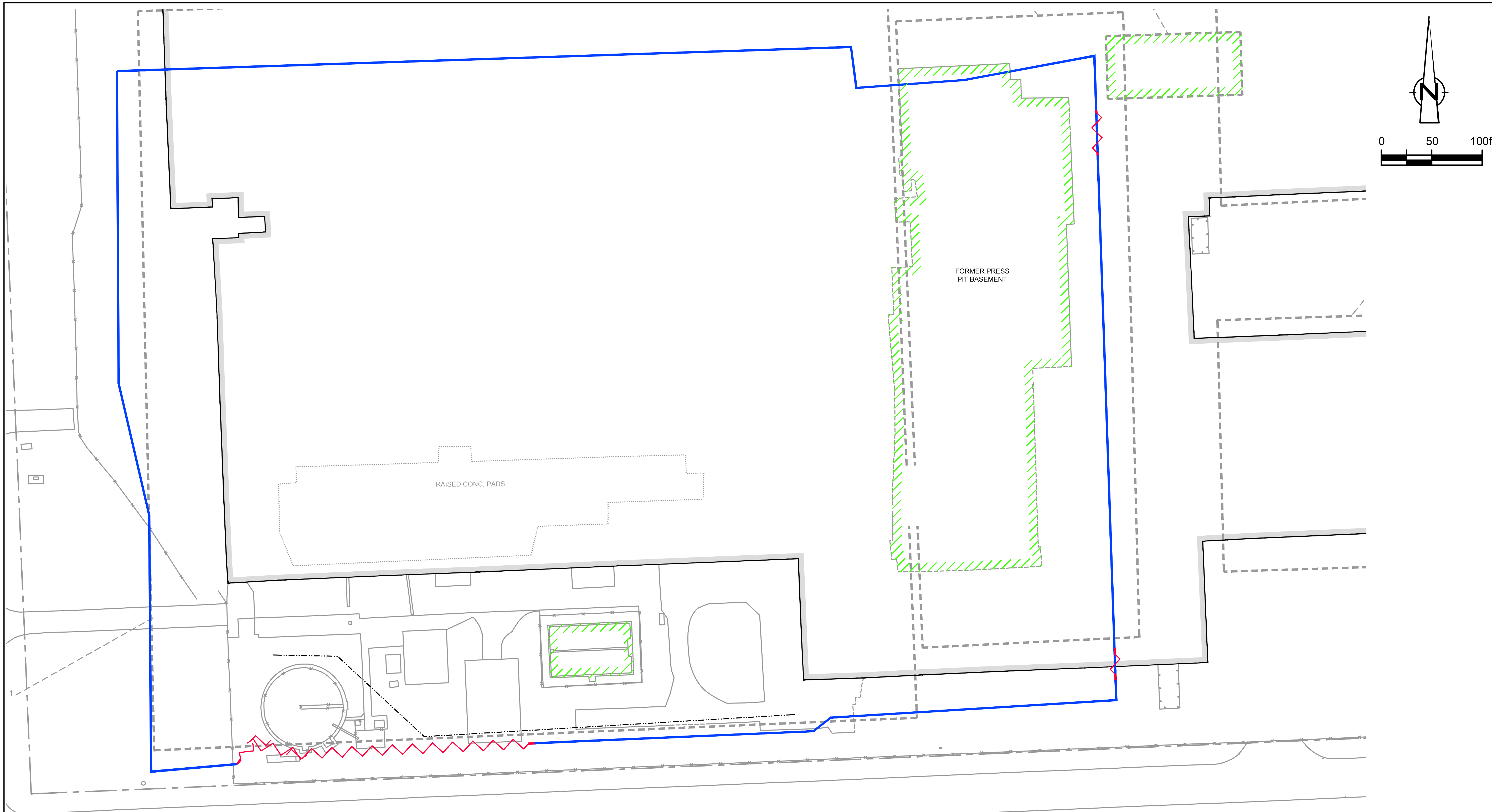


figure 1.2

HISTORICAL PROCESS AND BUILDING LOCATIONS
13000 ECKLES ROAD SITE
Livonia, Michigan

GHD

12607-T06Y17(072)GN-WA002 JUN 5, 2017



LEGEND

- SITE BOUNDARY
- EXISTING CONCRETE SLAB
- EXISTING FRENCH DRAIN COLLECTION SYSTEM
- EXISTING FENCE
- EXISTING AOI AREA
- SUBSURFACE STRUCTURE
- SURVEYED SLURRY WALL - 3/1/2005
- JET GROUTED BARRIER WALL

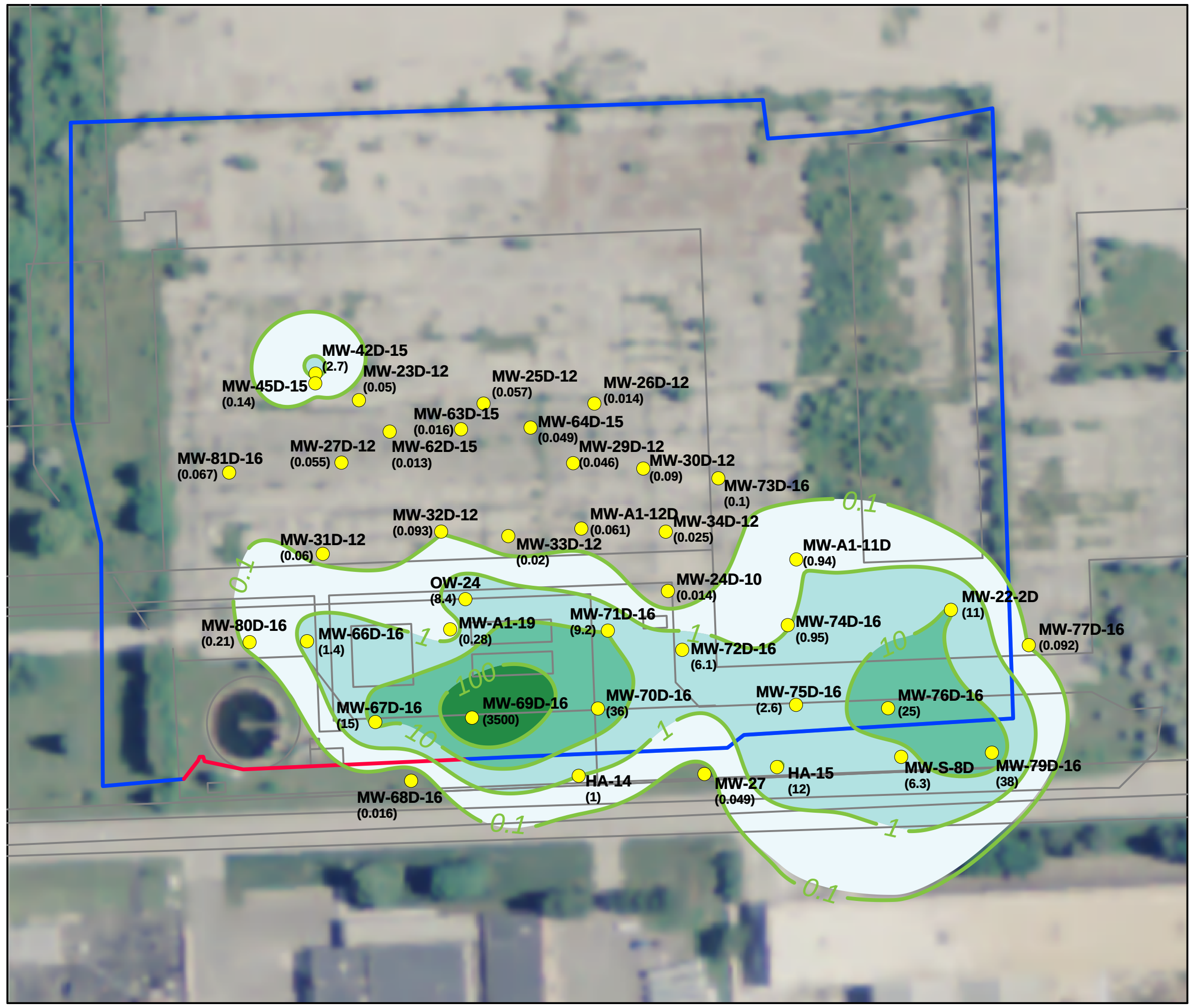
GHD

figure 1.3

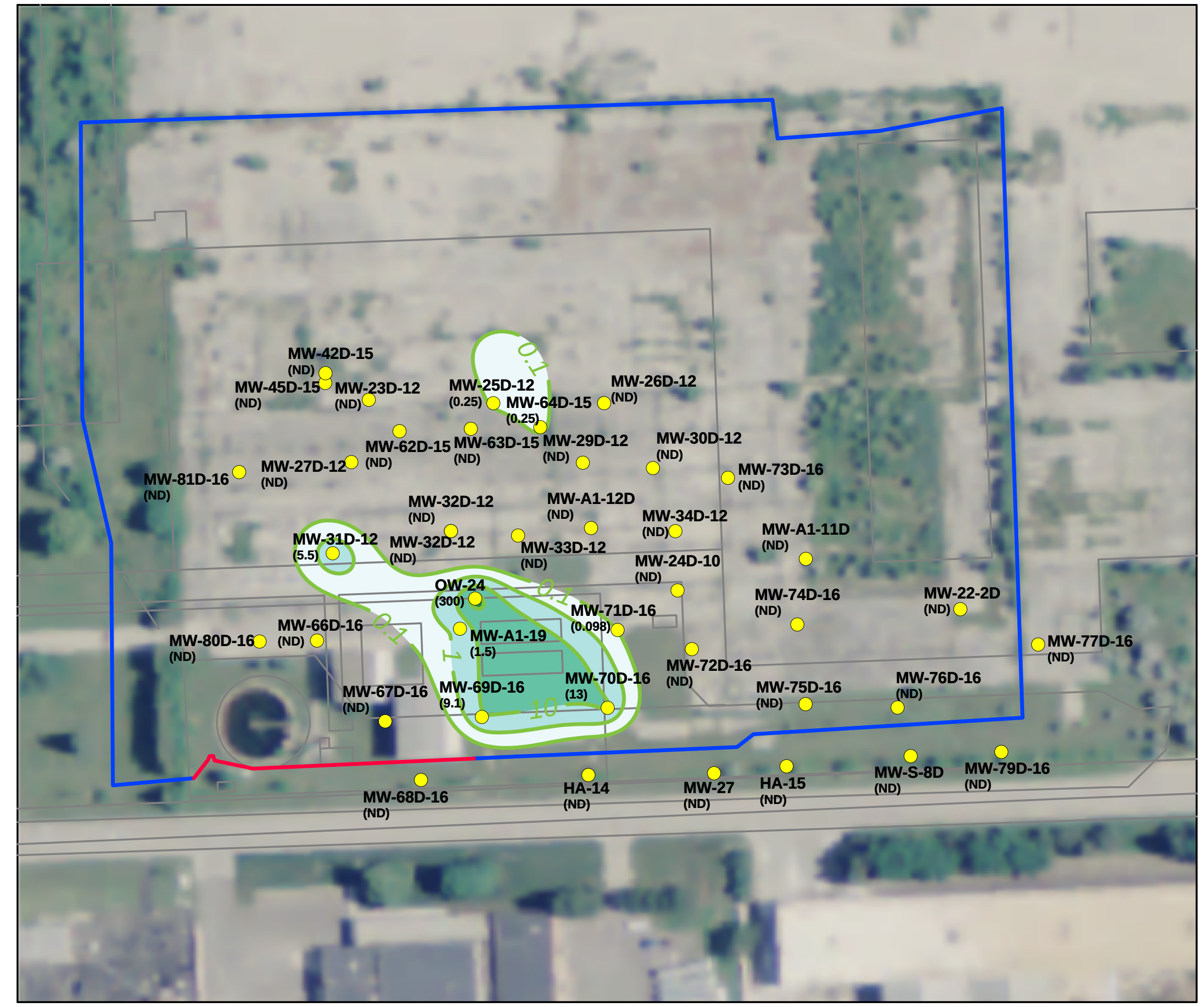
BARRIER WALL ALIGNMENT
13000 ECKLES ROAD SITE
Livonia, Michigan

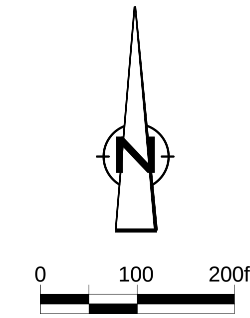
12607-T06Y17(072)GN-WA003 JUN 12, 2017

NICKEL



HEXAVALENT CHROMIUM





LEGEND

MONITORING WELL LOCATION

MW-70D-16 (36) MONITORING WELL IDENTIFICATION
2017 MEASURED DISSOLVED METAL CONCENTRATION (mg/L)

—1— 2017 MEASURED DISSOLVED METAL CONCENTRATION CONTOUR (mg/L)

SLURRY WALL

JET-GROUTED BARRIER WALL

2017 MEASURED DISSOLVED METAL CONCENTRATION (mg/L)

0.1 | 1 | 10 | 100

figure 1.4

JANUARY 2017 NICKEL AND HEXAVALENT CHROMIUM CONCENTRATIONS
13000 ECKLES ROAD SITE
Livonia, Michigan

12607-T02Y17(072)GN-WA-HYD (Z:\HEG\012607\DOCUMENTATION\REPORTS\012607-RPT-72\FIGURES\12607-2017ObservedConcs.srf) JUN 13/2017

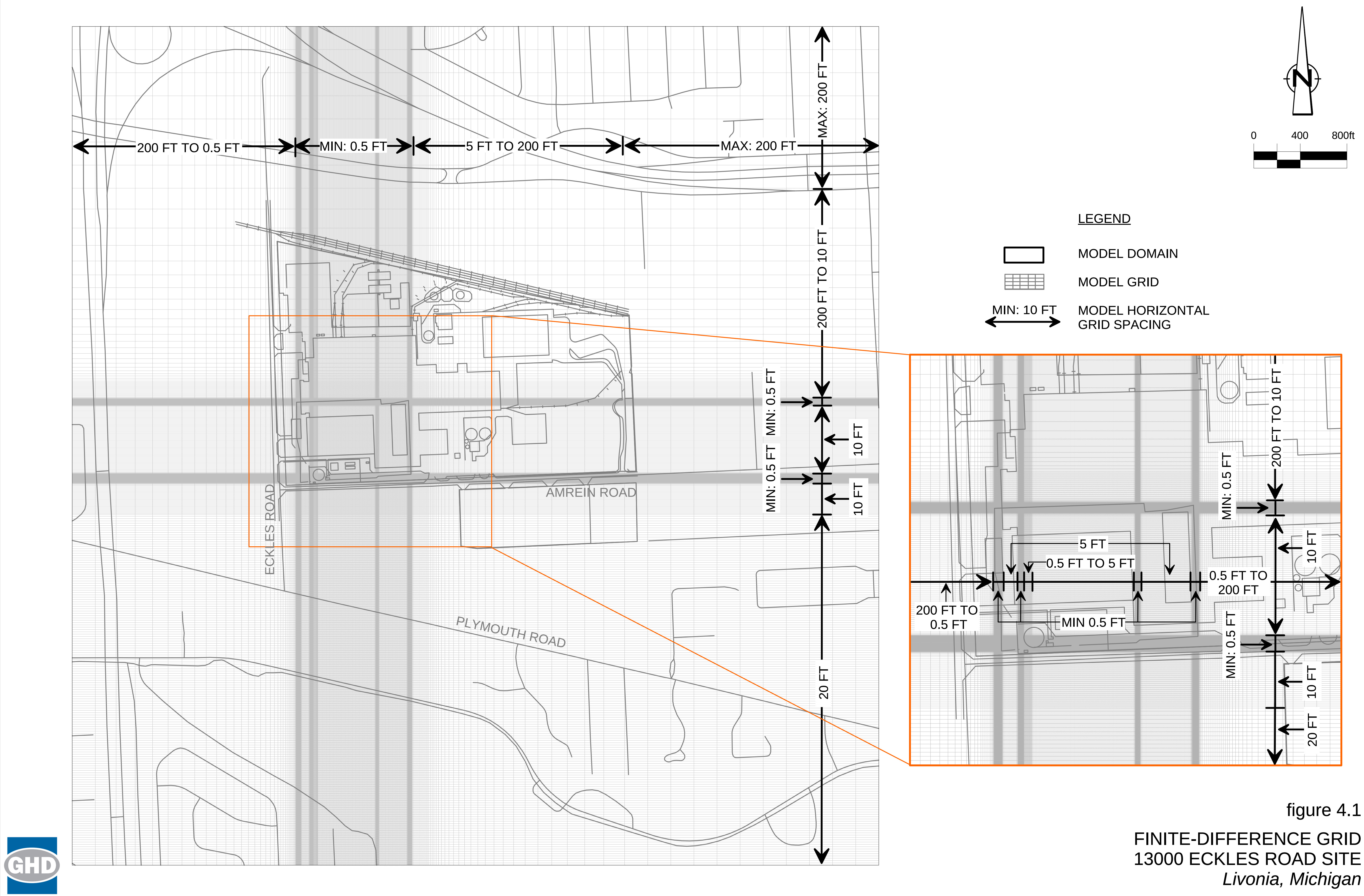
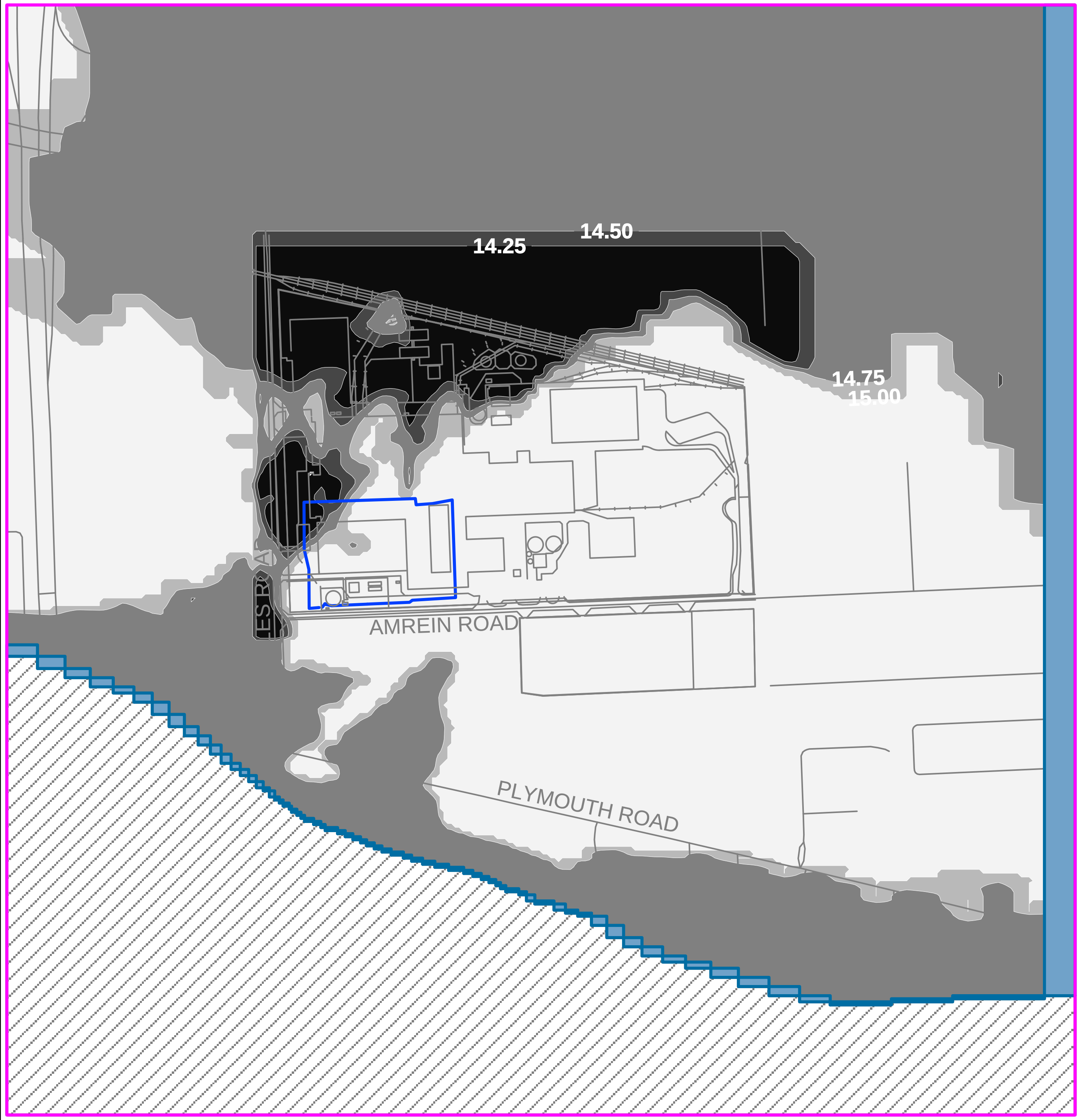


figure 4.1

FINITE-DIFFERENCE GRID
13000 ECKLES ROAD SITE
Livonia, Michigan

12607-T02Y17(072)GN-WA-HYD (Z:\HEG\012607\DOCUMENTATION\REPORTS\012607-RPT-72\FIGURES\12607-FiniteDifferenceGrid.srf) JUN 12/2017

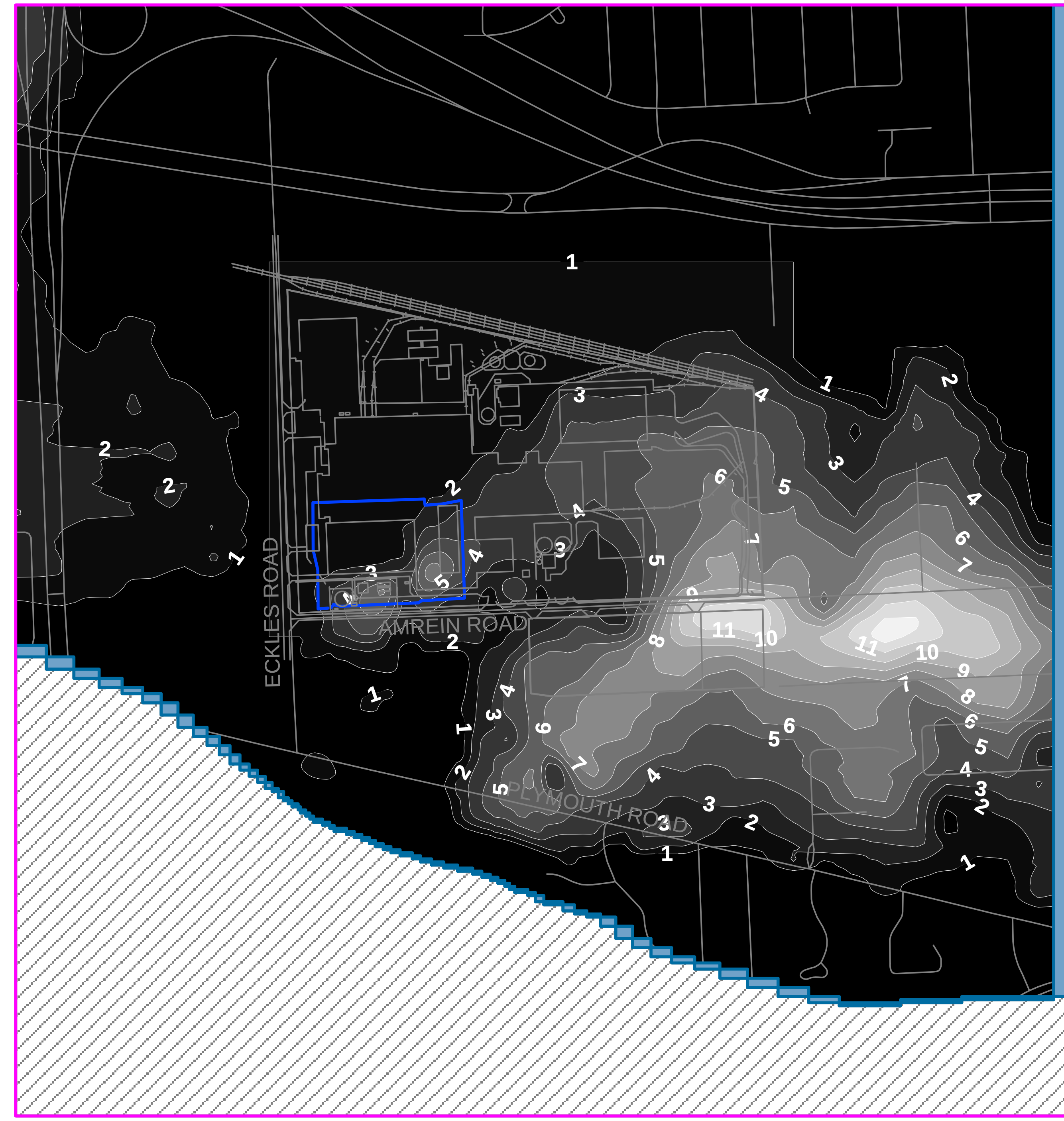
MODEL LAYER 1 THICKNESS CONTOURS



MODEL LAYER 1 (LAYER THROUGH WHICH WATER WILL FLOW THROUGH THE PRG) THICKNESS (FEET)

14.00 14.25 14.50 14.75 15.00

MODEL LAYER 7 THICKNESS CONTOURS



MODEL LAYER 7 (LAYER THAT INCLUDES FRENCH DRAIN SYSTEM) THICKNESS (FEET)

1 2 3 4 5 6 7 8 9 10 11 12 13

LEGEND

- MODEL DOMAIN
- NO-FLOW BOUNDARY CONDITION
- LINEARLY VARIABLE CONSTANT HEAD BOUNDARY CONDITION
- –14.25– MODEL LAYER THICKNESS CONTOUR
- BARRIER WALL

0 500 1,000ft

figure 4.2

MODEL LAYER THICKNESSES (LAYERS 1 AND 7)
13000 ECKLES ROAD SITE
Livonia, Michigan

12607-T02Y17(072)GN-WA-HYD (Z:\HEG\012607\DOCUMENTATION\REPORTS\012607-RPT-72\FIGURES.srf) JUL 20/2017

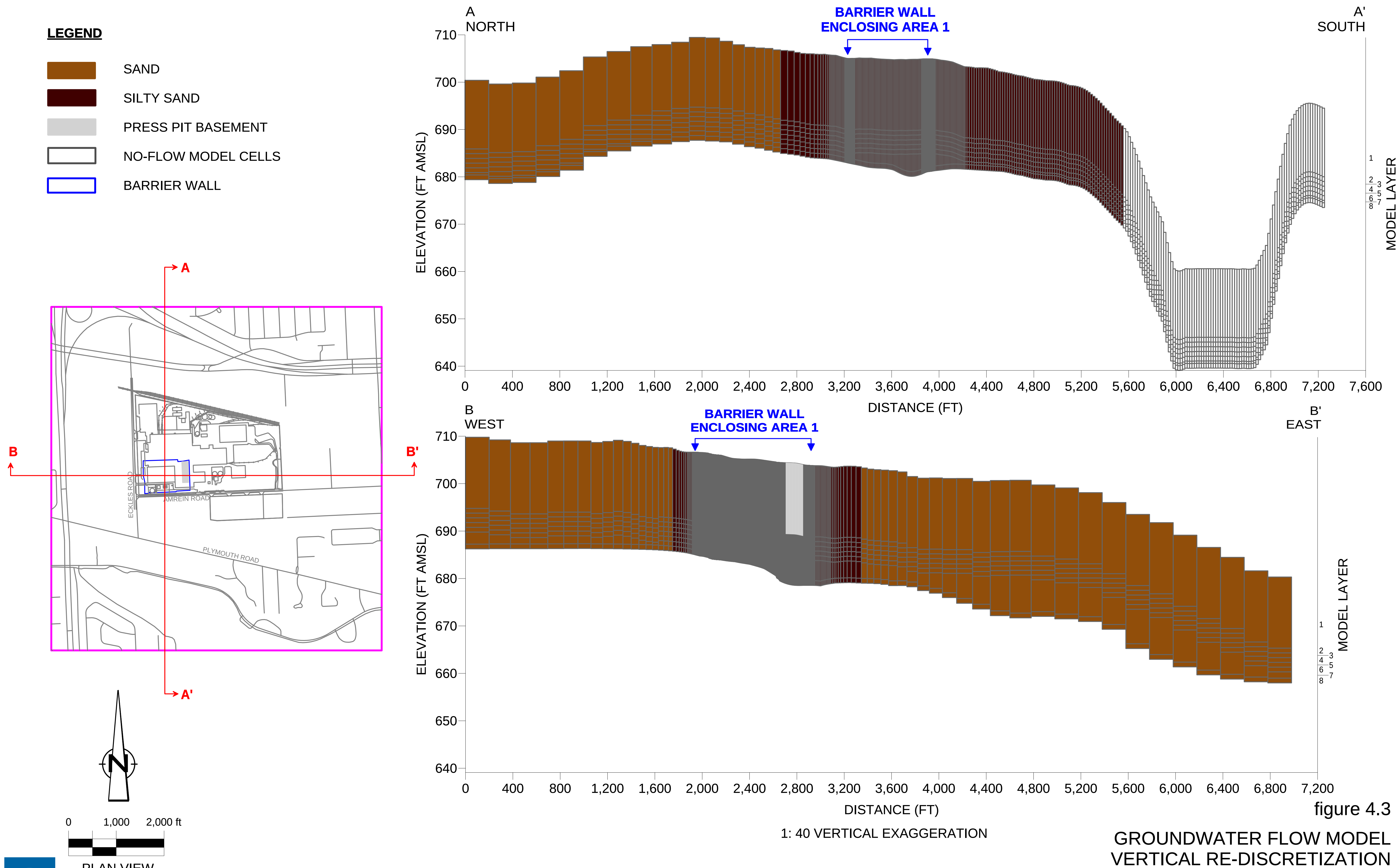


figure 4.3

GROUNDWATER FLOW MODEL
VERTICAL RE-DISCRETIZATION
13000 ECKLES ROAD SITE
Livonia, Michigan

12607-T02Y17(072)GN-WA-HYD (Z:\HEG\012607\DOCUMENTATION\REPORTS\012607-RPT-72\FIGURES\12607-VerticalDiscretization.srf) JUN 12/2017

LEGEND

MODEL DOMAIN

NO-FLOW BOUNDARY CONDITION

LINEARLY VARIABLE CONSTANT HEAD BOUNDARY CONDITION

FRENCH DRAIN COLLECTION SYSTEM

-0.005 GROUNDWATER FLOW MODEL - 8 LAYER MODEL GROUNDWATER ELEVATION DIFFERENCE CONTOUR (FEET)

0 400 800ft

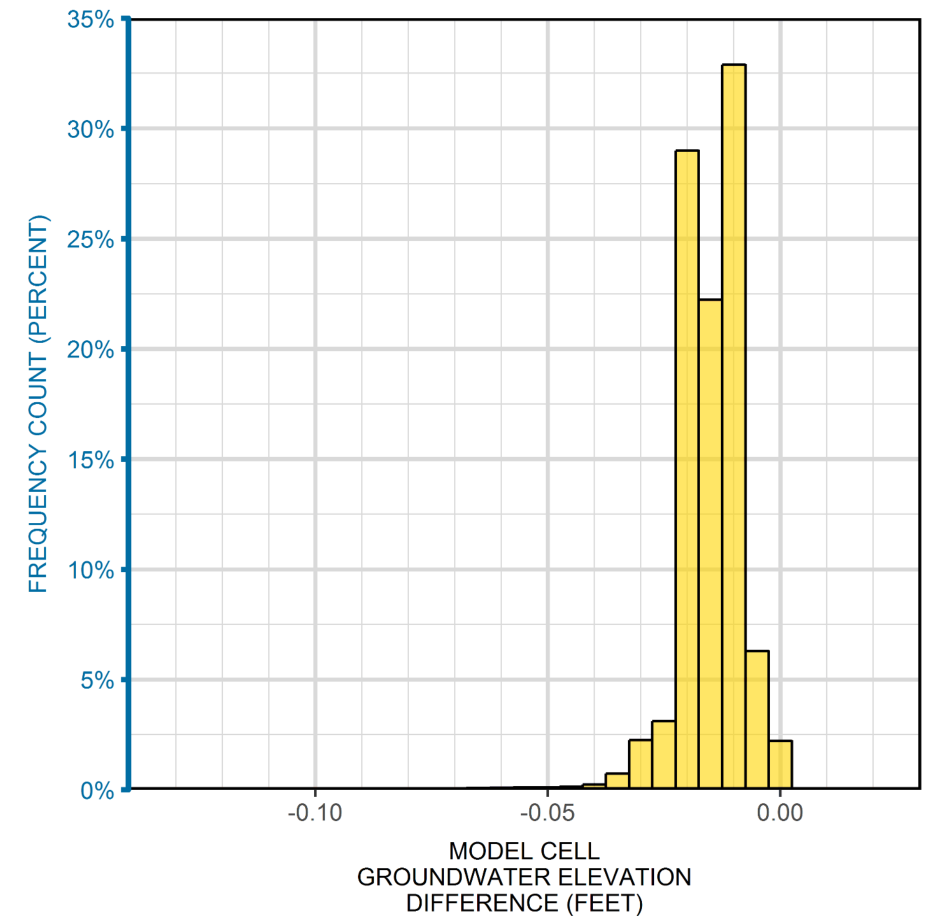


figure 4.4

GROUNDWATER FLOW MODEL - 8 LAYER MODEL
GROUNDATER ELEVATION DIFFERENCES
13000 ECKLES ROAD SITE
Livonia, Michigan

12607-T02Y17(072)GN-WA-HYD (Z:\HEG\012607\DOCUMENTATION\REPORTS\012607-RPT-72\FIGURES\12607-modeldifference.srf) JUN 30/2017

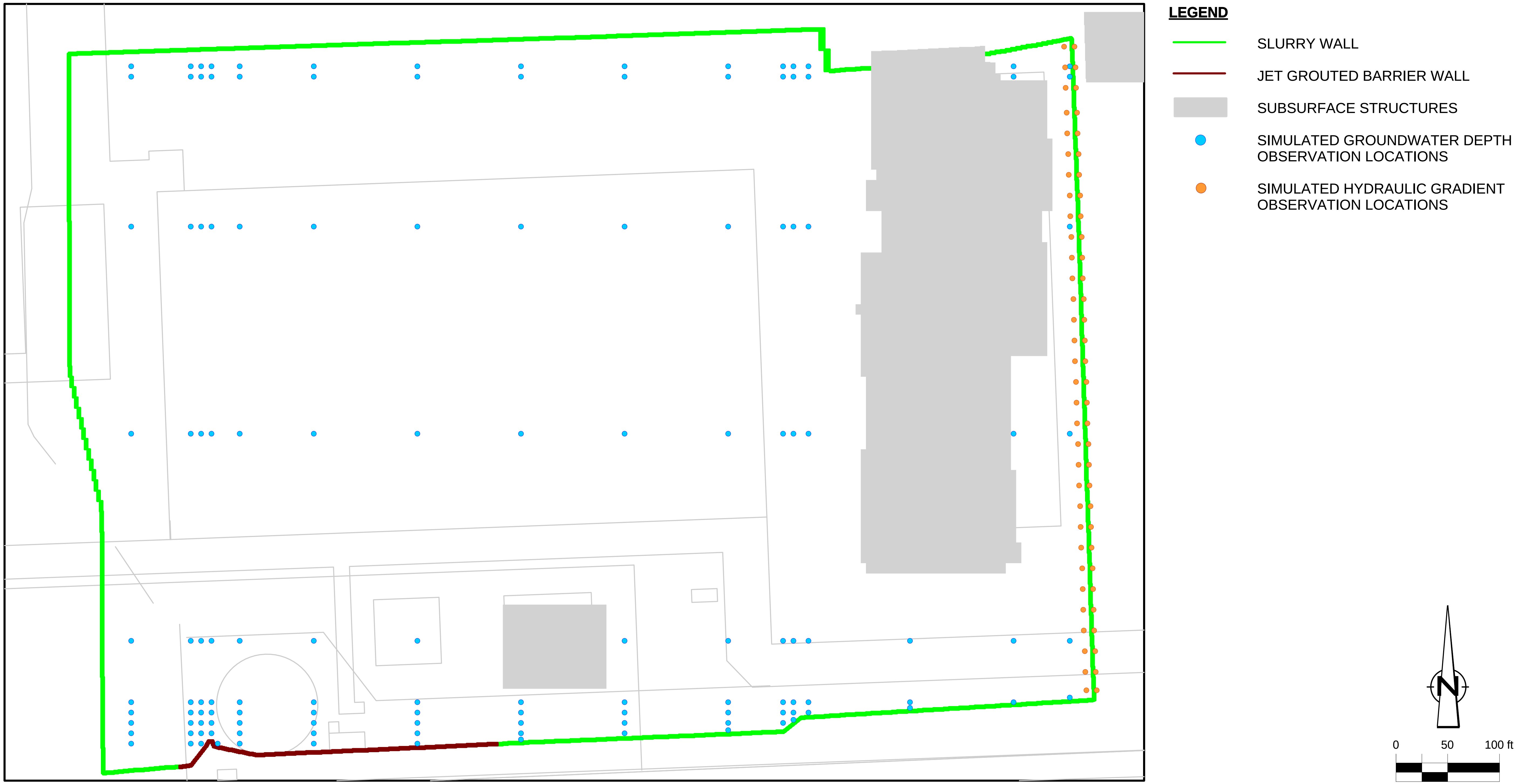


figure 4.5

SIMULATED GROUNDWATER DEPTH
AND HYDRAULIC GRADIENT OBSERVATION LOCATIONS
13000 ECKLES ROAD SITE
Livonia, Michigan

100 FT PERMEABLE REACTIVE GATES (PRGs)

SOUTHEAST PRG

OFFSET SOUTHEAST PRG

MAXIMUM-SIZED PERMEABLE REACTIVE GATES (PRGs)

SOUTHEAST PRG

OFFSET SOUTHEAST PRG

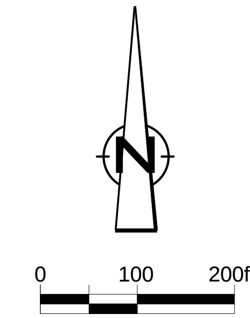


figure 4.6

PERMEABLE REACTIVE GATE SCENARIO LOCATIONS
13000 ECKLES ROAD SITE
Livonia, Michigan

GHD

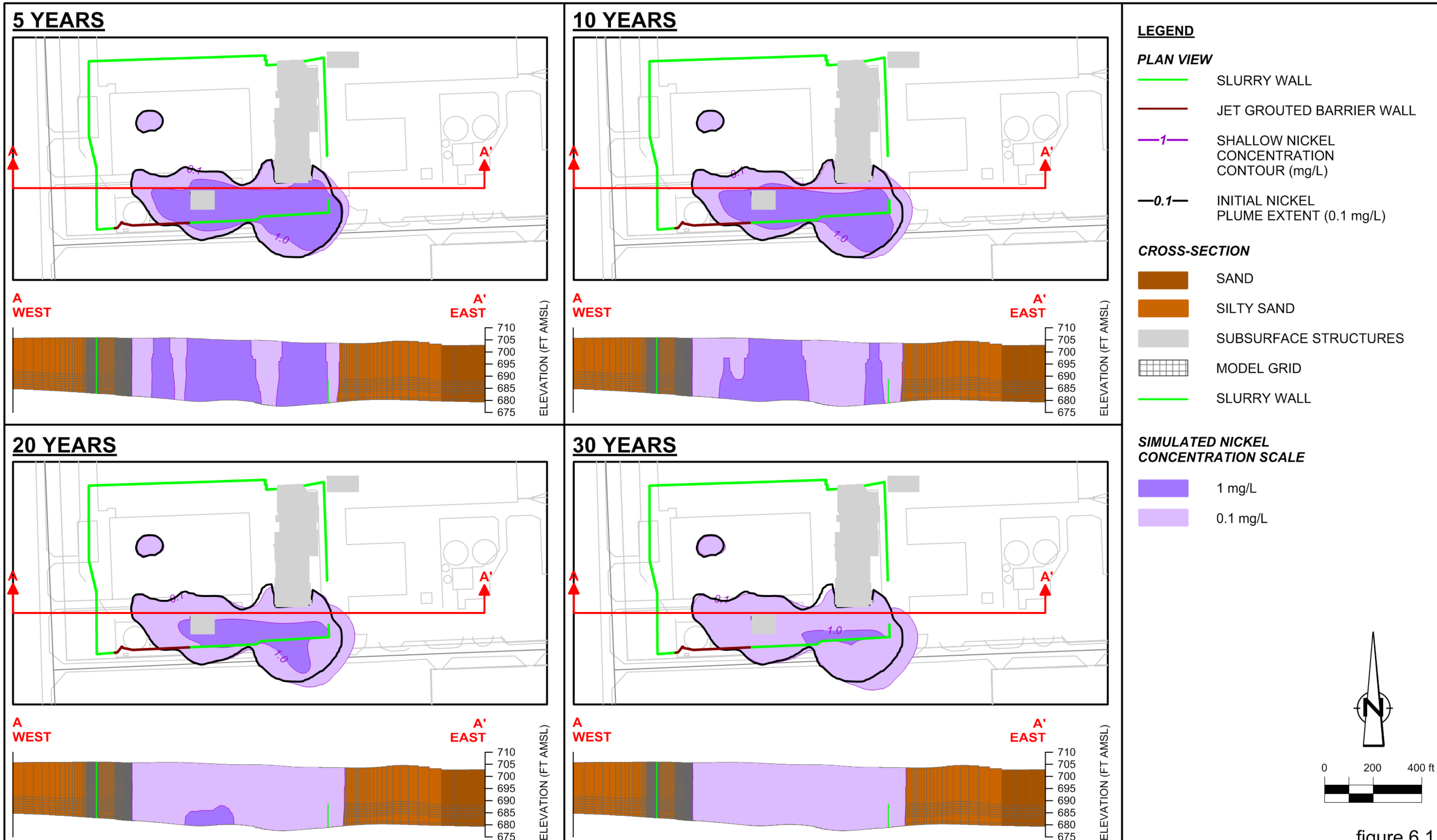


figure 6.1

PLAN VIEW AND CROSS-SECTION SIMULATED GROUNDWATER NICKEL PLUMES (20% ZVI PRG MEDIA)
13000 ECKLES ROAD SITE
Livonia, Michigan

GHD

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Table 5.1

Summary of Southeastern PRG Model Results
13000 Eckles Road Site
Livonia, Michigan

Recharge (in/year)	9.6	10.1	10.5	10.9	11.4	11.8	12.0	12.3	12.7	13.1	13.6	14.0	14.5	14.9	15.3	15.8	16.2	16.6	17.1	17.5	18.0
Gate Length (ft)	**Minimum Depth (ft bgs)(1)**																				
100	5.58	5.56	5.54	5.52	5.50	5.48	5.48	5.46	5.45	5.43	5.41	5.39	5.37	5.35	5.34	5.32	5.30	5.28	5.26	5.24	5.23
140	5.58	5.56	5.54	5.52	5.51	5.49	5.48	5.47	5.45	5.43	5.41	5.39	5.38	5.36	5.34	5.32	5.30	5.28	5.27	5.25	5.23
180	5.58	5.57	5.55	5.53	5.51	5.49	5.49	5.47	5.45	5.44	5.42	5.40	5.38	5.36	5.34	5.33	5.31	5.29	5.27	5.25	5.23
220	5.59	5.57	5.55	5.54	5.52	5.50	5.49	5.48	5.46	5.44	5.43	5.41	5.39	5.37	5.35	5.33	5.31	5.30	5.28	5.26	5.24
260	5.60	5.58	5.57	5.55	5.53	5.51	5.50	5.49	5.47	5.46	5.44	5.42	5.40	5.38	5.36	5.34	5.33	5.31	5.29	5.27	5.25
300	5.62	5.60	5.58	5.56	5.55	5.53	5.52	5.51	5.49	5.47	5.45	5.43	5.42	5.40	5.38	5.36	5.34	5.32	5.31	5.29	5.27
340	5.64	5.62	5.60	5.59	5.57	5.55	5.54	5.53	5.51	5.49	5.48	5.46	5.44	5.42	5.40	5.38	5.36	5.35	5.33	5.31	5.29
380	5.67	5.65	5.64	5.62	5.60	5.58	5.57	5.56	5.54	5.53	5.51	5.49	5.47	5.45	5.43	5.41	5.40	5.38	5.36	5.34	5.32
420	5.71	5.69	5.68	5.66	5.64	5.62	5.62	5.60	5.58	5.57	5.55	5.53	5.51	5.49	5.47	5.46	5.44	5.42	5.40	5.38	5.36
460	5.76	5.74	5.72	5.70	5.69	5.67	5.66	5.65	5.63	5.61	5.59	5.58	5.56	5.54	5.52	5.50	5.48	5.47	5.45	5.43	5.41
500	5.80	5.78	5.77	5.75	5.73	5.71	5.71	5.69	5.68	5.66	5.64	5.62	5.60	5.58	5.57	5.55	5.53	5.51	5.49	5.47	5.46
540	5.83	5.81	5.80	5.78	5.76	5.74	5.74	5.72	5.71	5.69	5.67	5.65	5.63	5.61	5.60	5.58	5.56	5.54	5.52	5.50	5.49
580	5.82	5.81	5.79	5.77	5.75	5.73	5.73	5.71	5.70	5.68	5.66	5.64	5.62	5.60	5.59	5.57	5.55	5.53	5.51	5.49	5.48
620	5.69	5.67	5.65	5.63	5.62	5.60	5.59	5.58	5.56	5.54	5.52	5.50	5.49	5.47	5.45	5.43	5.41	5.39	5.38	5.36	5.34
636.5	5.64	5.62	5.60	5.58	5.56	5.54	5.54	5.52	5.50	5.49	5.47	5.45	5.43	5.41	5.39	5.37	5.36	5.34	5.32	5.30	5.28

Recharge (in/year)	9.6	10.1	10.5	10.9	11.4	11.8	12.0	12.3	12.7	13.1	13.6	14.0	14.5	14.9	15.3	15.8	16.2	16.6	17.1	17.5	18.0
Gate Length (ft)	**Hydraulic Residence Time (hours)(2)**																				
100	22.5	22.6	22.6	22.6	22.7	22.7	22.8	22.8	22.8	22.9	22.9	23.0	23.1	23.1	23.2	23.2	23.2	23.3	23.4	23.4	23.5
140	23.6	23.7	23.7	23.8	23.8	23.9	23.9	23.9	24.0	24.0	24.1	24.1	24.2	24.2	24.3	24.4	24.4	24.5	24.5	24.6	24.6
180	24.2	24.2	24.3	24.4	24.4	24.5	24.5	24.5	24.6	24.6	24.7	24.7	24.8	24.8	24.9	25.0	25.0	25.1	25.1	25.2	25.2
220	24.5	24.6	24.6	24.7	24.8	24.8	24.8	24.9	24.9	25.0	25.0	25.1	25.2	25.2	25.3	25.3	25.4	25.4	25.5	25.6	25.6
260	24.8	24.8	24.9	24.9	25.0	25.1	25.1	25.1	25.2	25.2	25.3	25.3	25.4	25.4	25.5	25.6	25.6	25.7	25.7	25.8	25.9
300	24.9	25.0	25.0	25.1	25.1	25.2	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.6	25.7	25.7	25.8	25.8	25.9	25.9	26.0
340	25.0	25.1	25.1	25.2	25.3	25.3	25.3	25.4	25.4	25.5	25.5	25.6	25.7	25.7	25.8	25.8	25.9	25.9	26.0	26.1	26.1
380	25.1	25.2	25.2	25.3	25.3	25.4	25.4	25.4	25.5	25.6	25.6	25.7	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.2	26.2
420	25.2	25.2	25.3	25.3	25.4	25.4	25.4	25.5	25.6	25.6	25.7	25.7	25.8	25.8	25.9	26.0	26.0	26.1	26.2	26.2	26.3
460	25.2	25.2	25.3	25.3	25.4	25.5	25.5	25.5	25.6	25.6	25.7	25.8	25.8	25.9	25.9	26.0	26.1	26.1	26.2	26.2	26.3
500	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.5	25.6	25.7	25.7	25.8	25.8	25.9	26.0	26.0	26.1	26.1	26.2	26.2	26.3
540	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.6	25.6	25.7	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.2	26.2	26.3	26.3
580	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.6	25.6	25.7	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.2	26.2	26.3	26.3
620	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.6	25.6	25.7	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.2	26.2	26.3	26.4
636.5	25.2	25.3	25.3	25.4	25.4	25.5	25.5	25.5	25.6	25.7	25.7	25.8	25.9	25.9	26.0	26.0	26.1	26.2	26.2	26.2	26.1

Notes:

(1) Minimum depths are colored red if groundwater is less than 2 ft bgs or green if groundwater is equal to or greater than 2 ft bgs.

(2) Hydraulic residence time are colored red if they are less than 30 hours or green if they are equal or greater than 30 hours.

Table 5.2

Summary of Offset Southeastern PRG Model Results
13000 Eckles Road Site
Livonia, Michigan

Recharge (in/year)	9.6	10.1	10.5	10.9	11.4	11.8	12.0	12.3	12.7	13.1	13.6	14.0	14.5	14.9	15.3	15.8	16.2	16.6	17.1	17.5	18.0
Gate Length (ft)	**Minimum Depth (ft bgs)(1)**																				
100	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.3	5.2	5.2
140	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.3	5.2	5.2
180	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.3	5.2
220	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.3	5.3
260	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.3
300	5.6	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3
340	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.3	5.3
380	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4
420	5.8	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4
460	5.8	5.8	5.8	5.8	5.7	5.7	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5
500	5.8	5.8	5.8	5.8	5.8	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5
540	5.8	5.8	5.8	5.8	5.7	5.7	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5
580	5.7	5.6	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3
586.5	5.6	5.6	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.4	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3

Recharge (in/year)	9.6	10.1	10.5	10.9	11.4	11.8	12.0	12.3	12.7	13.1	13.6	14.0	14.5	14.9	15.3	15.8	16.2	16.6	17.1	17.5	18.0
Gate Length (ft)	**Hydraulic Residence Time (hours)(2)**																				
100	25.6	25.6	25.7	25.7	25.7	25.8	25.8	25.8	25.8	25.9	25.9	26	26	26.1	26.1	26.1	26.2	26.2	26.3	26.3	26.4
140	28.2	28.2	28.3	28.3	28.4	28.4	28.4	28.5	28.5	28.5	28.6	28.6	28.7	28.7	28.7	28.8	28.8	28.8	28.9	28.9	29
180	30.1	30.2	30.2	30.3	30.4	30.4	30.4	30.5	30.6	30.6	30.7	30.8	30.8	30.9	30.9	30.9	30.9	31	31	31.1	31.1
220	30.7	30.7	30.8	30.8	30.9	31	31	31.1	31.1	31.2	31.2	31.3	31.4	31.4	31.5	31.6	31.7	31.7	31.8	31.9	32
260	31	31.1	31.1	31.2	31.2	31.3	31.4	31.4	31.5	31.5	31.6	31.7	31.7	31.8	31.9	32	32	32.1	32.2	32.3	32.3
300	31.2	31.3	31.4	31.4	31.5	31.6	31.6	31.6	31.7	31.8	31.8	31.9	32	32	32.1	32.2	32.3	32.3	32.4	32.5	32.6
340	31.4	31.4	31.5	31.6	31.7	31.7	31.8	31.8	31.9	31.9	32	32.1	32.1	32.2	32.3	32.3	32.4	32.5	32.6	32.7	32.7
380	31.5	31.5	31.6	31.7	31.8	31.8	31.8	31.9	32	32	32.1	32.2	32.2	32.3	32.4	32.5	32.5	32.6	32.7	32.7	32.9
420	31.5	31.6	31.7	31.8	31.8	31.9	31.9	32	32	32.1	32.2	32.3	32.3	32.4	32.5	32.5	32.6	32.7	32.7	32.8	32.9
460	31.6	31.7	31.7	31.8	31.8	32	32	32	32.1	32.2	32.2	32.3	32.3	32.4	32.5	32.6	32.6	32.7	32.8	32.9	33
500	31.6	31.7	31.8	31.8	31.9	32	32	32	32.1	32.2	32.3	32.3	32.4	32.5	32.5	32.6	32.7	32.8	32.9	32.9	33
540	31.6	31.7	31.8	31.8	31.9	32	32	32	32.1	32.2	32.3	32.3	32.4	32.5	32.5	32.6	32.7	32.8	32.9	32.9	33
580	31.6	31.7	31.7	31.8	31.9	32	32	32	32.1	32.1	32.3	32.3	32.4	32.5	32.5	32.6	32.7	32.8	32.8	32.9	33
586.5	31.6	31.7	31.8	31.8	31.9	32	32	32	32.1	32.2	32.2	32.3	32.4	32.4	32.5	32.6	32.7	32.7	32.9	32.9	33

Notes:

(1) Minimum depths are colored red if groundwater is less than 2 ft bgs or green if groundwater is equal to or greater than 2 ft bgs.

(2) Hydraulic residence time are colored red if they are less than 30 hours or green if they are equal or greater than 30 hours.

Table 6.1

Parameter Calculations
for Langmuir Nickel Adsorption Isotherm
13000 Eckles Road Site
Livonia, Michigan

Nickel[1]

Well ID	Soil Concentration (mg/kg)	Groundwater Concentration (mg/L)	C_w/C_{ads} (kg/L)
MW-A1/33-3S	4	0.007	0.002
MW-A1/33-4S	5	0.01	0.002
MW-A1/33-5S	5	0.004	0.001
MW-A1/33-7S	5	0.003	0.001
MW-A1/33-8D	7	0.01	0.001
MW-A1/33-8S	5	0.04	0.01
MW-A1-4D	4	0.04	0.01
MW-A1-5D	15	0.02	0.001
MW-A1-6S	7	0.004	0.001
MW-A1-7S	7	0.01	0.002
MW-A1-8D	4	18	5
MW-A1-9D	4	0.007	0.002
MW-A1-10D	5	0.01	0.003
MW-A1-11D	5	589[3]	125[3]
MW-A1-12D	6	29	5
MW-A1-13S	7	38	5
MW-A1-14D	7	0.01	0.002
MW-S-2S	6	0.02	0.003
MW-S-3S	6	40	7
MW-S-7S	8	18	2
MW-S-8D	6	17	3
MW-S-9S	5	0.5	0.1
MW-S-10D	6	0.02	0.003
MW-W-2S	6	0.003	0.001
MW-A1-5D	15	0.02	0.001
MW-A1-12D	38	29	0.8
MW-A1-13S	14	40	3
MW-S-3S	102	16	0.2
SB-2-1	5	0.01	0.002
SB-2-2	6	0.006	0.001
SB-2-3	6	0.008	0.001
SB-5-2	89	ND (0.025) U	-
SB-21-1	7	ND (0.025) U	-
SB-21-2	18	0.03	0.002
SB-22-1	8	0.01	0.002
SB-22-2	21	0.02	0.001
SB-28-1	18	0.006	0.0003
SB-28-2	321	0.06	0.0002
SB-28-3	15	0.004	0.0002
SB-A1/33-2	7	0.007	0.001
SB-A1/33-3	6	0.009	0.001
SB-A1/33-4	6	0.02	0.003

Table 6.1

Parameter Calculations
for Langmuir Nickel Adsorption Isotherm
13000 Eckles Road Site
Livonia, Michigan

Nickel[1]

Well ID	Soil Concentration (mg/kg)	Groundwater Concentration (mg/L)	C_w/C_{ads} (kg/L)
SB-A1-7	675	0.3	0.0004
SB-A1-10	95	1	0.01
SB-A1-20	138	0.09	0.001
SB-A1-22	2760	70	0.025

Parameter Calculations[2]

Calculated $C_{ads, max}$ (mg/kg) = 14
Calculated K_{ads} (L/mg) = 0.3
Calculated K_{ads} (L/kg) = 347

Notes:

(1) Based on concentrations presented in Field Pilot Test Work Plan - Area 1 (Chrome Plating Area) (CRA, 2004)
(2) Parameter calculations based on Equations 8.4 and 8.5 in main report
(3) Concentration value not used in calculations of $C_{ads, max}$ and K_{ads}

Table 6.2

Column Study Groundwater Analysis Column 3 - OW-24 - High Chromium
Area 1 - Former Plating Area
13000 Eckles Road Site, Livonia, Michigan

Parameters	Units	Initial	1st Sampling	2nd Sampling	3rd Sampling	4th Sampling*	5th Sampling
Flow Rate	mL/min	-	2.0	1.0	0.1	0.1	0.2
HRT	hours		1.5	3.0	30.0	30.0	15.0
Volume of GW Passed Through	mL	-	570	460	820	250*	1140
Dissolved Metals							
Dissolved Chromium	µg/L	199000	195000	106000	75033	23.4	87732
Dissolved Nickel	µg/L	30600	11400	9360	1094	3.78 J	108
Dissolved Zinc	µg/L	54.7	35.9	29.3	21.6	8.69	ND (20)
Percent Removal of Chromium	%		2.0	46.7	62.3	>99.9	55.9
Percent Removal of Nickel	%		62.7	69.4	96.4	>99.9	99.6
Percent Removal of Zinc	%		34.4	46.4	60.5	84.1	91.9

Notes:

ND (x) Not detected at reporting limit.
J Estimated result.
* Columns were repacked with 20% ZVI.