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**HIERARCHICAL GROUNDWATER MODELING AT THE
ZEPHYR SITE, MUSKEGON, MICHIGAN: EVALUATING THE
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SYSTEM**

presented by

Yang Li

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**HIERARCHICAL GROUNDWATER MODELING AT THE ZEPHYR SITE,
MUSKEGON, MICHIGAN: EVALUATING THE EFFECTIVENESS OF THE
REMEDATION CAPTURE SYSTEM**

By

Yang Li

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

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Civil Engineering

2009

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ABSTRACT

HIERARCHICAL GROUNDWATER MODELING AT THE ZEPHYR SITE, MUSKEGON, MICHIGAN: EVALUATING THE EFFECTIVENESS OF THE REMEDATION CAPTURE SYSTEM

By

Yang Li

In this thesis, a hierarchical groundwater modeling system integrating the 10m Digital Elevation Model and site-specific hydrogeologic data was developed for the Zephyr site, Muskegon, Michigan. The site is currently under active remediation using pump and treats through a network of 60 low capacity wells and 10 injection trenches. The hierarchical system was calibrated to steady state water level data from 128 on-site monitoring wells with and without remediation stresses.

Through a series of nested “patch dynamic” models, the hierarchical system enables accurate simulation of detailed, complex well dynamics and capture zone distributions associated with very low capacity wells. Systematic model simulations, including forward and reverse particle tracking, as well as, integrated water budget analyses, were performed to evaluate the effectiveness of the remediation.

The results show that current remediation system is unable to capture contaminated groundwater and significant gaps exist between purge wells and offsite migration exists.

DEDICATION

**TO MY PARENTS
FOR THEIR SUPPORT AND UNDERSTANDING**

ACKNOWLEDGEMENTS

I gratefully acknowledge the contribution of those who have made this thesis possible.

My deepest gratitude goes to Dr. Shu-guang Li, Professor, Department of Civil and Environmental Engineering, Michigan State University, for his advice, patience, and encouragement.

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LIST OF ABBREVIATIONS

GPM: Gallon per Minute;

BETX: Benzene, Toluene, Ethylbenzene, Xylene;

**Hierarchical Groundwater Modeling of a Remediation Capture System in
Muskegon, Michigan**

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ABSTRACT

In this paper, we demonstrate a generalized hierarchical approach for modeling complex groundwater systems. In particular, we demonstrate how the “hierarchical patch dynamics modeling” approach developed by Li and his co-workers [Li et al., 2005, 2006, 2007; 2009; Afshari et al., 2009] enable simulating, in a highly flexible and efficient manner, a complex plume capture system at one of the largest groundwater remediation operations in Michigan. The groundwater flow system at the site, because of the complex interaction between ambient hydrologic stresses and on-site remediation operations, exhibits a unique multiscale pattern that proves to be difficult to simulate using standard modeling tools. The hierarchical modeling system was calibrated to water level measurements collected from more than 120 monitoring wells located both on site and in the immediate proximity. Systematic hierarchical simulations, including forward and reverse particle tracking, as well as, integrated water budget analyses, were performed to evaluate the effectiveness of the on-going remediation. The results provided critical information that is being used to improve the design of the pump and treat system.

INTRODUCTION

The site under study is located in Muskegon Township, a historically industrial area of approximately 150 acres surrounded by wetlands and surface water bodies, including Muskegon Lake, Bear Lake, Muskegon River, and Bear Creek (Figure 1). Decades of industrial activities in the area including petroleum refinery operations resulted in significant soil and groundwater contamination characterized by high concentrations in BETXs, chlorinated organic compounds, semi-volatile organic compounds, and free phases. Monitoring suggested that contamination had migrated offsite.

Since 2000, the State of Michigan has been operating and maintaining a pump and treat remediation system on the site, with a goal to hydraulically contain the large plumes, minimize offsite impact, recover free products, and ultimately cleanup the contamination. The remediation system is composed of a large network of 59 low capacity extraction wells (1 to 10 GPM), an extraction trench system, and 10 injection trenches, two 60,000 gallon above-ground bioreactors, and one 60,000 gallon clarifier tank (Figure 2). The extracted groundwater is treated on-site in the bioreactors and clarifier tank prior to re-injecting the treated groundwater into the ground through infiltration trenches. The network was designed to operate at a total flow rate of approximately 250 GPM.

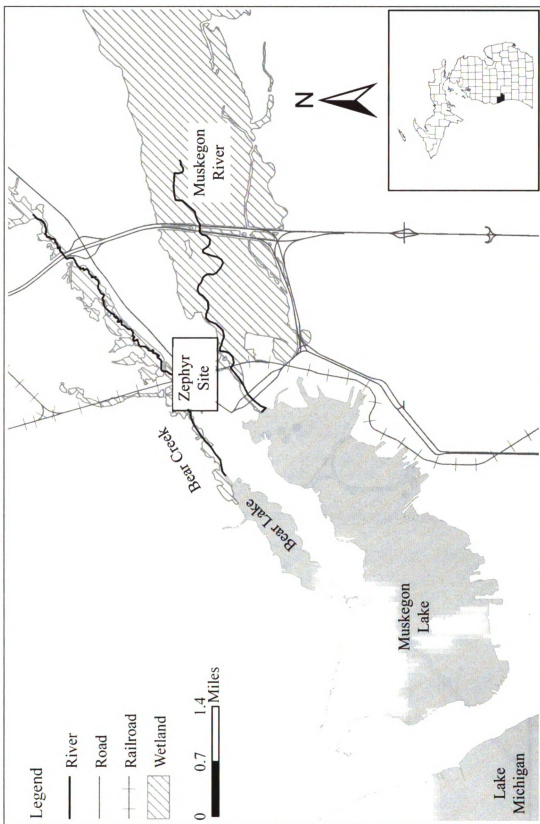


Figure 1 Site Map

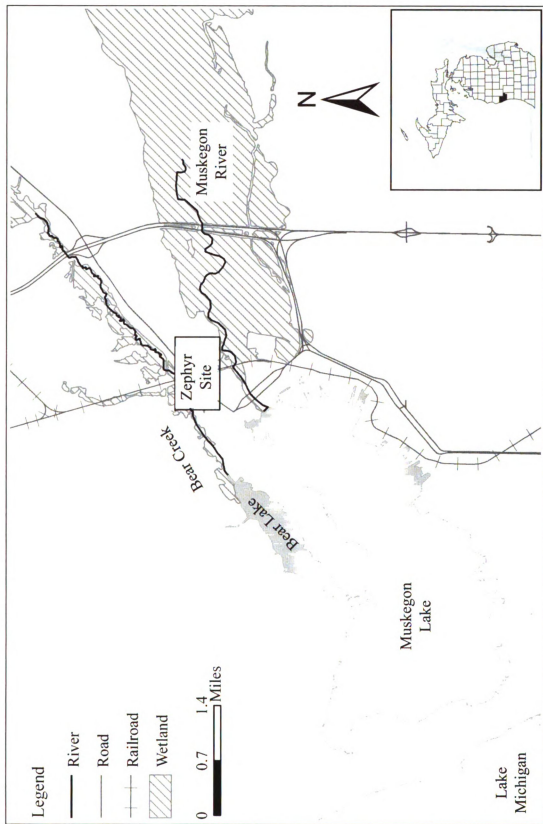


Figure 1 Site Map

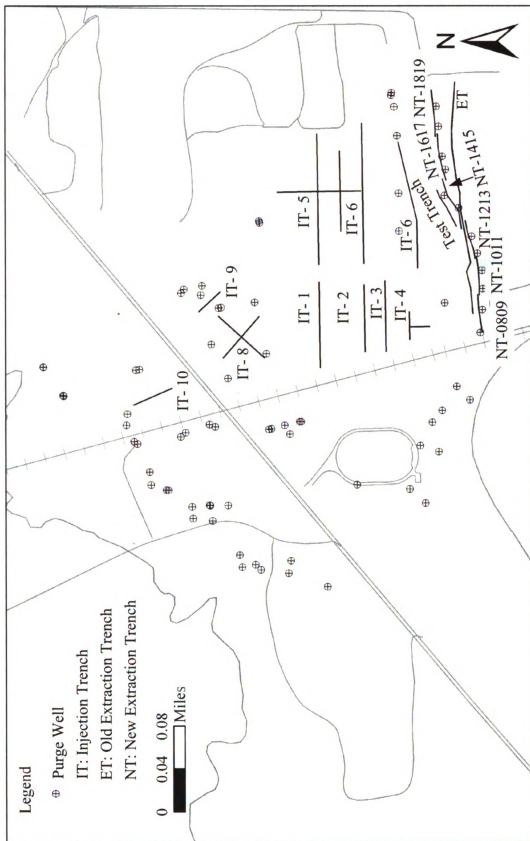


Figure 2 Purge Wells, and Injection/ Extraction Trench System

Systematic sampling over years shows that concentrations of key contaminants in many monitoring wells, especially those in the source areas, have significantly declined.

Many questions, however, still remain:

- How are the site wide plumes responding to the complex pumping and injection stresses?
- Is the remediation system containing the contamination?
- Can the remediation system be optimized to significantly improve cleanup efficiency and reduce operational costs?

One earlier investigation tackled these issues through a systematic groundwater modeling study, but the effort was not particularly effective. One major limitation of the earlier effort lies in that the model developed was unable to capture critical details and multiscale interactions essential to remediation system evaluation and optimization.

The groundwater flow in the area is characterized by complex interplay of significant variability across disparate length scales. These include variations at “well scale”, “site scale”, and “regional scale”. At the well scale, pumping by extraction wells across the site creates a network of small drawdown cones, each with a characteristic length scale of 1 to 5ft. At the site scale, the combined effects of aggregated pumping, injection, natural recharge, and drainage to extraction trenches, surface seeps, local wetlands, and surface water bodies create a complex, large groundwater mound spanning across thousands of feet. Regionally, groundwater flow is controlled by Muskegon Lake and Muskegon River,

the global sink in the Muskegon watershed. These different scales of variations must all be properly taken into account in order to simulate properly the groundwater flow system at the site and to quantify and optimize remediation system performance.

Several methods can in principle be used to model the multiscale groundwater flow system, but they all have limitations. The most commonly used methods include: 1) local grid refinement (e.g., Fung, L.S.-K, 1992; Gable et al., 1996; Heinemann, 1983), 2) local nested analytical correction (Prickett, 1967; Peaceman, 1978; Pritchett and Garg, 1980), and 3) local nested numerical correction (e.g., Ward et al., 1987; Efendiev et al., 2000; Mehl and Hill, 2002). In the following paragraphs, we briefly review the advantages and disadvantages of these methods.

Local Grid Refinement.

Local grid refinement represents the most commonly used method to predict detailed well dynamics in a numerical model. Relatively-large-size cells in a numerical model grid are subdivided or refined with progressively smaller spatial dimensions in the areas of interest (e.g., Fung, L.S.-K, 1992; Gable et al., 1996; Heinemann, 1983). This results in a more accurate estimation of hydraulic head or drawdown at the well scale. In other words, there will be less approximation error involved with averaging the predicted head for that particular well node. In using local refinement for simple or small-scale problems, the solution is obtained quickly, and the consistency between the regional and local area

around the wells is maintained. However, for large-scale, regional groundwater models where there may be a significant increase in the number of nodes (e.g., millions rather than thousands), the cost of computation increases exponentially and the process can become very expensive in terms of time and computer resources required.

Local Analytical Correction

An alternative approach to represent detailed well dynamics in a regional model is to use a local analytical correction within the cell containing the well based on the steady-state Thiem equation (Thiem, 1906; Anderson and Woessner, 1992). Trescott et al. (1976) systematically evaluated the performance of local analytical correction and showed that corrected drawdown is approximately applicable if the following assumptions are satisfied: (1) flow to the well is within a square finite-difference cell and can be described by a steady-state equation with no source term except for the well discharge, (2) the aquifer is isotropic and homogenous in the well cell, (3) only one well, located at the cell center, is in the well cell, and (4) the well fully penetrates the aquifer. Prichett and Garg (1980) provided formulas for analytical correction for model grid cell geometries other than square. Our own empirical experience shows that local analytical correction can lead to problematic flow pattern around wells although the corrected drawdown is reasonably accurate.

Local Numerical Correction

A more general approach for modeling detailed local well dynamics is through “local numerical correction” or nested grid modeling. In this approach, grid-dependent information from the regional model is used to construct a separate model with finer grid spacing to obtain more information around the area of interest (Ward et al., 1987; Efendiev et al., 2000; Mehl and Hill, 2002). The model with the finer grid is called a “submodel”, “patch model”, or “local model” which derives its initial and boundary conditions from the parent model (Townley and Wilson 1980; Ward et al. 1987; Buxton and Reilly 1986). The boundary conditions can be either interpolated heads or fluxes. Once the local model is created, it performs as an independent model. A nested grid approach avoids the potential difficulties encountered with local grid refinement by converting the original problem of solving a very large matrix system into one that solves multiple, much smaller matrix systems.

A major drawback in implementing the nested model approach is that the interaction between the parent and local models (of which there can be many) depends on the offline analysis and processing of model modifications or simulation results from the parent model to obtain the boundary and starting conditions for the local model. For example, once a new simulation is completed using the regional model, new boundary conditions and starting flow and solute transport conditions, if applicable, are determined for each local model at the local model grid spacing. Making modifications to models or

processing simulation results for use in different scales of models can be very time consuming; especially when the problem is a transient-flow or coupled with solute transport simulation, or a feedback loop is needed to account for potential significant two-way interaction between parent-nested submodels. The effort involved may become impractical when the offline conceptual changes must be made iteratively or in more than one model. Because of this, applications of the nested grid approach are limited, in most cases, to a very small number of submodels (e.g., 1 or 2), and are implemented with little flexibility. This practical implementation difficulty has severely limited our ability to take full advantage of the nested grid approach for solving complex groundwater problems, especially those that span across multiple spatial scales.

Hierarchical Groundwater Modeling

Li et al. (2006) recently developed a new method of implementing nested grid modeling. In particular, Li et al. (2006) took advantage of two emerging computing strategies – “dynamic fusion” and “interactive steering” to develop a dynamically-integrated, human-centered “hierarchical patch dynamics paradigm (HPDP)” for generalized hierarchical groundwater modeling. The HPDP was originally developed by Wu and his co-workers to address complexities and scale interactions in the context of landscape ecology and ecological modeling (Wu and Loucks 1995, Wu 1999, Wu and David 2002). The two modern computing strategies make it possible to employ arbitrary numbers of nested submodels (patch models) for solving much more complex groundwater

problems. Dynamic fusion enables realtime integration of modeling, subscale modeling, and visualization, eliminating a major bottleneck in nested grid modeling. In particular, it allows dynamically integrate all patch models at the end of each time-step during the simulation so that results from the parent-models (e.g., boundary-conditions), and any changes to the parent-models propagate dynamically and automatically to all patch models, without the need for offline post-processing.

The basic concept behind this strategy is straightforward. Instead of treating the simulation of groundwater flow and solute transport separately, Li et al. (2006) model both processes concurrently (sequential within a time step). Instead of treating the various scales of patch dynamic modeling (regional, subregional, local, site, hot spots) as different phases in a long sequential batch-process, the multi-scaled processes are coupled and modeled simultaneously. Instead of relegating the presentation and analysis of graphical results for each patch of interest to the “post-processing” phase, at the end of a time-consuming sequence of many disjointed steps, all results are presented at the end of each simulation step to permit the interpretation of results as soon as they become available.

Computational steering enables a new way of model-user interaction that is particularly beneficial for hierarchical modeling. It provides a mechanism to incorporate human intelligence in the incremental simulation process. It allows a modeler to interactively

steer the hierarchical computation, to control the program execution-sequence, to guide the evolution of the aquifer dynamics, to control the visual data representation during processing, and to dynamically modify the hierarchical computational process during its execution. At anytime, the modeler can interrupt the program to assess the solution, and based on this assessment, to insert patches in selected areas and layers of interest. As the modeling-hierarchies are dynamically-coupled, the modeler can work with large numbers of modeling patches, as if they are working with a single modeling system. The modeler can perform sensitivity analysis of the integrated system, making changes to patch boundaries, resolutions, conceptual representations, solvers, and iteratively assessing the influence of these changes on the final solutions.

ZEPHYR GROUNDWATER MODELING SYSTEM

We apply in this paper the dynamically integrated HPDP to model the multiscale groundwater flow system at the Zephyr site. Images in this thesis are presented in color.

Conceptual representation

Our modeling effort was systematically integrated with field investigations. Data were collected on-site to specifically support the modeling study. Additional data from the Michigan statewide geospatial databases and the statewide groundwater database were used to construct the modeling system. Figure 3 shows the sampling network that consists of 128 monitoring wells onsite and in the vicinity. Figure 3 shows conceptual aquifer cross section for Zephyr Site. Figure 4 shows a conceptual site representation created using the data available, depicting key sources, and sinks. Details of remediation components are shown by Figure 2. Some of the most salient hydrological features are summarized below:

- The site is located on a topographic plateau bordered immediately by wetlands and surface waters. A cliff exists between the site in the highland area and surrounding wetlands at lower elevations. Surface seeps can be detected at the cliff at some locations.

- The aquifer, formed of glaciofluvial deposits, outwash and till, has a relatively low conductivity, especially at lower elevations in the wetland area.
- The aquifer is underlain by a continuous layer of clay, providing an effective barrier to vertical migration of contaminants. The clay layer was encountered at approximately 115 boring locations and was not completely penetrated.
- The area within the Zephyr site, being relatively flat and covered by permeable top soil, has high potential for infiltration.
- Extracted and treated water is injected entirely back into the aquifer in and around the contamination source areas.

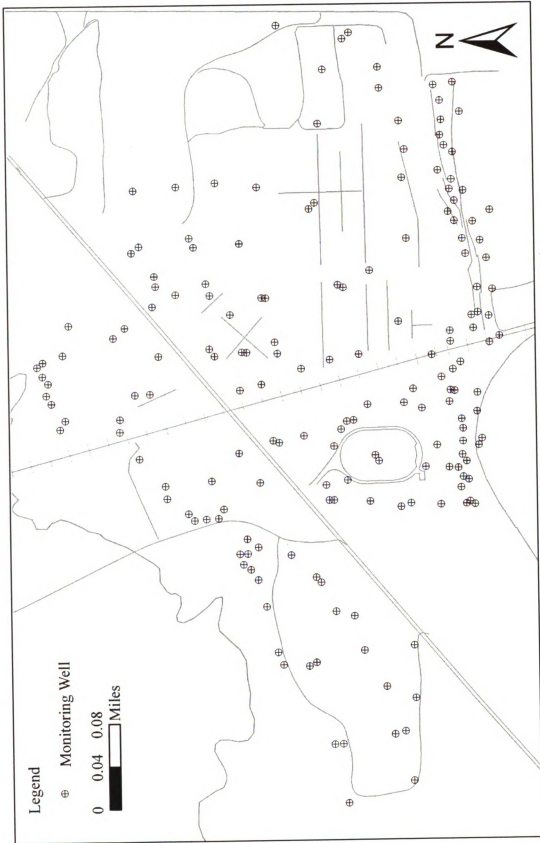


Figure 3 Sampling Network on site and in the vicinity

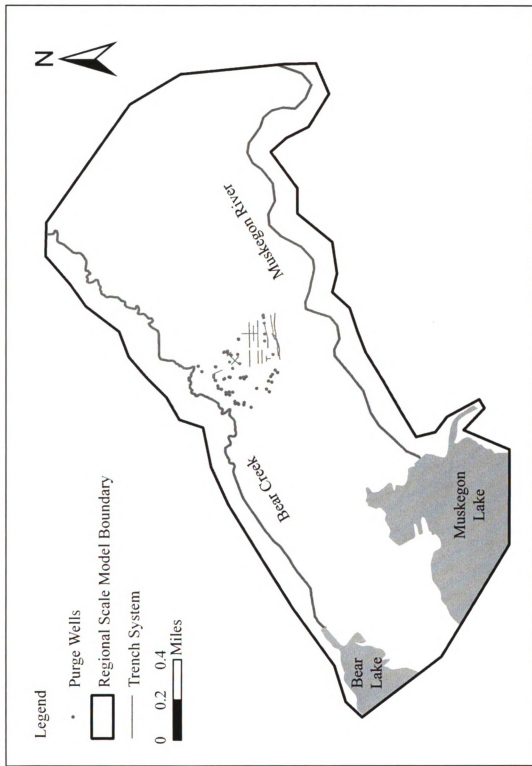


Figure 4 Conceptual Representation of key Sources, Sinks and Remediation

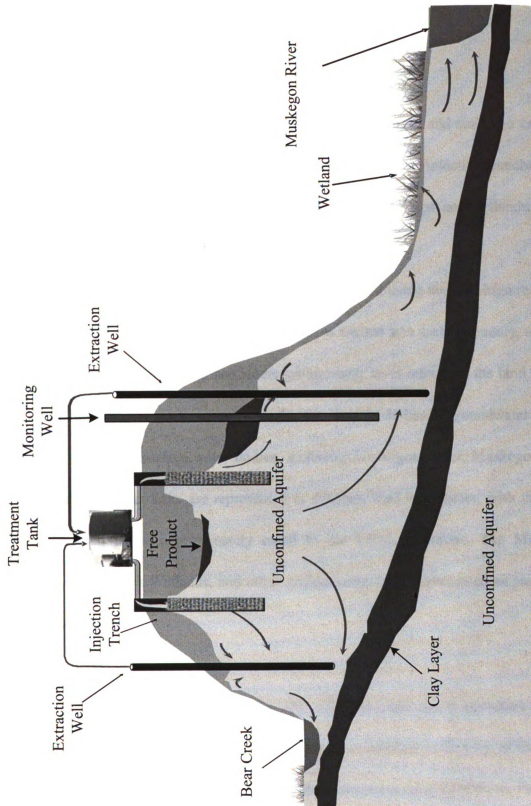


Figure 5. Conceptual Cross-section for Zephyr Site

All of this contributes to the significant, site-wide groundwater mound, with a network of “embedded”, well-scale drawdown cones, resulting in a multiscale groundwater flow system.

To quantify such a complex flow system, the following sources and sinks are explicitly modeled: natural recharge, extraction wells, extraction trenches, injection trenches, Bear Creek, Bear Lake, Muskegon River, Muskegon Lake, surface seeps, and wetlands.

The highly variable terrain in the model area is represented using the 10m high resolution digital elevation model (DEM). The land surface is treated as a drain boundary, allowing groundwater to discharge to surface where groundwater level intercepts the land surface. The drain elevation is set to be equal to the detailed, DEM-based groundwater surface elevation. All major surface water bodies, including Muskegon River, Muskegon Lake, Bear Creek, and Bear Lake are represented as constant head boundaries, with the water levels assumed to be approximately equal to the DEM elevations. The Muskegon wetlands, Bear Creek Wetlands, and other surface seeps were represented as part of the land surface drains.

A total of 55 wells out of the 59 extraction wells are currently in operation and are included in the model. Although pumping rates of extraction wells vary at times, the slight changes were not represented as we focus on long term mean conditions. Pumping

rates used in the model are summarized in Table A1 in the Appendix. The extraction trench system, including both the new and old trenches, is modeled as line drains or head dependent fluxes. The new trenches are relatively deep (14 ft) but narrow (1ft) while the old trench is shallow (4 ft) but wide (3ft). The injection trenches, 8 in the south part of the site, and 2 in the north, are represented as line sources with prescribed fluxes. The injection trenches are filled with highly permeable peat gravels and treated water is continuously injected to the trench through a well. The prescribed line flux per length is set to be equal to the rate of injection well divided by the length of the trench. The flux values for all injection and extraction under the current design condition are presented in Table 1 and Table 2. The total injection rate for all injection trenches is equal to the total pumping rate of all extraction wells and trenches.

Table 1 Flux Values for All Injection

Injection Trench	Injection Rate in GPM
IT-1	5.28
IT-2	20.52
IT-3	32.25
IT-4	26.97
IT-5	29.32
IT-6	32.83
IT-7	31.66
IT-8	24.04
IT-9	25.80
IT-10	19.93

Table 2 Flux Values for all Extraction

Extraction Trench	Extraction Rate in GPM
NT0809	0
NT1011	-2.6
NT1213	-6.1
NT1415	-2.7
NT1617	-7.6
NT1819	-6.5
Old Extraction Trench	-64
Test Trench for Free Product	-2.4

Natural recharge is modeled as spatially variable and divided into five zones based on land use (Figure 6). The five recharge zones are: site proper, two residential districts on the plateau (NE and SW side of site), the Muskegon wetland area, and the Bear Creek Wetland area. Hydraulic conductivity is divided into three zones based on how the aquifer materials were generated geologically and the Michigan land system information available from the statewide groundwater database. The different conductivity zones are shown in Figure 7.

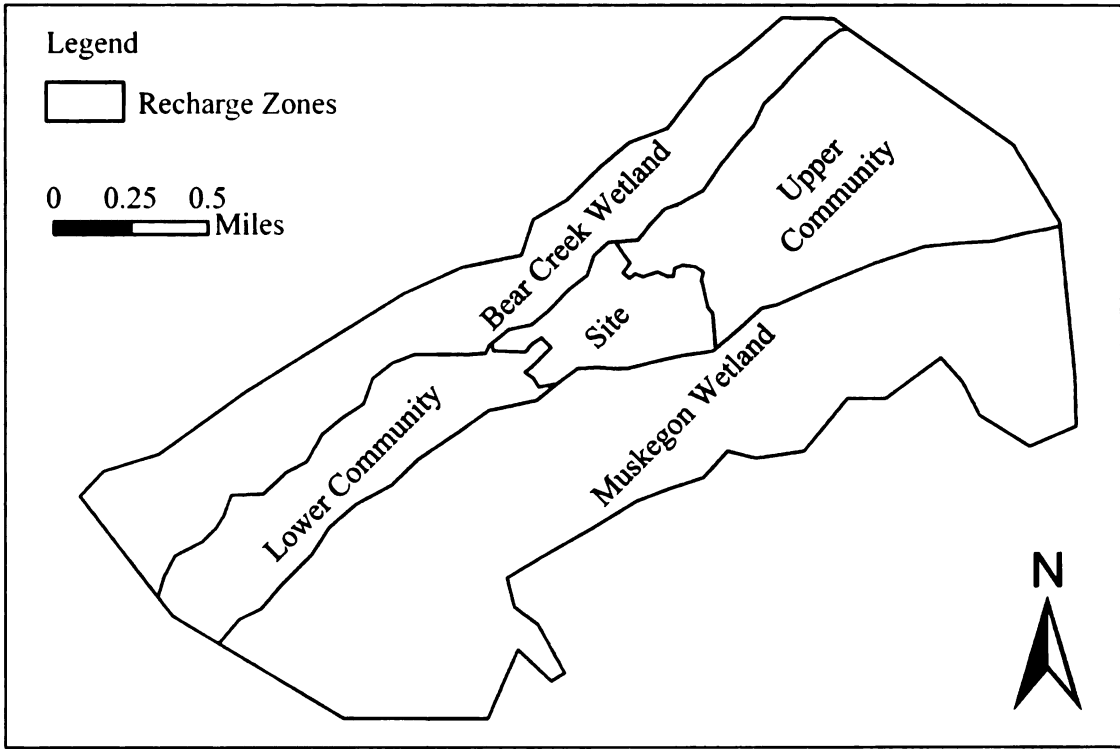


Figure 6 Divisions of Recharge Zone

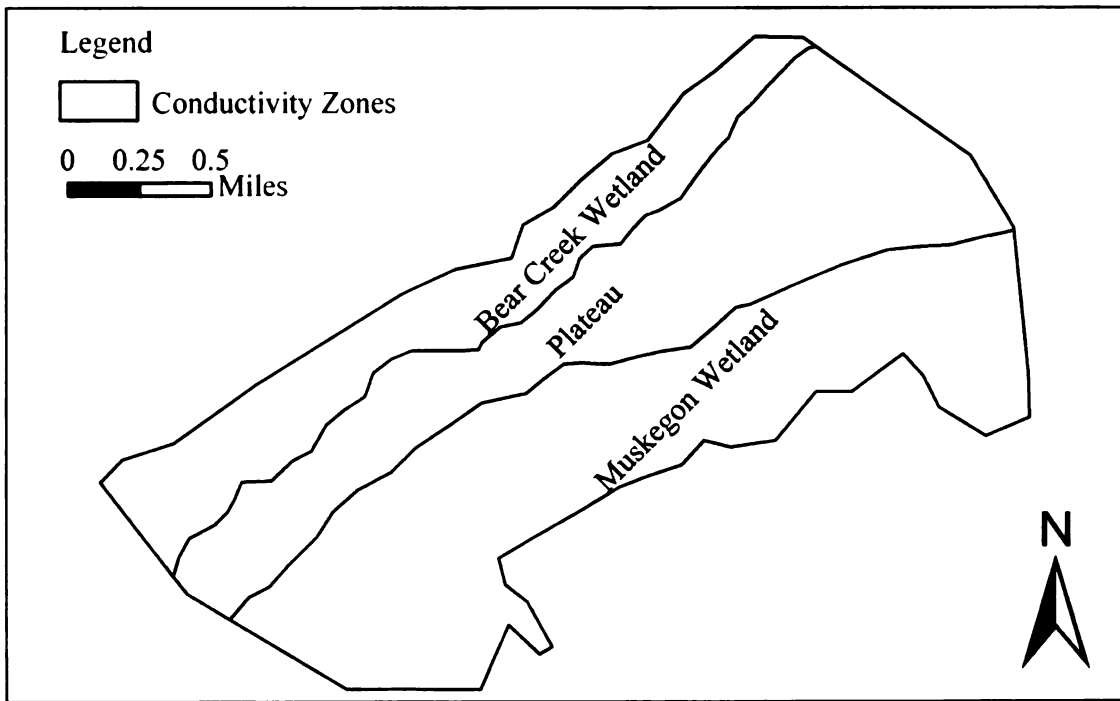


Figure 7 Divisions of Conductivity Zone

The clay layer underneath the aquifer is assumed to be impervious. The clay elevation was interpolated using universal Kriging with a linear drift. The northeastern model boundary is selected such that it coincides with a streamline and can thus be represented as an approximately no flow hydraulic boundary. The “remote” streamline is delineated based on regional static water levels from the Michigan statewide groundwater database.

Hierarchical Flow Modeling

Under the HPDP, we model the complex flow system incrementally, visualize the results in realtime, and “zoom” into subareas when and where we feel there is a need to. Groundwater flow is modeled as unconfined and two-dimensional. Slight vertical variation in the center of the mound and in the discharge area is ignored.

We begin with modeling the entire area using a coarse-grid and then make localized corrections by adding patches or patches-in-a-patch (submodels nested within submodels) where the solution is judged to be inaccurate. The patch boundaries are interactively located where the parent model dynamics are deemed to be adequately resolved. The boundary conditions for each new submodel are represented as prescribed heads based on linear interpolation of the nearest 4 nodal heads from the preceding parent model under a shared node based grid system. For this example, no feedback loop is considered between parent models and their nested submodels (only one-way interaction is implemented). A

visual sensitivity analysis is used to evaluate the sufficiency of the patch boundary location.

Model results, including calibration, sensitivity analysis, and application to remediation performance evaluation are presented in the sections that follow.

Model Calibration

The groundwater flow model was calibrated under a steady state condition. Considering computer computation compatibility and to increase calculation efficiency, one site scale model is created with boundary perpendicular to head contours generated by regional scale size model (Figure 8). The calibration is conducted based on Site Scale Model. The calibration parameters are conductivities and recharge in different zones (Figure 9 and Figure 10), and bottom elevation and leakancy of new extraction trenches, old extraction trench and test trench of free product. The calibration targets are static water levels collected at 128 monitoring wells throughout the site on October 28, 2008 with remediation system on and seepage flux from new trenches, test trench and old extraction trench. Calibration is achieved by minimizing the Sum of Squared Differences between the simulated and observed heads, and simulated and observed flux. The final calibrated conductivities and recharge are presented in Table 3. The bullets below provide several comments regarding the calibration.

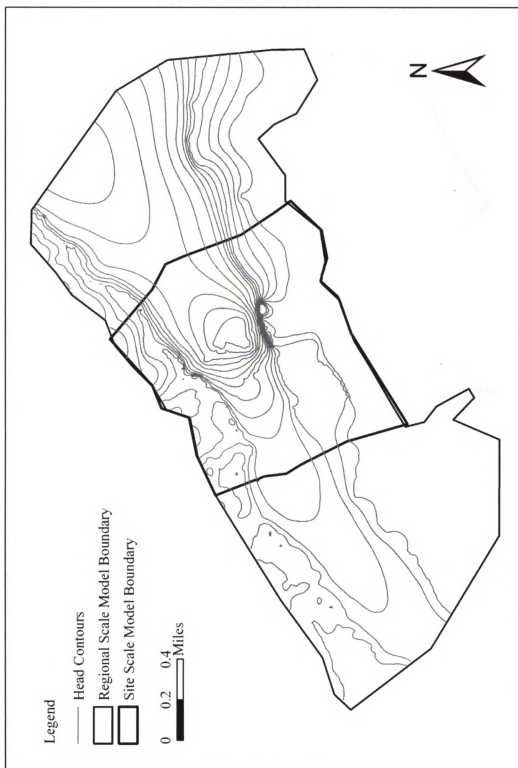


Figure 8 Determination of Site Scale Model based on Simulation Results from Regional Scale Model

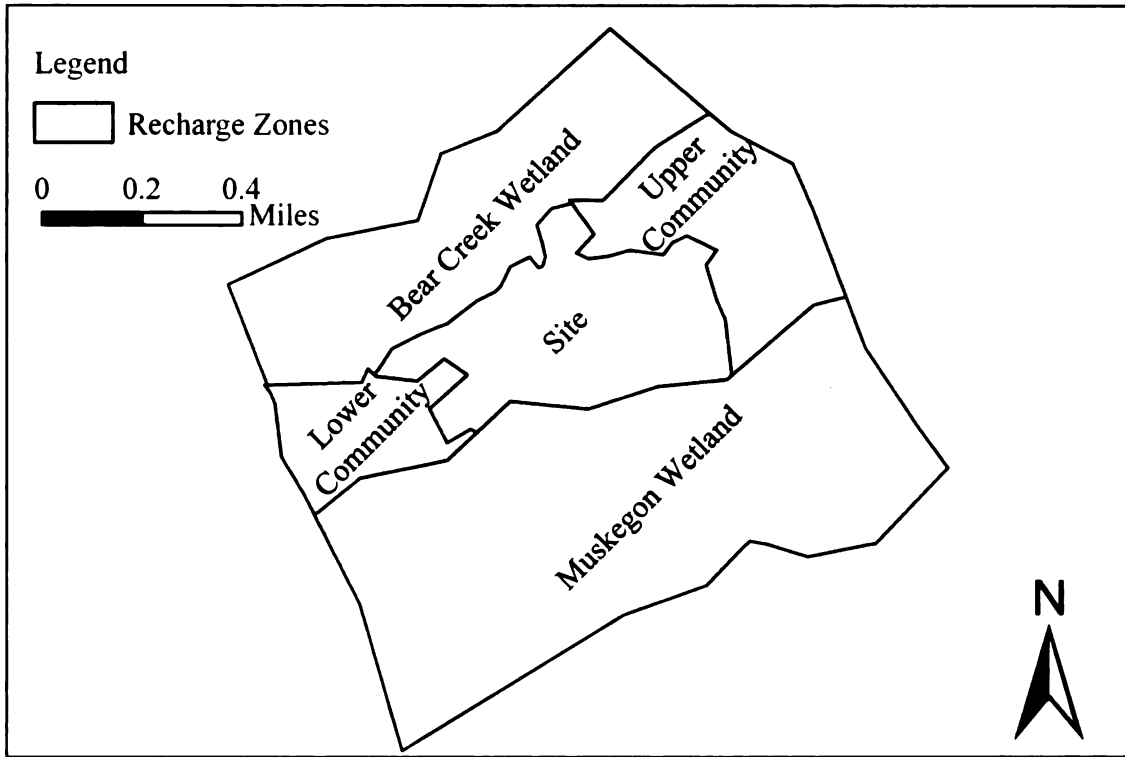


Figure 9 Divisions of Recharge Zones for Site Scale Size Model

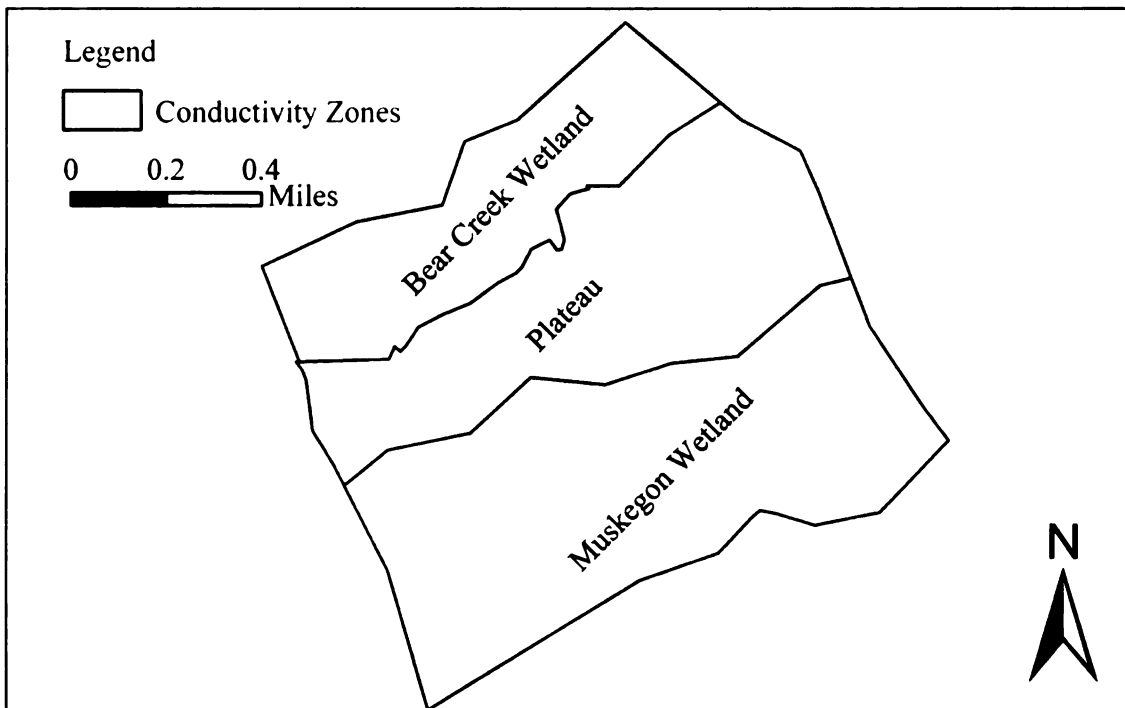


Figure 10 Divisions of Conductivity Zones for Site Scale Size Model

Table 3 Values of Parameters selected as model input

	Conductivity (ft/ day)	Recharge (inch/ year)
Zephyr Site	12.39	18.29
Muskegon Wetland	11.41	-1.00
Bear Creek Wetland	2.41	1.00
Upper Community	12.39	1.00×10^{-5}
Lower Community	12.39	10.37

Table 4 Values of Parameters selected as model input for extraction trench system

	Bottom Elevation in m	Leakancy in m/ day
NT1011	178.43	0.51
NT1213	175.82	0.92
NT1617	178.46	1.40
NT1819	179.04	92.48
Test Trench	178.96	0.32
Old Extraction Trench	177.12	2.09

- Although same uniform values in conductivity and recharge are used as initial guesses for all zones, automatic calibration leads to spatially variable values in different zones.
- Different initial guesses for the calibration parameters lead to essentially the same estimated values for recharge and conductivity in the site polygon. The large numbers of water level measurements enable unique calibration, given the

relatively physically-based parameter zonation.

- The distribution of the calibrated values for recharge, conductivity, and bottom elevation for extraction trenches makes sense and is consistent with data and our conceptual understanding
- Estimated recharge at the site polygon is significantly higher than the estimated values in the residential areas and in the wetland areas.
- Estimated conductivity at the site polygon is relatively low, but higher than that in the wetland areas

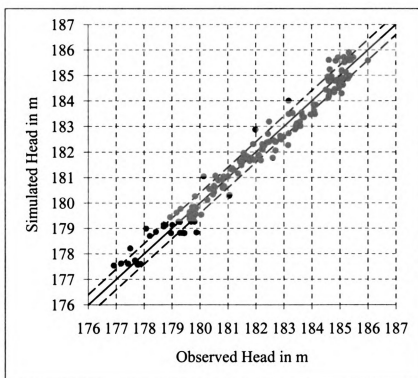


Figure 11 Comparison of observed and simulated heads at steady state for 176 monitoring wells in the site scale size model

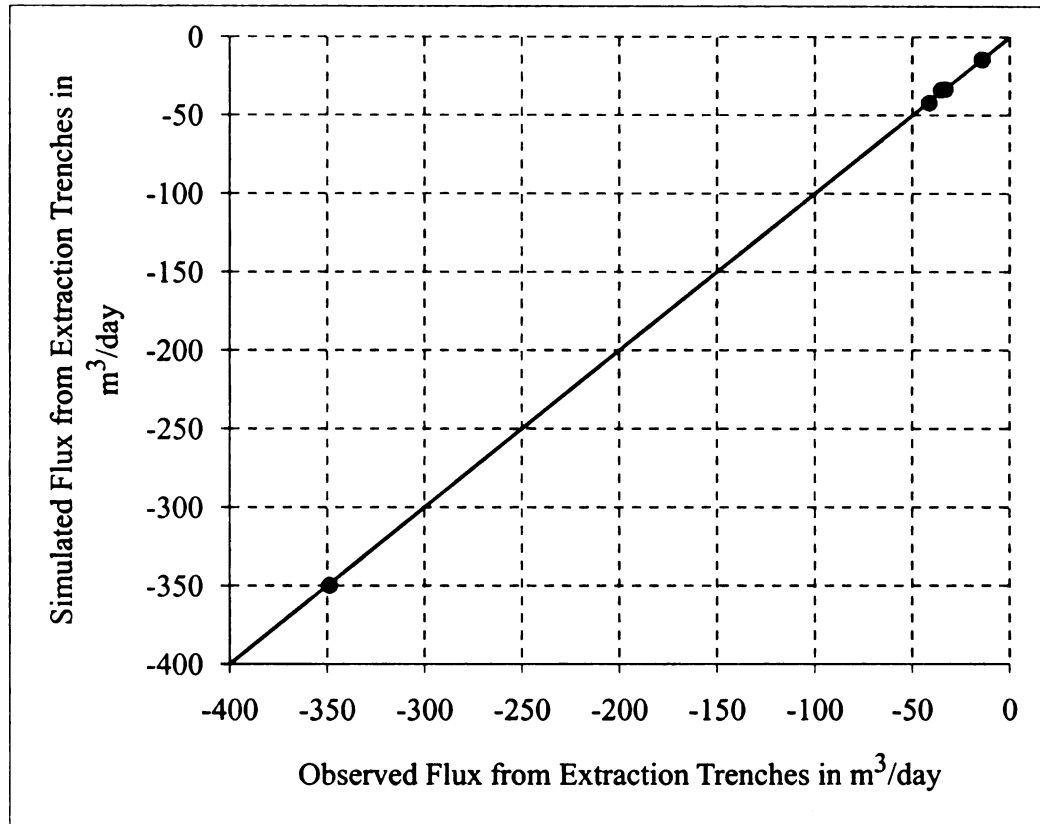


Figure 12 Comparison of observed and simulated flux at steady state for extraction trenches

Figure 11 presents the comparison of observed and simulated heads at steady state for 176 monitoring wells in the site model. The predicted head distribution matches well with the observed. The root mean square error is approximately 0.40 m or 5% of the maximum observed head difference across the site. The arithmetic mean error is almost zero at 0.1 m or 0.5% of the maximum observed head difference. The errors at the vast majority of the 128 monitoring wells are within one standard deviation. These results clearly show that the model is accurate, unbiased and able to capture the dominant processes. Figure 12 presents the comparison of observed and simulated flux from extraction trench at steady

states. The calibration result shows the simulated extraction trench system in the model is in a working condition close to reality.

Model Sensitivity Analysis

A sensitivity analysis of the steady-state model was conducted to assess the uncertainty in the input values. The analysis was used to determine if the differences between simulated and observed data values could be accounted for by the range of uncertainty in the values of input parameters. The analysis provided a measure of the sensitivity of the model results to changes in the values of key parameters and, thus, provided a check on the calibrated model. Throughout the model area, the principal input parameters were independently decreased by a constant factor of 2%, while other parameters were left unchanged. The gradient of the objective function based on parameters was used as a measure of sensitivity. A summary of the gradient for all parameters is included in Table 5. The analysis indicated that model simulations are most sensitive, in decreasing order of importance, to (a) the conductivity of the plateau and recharge of the site (b) the recharge in the Muskegon wetland area and (c) conductivity in Muskegon wetland and Bear Creek wetland respectively. Other parameters including grid size, and recharge of lower community had a relatively small influence.

Table 5 Results for Sensitivity Analysis

Parameters	Gradient
Recharge of the site	0.0407
Conductivity of Plateau	0.0360
Recharge of Muskegon Wetland	0.0170
Conductivity of Bear Creek Wetland	0.0128
Conductivity of Muskegon Wetland	0.0103
Grid Size	0.0018
Recharge of Lower Community	0.0006
Recharge of Bear Creek Wetland	0.0000
Recharge of Upper Community	0.0000

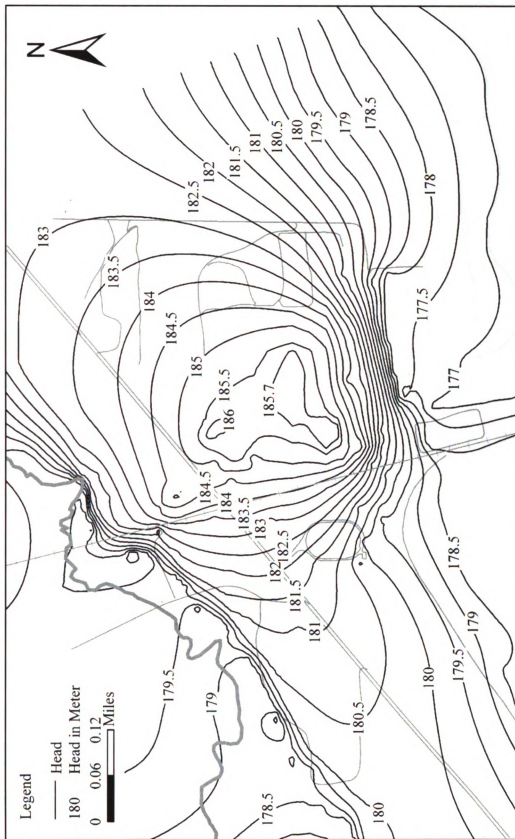


Figure 13 Head Distribution with remediation system on under steady state

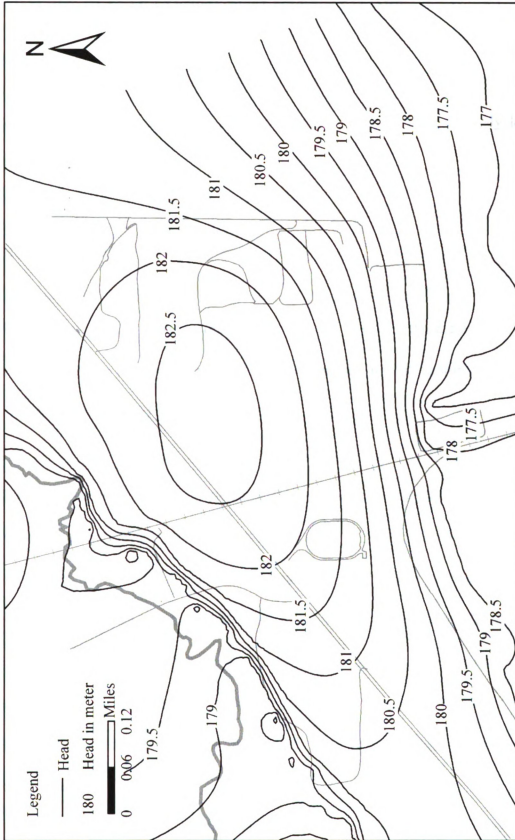


Figure 14 Head distribution with remediation system off under steady state

ANALYSIS OF REMEDIATION SYSTEM PERFORMANCE

In this section, we investigate systematically the remediation system performance at the Zephyr site, taking advantage of the model's ability to simulate not only large scale dynamics but also detailed near-well dynamics.

Hierarchical Capture Zone Analysis

We begin with an analysis to quantify the capture zones for the extraction system. We achieve this by performing reverse particle tracking for all capture wells based on hierarchically-modeled velocity fields.

Figure 15 presents results from hierarchical reverse particle tracking. Up to three levels of sub-models are created with spatial step size of 30 ft, 10ft, and 3.3 ft, respectively. At each level, multiple patch models are created. Level I model represents the regional model described above. Level II model is the first level of sub-model that uses the prescribed heads simulated in the level I model. Similarly, level III models were created, using prescribed heads at the boundaries simulated in the previous level of the model. Figure 16 presents a hierarchical "family tree" illustrating the relationships between the patch models.

Although the models were developed hierarchically at multiple resolutions, only the ones

finest resolution properly represent rapidly varying well dynamics and their capture zones. Level I model, at a resolution of 30ft, is only sufficient in delineating the general orientation of the capture zones. Level 2 model, at an improved resolution of 10 ft, can be used to delineate the general outline of the capture zones, but significantly underestimates the capture widths. Level III models, zooming into five focused areas at a substantially refined resolution at 3ft, enable resolving detailed capture zones for wells that pump at relatively high rates (closer to 10 GPM). making it possible to delineate in detail small-scale drawdown cones of depression and the associated capture zones even for wells with pumping rates less than 5gpm in a large, complex model.

The hierarchical modeling results clearly show the challenges in containing the contamination at the Zephyr site, given the large plume size, small sustainable extraction rates, and diverging flow pattern. The models show that significant gaps exist in the current capture system despite the large numbers of extraction wells used. The area that is most problematic is north side of the site where the well distribution is relatively sparse and hydraulic gradient is strong. The widths of the predicted gaps between individual capture zones range from 100ft to 500 ft.

The models predict even wider gaps in the well capture zones on the south side of the site (north of the cliff) where the hydraulic gradient present is strongest. But this area, unlike the north site, is also protected a series of “new” and “old” extraction trenches further

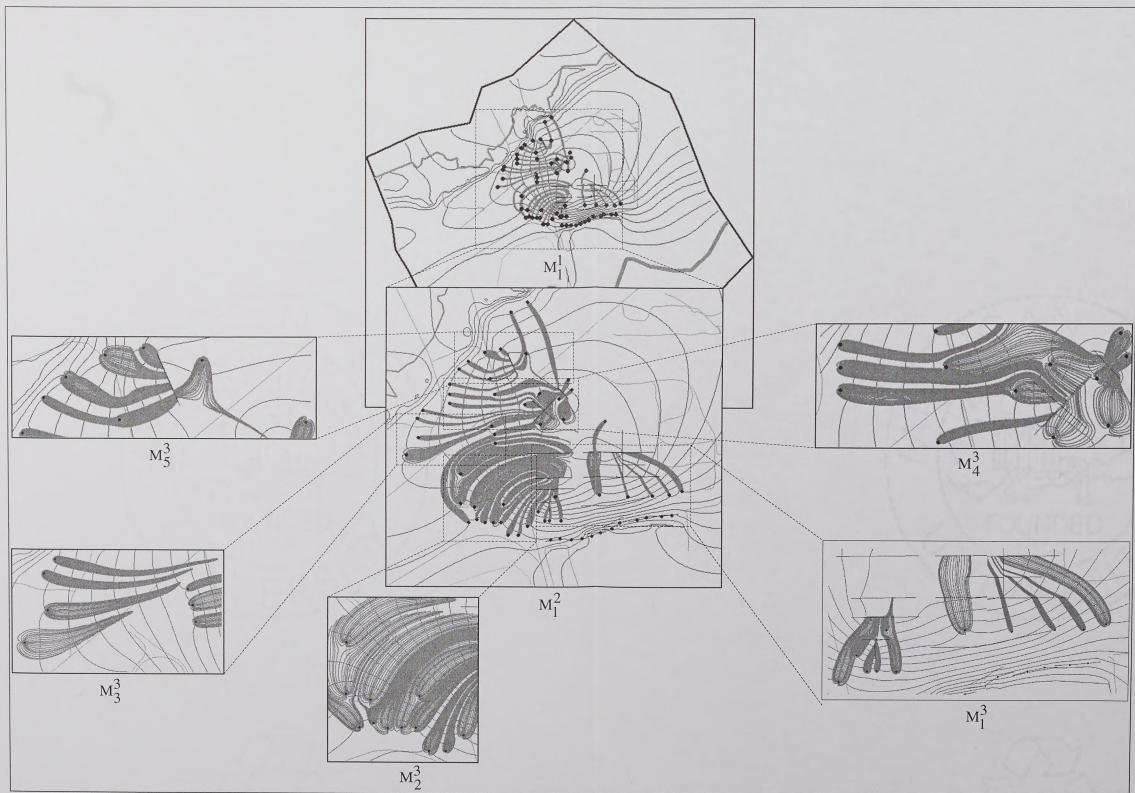


Figure 15 Hierarchical Reverse Particle Tracing

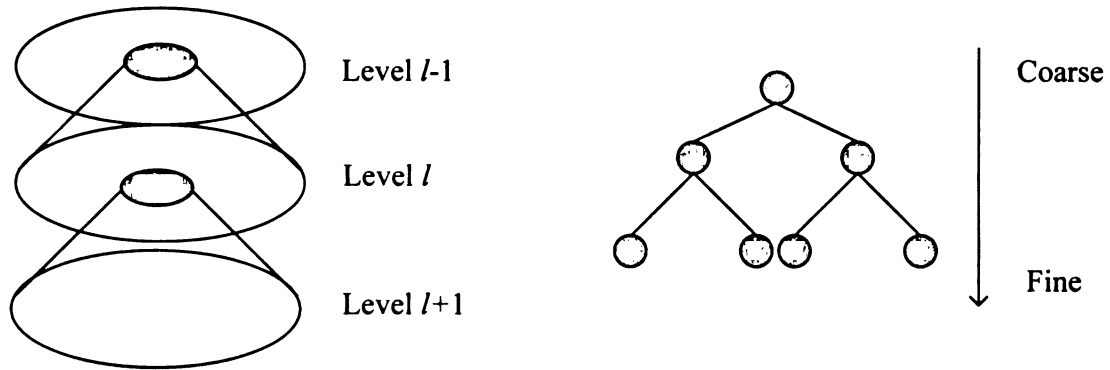


Figure 16 Hierarchical “family tree” to illustrate the relationships between the patch models.

downstream. Contamination that escapes the wells can be potentially captured by the extraction trenches. The effectiveness of the trench system is further evaluated in the next section.

The area that is best protected, based on the model prediction, is in the southwest portion of the site where the well distribution is denser and pumping rates are higher. Individual capture zones for the different wells overlap to form a contiguous, larger capture zone.

Hierarchical Forward Particle Tracking

In this section, we investigate how contamination at the Zephyr site can potentially migrate offsite, given the predicted gaps in the capture system.

To obtain a conservative estimate about the plume migration, we model only advective transport, ignoring degradation and sorption. We release particles throughout the site

where data shows elevated contaminant concentrations and use forward particle tracking to simulate plume evolution under steady flow condition.

Fig. 18 presents the final hierarchical forward particle tracking solutions presented in 7patch models across 3 levels. Figure 17 presents data showing total BTEX distribution at the site. Fig. 18 M_1^1 shows the regional solution at the top of the hierarchical-tree. Fig. 18 M_1^2 describes in more detail the subregional dynamics and wellfield interactions. Fig. 17, from M_1^3 to M_5^3 , presents, respectively, a subsubmodel for each wellfield capturing more detailed well interferences. The rest of the subplots present successions of patch-models zooming into 5 focused-areas that play critical roles in the overall scheme of integrated management.

The models clearly show that the particles expand in all directions. The most dominant migration pathways are towards west, south, and north. The west movement eventually branches into two directions - northwest and southwest. The northwest branch moves towards Bear Creek but stopped expanding in the wetland area near Bear Creek. The southwest branch moves toward the Muskegon River but stopped spreading in the Muskegon wetlands.

Particle transport towards the south boundary is probably most intense because eight of the ten injection trenches are located on the south site and are close to the site boundary.

Models xxx clearly show that particles migrate past the capture wells through the gaps between the well capture zones. The models also show that particles that escape the capture wells also passes through the new trenches and old capture trench before being captured by the Muskegon wetlands.

Particle transport towards north boundary is also significant because Bear Creek bends towards the site and is closest to contamination at the junction where Little Bear Creek and Bear Creek meet. At this location Bear Creek almost directly borders the site with virtually no buffer zone in between. Forward Particle Tracking shows that particles eventually expands into Little Bear Creek, which is connected with Bear Creek, and will finally move towards the Bear Lake at the downstream end.

The models also show that particles released at the site migrate east in a direction opposite to the natural regional gradient. The east movement also bifurcates in two directions - northeast toward Bear Creek and southeast toward Muskegon River. But the movement in both directions stopped in the wetland areas near Bear Creek and Muskegon River.

It becomes clear that the wetlands on both side of the site act as buffer zones that absorb contamination and arrest further migration of the contamination.

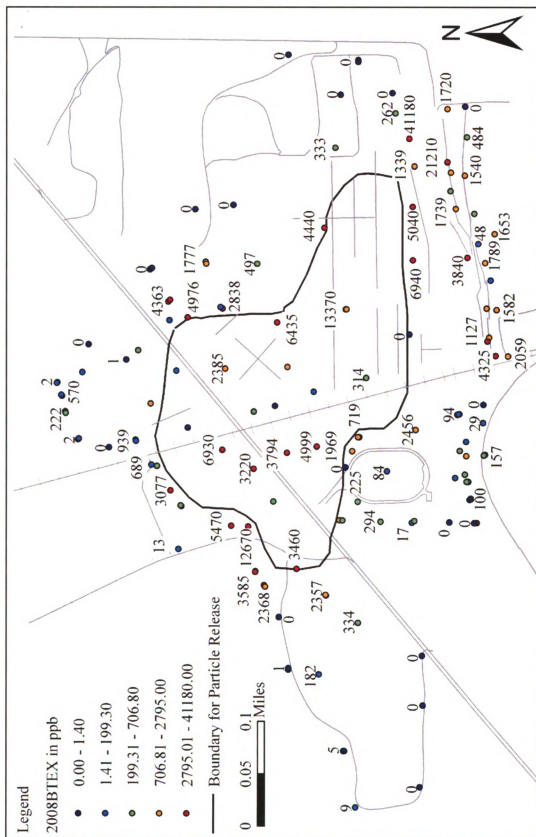


Figure 17 2008 BTEX Analysis Result for Sampling

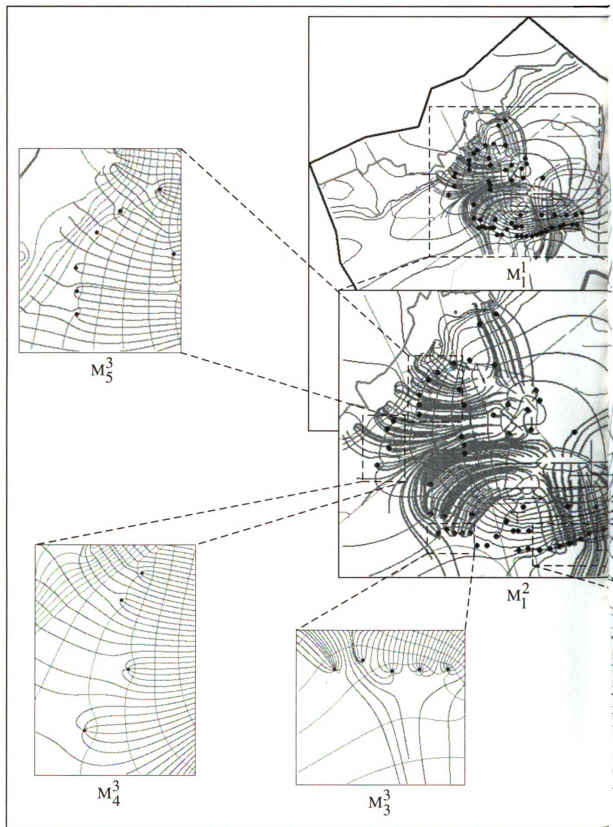
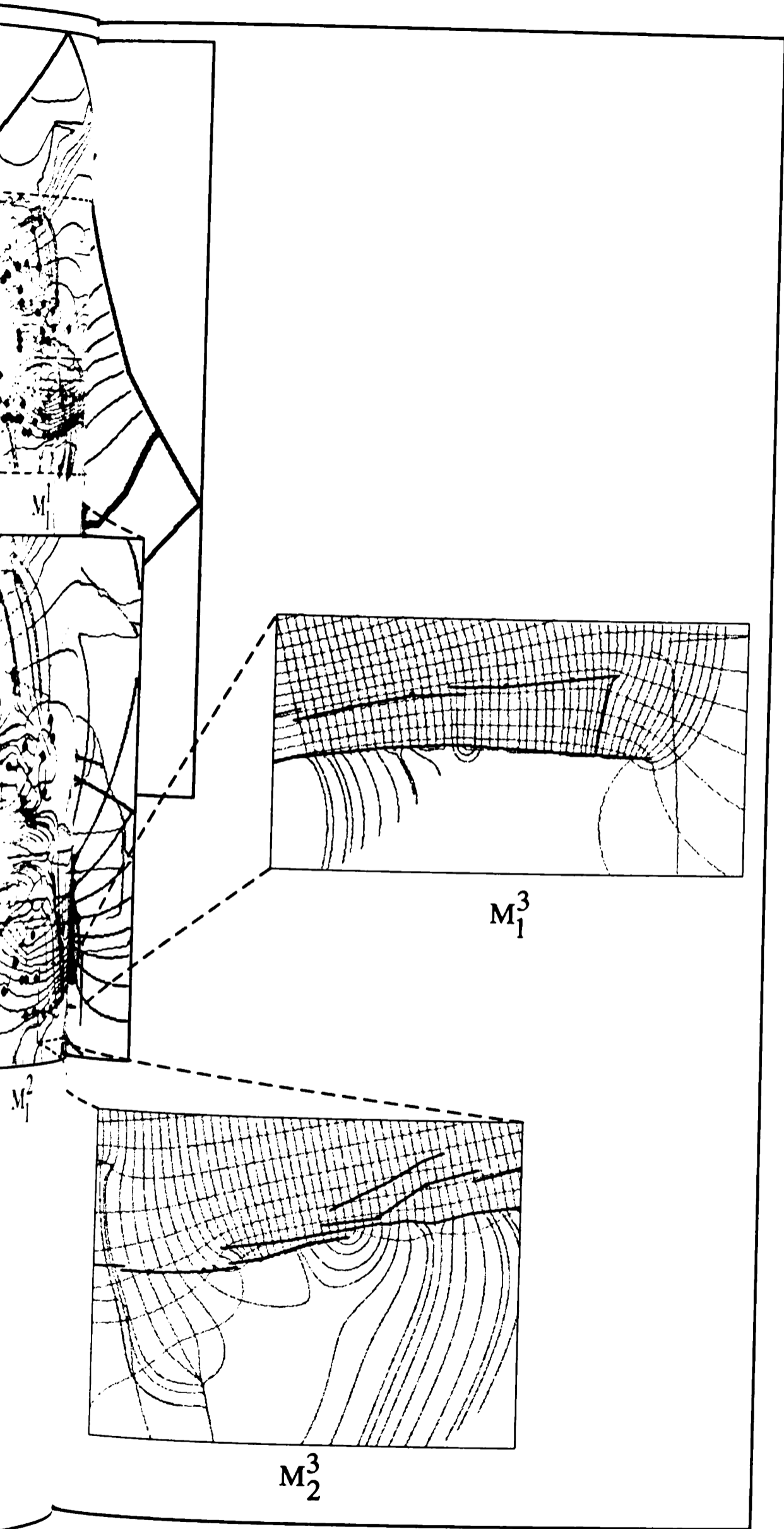


Figure 18 Hierarchical Forward Particle Tracking



Partic...

Water Balance Analysis

In this section, we quantify the total seepage flux off-site. We achieve this by creating a water budget for the aquifer in the site area. The budget analysis is performed based on modeling results, both for natural condition and under active remediation. The analysis area and the results are presented in Figure 19.

One significant message from the budget analysis is: with or without remediation the seepage flux offsite is about the same and is approximately equal to natural recharge in the site area. Specifically, the predicted seepage flux out of site boundaries was approximately 349m^3 /day without remediation, and approximately 356 m^3 /day with remediation.

We were initially puzzled by the finding, but it becomes immediately obvious upon a closer examination of the water budget. The flux offsite has not change much is simply because what is pumped out of the site is injected back into the ground within the same area. Under natural condition, flow out of the site at steady state is essentially balanced by natural recharge, as other sources and sinks (e.g., inflow from the boundaries and surface seeps) are relatively small. Under active remediation, the flow offsite is still balanced by natural recharge, since total injection on-site is designed to be equal to total

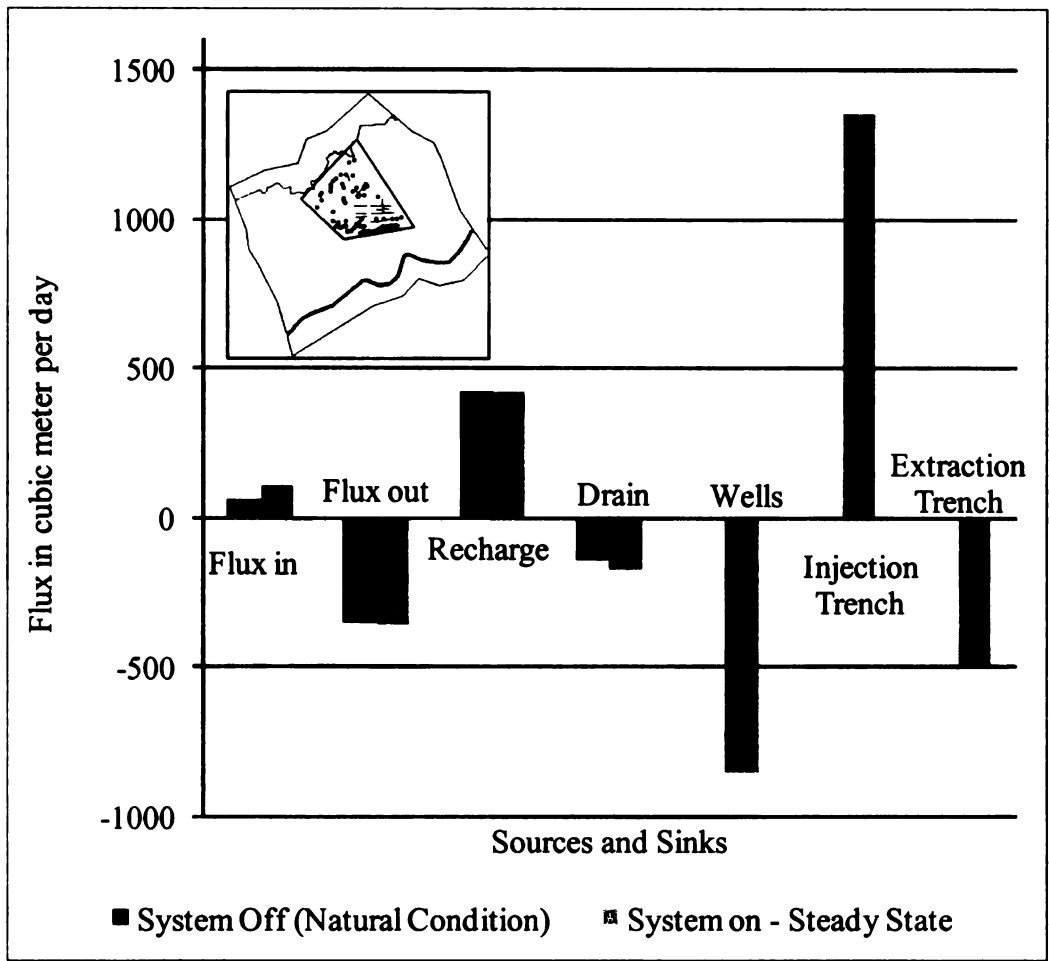


Figure 19 Water Budget for Site Area

pumping, and boundary inflows and surface seeps are again relatively small. Of course, the quality of the water moving offsite with and without remediation should be significantly different, and contaminant flux offsite should decrease with time.

CONCLUSION

In this thesis, we investigated the impact of the current remediation system on the groundwater flow and contaminant migration at the Zephyr site in Muskegon, Michigan. A two-dimensional hierarchical groundwater modeling system is created to evaluate in detail the efficiency and effectiveness of the remediation system. Water balance analysis based on the modeling results show that it is not possible to capture all the groundwater moving offsite unless part of the extracted water is disposed offsite. Hierarchical reverse particle tracking reveals that significant gaps exist among purge well capture zones, contributing to leakage of contaminant. Hierarchical forward particle tracking shows that contamination that escaped capture is eventually “arrested” by the Muskegon and Bear Creek wetland system. The hierarchical modeling system is being applied to redesign remediation injection, extraction, and offsite disposal needed for maximal cleanup efficiency and effectiveness.

APEENDIX A

Table A 1 Pumping Rate for Purge Wells

Well	Longitude in Meter	Latitude in Meter	Pumping Rate in GPM
PW-1	480465.95	302234.15	-2.40
PW-2	480419.61	302194.20	-6.19
RW1	480231.61	302163.02	-1.60
RW2	480253.30	302169.86	-0.80
RW3	480275.18	302161.82	-2.80
RW4	480295.92	302162.52	-4.19
RW5	480317.82	302162.41	-3.69
RW6	480337.97	302126.56	-2.70
RW7	480364.57	302126.92	-1.90
RW-8	480453.37	302113.75	0.00
RW-9	480477.47	302117.67	0.00
RW-10	480509.74	302115.80	-1.36
RW-11	480535.92	302117.83	-1.20
RW-12	480564.73	302124.77	-3.52
RW-13	480587.74	302133.05	-2.64
RW-14	480620.19	302146.54	0.00
RW-15	480643.74	302163.01	-2.72
RW-16	480688.74	302171.46	-3.28
RW-17	480714.37	302176.93	-4.32
RW-18	480754.75	302181.56	-3.04
RW-19	480782.44	302184.78	-3.52
RW-20	480775.28	302238.36	-2.40
RW-21	480730.23	302237.75	-1.90
RW-22	480663.90	302234.25	-1.60
RW-23	480587.58	302235.70	-9.99
RW-24	480481.17	302168.51	-6.39
RW-25	480210.44	302215.59	-4.59
RW-26	480210.17	302297.20	-3.99
RW-27	480424.57	302432.15	-9.59
RW-28	480487.69	302445.71	-2.60
RW-29	480380.98	302486.25	-4.99
RW-30	480419.73	302518.00	-6.19
NW-1	480474.43	302501.45	-3.79
NW-2	480507.12	302526.98	-3.40
NW-3	480499.89	302553.87	-3.99
NW-4	480386.86	302766.01	-2.00

NW-5	480382.63	302624.29	-1.70
NW-6	480316.46	302637.67	-3.79
NW-7	480273.32	302630.13	-1.60
NW-8	480228.50	302604.85	-2.00
NW-9	480177.98	302541.02	-1.00
NW-10	480179.30	302513.72	-1.60
NW-11	480179.34	302487.45	-1.60
NW-12	480105.64	302469.06	-0.80
NW-13	480090.74	302447.85	-0.80
NW-14	480095.59	302395.75	-1.20
NW-15	480299.89	302403.25	-3.20
NW-16	480601.20	302438.43	-0.80
NW-17	480202.76	302581.23	-0.80
NW-18	480300.88	302514.57	-2.80
NW-19	480288.58	302555.75	-1.60
NW-20	480293.06	302426.92	-1.20
NW-21	480304.38	302379.31	-2.40
NW-22	480344.45	302736.74	-1.80
NW-23	480809.61	302247.85	-4.39
NW-24	480061.82	302348.25	-1.60
SL-1	480248.41	302206.09	-5.59
SL-2	480323.22	302212.44	-5.59
SL-3	480391.17	302151.56	-6.39
SL-4	480435.43	302167.97	-4.79
SL-5	480450.21	302169.26	-3.79

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