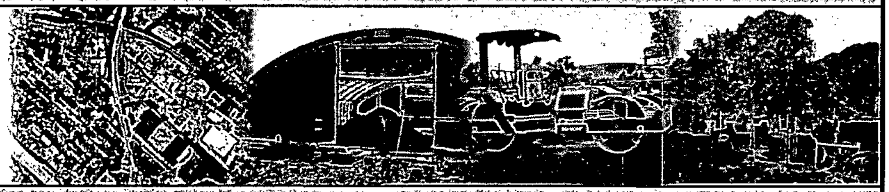
FUSRAP
Maywood Superfund Site



Final
Groundwater Feasibility Study Report

Volume 2 of 2 Appendix C
Groundwater Flow and Solute Transport Modeling Results

Formerly Utilized Sites Remedial Action Program
Maywood Superfund Site

Prepared by:

US Army Corps
of Engineers.

With Assistance from:

Shaw Environmental, Inc.
100 West Hunter Avenue
Maywood, New Jersey 07607

Contract No. DACW41-99-D-9001

September 2010

FINAL
GROUNDWATER FEASIBILITY STUDY
FUSRAP MAYWOOD SUPERFUND SITE
MAYWOOD, NEW JERSEY

SITE-SPECIFIC ENVIRONMENTAL RESTORATION
CONTRACT NO. DACW41-99-D-9001
TASK ORDER 0004
WAD 03

Prepared by:

Department of the Army
U.S. Army Engineer District, New York
Corps of Engineers
FUSRAP Project Office
26 Federal Plaza
New York, New York 10278

Department of the Army
U.S. Army Engineer District, Kansas City
Corps of Engineers
700 Federal Building
Kansas City, Missouri 64106

With Assistance from:

Shaw Environmental, Inc.
100 West Hunter Avenue
Maywood, New Jersey 07607

September 2010

Volume 2 of 2 - Appendix C

Groundwater Flow and Solute Transport Modeling Results

Issued to: ____________________ Date: ______________

Copy No. ______ ☐ Controlled ☐ Uncontrolled

APPENDIX C

GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING RESULTS

TABLE OF CONTENTS

LIST OF TABLES

This page intentionally left blank.

LIST OF FIGURES

This page intentionally left blank

LIST OF ATTACHMENTS

This page intentionally left blank.

LIST OF ACRONYMS

Δx, Δy and Δz	dimensions of the cell in the respective coordinate directions.
ρ_b	bulk density of the porous medium
λ	rate constant of the first-order rate reactions
µg/L	micrograms per liter
AOC	Area of Concern
BTEX	benzene, toluene, ethylbenzene, and xylenes
C	concentration of contaminants dissolved in groundwater
C_s	source/sink concentration
C'	sorbed phase concentration
CD	Compact Disk
cfs	cubic feet per second
cm/s	centimeters per second
COC	Constituent of Concern
D_{ij}	Hydrodynamic dispersion coefficient
EPA	United States Environmental Protection Agency
EPM	Equivalent Porous Media
FMSS	FUSRAP Maywood Superfund Site
FUSRAP	Formerly Utilized Sites Remedial Action Program
GMS	Groundwater Modeling System
GPM	gallons per minute
GWFS	Groundwater Feasibility Study
GWRI	Groundwater Remedial Investigation
h	hydraulic head
i	index for grid rows
j	index for grid columns
k	index for grid layers
K_{ii}, K_{ij}	hydraulic conductivity tensors
Kxx	hydraulic conductivity tensor in direction of x-axis in the plane normal to x-axis
Kyy	hydraulic conductivity tensor in direction of y-axis in the plane normal to y-axis
Kzz	hydraulic conductivity tensor in direction of z-axis in the plane normal to z-axis
L	distance dimension
M	mass dimension
MAE	Mean Absolute Error
ME	Mean Error
MISS	Maywood Interim Storage Site
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model

MSL	mean sea level
MT3D	Modular Three-Dimensional Transport Model
n	porosity
NCOL	total number of grid columns
NE	northeast
NJGS	New Jersey Geological Survey
NLAY	total number of grid layers
NNE	north-northeast
NRC	Nuclear Regulatory Commission
NROW	total number of grid rows
NW	northwest
OU	Operable Unit
PCE	tetracholorethene
PCG2	Preconditioned Conjugate Gradient 2
q_s	volumetric flux per unit aquifer volume
Q	volume flow rate across a cell face
R	retardation factor
R_k	chemical reaction term
REV	Representative Elementary Volume
RMSE	Root Mean Square Error
S_s	specific storage
SIP	Strongly Implicit Procedure
SOR	Slice-successive Overrelaxation
SSL	Soil Screening Level
SSW	south-southwest
SW	southwest
t	time
T	time dimension
TCE	trichloroethene
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VC	vinyl chloride
v_i	seepage velocity
V_x, V_y, V_z	principal components of the average linear groundwater velocity vector
W	volumetric flux per unit volume
WNW	west-northwest
WSW	west-southwest
x_i, x_j	distance along principal system coordinate axis
X1, X2, Y1, Y2, Z1 and Z2	six cell faces

1.0 INTRODUCTION

1.1 MODELING PURPOSE AND OBJECTIVES

Groundwater modeling was conducted for the Formerly Utilized Sites Remedial Action Program (FUSRAP) Maywood Superfund Site (FMSS) to evaluate groundwater flow, solute transport, and groundwater remedial scenarios as part of the Groundwater Feasibility Study (GWFS). The FMSS consists of property owned by the Federal Government, the Stepan Company (Stepan), and other government, commercial, and private properties in Maywood, Lodi, and Rochelle Park, New Jersey. Detailed information regarding the site history and regulatory background is provided in the *Final Groundwater Remedial Investigation Report* (GWRI) prepared by Shaw Environmental, Inc. for the United States Army Corps of Engineers (USACE 2005). The numerical model was utilized due to the complexity of evaluating the combined overburden/bedrock water-bearing unit. The numerical model provided a comprehensive tool for fate and transport analysis and remedial alternative evaluations.

1.2 SCOPE OF WORK

During the first phase of the Groundwater Flow and Solute Transport model development, a groundwater flow model was constructed. The model was constructed in accordance with the approach that was proposed in the *Groundwater Flow and Solute Transport Modeling Work Plan* (Modeling Work Plan) dated June 2004 (USACE 2004a). The purpose of the computer modeling was to perform on- and off-site groundwater flow analysis. Results of the flow model were used for solute transport modeling, and eventually for a detailed analysis of the groundwater remediation feasibility study alternatives.

Computer model input data were derived mainly from existing site data and reports, and from the GWRI Report. The model area-of-interest includes the FMSS property including the Maywood Interim Storage Site (MISS), Areas of Concern (AOCs), and several parcels of adjacent properties. Salient features of the facility physiographic setting, climatology, and hydrology are discussed in **Section 2.0**. To the west of the FMSS, the model area-of-interest extends to the Saddle River, which is assumed to act as a hydrologic boundary. The northern boundary of the model area-of-interest extends north of the Dixo Corporation property and includes reaches of Westerly Brook. To the south, the model area-of-interest extends to include the Sears property, and the head waters and the upper reaches of Lodi Brook. To the east, the model area-of-interest extends to Maywood Avenue, and includes the Myron Manufacturing and DeSaussure Equipment properties. A conceptual groundwater flow model is presented in **Section 3.0**.

Groundwater flow was modeled using the Groundwater Modeling System (GMS), Version 5.0 (Environmental Modeling Systems 2004)/MODFLOW-2000 Version 1.15 (Harbaugh et. al. 2000) package. The model code selection procedure is presented in **Section 4.0**. The flow model was calibrated by matching the model simulations to an appropriate and comprehensive groundwater elevation data set. Details of model input parameters, setup, and construction are provided in **Section 5.0**. The reliability of model predictions was established through model calibration and the statistical error associated with the model predictions was quantified. The model calibration process was an iterative process where a single input parameter was changed, and the effects evaluated. The iterative calibration process continued until the model prediction error ranges were within acceptable limits, as prescribed in the Modeling Work Plan. The results of calibration and sensitivity analysis of the groundwater flow model are presented in **Section 6.0**.

The sensitivity of the flow model to the various input parameters such as groundwater recharge rate, hydraulic conductivity values, anisotropy ratio of horizontal hydraulic conductivities, flow between shallow and deep bedrock, and model boundary condition selection were evaluated. Details of sensitivity analysis process and findings are summarized in the Sensitivity Analysis section of **Section 6.0**.

Particle tracking was used to trace the flow paths (also called path lines) in the overburden and the shallow bedrock aquifers. The modeled groundwater flow directions, gradients, and velocities were compared to the results documented in the GWRI Report. These are discussed in **Section 7.0**.

Proposed groundwater remedial alternatives include no action, natural attenuation, groundwater extraction followed by ex-situ treatment, and in-situ treatment. Detailed evaluations of these alternatives required three-dimensional groundwater flow modeling combined with solute transport modeling for the MISS property, AOCs, and downgradient off-site areas for FUSRAP Constituents of Concern (COCs). The purpose of the solute transport modeling was to determine the fate and future extent of selected solute plumes when subjected to the various groundwater remedial alternatives. The procedures used to perform solute transport modeling and the results are provided in **Section 8.0**. Solute transport model simulations were limited to the solutes that were associated with the MISS and potentially migrating downgradient from the MISS, and the AOCs. These solutes were identified in the GWFS Report, **Volume 1** as COCs.

The requirements, standards, and quality assurance/quality control procedures used for the groundwater flow and solute transport modeling are provided in **Section 9.0**. The model was reviewed by technical peer reviewers, and issues raised during the technical review were documented and resolved. A summary of the model findings and conclusions are presented in **Section 10.0**. References used in the development of the models and preparation of this report are listed in **Section 11.0**. The input and output files for the flow model and the feasibility study scenario modeling are included on compact disks (CDs) as **Attachments A** and **B**.

2.0 SITE SETTING

An overview of the site setting related to developing the groundwater flow and solute transport numerical model is described below. The information is extracted from the GWRI Report (USACE 2005). Additional site setting information derived from the GWRI is presented in the GWFS Report, **Volume 1**.

Site Location - The FMSS model area-of-interest consists of property owned by the Federal Government, the Stepan Company (Stepan), other government, commercial, and private properties in Maywood, Lodi, Rochelle Park, down gradient, and side gradient locations. The FMSS and the surrounding properties are shown on **Figure 1-1** of the GWFS Report, **Volume 1** (GWRI Figure 1-1). The site is located approximately 12 miles northwest (NW) of New York City and 13 miles northeast (NE) of Newark, New Jersey. The site location is shown on the GWFS Report **Volume 1, Figure 1-2** (GWRI Figure 1-2).

Facility Background - The FMSS consists of 88 designated properties: the Stepan property, which includes contaminated buildings and 3 Nuclear Regulatory Commission (NRC) licensed burial pits; MISS and contaminated building; 59 residential properties; 3 properties owned by the State or Federal Government; 4 municipal properties; and 20 commercial properties. Surface remediation of 64 of the 88 properties and adjacent properties has been completed. Past chemical processing operations involved radioactive thorium ore, lithium compounds, detergents, alkaloids, essential oils, and products of tea and cocoa leaves generating large quantities of process wastes. Seven groundwater AOCs were identified during the groundwater RI.

Facility Setting - The FMSS is located in a highly developed area of Bergen County. As described in the Facility Background section, the area is developed with 88 industrial, commercial, and residential properties.

Climatology - The FMSS lies within the Middle Atlantic Seaboard, which is characterized by four distinct seasons and moderate summers and winters. The regional climate is humid. The average annual rainfall ranges between 43 and 47 inches. The 30-year average rainfall, as measured in Newark, New Jersey, is 46.3 inches. The 5-year average precipitation, as measured in nearby (3 miles) Teterboro, New Jersey, is 37.7 inches. The 5-year average precipitation, as measured in New Milford, New Jersey (5 miles away), is 41 inches.

Meteorology - Precipitation is distributed fairly uniformly throughout the year.

Physiography - The FMSS area generally slopes to the southwest (SW), with the exception of a north-south trending ridge located along the western boundary. The maximum elevation is 75 feet mean sea level (MSL) (based on National Geodetic Vertical Datum of 1929) along the ridge. The minimum elevation, 28 feet MSL, is near the SW FMSS boundary. The land surface is generally composed of fill, sand, undifferentiated silt, sand, clay, and sand and gravel deposits.

Surface Water Hydrology - Westerly and Lodi Brook watersheds drain the FMSS with the vast majority of the runoff going to the Saddle River. Westerly Brook originates outside the model area-of-interest, and is a perennial stream with an estimated base flow of 4 cubic feet per second (cfs). Lodi Brook also originates outside the model area-of-interest and is perennial in its headwaters. Some of the Lodi Brook flow originates in two marshy areas on the FMSS. Some additional flow comes from off site to the east. Lodi Brook has an estimated base flow of 2 cfs. The GWRI report indicates that the base flow rate estimates for the Westerly and Lodi Brooks were based on the *Remedial Investigation Report for the Maywood Site*, (U. S. Department of Energy 1992). The Report indicates that there is no available stream gage flow data for Lodi and Westerly Brooks, and that flow rates were "visually estimated" to provide "order of magnitude" estimates. Some reaches of both Westerly and Lodi Brooks flow in culverts and reinforced concrete pipes.

Detailed cross-sections, aerial maps, and drawings showing sections of the Brooks where flow is in open channels, and the sections where flow is in culverts or pipes, are provided in GWRI Report Volume II – Figures 3-22a, b, c and GWRI Report Appendix C. GWRI Report Appendix O provides the results of a video survey and other observations made at the Westerly and Lodi Brooks in 2000. During model construction, these resources were used to define the groundwater and surface water interaction for different reaches of the Brooks, and accordingly, the reaches were modeled as streams or drains. Since the culvert sections were documented in the video inspections to be leaking throughout their lengths, they were treated as drains that receive flow from the adjacent groundwater. The possibility of the culvert sections acting as low conductivity flow barriers was therefore ruled out.

Hydrogeology - Groundwater at the FMSS and surrounding areas flows within overburden and bedrock formations. Saturated, laterally continuous undifferentiated till, and sand and gravel deposits comprise the overburden aquifer. The thickest overburden aquifer sediments were mapped in the southern FMSS along Westerly Brook and in the MISS in the area of the Former Retention Ponds A, B, and C. The overburden aquifer thins locally and pinches out against bedrock highs (See GWRI Report figures for illustrative purposes – for example, GWRI Report Figure 3-7 and Figures 3-8a through 3-8e). Groundwater generally exists under unconfined conditions in the overburden water bearing unit. Semi-confined conditions may exist in localized areas of the overburden aquifer, such as in the area of the Former Retention Ponds.

The local bedrock aquifer is characterized in the GWRI as an unconfined, multi-unit system with a shallow weathered unit overlying more competent deep bedrock. The bedrock aquifer is systemically fractured by joints and open partings along bedding planes (bedding fractures), and conducts groundwater horizontally and vertically within the aquifer. Shallow bedrock was simulated as the lowermost hydrogeologic unit in the model, and is bounded at its base by a "no flow" boundary. The term "shallow bedrock" and "shallow bedrock aquifer" is described in the GWRI as the bedrock interval investigated and sampled by shallow bedrock wells, and typically extends 35 feet into rock.

For the purpose of groundwater modeling, the bottom of the shallow bedrock was located at an elevation of 0 feet below MSL. Groundwater flow in the shallow bedrock beneath the MISS is west-southwest (WSW) towards the Saddle River, whereas flow is south-southwest (SSW) on 149-151 Maywood Avenue property, and in Lodi again directed towards the Saddle River. Therefore, groundwater flow is mostly toward the Saddle River in both overburden and shallow bedrock water-bearing units (see GWRI Report Figures 3-15a and 3-19a provided in the GWFS Report, **Volume 1, Figures 1-4** and **1-5** for illustrative purposes). The prevailing flow direction within deeper aquifer units is parallel to the north-northeast (NNE)-SSW strike of the beds. The shallow bedrock wells were typically installed 35 feet into the bedrock, with a 25 foot open borehole on an average. Deep bedrock wells were generally installed 75 feet below the bedrock surface, and were constructed with a 25-foot open borehole or screened interval.

The hydraulic conductivities of the overburden and the shallow bedrock aquifers were characterized on the basis of the pumping tests, slug tests, pressure injection tests, and packer tests. Data from these tests were reported in the GWRI Report, the Stepan Company *Remedial Investigation Report* (Stepan Company 1994), and the *Remedial Investigation Report for the Maywood Site* (U.S. Department of Energy 1992). In addition, permeability data were available from specific capacity testing at 14 bedrock wells that was conducted during the GWRI. The specific capacity results provided an order of magnitude estimate of hydraulic conductivity, since these were calculated on the basis of empirical formulas that may or may not be representative of the FMSS conditions. Therefore, the specific capacity data were not used in the model.

An evaluation of the measured hydraulic conductivity values for the overburden and the shallow bedrock indicates the lack of trends or patterns in the distributions of hydraulic conductivities across the modeled area. Therefore, groundwater flow was described by the bulk hydraulic conductivity values which were equal to the median hydraulic conductivity values for each layer. The median hydraulic conductivity for the overburden aquifer was calculated to be 2.41 feet/day, while the geometric mean was 2.63 feet/day. The median hydraulic conductivity for the shallow bedrock aquifer was 2.94 feet/day, while the geometric mean was 2.79 feet/day.

Land Use/Soil Cover - The site and surrounding area is residential and commercial property. A large percentage of FMSS is covered by buildings and paved. Off-site land area that is within the model area-of-interest is also a mixture of residential and commercial properties, with a large percentage of off-site area paved.

This page intentionally left blank.

3.0 CONCEPTUAL GROUNDWATER FLOW SYSTEM AND MODELING ASSUMPTIONS

3.1 CONCEPTUAL MODEL

The groundwater model area-of-interest proposed in the Modeling Work Plan is approximately 40 acres, as shown in **Figure 3-1**. The horizontal model domain included this area and some additional adjacent areas based on the orientation of the model grid.

Vertically, the model was divided into three layers. Conceptualization of the vertical model domain was done from available geologic data and interpretations. This data included the soil and rock boring logs, geologic cross-sections, and estimates of hydraulic conductivity values from several locations across the model domain.

The aquifer system was divided vertically into three hydrostratigraphic units (**Figure 3-2**). The hydrostratigraphic units are comprised of geologic units of similar hydraulic properties. In the conceptual model, the hydrostratigraphic unit is considered stratigraphically homogeneous. The three hydrostratigraphic units and their approximate thicknesses are listed below.

Layer 1: Overburden - variable thickness, ranging from 0 to 25 feet (unsaturated in certain areas).

Layer 2: Till - 2 feet thick (may not be present at all site locations).

Layer 3: Shallow bedrock - extends to approximately 0 feet below MSL (28 to 75 feet below land surface); with thickness ranging from 23 to 82 feet (approximately 44 feet average thickness).

The three layer vertical discretization of the model domain is a simplification of the subsurface site lithology presented in geologic cross-sections shown on GWRI Report Figures 3-7 and 3-8a through 3-8e.

Hydraulic conductivity may vary spatially between different locations, commonly referred to as heterogeneity. Heterogeneity may occur in vertical and/or horizontal dimensions. Vertical heterogeneity is caused by the variation of hydraulic conductivity with depth, and may be the result of layers within the aquifer media. Within the study area, three layers with unique hydraulic conductivity values were identified - overburden, till, and shallow bedrock. Horizontal heterogeneity represents the lateral change in hydraulic conductivity and typically results in delineation of hydraulic conductivity zones. The measured hydraulic conductivity data for the overburden and the shallow bedrock layers were plotted in an effort to delineate hydraulic conductivity zones. The site data indicated that the lateral variation in hydraulic conductivity is apparently random. No zones could be delineated within the individual layers. Therefore, for the initial model setup, the hydraulic conductivity was assumed to vary vertically, but not horizontally.

Horizontal hydraulic conductivities for the overburden and the shallow bedrock were initially set equal to the median hydraulic conductivities measured from field testing. The intermediate till layer was initially assigned a hydraulic conductivity that was equal to the average of the median overburden and the median shallow bedrock hydraulic conductivity values presented in **Section 2.0**.

Hydraulic conductivity may also vary as a function of spatial orientation (i.e., at the same physical location, the hydraulic conductivity may be different in different directions). The directional hydraulic conductivity variation is referred to as anisotropy. For the initial model setup, an anisotropy of 1.0 (same hydraulic conductivity in different directions) was used and varied, as required, during the model calibration process.

Boundary conditions were specified at the edges, top, and bottom of the groundwater flow system. At the edges, boundary conditions included rivers and streams or groundwater elevation conditions. The Saddle River was selected as the western model boundary. The other model boundaries were not hydrologic boundaries. Rather, these boundary locations were selected to encompass the MISS and AOCs, and areas in the immediate vicinity. The bottom boundary of the model was located at the shallow/deep bedrock interface at approximately 0 feet MSL.

Although some contamination has been found in deep bedrock, the majority of site contamination lies within overburden deposits and shallow bedrock. The model (as proposed in the Model Work Plan) considers the deep bedrock/shallow bedrock interface as a no-flow boundary condition. This is generally consistent with the GWRI Report findings. Historical groundwater elevation data was evaluated in shallow and deep bedrock monitoring well clusters PT-1DA/1DB, MW-23D/DD, MW-24D/DD, BRPZ-4/PW-1D and MW-19D/DD. All clusters except for PT-1DA/PT-1DB show weak and/or inconsistent vertical gradients. Groundwater gradients during July 2001 were also weak, ranging from -0.03 feet/feet (upwards) to 0.10 feet/feet (downwards).

For the initial model setup, the Saddle River boundary was treated as a constant head boundary. The other three boundaries were treated as open (variable heads, no flow) boundaries. These boundary conditions were later changed during the calibration process. The groundwater elevations at this boundary were specified based on site data and data from literature sources including the United States Geological Survey (USGS) stream flow data and topographic maps.

At the top of the aquifer system, the boundary condition included net precipitation recharge (rainfall minus runoff and evapotranspiration). At the base of the aquifer system, the boundary condition included specified flux of water to and from the deep bedrock underlying the shallow bedrock. In case the specified flux is zero (as determined later during sensitivity analysis process), the boundary at the model base will effectively become a no-flow boundary.

3.2 MODELING ASSUMPTIONS

The following site conditions and boundary assumptions were developed to complete the modeling task.

- The model was constructed with three layers: overburden, till, and shallow bedrock.
- Groundwater flow in the shallow bedrock aquifer was initially assumed to be horizontally isotropic. The analysis of shallow bedrock pumping tests conducted at the Stepan and Sears properties (Stepan Company 1994) supports this assumption. During the pumping tests, similar transmissivity values were estimated at observation wells located along arrays that were oriented perpendicular to each other, indicating horizontally isotropic conditions or low anisotropy ratios for horizontal hydraulic conductivity. The measured ratios of transmissivities along the flow direction and the perpendicular direction were 0.9 for the

Stepan pumping test and 1.6 for the Sears pumping test, indicating the lack of significant anisotropy in the shallow bedrock hydraulic conductivity.

- Results of shallow bedrock pumping tests indicate that the aquifer representative elementary volume (REV) is small as compared to the model area-of-interest. Based on the approximate 50 foot spacing between the pumping test wells and the associated observation wells, it appears that the hydraulic conductivity values approach uniformity at a scale of approximately 50 feet horizontally. The REV for the shallow bedrock aquifer was estimated to be approximately 87,500 cubic feet (50 foot length x 50 foot width x 35 foot depth). The REV is the scale beyond which hydraulic conductivity values are uniform and approach a constant value (Cook 2003). For comparison, the volume of the shallow bedrock aquifer corresponding to the model area-of-interest proposed in the Modeling Work Plan was approximately 700 times larger than the REV.

- Shallow bedrock within the vertical model domain was considered equivalent porous media (EPM). The EPM approach treats the fractured rock system as if it were an unconsolidated porous medium. This approach is most likely to be successful for systems where the fractures are interconnected and the fracture spacing is small compared to the scale of the system being studied (U. S. Environmental Protection Agency [EPA] 1989).

  The use of EPM to describe shallow bedrock groundwater flow at the FMSS was based on geologic structure and fracture mapping, pumping test results, and the distribution of hydraulic conductivity data. Pumping test results (Stepan RI) indicate the lack of preferential flow directions in the shallow bedrock and the presence of isotropy in horizontal hydraulic conductivity values. The small range in the measured hydraulic values calculated from monitoring wells installed in different directions from the pumping well may indicate small variations in fracture aperture, fracture density, fracture length, and fracture connectivity. As shown in the GWFS Report, **Volume 1, Figure 1-3** (GWRI Report Figure 3-14b), groundwater movement in the shallow bedrock is controlled by a dense network of open bedding plane fractures (almost horizontal) and sets of open joint fractures (almost vertical), resulting in an evenly spaced fractured media. The lack of anisotropy and the presence of evenly spaced high density fracture patterns at the site support the use of EPM to describe groundwater flow.

- The Saddle River was assumed to be fully penetrating in the model area-of-interest (through the shallow bedrock). It was treated as a specified (constant) head boundary. The appropriateness of this assumption was evaluated during model calibration.

- Westerly and Lodi Brooks were evaluated along their lengths for proper inclusion in the model as potential drains, streams, or low conductivity barriers to groundwater flow.

- The model was constructed with different boundary conditions for each layer, since the overburden is not saturated across the entire model domain. To allow for seasonal variation in the saturated extent of the overburden, no flow boundaries were set at a distance from the July 2001 zero-saturated thickness point in the overburden.

- Data generated during the GWRI and numerical interpolation techniques were used to define the ground surface and cell top and bottom elevations, as well as the groundwater surface. All overburden cells, for which the July 2001 groundwater elevations were less than the elevations of the overburden cell bottom, were determined to be dry and treated as inactive cells by the model.

- For shallow bedrock, open (variable head) model boundaries were used for the initial model calibration for all the boundaries, except the entire west boundary, where constant heads were assigned for Saddle Brook.
- The NE corner of the model domain is upgradient and far from the groundwater AOCs. Very limited hydrogeologic data is available for this area. Open (variable head) boundaries were used for the initial model run.
- The southern boundary of the model domain is at a sufficient distance from the areas of concern that specified heads may be assigned and adjusted during model calibration in the bedrock layer. An open (variable head) boundary was used for the initial model runs and tested for appropriateness.
- A till layer was assigned at the bottom of the overburden layer to allow for matching observed site conditions.
- July 2001 groundwater elevation data was used to calibrate the flow model, since this is the most complete data set for the model domain. Period-of-record site groundwater elevations were evaluated to determine if this is an average, low, or high groundwater condition. An examination of the hydrographs for selected wells indicates that the July 2001 data tends be towards the middle to low end of the range of historical groundwater data set. Acceptable model calibration residual target values were determined based on the July 2001 data set hydrologic evaluations.
- There are no known groundwater extraction wells currently operating in the area that would affect the model domain.

4.0 MODEL CODE SELECTION

Code selection is an important step in modeling. It essentially consists of matching the modeling needs of the project and known hydrogeologic site conditions to the key characteristics or capabilities of existing computer codes. The selected code should possess essential characteristics or capabilities to effectively address the problem to be answered while representing known site conditions.

Computer modeling software, which could accurately and efficiently simulate groundwater flow and solute transport occurring at the site, was selected for the FMSS. The model codes selected are also available in the public domain and have been verified by various Federal agencies such as the USACE, the USGS, and the EPA. The software selected is flexible and expandable for future applications not covered by the present modeling objectives. The groundwater modeling software package selected for application at the FMSS was GMS, a graphical user interface program that supports various flow and transport codes.

4.1 FLOW MODEL CODE

MODFLOW was selected for modeling the groundwater flow at the FMSS. The software package GMS Version 5.0/MODFLOW-2000 was used to develop the input parameters for the groundwater flow model. GMS/MODFLOW provides computer-aided graphics to facilitate the development of the input data and to visualize results. Model parameters were input and displayed on a graphical representation of the selected finite-difference grid.

MODFLOW is a modular three-dimensional groundwater flow model developed by the USGS. The three-dimensional flow model assumes flow through a porous material using constant density and isothermal conditions. The following equation describes this process:

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) - W = S_s\left(\frac{\partial h}{\partial t}\right)$$

Where:

x_i, x_j	=	principal coordinates of the system (i.e., x, y, and z) which are assumed to be parallel to the major axes of hydraulic conductivity (L)
K_{ij}	=	hydraulic conductivity tensor along the principal coordinate axes (L/t)
h	=	hydraulic head (L)
W	=	volumetric flux per unit volume and represents sources and/or sinks of water (l/t)
S_s	=	specific storage of the porous material (l/L)
t	=	time (t)

The above equation describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions, in which case, the hydraulic conductivity tensor becomes:

$$K_{ij} = \begin{matrix} Kxx & 0 & 0 \\ 0 & Kyy & 0 \\ 0 & 0 & Kzz \end{matrix}$$

In general, S_s, Kxx, Kyy, and Kzz may be functions of space, $S_s = S_s(x,y,z)$, Kxx = Kxx(x,y,z), etc., and W may be a function of space and time.

The above partial differential equation for groundwater flow is suitable for analytical solution techniques only for simple geometries and limiting assumptions. For complicated conditions, including heterogeneous and anisotropic porous media, MODFLOW applies a finite-difference numerical technique. The finite-difference method discretizes a real groundwater system into a network of blocks called cells. The block-centered, finite-difference formulation places a "node" at the center of each cell where hydraulic heads are calculated by the code. The location of the cells and their nodes are referenced using three-dimensional (i,j,k) indices. The finite difference mesh consists of NROW rows referenced by the first index (i), NCOL columns referenced by the second index (j), and NLAY layers referenced by the third index (k).

MODFLOW provides three main solvers: (1) Strongly Implicit Procedure (SIP), (2) Slice-successive Over Relaxation (SOR), and (3) Preconditioned Conjugate Gradient 2 (PCG2).

The SIP is a method for solving a large system of simultaneous linear equations by iteration. All of the equations for the model grid are solved simultaneously. The SIP solver is very stable and generally converges to a satisfactory solution.

SOR is a method for solving large systems of linear equations by means of iteration. It is implemented in the SOR package by dividing the finite difference grid into vertical slices and grouping the node equations into discrete sets. Each set corresponds to a slice; in every iteration, these sets of equations are processed in turn, resulting in a new set of estimated head values for each slice.

The PCG2 solver uses the preconditioned conjugate-gradient method to solve the simultaneous equations produced by the model. Linear and nonlinear flow models may be simulated. Convergence of the solver is determined using both the head change and residual criteria. This solver is best suited to models where certain flow cells are expected to be dewatered. A number of overburden cells at the FMSS are dry, at least seasonally. The PCG2 solver was used for modeling groundwater flow at the FMSS.

4.2 PARTICLE TRACKING CODE

GMS/MODPATH modeling program was used to perform particle tracking analysis. MODPATH (Pollock 1994) is a three-dimensional particle tracking code that uses the flow field output from MODFLOW to generate particle pathways (representing movement of discrete particles of groundwater) over time from selected initial points. In addition to computing particle paths, MODPATH keeps track of the time of travel for particles moving through the system, thereby enabling estimation of groundwater flow velocities.

MODPATH uses the following partial differential equation to describe conservation of mass in a steady-state, three dimensional groundwater flow system.

$$\frac{\partial}{\partial x}(nV_x) + \frac{\partial}{\partial x}(nV_y) + \frac{\partial}{\partial x}(nV_z) = W$$

Where:

V_x, V_y, and V_z	=	principal components of the average linear groundwater velocity vector
n	=	porosity
W	=	volume rate of water created or consumed by internal sources and sinks per unit volume of aquifer

The above equation expresses conservation of mass for an infinitesimally small volume of aquifer. The finite difference approximation of this equation can be thought of as a mass balance equation for a finite-sized cell of aquifer that accounts for water flowing into and out of the cell, and for water generated or consumed within the cell.

The average linear velocity component across each face in the cell (i,j,k) is obtained by dividing the volume flow rate across the face by the cross sectional area of the face and the porosity of the material in the cell.

$$V_{X1} = Q_{X1} / (n\,\Delta y \Delta z), \qquad V_{X2} = Q_{X2} / (n\,\Delta y \Delta z)$$

$$V_{Y1} = Q_{Y1} / (n\,\Delta y \Delta z), \qquad V_{Y2} = Q_{Y2} / (n\,\Delta y \Delta z)$$

$$V_{Z1} = Q_{Z1} / (n\,\Delta y \Delta z), \qquad V_{Z2} = Q_{Z2} / (n\,\Delta y \Delta z)$$

Where:

X1, X2, Y1, Y2, Z1 and Z2	=	six cell faces
Q	=	volume flow rate across a cell face
Δx, Δy and Δz	=	dimensions of the cell in the respective coordinate directions

In order to compute path lines, MODPATH uses the linear interpolation method to compute values of the principal components of the velocity vector at every point in the flow field based on the inter-cell flow rates from the finite difference model.

4.3 SOLUTE TRANSPORT CODE

Solute transport modeling was conducted using the software package GMS/MT3D (Modular Three-Dimensional Transport). MT3D, developed by S. S. Papadopulos & Associates (Zheng 1990), was selected for conducting the groundwater contaminant fate and transport modeling. MT3D is the most widely used and accepted solute transport model code for use with equilibrium controlled sorption or first-order chemical reactions. The model code is available in the public domain and is coupled with MODFLOW on GMS and other major groundwater modeling platforms.

MT3D is a model for the simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems. The model program uses a modular structure similar to that implemented in MODFLOW. The MT3D model uses a mixed Eulerian-Lagrangian approach to the solution of the three-dimensional advective-dispersive-reactive equation in three basic options. The MT3D model is intended to be used in conjunction with any block-centered finite-difference flow model (e.g., MODFLOW), and is based on the assumption that changes in the concentration field will not affect the flow field measurably. MT3D retrieves the hydraulic heads and the various flow and sink/source terms saved by MODFLOW, automatically incorporating the specified hydrologic boundary conditions.

The partial differential equation describing three-dimensional transport of contaminants in groundwater can be written as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_i}\right) - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{n}C_s + \sum_{K=1}^{N} R_k$$

Where:

C	=	concentration of contaminants dissolved in groundwater (ML^{-3})
t	=	time (t)
x_i, x_j	=	distance along the respective Cartesian coordinate axis (L)
D_{ij}	=	hydrodynamic dispersion coefficient (L^2T^{-1})
v_i	=	seepage or linear pore water velocity (LT^{-1})
q_s	=	volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative) (T^{-1})
C_s	=	concentration of the sources and sinks (ML^{-3})
n	=	porosity of the porous medium (dimensionless)
R_k	=	chemical reaction term ($ML^{-3}T^{-1}$)

Assuming that only equilibrium-controlled linear or nonlinear sorption and first-order irreversible rate reactions are involved in the chemical reactions, the partial differential equation above can be simplified and written as follows:

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s - \lambda\left(C + \frac{\rho_b}{\theta}C'\right)$$

Where:

ρ_b	=	bulk density of the porous medium (ML^{-3})
C'	=	sorbed phase contaminant concentration (MM^{-1})
λ	=	rate constant of the first-order rate reactions (T^{-1})
R	=	retardation factor (dimensionless).

The previous transport equation is linked to the flow equation through the following relationship:

$$v_i = -\frac{K_{ii}}{n} = \frac{\partial h}{\partial x_i}$$

Where:

K_{ii} = principal component of the hydraulic conductivity tensor (LT^{-1})

h = hydraulic head (L)

The hydraulic head is obtained from the solution of the three-dimensional groundwater flow equation presented in Section 4.1.

Process Simulated in MT3D

Advection: Describes the transport of miscible contaminants at the same velocity of groundwater. The advection term usually dominates for many practical problems concerning contaminant transport in groundwater. For advection-dominated problems, the solution of the transport equation is affected to some degree by two types of numerical problems: (1) numerical dispersion caused by truncation error, and (2) artificial oscillation caused by overshoot and undershoot of the solution. The mixed Eulerian-Lagrangian method implemented in the MT3D model is virtually free of any of the above errors.

Dispersion: In porous media, dispersion refers to the spreading of contaminants over a greater region than would be predicted solely from the groundwater velocity vectors. Dispersion may result from (1) deviations of actual velocity on a micro scale from the average groundwater velocity (mechanical dispersion), and (2) molecular diffusion resulting from concentration variations. The molecular diffusion effect is generally secondary and negligible compared to the mechanical dispersion effect, and only becomes significant when groundwater velocities are very low. The sum of the mechanical dispersion and the molecular diffusion is termed hydrodynamic dispersion.

Sinks and Sources: Sink/source terms in the transport equation represent solute mass dissolved in water entering the simulated domain through sources, or solute mass dissolved in water leaving the simulated domain through sinks. Model sinks or sources may be classified as "distributed" or "point input/output" features. The distributed sinks, or sources, include recharge and evapotranspiration. The point sinks, or sources, include features such as wells, drains, and rivers.

Chemical Reactions: Included in the MT3D model are equilibrium-controlled linear or nonlinear sorption and first-order irreversible rate equations (e.g., biodegradation and radioactive decay).

This page intentionally left blank.

5.0 CONSTRUCTION OF THE GROUNDWATER FLOW MODEL

The flow model was constructed and calibrated as a steady state model, following the approach presented in the Model Work Plan. The steady state approach was based on the assumption that the variability in groundwater flow over time is small in comparison to the variability in groundwater flow conditions across the model area. The effects of seasonal groundwater fluctuations and any small capacity groundwater pumping can be ignored while predicting the long-term (30 plus years) behavior of the groundwater flow field and solute plume migration, if near average groundwater conditions are input into the model. Therefore, the steady state modeling approach was appropriate for the model use as a tool for the analysis of long-term feasibility study scenarios, such as no action, natural attenuation, and groundwater extraction for a period of 30 years. Model construction details are described below.

5.1 DELINEATION AND DISCRETIZATION OF SPATIAL DOMAIN

The model grid was oriented so that it was aligned along the predominant NNE strike of the bedrock fractures in order to reduce simulation error caused by deviation of the directions of principal hydraulic conductivity tensor. Bedrock outcrop and borehole logging data indicate that the aquifer has dominant NNE striking bedding plane and joint fractures. The fracture rose diagram (Figure 3-12 of the GWRI Report) shows that the prevalent dip of the bedrock fracture orientations is west-northwest (WNW) and NW. The strike is perpendicular to the dip along NNE and NE. The rose diagram of the water bearing (conductive) fracture orientations also indicates a WNW to NW dip and NNE to NE strike.

The model was spatially discretized into a number of three dimensional cells. This was achieved by spatially dividing the model domain into 142 rows and 151 columns and vertically into 3 layers.

The cell size was varied, with 20 feet x 20 feet or less cell dimensions in the AOC areas. The cell size gradually increased as one moved from the AOC areas to the model boundaries. In order to control the numerical errors, the increase in cell dimensions between adjacent cells was 50 percent or less. The largest cells at the model boundary were less than 200 feet x 200 feet in dimensions.

5.2 DETERMINATION OF LAYER THICKNESS AND ELEVATIONS

The thickness of the top and the bottom layers were variable across the model domain, depending upon ground surface elevation and the depth at which bedrock was encountered below the ground surface. The middle layer (till) was a thin layer of constant thickness. The layers are described below.

Layer 1: **Overburden.** The overburden includes fill material, sand, silt, and gravel. The overburden extends from the water table to the top of the till (layer 2), with varying top and bottom elevations across the model domain. The elevations of the top of the overburden layer were defined by the July 26, 2001 groundwater elevation measurements. Overburden thickness is variable and ranges from 0 to 25 feet.

Layer 2: **Till.** The till layer in the model is 2 feet thick. It is located between the overburden and the shallow bedrock layers. The elevations of the bottom of the till layer were calculated from the elevations for the top of the bedrock that were provided electronically by Malcolm Pirnie, Inc.

Layer 3: **Shallow Bedrock.** Bedrock within the model area-of-interest is a weathered and highly fractured layered series of fine to coarse-grained sandstones, mudstones, and siltstones generally with a NNE strike, and a 7 to 12 degree dip. The shallow bedrock extends from the top of the rock (elevation data set provided by Malcolm Pirnie, Inc.) to 0 feet below MSL. The shallow bedrock thickness is variable, and ranges from 23 to 82 feet (approximately 44 feet average thickness).

5.3 DETERMINATION OF HYDROGEOLOGIC PROPERTIES

5.3.1 Hydraulic Conductivity

Slug tests and long-term pumping tests were conducted in the unconsolidated overburden material and the till layer that lies between the overburden material and the bedrock. The wells selected for slug testing were screened across several lithologies such as fill material, sand, silt, gravel, till, and weathered bedrock. The hydraulic conductivity values were plotted for the overburden and the shallow bedrock layers in the plan view for evaluation of spatial distribution. No spatial patterns were identified within each layer, and the magnitude of the hydraulic conductivity values appear to be randomly distributed. Each model layer was therefore assigned a common hydraulic conductivity value based upon site testing data for that media (i.e., overburden, till, and shallow bedrock). The geometric mean of the hydraulic conductivity values for the wells screened in the overburden was 2.63 feet/day (9.3E-04 centimeters per second [cm/s]). The median hydraulic conductivity value was 2.41 feet/day (8.5E-04 cm/s). For the initial model input, the hydraulic conductivity of the overburden was estimated to be equal to the median value of 2.41 feet/day.

Several slug tests, packer tests, pressure injection tests, pumping, and specific capacity tests were conducted in the shallow bedrock. The specific capacity results provided an order of magnitude estimate of hydraulic conductivity, since these were calculated on the basis of empirical formulas that may or may not be representative of the FMSS conditions. Therefore, the specific capacity data were not used in the model. Based on the other aquifer testing methods, the geometric mean of the hydraulic conductivity values for the wells screened in the shallow bedrock was 2.79 feet/day (9.8E-04 cm/s). The median hydraulic conductivity value was 2.94 feet/day (1.0E-03 cm/s). For the initial model input, the hydraulic conductivity of the shallow bedrock was estimated to be equal to the median value of 2.94 feet/day.

A thin layer of till material overlying the bedrock was reported to be encountered during well installation activities at the site. Hydraulic conductivity data is not available for the till layer. Qualitatively, it has been described as a dense, lower conductivity material as compared to the underlying shallow bedrock (GWRI Report). Therefore, for the initial model input, the hydraulic conductivity was estimated to be 2.41 feet/day, similar to the overburden material, but lower than the hydraulic conductivity of the shallow bedrock.

5.3.2 Horizontal Hydraulic Conductivity Anisotropy

Groundwater flow in bedrock is influenced by the orientation of bedding planes, joints, and fractures. Bedrock outcrop and borehole logging data indicate that the aquifer has dominant NNE striking bedding planes and joint fractures. Regionally, there is widely reported NNE trending anisotropy in literature for Passaic Formation. In the vicinity of the FMSS, the transmissivity values calculated from the two shallow bedrock aquifer tests do not indicate the presence of significant anisotropic factors. Based on the average results of drawdown and recovery values, the Stepan pumping test indicates that the transmissivities for wells located along perpendicular transects intersecting at the pumping well may vary locally by a ratio of 0.9; while the Sears pumping test (located off site) indicates that the transmissivities for wells located along perpendicular transects intersecting at the pumping well may vary locally by a ratio of 1.6.

Initially, the anisotropy was assumed to be 1.0 for each of the three model layers (isotropic conditions). Anisotropy was changed to various factors (i.e., 1.0, 1.5, 2.0, 2.5, and 3.0) during calibration and sensitivity analysis for evaluating impacts to modeling results.

5.3.3 Vertical Hydraulic Conductivity Anisotropy

The initial vertical anisotropy was assumed to be 1.0 for each of the three model layers. No site-specific, vertical anisotropy data were available. Vertical changes in hydraulic conductivity were accounted for by the layered structure of the model. Groundwater flow is primarily horizontal throughout the model domain. A greater vertical anisotropy would have some effect on model results in recharge and discharge areas. However, the effect would not be significant in a steady-state model.

5.3.4 Groundwater Recharge

Precipitation is reported to be distributed uniformly over the year at the FMSS. The recharge rate for the Maywood Borough section of Bergen County, New Jersey is approximately 7.4 inches/year (New Jersey Geological Survey [NJGS] DGS02-3: Groundwater Recharge for New Jersey). This recharge rate ranges from 0 inches/year to 12.62 inches/year in Maywood Borough. Due to FMSS being located in an urban setting that is heavily constructed with both industrial and residential sections, the amount of precipitation that eventually recharges the aquifer is expected to be smaller than the average for Bergen County.

Initially, one recharge zone with a recharge rate of 7.4 inches/year was prescribed to the model. The recharge was applied to the highest active cell, i.e., to the overburden cells where saturated overburden material is present and directly to the till or shallow bedrock where saturated overburden is absent. Through the model calibration process, four recharge zones were identified. These are described in detail in the Model Calibration section (**Section 6.1**).

5.3.5 Hydraulic Head Distribution

The July 26, 2001 groundwater elevation data was used to calibrate the flow model, since this is the most complete data set for the model domain. Period-of-record site groundwater elevations were evaluated to determine if this is an average, low, or high groundwater condition. An examination of the hydrographs for selected wells indicates that the July 26, 2001 data tends be towards the middle to low end of the range of historical groundwater data set (**Figures 5-1** and **5-2**). Acceptable model calibration residual target values were determined based on the July 26, 2001 data set hydrologic evaluations.

5.4 ESTABLISHMENT OF BOUNDARY CONDITIONS

The Saddle River was modeled as a specified (constant) head boundary. This boundary condition was applied to each of the three layers. The modeling input river stage for the downgradient end (south) of this boundary, 27.05 feet MSL, was based on records from USGS stream flow data at Station No. 01391500 located approximately 0.5 miles south of the site (shown on GWRI Figure 1-2). The stage for the upgradient end (north) of this boundary, 32.65 feet MSL, was based on the topographic gradient along this section of the Saddle River. The topographic gradient was obtained from the USGS topographic quadrangle map for Hackensack, New Jersey.

For the initial model run, all other boundaries were modeled as open (variable head, no flow) boundaries. The boundary conditions were modified, as appropriate, during the model calibration process. Details of the final boundary type selected are provided in the Model Calibration section (**Section 6.1**).

Lodi Brook and Westerly Brook were simulated using the MODFLOW RIVER package, except for the sections where the Brooks flow within culverts. The reaches of Brooks flowing within culverts were modeled using the MODFLOW DRAIN package. Both of these packages allow for groundwater/surface water interaction. Groundwater may flow to the RIVER cells from the adjacent aquifer cells if the groundwater elevations in the aquifer are higher than the RIVER stage. Conversely, the RIVER cells may lose water to the aquifer cells if the aquifer groundwater elevations are lower than the stage in the RIVER cells. However, in the DRAIN cells, groundwater may flow from the aquifer to the drains (provided aquifer groundwater elevations are higher than the water level in the DRAIN cells), but not from the DRAIN cells to the aquifer (when the aquifer groundwater elevations are lower than the water level in the DRAIN cells). The specification of DRAIN type cells for the reaches of the Brooks flowing through the culverts is justified, because video inspections of culverts have revealed numerous instances of leakages throughout the lengths of the culverts.

GWRI Report Figure 3-22a through 3-22c show profiles of the culvert sections of Westerly Brook. The elevations of DRAIN cells were interpolated from data in these profiles and input into the model. The DRAIN cell elevations for Lodi Brook were approximated from surrounding topographic information, since profiles for the culvert section of Lodi Brook in the model domain are not available. The stage in the RIVER cells was approximated from the topographic information for the adjacent cells. For an initial approximation, the stage was set at a high level, and therefore, the RIVER bed elevation was assumed to be 6 feet below the stage in the RIVER cells.

The RIVER cells for the open reaches of Lodi and Westerly Brooks were prescribed a conductance value that was based on the assumption that the river bed sediment has a hydraulic conductivity of 0.27 feet /day (approximately one tenth of median overburden hydraulic conductivity). It was also assumed that the river bed material was approximately 2 feet thick, and the river width was approximately 10 feet. The DRAIN cells were prescribed a conductance that was 10 times higher than the RIVER cells (approximately the same as the median overburden hydraulic conductivity) to account for leakage through the culverts (open pipes).

The DRAIN and the RIVER cells that define Lodi and Westerly Brooks were prescribed to the top layer of the model, i.e., the overburden layer. The stage/water levels in these cells, and the cell conductance values, were input as initial approximations and adjusted during the model calibration process.

5.5 GROUNDWATER EXTRACTION

There are no known groundwater extraction wells operating in the model domain.

This page intentionally left blank.

6.0 FLOW MODEL CALIBRATION RESULTS

6.1 CALIBRATED MODEL DESCRIPTION

Before using the model to make predictions regarding groundwater flow and solute transport at the FMSS, the ability of the model to replicate field observed groundwater levels was established. This was performed by determining a set of hydraulic features and hydrogeologic parameters such as recharge, hydraulic conductivity values, anisotropy ratios, and boundary conditions (calibration parameters) that allowed the model to reproduce a set of field measurements, such as groundwater elevations at selected wells (calibration targets) within an acceptable range of error. The July 26, 2001 groundwater elevation data set was used for this purpose. Fifty-three monitoring wells and piezometers located in the overburden layer, and 54 monitoring wells and piezometers screened across the shallow bedrock, were used as calibration targets.

Model calibration was performed through an iterative process of varying the input parameters until acceptable results were obtained. Documentation of each calibration run, including the error statistics and predicted head values, were maintained electronically, as well as in hard copy. The 137th model iteration resulted in the best statistical fit to the observed data. The best statistical fit run was called FLOW_137. Model parameters for this run are summarized on **Table 6-1** and described in detail below.

Recharge

The best statistical fit model had four recharge zones with the following recharge rates. The zones are shown graphically in **Figure 6-1**.

- Zone I Area to the east of Westerly Brook Culvert - 1.0 inches/year
- Zone II Area in the middle of AOCs - 24 inches/year
- Zone III Area to the east of AOCs - 4 inches/year
- Zone IV Remainder of model domain - 0.1 inches/year

Zone II recharge exceeds the upper range of 12.62 inches for the Maywood Borough. This is anomalously higher than the average recharge value for Maywood Borough, which is generally urban and developed/paved. The higher recharge rate for Zone II may be attributed to processes associated with the manufacturing facilities in the area and some of the older water infrastructure that may be leaking, resulting in an additional source of recharge. Zone IV recharge is low for a residential area; however, this zone is covered by buildings/pavement, resulting in low recharge.

Hydraulic Conductivity

The best statistical fit model had the following horizontal hydraulic conductivity values.

- Overburden - 7.83 feet/day (approximately three times higher than initial value)
- Till - 2.67 feet/day (same as initial value)

- Shallow Bedrock - 2.94 feet/day (same as initial value)

Anisotropy

The best statistical fit model had the following horizontal hydraulic conductivity anisotropy ratios.

- Overburden - 1.0
- Till - 1.0
- Shallow Bedrock - 1.0

Boundaries

- Saddle River - specified (constant) head boundary, all three layers
- Southern Boundary - specified head boundary in layer 3
- Southern half of Eastern Boundary - specified head boundary in layer 3
- Model Top - recharge boundary
- Model Bottom - no flow boundary
- Lodi and Westerly Brooks, open reaches - RIVER type boundary condition in layer1
- Lodi and Westerly Brooks, culvert sections - DRAIN type boundary condition in layer 1

All other model boundaries were treated as open (variable heads, no flow) boundaries. The model grid and boundary conditions are graphically shown on **Figure 6-2** (overburden boundaries), **Figure 6-3** (till layer boundaries), and **Figure 6-4** (shallow bedrock boundaries).

6.2 EVALUATION OF MODEL CALIBRATION

6.2.1 Statistical Evaluation

Model calibration results were quantitatively evaluated on the basis of the overall statistical match between the measured and simulated groundwater elevations across the flow field. As recommended by Anderson and Woessner (1992), three ways of expressing the difference between the measured and simulated groundwater elevations were utilized. These statistical parameters were calculated separately for the overburden and the bedrock aquifers, and expressed as a percentage of the total head drop measured across the modeled area.

Model calibration objectives were established in the Model Work Plan and are described below.

- **Mean Error (ME)** is a measure of the average difference between the simulated and the measured groundwater elevations (residual mean). As a model calibration objective, it was proposed that the ME for the calibrated model be no more than approximately ±3 percent of the total head change across the model domain. The best statistical fit model (Model Run FLOW_137) has a ME of -0.5 percent, which was well below the model calibration objective.

- **Mean Absolute Error (MAE)** is a measure of the average absolute difference between the simulated and the measured groundwater elevations (residual absolute mean). As a model calibration objective, it was proposed that the MAE for the calibrated model be no more than approximately 3 percent of the total head change across the model domain. The best statistical fit model has a MAE of 3.2 percent, which approximately satisfies the model calibration objective.

- **Root Mean Square Error (RMSE)** is a measure of the standard deviation of the simulated values from the measured groundwater heads (standard deviation of residuals). Since the RMSE measures the average of the squared differences in the simulated and observed data, it is typically higher than the ME or the MAE. As a model calibration objective, it was proposed that the RMSE for the calibrated model be no more than approximately 5 percent of the total head change across the model domain. The best statistical fit model has a RMSE of 4.2 percent, which satisfies the model calibration objective.

- Groundwater flow model calibration results are reported in **Table 6-2** by providing a listing of the measured and simulated groundwater elevations at each of the 107 calibration targets (53 located in the overburden and 54 located in the shallow bedrock).

6.2.2 Groundwater Flow Patterns and Gradients

The results of the flow model calibration were also evaluated qualitatively. Groundwater elevation contours generated on the basis of the modeled data set were plotted on the site map for the overburden (**Figure 6-5**) and shallow bedrock (**Figure 6-6**) aquifers. While there are some differences, including differences due to interpretation, the contours are generally similar to those based on the July 26, 2001 measurements presented in the GWFS Report, **Volume 1, Figures 1-4** and **1-5** (GWRI Report Figures 3-15a and 3-19a). A spatial evaluation of error trends was performed by posting the residuals (difference between predicted, measured, and groundwater elevations) on a site map; and was performed separately for the overburden and the bedrock aquifers. A positive residual indicates that the model prediction is higher than the measured value and vice versa. It was concluded that the errors were spatially distributed and more or less random, thereby precluding the presence of significant errors in model input parameters.

The average hydraulic gradients obtained from the model (based on particle tracking transects) for the overburden and the shallow bedrock aquifers are 0.010 and 0.009, respectively. The hydraulic gradients calculated on the basis of groundwater elevations measured on July 26, 2001 were 0.009 for the overburden and 0.011 for the shallow bedrock. The modeled hydraulic gradients are very similar to the measured gradients.

6.2.3 Evaluation of Systematic Bias

Scatter plots of the measured versus simulated heads (correlation among residuals) were prepared for the overburden (**Figure 6-7**) and the shallow bedrock (**Figure 6-8**) aquifers. The scatter-plots were utilized to qualitatively evaluate the randomness of the calibration errors. No systematic biases were observed in the best statistical fit model (Model Run FLOW_137).

6.2.4 Mass Balance Errors

The mass balance error associated with best statistical fit model was 0.0 percent. This indicates that the principle of conservation of mass was honored, i.e., the volume of water inflow is equal to the amount of water outflow from the model domain. Mass balance errors of less than 1 percent are acceptable for adequately calibrated models (Anderson, et. al. 1992).

6.3 SENSITIVITY ANALYSIS

An analysis of the sensitivity of model calibration to key input parameters was conducted. During the sensitivity analysis process, changes were made in key model input parameters and the effects of these changes on the model output were documented. The parameters and the range of parameter values used for sensitivity analysis are as follows:

- Boundary Conditions (no flow vs. specified head, specified head vs. specified flux, as appropriate)
- Precipitation Recharge (± 20 percent of the best statistical fit values)
- Flow to Deep Bedrock (zero and ± 0.1 and ±1.0 inch/year)
- Bedrock Anisotropy (1.5, 2.0, 2.5, 3.0)
- Hydraulic Conductivity (± 50 percent of the best statistical fit values)

The results of the model sensitivity analysis were tabulated and are summarized below.

1. **Horizontal Hydraulic Conductivity Anisotropy** - Model calibration is sensitive to changes in anisotropy for the overburden and shallow bedrock layers, but not for the till layer. The best statistical fit is obtained for anisotropy ratios of 1.0 for the overburden, the shallow bedrock, and the till layers. Results of detailed analysis of the flow model sensitivity to horizontal anisotropy are tabulated in **Table 6-3**.

2. **Recharge** - Model calibration is primarily sensitive to changes in Zone II (area in the middle of AOCs). Results of detailed analysis of the flow model sensitivity to groundwater recharge rates are tabulated in **Table 6-4**.

3. **Horizontal Hydraulic Conductivity** - Model calibration is slightly sensitive to changes in hydraulic conductivity of the overburden. Model calibration is sensitive to changes in the shallow bedrock layer, but not in the till layer. Results of detailed analysis of the flow model sensitivity to horizontal hydraulic conductivity values are tabulated in **Table 6-5**.

4. **Flow at Shallow/Deep Bedrock Interface** - Model calibration is sensitive to changes in flow at this interface. The least amount of calibration error is for the situation when flow across this interface is zero. Results of detailed analysis of the flow model sensitivity to flow at the shallow/deep bedrock interface are tabulated in **Table 6-6**.

5. **Boundary Conditions** - Model is sensitive to changes in the Saddle River and southeast model edge boundary conditions from specified (constant) head to no flow boundary

conditions. Results of detailed analysis of the flow model sensitivity to changes in model boundary conditions are tabulated in **Table 6-7**. Quantitatively, the overall model is not very sensitive to the boundary conditions at the other model edges. However, local groundwater patterns in the vicinity of these boundaries are impacted.

This page intentionally left blank.

7.0 PARTICLE TRACKING ANALYSIS

Particle tracking was used to trace the flow paths (also called path lines) in the overburden and the shallow bedrock aquifers. Particle tracking was performed by using the calibrated flow model (Model Run FLOW_137) to track the movement of particles of water starting at the approximate locations of the AOCs and other areas of interest. The results of the MODPATH simulations were used to delineate the particle trajectories, and calculate average travel times in the overburden and the shallow bedrock aquifers.

Figure 7-1 shows the particle path lines for the overburden aquifer. Particle locations after each year of travel are marked on the individual trajectories. Path lines and yearly particle locations for the shallow bedrock aquifer are shown on **Figure 7-2**. An inspection of the four particle trajectories for the overburden and the shallow bedrock aquifer indicates that two of the particle trajectories terminate at the Saddle River, one in Westerly Brook and one in Lodi Brook. The base elevation of the open and culverted sections of both Westerly and Lodi Brooks is higher than the top of the bedrock aquifer. The particle tracking results suggest an upward groundwater flow from shallow bedrock to the overburden aquifer, and probable groundwater discharge into Westerly and Lodi Brooks. To confirm the presence of upward gradients in these areas, the measured vertical gradients at monitoring well pairs B38W14S/D and B3815S/D (located near Westerly Brook) and B38W12A/B (located near Lodi Brook) were evaluated. As shown in GWRI Table 10a, over a 2.5 year period from June 1999 to December 2001, the average groundwater gradients at these well pairs were upwards: -0.024 feet/feet at B38W14S/D, -0.038 at B3815S/D, and -0.006 at B38W12A/B. The measured vertical gradients show an upward groundwater gradient in those areas and support the findings of the model particle tracking data.

The average groundwater gradients and velocities were calculated on the basis of **Figures 7-1** and **7-2** and are listed in **Table 7-1**. The results of the particle tracking simulations are consistent with the findings reported in the GWRI Report. The modeled groundwater flow directions are similar to those presented in the GWRI Report (see GWFS Report, **Volume 1, Figures 1-4** and **1-5** [GWRI Figures 3-15a and 3-19a]). The average groundwater velocities obtained from the model for the overburden and the shallow bedrock aquifers are 0.40 feet/day and 0.52 feet/day, respectively. The average groundwater velocities reported in the GWRI Report were 0.42 feet/day in the overburden aquifer, and 0.56 feet/day for the shallow bedrock, which are very similar to the particle tracking results. Similarly, the average hydraulic gradients derived from particle tracking for the overburden and the shallow bedrock aquifers (0.010 and 0.009 feet/feet, respectively) were very similar to the average gradients reported in the GWRI Report (0.009 and 0.011 feet/feet, respectively). It appears that the flow model replicates the groundwater flow field parameters estimated in the GWRI Report.

This page intentionally left blank.

8.0 FEASIBILITY STUDY SCENARIO MODELING

8.1 MODELING ASSUMPTIONS

The following assumptions were made to construct the solute transport models used for conducting the feasibility study scenario analysis.

- Source areas soils (COCs) were assumed to have been removed prior to implementation of the feasibility study scenarios. It is proposed to excavate impacted soils to meet approved COC Soil Screening Levels (SSL) (USACE 2004b), thereby eliminating the ongoing source of groundwater contamination. SSLs will be protective of groundwater and meet the regulatory limits listed in the GWFS Report, **Volume 1, Table 2-2**.

- The MISS groundwater is the source of surface water COCs in Westerly Brook. This source will be cut off, once the culvert pipe is replaced/repaired during the Soils Operable Unit (OU) remediation. The solute transport model presented in this chapter was constructed using the existing conditions of the culvert sections with MISS groundwater discharging into the Westerly Brook culvert. The elimination of the MISS groundwater source will have no impact on the no action alternative; however, it could potentially have some impact on the outcomes of the natural attenuation, groundwater extraction, and in-situ treatment alternatives. The potential for these impacts were evaluated. Analytical calculations and model simulations indicate that culvert replacement/repair will eliminate the small discharge (approximately 0.024 cfs) to Westerly Brook and will have minimal impact on the groundwater flow paths. Although the replaced culvert will be impermeable, it will occupy a small fraction of the overburden saturated thickness and will be installed in a trench that may be backfilled with a more permeable material. Also, shallow bedrock below the trench is fractured and weathered. Groundwater will flow above and below the culvert. The net effect of culvert replacement on the groundwater flow field and feasibility study scenario evaluation is expected to be minimal.

- Initial concentrations for solute transport modeling and/or analytical analysis are based on data presented in the GWRI collected between 2000 and 2002.

- Chemical constituent concentrations derived from non-FUSRAP waste sources or CERCLA non-hazardous substances are not incorporated in the feasibility study scenario analysis. These chemical constituents are listed below:

  - Tetrachloroethene (PCE)
  - Trichloroethene (TCE)
  - Vinyl Chloride (VC)
  - Beryllium
  - Thallium
  - Toluene
  - Xylene
  - Iron
  - 2-chlorotoluene
  - Arsenic (non-MISS Sources)
  - Lithium (non-MISS sources)
  - Barium
  - Lead
  - Methylene chloride
  - Manganese

  These constituents were found in monitoring wells within the groundwater extraction capture zone and in-situ treatment areas.

- Scenarios, such as groundwater extraction and in-situ treatment, were developed to remediate only MISS-related groundwater COCs (derived from FUSRAP waste as defined in GWFS **Volume 1**).

- The following COCs were selected for feasibility study scenario analysis.

  - Lithium
  - Benzene
  - Arsenic

- Isolated groundwater exceedances of chemical constituents were not modeled.

- For chemical constituents with well delineated solute plumes (lithium, benzene, and arsenic) in groundwater, three-dimensional solute transport models were constructed.

- Solute attenuation within the aquifers, if any, is due to equilibrium controlled sorption and/or first-order chemical reactions such as biodegradation and radioactive decay.

- Media specific transport properties of the till layer are similar to the overburden aquifer.

- Solute transport model runs are carried out to 30 years into the future (or longer if needed); results are generally presented at zero time (2000 - 2002 conditions), and 5, 10, 20, 25 and 30 years into the future, or as appropriate. Benzene results are presented at zero time and 2, 4, 6, and 9 years. Biodegradation will reduce the benzene concentrations to less than the regulatory limits in 10 years or less.

- The source terms for the chemical constituents to be modeled were derived from the monitoring well analytical data collected between 2000 and 2002. For making future projections of solute concentrations under various feasibility study scenarios, it was assumed that these initial concentrations represent the "year zero" conditions (point of time when contaminated soils above SSL values or other soil to groundwater leaching limits are removed). Since total remediation of source soils is assumed prior to simulation of the remedial scenarios, there is no solute input in the groundwater model.

- Groundwater extraction scenarios were designed to minimize the capture/influence of off-MISS non-FUSRAP chlorinated solvents (PCE and TCE) and other solute plumes located downgradient from the MISS. However, isolated exceedances of these non-FUSRAP chemical constituents located on the MISS would possibly be captured along with the FUSRAP groundwater.

- Groundwater extraction was modeled for a maximum of 30 years to evaluate the viability of this remedial scenario in remediating MISS groundwater. Remaining solute in the aquifer after this time period was simulated using the no action/natural attenuation scenario.

8.2 MODELING PROCEDURES AND MODEL INPUT PARAMETERS

Information regarding the solute transport parameters for the chemical constituents to be modeled was obtained from the GWRI and **Appendix B, Volume 1** of the GWFS Report. Media specific transport parameters, such as aquifer porosity values and bulk density of aquifer materials for the overburden and the shallow bedrock, were presented in the GWRI. Transport parameters, including adsorption coefficients and biodegradation half-lives, were obtained from the GWRI and **Appendix B, Volume 1** of the GWFS Report, and published literature sources such as Howard, et. al. (1991). Treatment half-lives (the effective half-lives of solutes when subject to in-situ treatment using redox alteration techniques) of select chemical constituents, were obtained from **Appendix B, Volume 1** of the GWFS Report. Dispersion coefficients were initially based on published literature recommendations and later adjusted to site conditions during model construction. A summary of solute modeling input parameters is provided in **Table 8-1**.

Three chemical constituents related to the FUSRAP waste were identified for transport modeling. Time-concentration trends associated with these chemical constituents are presented in the GWFS Report, **Appendix A, Volume 1**. It is noted that soil sources have not been removed to date. The trends were generated using data that accounts for any potential releases from the soil sources.

The chemical constituents modeled are listed below.

Metals: arsenic and lithium.

Organic Compounds: benzene.

The applicable regulatory limits for the chemical constituents are listed in the GWFS Report, **Volume 1, Table 2-1**.

For each of the COCs the following feasibility study alternatives were evaluated using transport modeling or analytical methods:

- No Action
- Natural Attenuation (similar modeling results as for the No Action Scenario)
- In-Situ Treatment using bioremediation and/or redox alteration (if applicable)
- Groundwater Pumping and Ex-Situ Treatment (if applicable)

The no action and the natural attenuation scenarios were modeled concurrently. These scenarios were similar, except that at some future date, the Westerly Brook culvert will be replaced or repaired, thereby eliminating groundwater discharge to Westerly Brook. The model estimated groundwater flow to the culvert sections is 0.024 cfs. The net effect of culvert repair/replacement on groundwater flow direction and solute plume migration rate and direction is expected to be minimal.

In-situ treatment was considered for lithium, arsenic, and benzene. Of these constituents, only arsenic and benzene were amenable to in-situ treatment; however benzene will attenuate naturally due to biodegradation and will not be treated. In-situ treatment will be implemented for arsenic in the overburden due to the extent of the plume. Arsenic in shallow bedrock will not be treated due to its limited extent. The modeling of the in-situ treatment of arsenic in the overburden was performed by adjusting the solute half-life to simulate the degradation of the plume with time after the in-situ treatment. Details of the in-situ remedial processes are provided in the GWFS Report, **Appendix B, Volume 1**.

The scenario involving groundwater extraction was evaluated only for those constituents that had a well delineated solute plume related to FUSRAP waste. These constituents were arsenic and benzene. Groundwater extraction scenarios were run for each selected chemical constituent until groundwater cleanup standards (GWFS, **Volume 1, Table 2-2**) were achieved, or out to a maximum 30 year period. If groundwater cleanup was not achieved at the end of the 30 year period, the model groundwater extraction was stopped and the no action/natural attenuation scenario was run until groundwater standards for the chemical constituents were achieved.

8.3 ALTERNATIVE ANALYSIS MODELING RESULTS

The results of modeling of the applicable alternatives (no action/natural attenuation, groundwater extraction, and in-situ treatment) are summarized in **Table 8-2**. Detailed discussions for each of the individual chemical constituents are provided here.

<u>**Lithium**</u>

FUSRAP lithium groundwater exceedances were detected in a total of 30 overburden and bedrock wells located on and downgradient of the MISS. A risk-based action level of 730 micrograms per liter (μg/L) was calculated for lithium using the Baseline Risk Assessment approach (GWFS Report **Volume 1, Section 1.2.6**). The locations of MISS-related lithium exceedances and their respective concentrations are listed in the GWFS Report, **Volume 1, Table 1-1**. The lithium concentration data for the overburden and shallow bedrock aquifers for the period 2000 – 2002 are graphically shown on the GWFS Report, **Volume 1, Figures 1-6** and **1-7** (GWRI Figures 5-5 and 5-16). Some of the lithium groundwater exceedances shown are not derived from the MISS; however, they are included in the no action/natural attenuation scenario model for completeness. Evaluation of active groundwater remedial scenarios (i.e., groundwater extraction) focused on capture/treatment of COCs identified in the GWFS Report, **Volume 1**.

Initial (year zero) lithium concentrations were assigned to the feasibility study model on the basis of groundwater analytical data collected during the 2000-2002 time period. The modeled year zero lithium concentration distribution for overburden aquifer is shown on **Figure 8-1A**. The model concentration distribution is generally similar to the measured distribution presented in GWRI Figure 5-5. The differences are primarily due to the fact that the model does not assign concentrations to overburden cells that are dry. Some minor differences may be related to the differences in the interpolation approaches utilized for contouring the concentration distributions.

The modeled year zero lithium concentration distribution for the shallow bedrock is shown on **Figure 8-2A**. The model concentration distribution is generally similar to the measured distribution presented in the GWRI Report, Figure 5-16 (with the exception of an improperly located well). The differences are primarily due to the fact that the model does not utilize lithium concentration data from the deep bedrock wells such as BRPZ-7, PT1DB, MW-23DD, and MW-24DD. In addition, the concentration measured at B38W06B was assigned to the correct coordinates, thereby changing the shape of the southern lithium plume. As with the overburden, minor differences are due to the differences in the interpolation approaches.

The no action and the natural attenuation scenarios were modeled concurrently, since the functional difference between these scenarios is the requirement for continued monitoring. The culvert will be repaired/replaced at some future date, eliminating groundwater discharge to the culvert sections of Westerly Brook. However, the net effect on lithium plume migration is expected to be minimal. The groundwater flow direction and the associated solute transport will not be affected by the culvert repair. From the perspective of solute fate and transport modeling, there is little difference between these two scenarios. The distributions of the lithium concentrations (MISS and non-MISS-related) in the overburden and shallow bedrock aquifers for the no action scenario were plotted at 5, 10, 15, 20, 25, and 30 years into the future (**Figures 8-1B** through **8-1G** and **8-2B** through **8-2G**).

Based on model results, it is estimated that it will take approximately 280 years for the MISS-related lithium concentrations to attenuate naturally to levels below the risk-based action level of 730 µg/L. During the 280 year time period, the lithium plumes are expected to travel downgradient to a distance of approximately 2,550 feet from the year zero center of mass in the overburden aquifer, and approximately 2,150 feet from the year zero center of mass in the shallow bedrock aquifer.

Under the no action scenario, approximately 8 percent of the current (year zero, based on 2000 - 2002 data) lithium mass will be discharged to the Westerly Brook during the initial 30 years. No mass is lost to the Saddle River during the initial 30 years. Over the next 250 years, 70 percent of the dissolved lithium mass will be discharged to the surface water (either Westerly Brook or the Saddle River) under the no action scenario. After 280 years, it is predicted for the no action scenario that approximately 22 percent of the lithium mass will remain in the aquifers, either in the form of lithium adsorbed to aquifer material or as dissolved concentrations diluted to levels less than the regulatory limit.

Under the natural attenuation scenario, no mass is lost to the Westerly Brook, since the culvert will be repaired/replaced. No mass is lost to the Saddle River for the initial 100 years. Over the next 180 years, 70 percent of the dissolved lithium mass will be discharged to the Saddle River. After 280 years, 30 percent of the dissolved lithium mass is expected to remain in the aquifers, which is higher than the residual aquifer mass for the no action scenario. The difference in residual aquifer masses between the no action and the natural attenuation scenarios is due to the elimination of the mass removal through the leaking culvert sections of the Westerly Brook under the natural attenuation scenario.

Under either of the no action or natural attenuation scenarios, it will take over 100 years for the lithium plume to reach the Saddle River. The concentration of lithium in groundwater discharging to the Saddle River is expected to peak at approximately 140 years from the current time. At this time, the concentration of lithium in groundwater discharging to the Saddle River is expected to range from 730 µg/L to 1,000 µg/L. The average discharge concentration is expected to be approximately 820 µg/L, as compared to the 730 µg/L risk-based action level for lithium in groundwater. Based on the low-flow discharge rate of 14.58 cfs measured in the Saddle River, the groundwater discharge is expected to be diluted 729 times. This dilution will result in a lithium concentration of approximately 1 µg/L in the Saddle River, well below the regulatory limit.

The groundwater extraction scenario model was run for a period of 30 years of pumping, followed by 245 years of no action. It included four extraction wells located on MISS property, pumping a total of 10 gallons per minute (GPM). The distribution of the well locations, and the allocated extraction rates (two wells with 3 GPM pumping rate and two wells with 2 GPM pumping rate), were designed to provide the desired capture zone while minimizing the possibility of any of the wells going dry during the course of the extraction system operation. The wells were simulated to be installed in the shallow bedrock, since the overburden saturated thickness is small (5-10 feet) in the area-of-interest, thereby precluding the capture of overburden plume through extraction wells placed in the overburden. The resultant capture zone for the overburden aquifer is shown on **Figure 8-3A**. The capture zone encompasses the MISS-related lithium plumes in the overburden aquifer. The location of the extraction wells, pumping rates, and the resultant capture zone in the shallow bedrock are shown on **Figure 8-3B**. The capture zone in the shallow bedrock aquifer encompasses the MISS-related on-site lithium concentrations, while minimizing off-site plume capture.

The distributions of the lithium concentrations (MISS and non-MISS-related) in the overburden and shallow bedrock aquifers for the groundwater extraction scenario were plotted at 5, 10, 15, 20, 25, and 30 years into the future (**Figures 8-4A** through **8-4F** and **8-5A** through **8-5F**). Although the extraction well locations were selected to maximize on-site lithium plume capture, on-site groundwater extraction also results in stabilization of the off-site lithium plume downgradient of the MISS. The off-site overburden and shallow bedrock plumes appear to stay in-place over the 30-year pumping duration and do not migrate further downgradient. Groundwater extraction also removes some of the non-FUSRAP lithium concentration dissolved in overburden and shallow bedrock groundwater to the south of the MISS.

Based on model results, it is estimated that after 30 years of pumping, groundwater concentrations in the overburden and the shallow groundwater will still exceed the risk-based action level. Assuming that after 30 years the groundwater extraction system is terminated, it will take another 245 years of no action for the MISS-related lithium concentrations to be reduced to levels below the risk-based action level, i.e., a total of 275 years.

During the initial 30 year groundwater extraction period, 25 percent of the current (year zero, based on 2000-2002 data) lithium mass will be removed by groundwater extraction. No mass is lost to the Saddle River. Over the following 245 years, an additional 52 percent of the dissolved lithium mass will be discharged to the Saddle River. After a total of 275 years, it is predicted that approximately 23 percent of the lithium mass will remain in the aquifers. The data indicates that groundwater extraction (for a 30 year period) does not significantly reduce the lithium cleanup time as compared to the no action/natural attenuation option. However, it eliminates the mass discharge to the Saddle River during the 30 year period.

In-situ treatment of lithium by redox alteration is not feasible, because the metal lithium is not redox active. Lithium mobility is not affected by redox manipulation; it is mostly controlled by adsorption on clay surfaces along the groundwater flow path. No proven in-situ remediation technology is available for lithium; therefore, the in-situ treatment scenario was not modeled for lithium (GWFS, **Appendix B, Volume 1**).

Benzene

During the period 2000 – 2002, MISS-related benzene concentrations (FUSRAP waste) were detected in exceedance of the regulatory limit at 15 monitoring well locations. The regulatory limit for benzene is 1 microgram per liter (μg/L). The locations of MISS-related benzene exceedances and their respective concentrations are listed in the GWFS Report, **Volume 1, Table 1-1**. The benzene concentration data for the overburden and shallow bedrock aquifers for the period 2000-2002 are graphically shown on the GWFS Report, **Volume 1, Figures 1-8** and **1-9** (GWRI Figures 5-6 and 5-17). The benzene plumes located on MISS property and downgradient of the MISS were used to evaluate the feasibility study scenarios.

Initial (year zero) benzene concentrations were assigned to the feasibility study model on the basis of groundwater analytical data collected during the 2000-2002 time period. The year zero benzene concentration distributions in the model for overburden and the shallow bedrock aquifers are shown on **Figures 8-6A** and **8-7A**. The model concentration distributions are similar to the measured distributions presented in the GWRI, Figures 5-6 and 5-17. Some minor differences may be related to the differences in the interpolation approaches utilized for contouring the concentration distributions.

The no action and the natural attenuation scenarios were modeled concurrently, since they amount to the same modeling approach. The differences between these two scenarios are related to monitoring requirements and elimination of groundwater discharge to culvert sections of Westerly Brook. As discussed earlier, neither of these are expected to affect the solute transport and plume migration. The distributions of the benzene concentrations under the no action scenario were plotted for the overburden aquifer at 2, 4, and 6 years into the future (**Figures 8-6B** through **8-6D**). A modeling anomaly was observed on these figures. Low level benzene concentrations were observed in some overburden areas where they were not previously measured in monitoring wells; typically these concentrations were present in areas overlying the shallow bedrock plume. The anomalous concentrations were investigated and found to be related to vertical dispersion and vertical anisotropy factors used in the model, which could not be altered. Benzene concentrations in the overburden are predicted to attenuate naturally to levels below the regulatory limit in less than seven years. The distributions of the benzene concentrations under the no action scenario were plotted for the shallow bedrock aquifer at 2, 4, 6, and 9 years into the future (**Figures 8-7B** through **8-7E**). Based on model results, it is estimated that it will take less than 10 years for the shallow bedrock benzene concentrations to attenuate naturally to levels below the regulatory limit.

During this period, all of the mass is removed by biodegradation. No mass is lost to the surface water (Westerly Brook or Saddle River), and no mass remains adsorbed to the aquifer material or dissolved in the groundwater after 10 years. During this time period, the benzene plumes are expected to travel downgradient to a distance of approximately 640 feet from the year zero center of mass in the overburden aquifer, and approximately 30 feet from the year zero center of mass in the shallow bedrock aquifer.

The groundwater extraction scenario model was run for a period of eight years. It included three extraction wells located on MISS property, pumping a total of 10 gallons per minute (GPM). The distribution of the well locations, and the allocated extraction rates (two wells each with 3 GPM pumping rate and one well with 4 GPM pumping rate), were designed to provide the desired capture zone while minimizing the possibility of any of the wells going dry during the course of the extraction system operation. The wells were simulated as installed in the shallow bedrock, since the overburden saturated thickness is small (5-10 feet) in the area-of-interest; thereby precluding the capture of overburden plume through extraction wells placed in the overburden. The resultant capture zone for the overburden aquifer is shown on **Figure 8-8A**. The capture zone encompasses the MISS-related benzene plume in the overburden aquifer. The location of the extraction wells, pumping rates, and the resultant capture zone in the shallow bedrock are shown on **Figure 8-8B**.

The distributions of the benzene concentrations in the overburden and shallow bedrock aquifers for the groundwater extraction scenario were plotted at 2, 4, and 7 years into the future (**Figures 8-9A** through **8-9C** and **8-10A** through **8-10C**). Groundwater extraction in the shallow bedrock leads to the benzene concentrations in some overburden areas where they were not previously measured in monitoring wells; typically these concentrations are present in overburden areas overlying the shallow bedrock plume. These concentrations were investigated and were found to be partly related to the vertical dispersion and vertical anisotropy factors used in the model and partly to the vertical mixing caused by the extraction wells. Based on model results, it is estimated that in less than eight years of groundwater extraction, groundwater concentrations in the overburden and the shallow groundwater will be less than the regulatory limit. During the eight years of groundwater extraction, approximately 14 percent of the current (year zero, based on 2000-2002 data) benzene mass will be removed by groundwater extraction, and the remainder 86 percent of the mass will be removed by biodegradation. No mass is lost to the surface water (Westerly Brook or Saddle River), and no mass remains adsorbed to the aquifer material or dissolved in the groundwater after eight years. Therefore, as compared to the no action scenario, groundwater extraction does not significantly reduce the total time taken for benzene concentrations to be less than the regulatory limit.

Arsenic

During the period 2000-2002, MISS-related arsenic concentrations (FUSRAP waste) were detected in exceedance of the regulatory limit at seven monitoring well locations. The regulatory limit for arsenic is 3 µg/L. The locations of MISS-related arsenic exceedances and their respective concentrations are listed in the GWFS Report, **Volume 1, Table 1-1**. The arsenic concentration data for the overburden and shallow bedrock aquifers for the period 2000-2002 are graphically shown on the GWFS Report, **Volume 1, Figures 1-10** and **1-11** (GWRI Figures 5-4 and 5-14). The arsenic plumes, located on MISS property and downgradient of the MISS, were used to evaluate the feasibility study scenarios.

Initial (year zero) arsenic concentrations were assigned to the feasibility study model on the basis of groundwater analytical data collected during the 2000-2002 time period. The year zero arsenic concentration distributions in the model for overburden and the shallow bedrock aquifers are shown on **Figures 8-11A** and **8-12A**. The model concentration distributions are similar to the measured distributions presented in GWRI Figures 5-4 and 5-14. Some minor differences in the shape of the contours may be related to the differences in the interpolation approaches utilized for contouring the concentration distributions, and the change in the lowest concentration contour from 8 µg/L to 3 µg/L. This change was necessitated due to a change in the applicable regulatory standard.

The no action and the natural attenuation scenarios were modeled concurrently. The differences between these two scenarios are related to monitoring requirements and elimination of groundwater discharge to culvert sections of Westerly Brook. As discussed earlier, neither of these are expected to affect the solute transport and plume migration. The distributions of the arsenic concentrations in the overburden and shallow bedrock aquifers for the no action scenario were plotted at 5, 10, 15, 20, 25, and 30 years into the future (**Figures 8-11B** through **8-11G** and **8-12B** through **8-12G**). Over the 30 year no action/natural attenuation period, the overburden and shallow bedrock plumes retain their approximate year zero configurations. The model indicates that, over time, concentrations may be observed in some shallow bedrock areas (in of the area between MW-20D and MISS01B) where they were not previously measured in monitoring wells; however, these concentrations underlie the core of the overburden plume. Over time, some flux of overburden concentrations into the shallow bedrock may occur due to dispersion. In addition, until the culvert sections are sealed, some of the shallow bedrock concentrations may discharge into Westerly Brook as shown on **Figures 8-12C** through **8-12G** following the upwards groundwater gradient documented in this area during the GWRI.

Based on model results, it is estimated that it will take approximately 3,850 years for the MISS-related arsenic concentrations to attenuate naturally to levels below the regulatory limit of 3 µg/L. The long duration is due to low groundwater velocities and high adsorption coefficients. This is assuming that first order arsenic attenuation is due to equilibrium controlled sorption or first-order chemical reactions.

During this time, approximately 97 percent of the current (year zero, based on 2000-2002 data) arsenic mass will be discharged to Westerly Brook for the no action scenario, while no arsenic mass is discharged to Westerly Brook under the natural attenuation scenario. No mass is directly discharged to the Saddle River. After 3,850 years, it is predicted that approximately 3 percent of the arsenic mass will remain in the aquifers under the no action scenario, while all of the arsenic mass will remain in the aquifers under the natural attenuation scenario, either in the form of arsenic adsorbed to aquifer material, or as dissolved concentrations diluted to levels less than the regulatory limit. During this time period, the arsenic plumes are expected to travel downgradient to a distance of approximately 1,100 feet from the year zero center of mass in the overburden aquifer, and approximately 350 feet from the year zero center of mass in the shallow bedrock aquifer.

The groundwater extraction scenario model was run for a period of 30 years of pumping, followed by 2,500 years of no action. It included six extraction wells located on MISS property, pumping a total of 10 GPM. The distribution of the well locations, and the allocated extraction rates (two wells each with 2 GPM pumping rate, one well at 3 GPM pumping rate, and three wells at 1 GPM pumping rate), were designed to provide the desired capture zone, while minimizing the possibility of any of the wells going dry during the course of the groundwater extraction system operation. The wells were modeled as installed in the shallow bedrock, since the overburden saturated thickness is small (5-10 feet) in the area-of-interest, thereby precluding the capture of overburden plume through extraction wells placed in the overburden. The resultant capture zone for the overburden aquifer is shown on **Figure 8-13A**. The capture zone encompasses the MISS-related arsenic plume in the overburden aquifer. The location of the extraction wells, pumping rates, and the resultant capture zone in the shallow bedrock are shown on **Figure 8-13B**. The capture zone in the shallow bedrock aquifer encompasses the MISS-related arsenic plume.

The distributions of the arsenic concentrations in the overburden and shallow bedrock aquifers for the groundwater extraction scenario were plotted at 5, 10, 15, 20, 25, and 30 years into the future (**Figures 8-14A** through **8-14F** and **8-15A** through **8-15F**). A modeling anomaly was observed on the overburden figures. Low level arsenic concentrations were observed in some overburden areas where they were not previously measured in monitoring wells; typically these concentrations were present in overburden areas overlying the shallow bedrock plume and the extraction wells in the shallow bedrock. The anomalous concentrations were investigated and found to be partly related to the vertical dispersion and vertical anisotropy factors used in the model and partly to the vertical mixing caused by the extraction wells. Similarly, the model indicates that, over time, arsenic concentrations may be observed in some shallow bedrock areas (in vicinity of MW-3D, MW-20D and MISS02B) where they were not previously measured in monitoring wells. These concentrations underlie the core of the overburden arsenic plume and coincide with the approximate locations of groundwater extraction wells in the shallow bedrock aquifer. Since the overburden thickness is small in this area, extraction wells cannot be screened in the overburden. The extraction wells were modeled as screened in the shallow bedrock aquifer underlying the overburden plume in this area to remove the arsenic plume.

Based on model results, it is estimated that after 30 years of pumping, groundwater concentrations in the overburden and the shallow groundwater will still exceed the regulatory limit. When the extraction system is terminated after 30 years of operation, it will take another 2,450 years of no action for the MISS-related arsenic concentrations to be reduced to levels below the regulatory limit, i.e., a total of 2,480 years, thereby reducing the time taken to meet regulatory limits by 1,370 years as compared to the no action scenario.

The model predicts that approximately 6 percent of the arsenic mass will be removed by 30 years of groundwater extraction. No arsenic mass will be discharged to the surface water (Westerly Brook or Saddle River) during these 30 years. After a total of 2,480 years, it is predicted that approximately 40 percent of the arsenic mass will remain in the aquifers, while approximately 54 percent of the arsenic mass will be discharged to the surface waters.

The in-situ treatment scenario for arsenic in the overburden aquifer was modeled for arsenic based on a treatment half-life of ten days. As referenced in the GWFS Report, **Appendix B, Volume 1**, chemical techniques involving the injection of redox altering agents may be used to immobilize arsenic. A treatment half-life of 10 days, in response to chemical treatment, is expected for arsenic.

The modeled area for the application of in-situ treatment technology for arsenic is shown in **Figure 8-16**. Arsenic treatment was modeled for the overburden plume. The area to be treated is approximately 4.5 acres in the overburden aquifer. Due to the short treatment half-life, it is expected that arsenic concentrations will be less than the regulatory limit in less than 3 months; in approximately 85 days for the overburden arsenic plume. During the treatment period, all arsenic mass in the overburden aquifer should precipitate in the aquifer matrix. The untreated bedrock arsenic plume will attenuate in approximately 180 years after the arsenic in the overburden is treated. During this time period no mass is lost to the surface water (Westerly Brook and Saddle River).

8.4 MODELING LIMITATIONS

The groundwater flow and solute transport models were constructed to generally represent the physical and geochemical system of the site, so that site-wide issues regarding the feasibility scenario analysis could be addressed. All models have application limitations. The degree of representativeness of the modeling results is dependent on the complexity of the site setting, the amount of available site data, the complexity of the model, the effort expanded to adjust the model to site conditions, and the scale of the model.

A potential limitation to the model involves the characterization of the bedrock aquifer as an equivalent porous media, and the assumption that site groundwater flow and solute transport conditions can be accurately replicated by the applied models. While this approach is appropriate to predict the bulk movement of the solute plumes, the degree of confidence associated with future predictions of fate and transport from isolated sources (single well) is certainly less than that associated with the prediction of larger scale plume movement. Unlike solutes for which well delineated plumes exist in the overburden and the shallow bedrock, transport of solutes, which were detected only at a few monitoring wells, may be dependent upon the presence or absence of major fractures in the vicinity of the isolated source areas.

The model was constructed and calibrated to use the existing groundwater flow conditions, including leakage through sections of the Westerly Brook culvert. In the future, when the Westerly Brook culvert is repaired or replaced, the groundwater flow field in the vicinity of the culvert may be altered. While the impact of culvert repair is estimated to be minimal, the magnitude of the impact will depend on the construction and trench backfilling methods.

An additional limitation is related to the assumption of first order geochemical reactions to describe adsorption and chemical reactions. This may not remain true as organic contaminants degrade and redox conditions change within the aquifer.

9.0 QUALITY ASSURANCE/QUALITY CONTROL

The modeling results will be used for decision-making during the feasibility study scenario evaluation presented in the GWFS Report, **Volume 1**. Consequently, it was important that the modeling effort be technically defensible and conducted following consistent requirements, standards, and/or procedures. The quality assurance/quality control procedures that were used during the modeling process, and after the construction of the model, are described below.

Initial Model Documentation

The site-specific problem for which the modeling was conducted was defined during this stage, and the conceptual model and description of the scope of the modeling program was compiled and documented. The model scope documentation included:

1. A basic description of the problem
2. Site background information
3. Regulatory frame work
4. Definition of the size of the area modeled
5. Calibration criteria
6. Model sensitivity analysis
7. Special factors, which may influence the modeling program.

The model scope was documented and presented in detail in the Model Work Plan.

Model Calibration Documentation

Documentation of the calibration process provides an unbroken record of the input parameters used in the calibration of the model, beginning with the initial parameters and ending with the parameters used for the final calibrated model. Each parameter changed during calibration was changed only within the range of possibilities defined during conceptual model development and model input parameterization. Documentation of each calibration run was made and included the following:

1. Modeler's name and date
2. Calibration run number
3. Input filename(s)
4. Output filename(s)
5. Purpose of the calibration run

6. Parameter(s) changed during the run and their values

7. Results of the calibration run

8. Plans for the next calibration run based on the present results, if necessary.

Documentation for each calibration run was filed in the project modeling records. Documentation includes a hard copy of results and an electronic copy of the model input and output files. An electronic copy of the model input/output files for the flow model are included in **Attachment A**. An electronic copy of the model input/output files for the solute transport model constructed for feasibility scenario analysis are included in **Attachment B**.

Other Model Documentation

Model application or simulation runs and sensitivity analysis were conducted as the modeling effort progressed. These runs required identical documentation as used in calibration runs, and also required documentation of their basic purpose as related to the scope of the modeling program. Sensitivity analyses considered key parameters, which were not well defined during the input parameterization step, and referenced the parameterization documentation. Paper and electronic copy documentation were made for each modeling run. These copies and accompanying run descriptions are included in the modeling documentation files (Project Files).

Preliminary Model Review

The conceptual model, initial model input parameters, and initial flow model results were reviewed during a working meeting held on November 9, 2004. The preliminary review meeting was attended by the Lead Modeler, the GWFS Modeling Task Manager, the GWRI Project Hydrogeologist, and the USACE's management and technical team for the project.

The conceptual model presented during the review included:

1. A definition of the system modeled

2. Definition of parameters used for model input

3. Description of the conceptual flow system

4. Definition of the conceptual solute transport system

5. Assumptions used in the development of the conceptual model.

Model input parameters, derived from site-specific studies and investigations covering site geology, hydrogeology, and geochemistry, were presented during the preliminary review. If site-specific parameter data were not available, data from local and regional geologic studies that were deemed suitable for the application, were used as model input parameters. If neither site-specific nor local or regional data were available, non-site-specific literature values were used. All data sources and their values were documented and included in the modeling documentation files.

Certain simplifying assumptions made to perform the groundwater flow and solute transport modeling for the site were presented and discussed during the preliminary review and are documented within this review. These simplifying assumptions were made to reduce model construction and calibration time, and were based on a review of site geologic and hydrogeologic data.

The preliminary review concluded with the approval of the modeling approach, and establishment of a path-forward approach to complete the model and provide a basis for the feasibility study scenario evaluation.

Model Technical Peer Review

The model site conceptualization, determination of site aquifer parameters and other hydrologic parameters (i.e., model input parameters), model calibration, and verification that model output was consistent with site conditions were performed by an in-house reviewer. The reviewer was a senior modeler not directly associated with the model development process. The reviewer was technically qualified and capable of conducting the modeling, and also understood and compared observed field data to the conceptual and numerical models.

The technical peer review considered and evaluated the following items:

- Applicability of selected code – The code selected for use was optimum for the described conceptual model and supported by observed site conditions.
- Model input parameters – Input parameters were clearly specified and their sources were appropriately documented; parameters were technically supportable.
- Model calibration – The calibration was consistent with the requirements of the Modeling Work Plan, and generation of results and conclusions were compatible with standard industry practice.
- Model sensitivity analysis – The conducted sensitivity analysis and generation of results and conclusions were compatible with standard industry practice.
- Model documentation – All documentation was completed.
- Model results – In general, all modeling results were supported by the field data and all errors were identified as to the root cause and corrected.

Issues raised during the technical review were resolved between the reviewer and staff conducting the modeling before submission of the model and modeling results. The technical review comments and issues, and corresponding resolution, have been documented and filed with the project records.

Model Results Review

The FMSS model and modeling results underwent reviews by the GWFS Task Manager and the GWRI Project Hydrogeologist prior to submission of the report. The review considered and evaluated the following items:

- Definition of problem – The basic description of the problem, as well as the basic scope of the modeling that was conducted.
- Site conceptual model – The hydrogeologic system modeled, as well as the conceptual flow and solute transport system, were appropriately defined and were supported by site data; parameters needed for model input were appropriately identified; conceptual model was approved by the Project Hydrogeologist.
- Model documentation – All documentation was completed.
- Model results – In general, all modeling results were supported by the field data and all errors were identified as to the root cause and corrected.
- Modeling assumptions – Any and all assumptions used for the modeling were appropriately documented and justified.

Issues raised during the technical review were resolved between the reviewer and the lead modeler before submission of the model.

10.0 SUMMARY AND CONCLUSIONS

A summary of the groundwater flow and solute transport modeling with conclusions reached are presented below.

Flow Model Construction

- A groundwater flow and solute transport model was constructed for the FMSS. The model replicates key aspects of the site groundwater flow and geochemical systems that were documented in the previous groundwater investigations conducted at the site.

- The model consisted of three layers: the overburden layer (0 to 25 feet thick), the till layer (2 feet thick), and the shallow bedrock layer (23 to 82 feet thick).

Flow Model Calibration

- The flow model was calibrated to the July 26, 2001 groundwater elevation data set. This data set represents the most comprehensive data available for the site.

- Model calibration statistics indicate that the model was capable of replicating field observed groundwater flow conditions. Calibration statistical parameters were within the acceptable ranges as proposed in the Model Work Plan.

- Model calibration errors were random; no systematic biases were detected in the calibrated flow model.

- The groundwater flow model honored the principle of conservation of mass. The volume of water entering the model domain was equal to the volume of water leaving the model domain.

- The results of the particle tracking simulations were consistent with the findings reported in the GWRI Report. Groundwater flow directions, hydraulic gradients, and velocities calculated by the model were similar to those estimated from field measurements and presented in the GWRI report.

- Model calibration was sensitive to changes in horizontal hydraulic conductivity anisotropy for the overburden and shallow bedrock layers, but not for the till layer. The best statistical fit was obtained using anisotropy ratios of 1.0 each for the overburden, the shallow bedrock, and the till layers.

- Model calibration was sensitive to changes in recharge, primarily in Zone II (the area in the middle of AOCs).

- Model calibration was sensitive to changes in flow at the shallow/deep bedrock interface. The least amount of calibration error was for the situation when flow across this interface was set to zero. This is in agreement with the GWRI findings.

- The model was sensitive to changes in the Saddle River and southeast model edge boundary conditions; the model was not very sensitive to the conditions at the other boundaries.

Scenario Modeling

- Solute transport models were created to evaluate the following feasibility study scenarios.
  1. No action/natural attenuation
  2. Groundwater extraction and ex-situ treatment (if applicable)
  3. In-situ treatment using redox alteration (if applicable).
- The no action and natural attenuation scenarios were modeled concurrently. These scenarios were similar, except that the natural attenuation scenario also included long-term monitoring requirements and Westerly Brook culvert repair/replacement. The long-term monitoring requirements have no bearing on fate and transport of the solutes in groundwater, and therefore, do not affect the modeling approach. The elimination of the small quantity groundwater discharge to Westerly Brook (0.024 cfs) is expected to have minimal impact on the model results.
- Three chemical constituents – lithium, benzene, and arsenic - were evaluated by transport modeling.
- Initial concentrations for solute transport modeling and/or analytical analysis are based on data presented in the GWRI and collected between 2000 and 2002. It was assumed that soil sources were removed prior to implementation of the feasibility study scenarios.
- The flow rate of the groundwater extraction system used for feasibility study scenario analysis was 10 GPM. Pumping wells were screened in the shallow bedrock due to the small saturated thickness of the overburden. The number of wells used for solute removal depended on the solute and ranged from three to six, with individual well flow rates ranging from 1 to 4 GPM. The groundwater capture zone was controlled to minimize off-MISS solute capture. Non-FUSRAP solutes present in MISS groundwater will be extracted along with the COCs and will require ex-situ treatment prior to discharge.
- Groundwater extraction scenarios were evaluated for 30 years to evaluate the viability of this remedial scenario. If chemical constituent concentrations at the end of 30 years of groundwater extraction still exceeded the regulatory limits, it was followed by no action/natural attenuation until the chemical constituent concentrations were less than regulatory limits.
- The long time period required for a number of chemical constituents to attenuate to levels below the regulatory limits is due to low groundwater velocities and high adsorption coefficients.
- MISS-related lithium concentrations in the overburden and the shallow bedrock will take approximately 280 years to attenuate naturally to levels below the risk-based action level using the no action/natural attenuation scenario. After groundwater extraction for 30 years, it

will take another 245 years to reduce lithium concentrations to below the risk-based action level. The results indicate that groundwater extraction for a 30 year period does not significantly reduce the lithium cleanup time as compared to the no action/natural attenuation options. As discussed in the GWFS, **Appendix B, Volume 1**, in-situ treatment is not feasible for lithium, because lithium mobility is not affected by redox manipulation. No proven in-situ remediation technology is available for lithium. Therefore, it was not evaluated as a feasibility study scenario.

- The lithium plume will reach the Saddle River after approximately 100 years. The average concentration of lithium in the Saddle River in 140 years is expected to reach a maximum of approximately 1 μg/L, well below the risk-based action level of 730 μg/L.

- MISS-related benzene concentrations will take less than 10 years to attenuate naturally to levels below the regulatory limit using the no action/natural attenuation scenario. It is predicted that in less than eight years of groundwater extraction, benzene concentrations will be reduced to less than the regulatory limit.

- MISS-related arsenic concentrations will take up to 3,850 years to attenuate naturally to levels below the regulatory limit using the no action/natural attenuation scenario. After groundwater extraction for 30 years, it will take another 2,450 years to reduce arsenic concentrations to below the regulatory limit. The results indicate that groundwater extraction for a 30 year period followed by the no action/natural attenuation scenario reduces the arsenic cleanup time by 1,370 years. In-situ treatment, using redox altering agents to immobilize arsenic in overburden groundwater, will reduce the cleanup time to less than three months and the remaining arsenic in shallow bedrock will naturally attenuate in approximately 180 years.

This page intentionally left blank.

11.0 REFERENCES

Anderson, M.P. and W.W. Woessner, 1992, *Applied Groundwater Modeling, Simulation of Flow and Advective Transport.*

Cook, P.G., 2003, *A Guide to Regional Groundwater Flow in Fractured Rock Aquifers*, Council for Scientific and Industrial Research, Australia.

Environmental Modeling Systems, Inc. Software, 2004, *Groundwater Modeling System (GMS), Version 5.0.*

Harbaugh, A.W., Banta E.R., Hill, M.C. and McDonald, M.G., *Modflow 2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modulization Concepts and the Ground-Water Flow Process*, U.S. Geological Survey Open-File Report 00-92, 121 p.

Howard, P. H., Boethling, R. S., Jarvis, W. F., and W. M. Meylan, and Michalenko, E. M., 1991, *Handbook on Environmental Degradation Rates,* Lewis Publishers, Chelsea, MI.

New Jersey Geologic Survey, 2004, *DGS02-3: Ground-water Recharge for New Jersey, http://www.state.nj.us/dep/njgs/geodata/dgs02-3/dgs02-3.htm*

Pollock, D. W, 1994, *User's Guide for MODPATH/MODPATH-PLOT, Version 3:A Particle tracking Post-Processing Package for MODFLOW, the U. S. Geological Survey Finite-Difference Ground-Water Flow Model*, U. S. Geological Survey Open-File Report 94-464.

Stepan Company, 1994, *Final Remedial Investigation Report, Stepan Company Property, Sears and Adjacent Properties*, prepared for USEPA Region II by CH2M Hill.

U.S. Army Corps of Engineers (USACE) 2004a, *Groundwater Flow and Solute Transport Modeling Work Plan*, prepared for USACE by Shaw Environmental, Inc.

U.S. Army Corps of Engineers (USACE) 2004b, *Soil Screening Level (SSL)*, Technical Memorandum prepared for USACE by Shaw Environmental, Inc.

U.S. Army Corps of Engineers (USACE) 2005, *Final Groundwater Remedial Investigation Report,* prepared for USACE by Shaw Environmental, Inc.

U.S. Department of Energy, 1992, *Remedial Investigation Report for the Maywood Site*, prepared by Bechtel National, Inc.

U.S. Environmental Protection Agency, *1989, Superfund Groundwater Issue – Contaminant Transport in Fractured Media: Models for Decision Makers, EPA/540/4-89/004..*

Zheng, C., 1990, "*A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reaction of Contaminants in Groundwater System (MT3D),*" S.S. Papadopulos & Associates, Inc., Maryland.

This page intentionally left blank.

TABLES

Table 6-1
Calibrated Flow Model Input Parameters
(Model Run Flow_137)

Parameter	Value
Horizontal Discretization of Model Grid	
Number of rows	142
Number of columns	151
Minimum cell dimensions in AOC areas	20 feet x 20 feet
Maximum increase in cell dimensions between adjacent cells	50%
Maximum cell dimensions	200 feet x 200 feet
Vertical Discretization of Model Grid	
Number of layers	3
Total number of model cells	64,326
Layer 1 (overburden) thickness range	0 to 25 feet
Layer 2 (till) thickness range	2 feet
Layer 1 (shallow bedrock) thickness range	23 to 82 feet
Hydraulic Conductivity	
Layer 1 (overburden)	7.83 feet/day
Layer 2 (till)	2.67 feet/day
Layer 1 (shallow bedrock)	2.94 feet/day
Anisotropy	
Horizontal anisotropy -Layer 1 (overburden)	1.0
Horizontal anisotropy -Layer 2 (till)	1.0
Horizontal anisotropy -Layer 3 (shallow bedrock)	1.0
Vertical anisotropy	1.0
Recharge	
Zone I	1.0 inches/year
Zone II	24.0 inches/year
Zone III	4.0 inches/year
Zone IV	0.1 inches/year
Calibration Target	
Target groundwater elevation measurement date	July 26, 2001
Number of calibration targets in overburden	53
Number of calibration targets in shallow bedrock	54
Boundaries	
Saddle River -all layers	Specified (constant) head
Southern edge - layer 3	Specified head
Southern half of eastern edge - layer 3	Specified head
Model Top	Recharge
Model Bottom	No Flow

Table 6-2
Flow Model Calibration Residuals
(Model Run Flow_137)

Overburden Wells			
Well ID	Measured Head, Feet MSL	Model Predicted Head, Feet MSL	Residual Head (= Simulated - Measured), Feet MSL
MW-11S	44.04	44.62	0.58
B38W01S	48.97	50.09	1.12
B38W12A	42.28	41.89	-0.39
B38W14S	38.51	38.99	0.48
B38W15S	40.15	39.58	-0.57
B38W17A	42.99	42.66	-0.33
B38W19S	43.33	43.78	0.45
B38W24S	44.67	45.63	0.96
B38W25S	49.15	46.36	-2.79
MISS01AA	44.76	44.83	0.07
MISS02A	50.47	49.56	-0.91
MISS03A	48.46	47.07	-1.39
MISS04A	46.27	46.08	-0.19
MISS05A	44.26	43.78	-0.48
MISS06A	45.24	45.47	0.23
MISS07A	46.37	43.88	-2.49
MW-10S	53.28	53.05	-0.23
MW-12S	42.12	42.12	0.00
MW-13S	40.46	39.52	-0.94
MW-20S	49.85	49.31	-0.54
MW-22S	41.49	42.50	1.01
MW-2S	40.08	39.05	-1.03
MW-3S	46.44	47.65	1.21
MW-4S	38.24	37.62	-0.62
MW-5S	33.53	35.78	2.25
MW-6S	35.57	34.55	-1.02
MW-8S	46.2	45.19	-1.01
OBMW1	42.37	44.02	1.65
OBMW10	47.24	47.62	0.38
OBMW11	44.75	46.69	1.94
OBMW12	39.8	40.52	0.72
OBMW13	42.43	43.60	1.17
OBMW14	42.17	43.37	1.20
OBMW17	54.26	52.98	-1.28
OBMW19	47.01	47.92	0.91
OBMW2	48.7	48.44	-0.26
OBMW3	41.31	41.81	0.50
OBMW6	44.12	44.75	0.63
OBMW7	41.8	41.66	-0.14
OBMW8	39.49	39.78	0.29
OVPW-1S	45.65	44.95	-0.70
OVPZ-10	45.62	44.94	-0.68
OVPZ-11	45.29	44.90	-0.39
OVPZ-12	45.62	44.87	-0.75
OVPZ-13	45.35	44.71	-0.64
OVPZ-15	45.76	44.96	-0.80
OVPZ-16	45.68	45.03	-0.65
OVPZ-17	45.05	44.89	-0.16
OVPZ-9	46.12	44.95	-1.17
PT-2S	49.31	48.11	-1.20
WELL 1	49.24	49.44	0.20
WELL 2	48.23	49.41	1.18
WELL 5	55.83	54.30	-1.53

Shallow Bedrock Wells			
Well ID	Measured Head, Feet MSL	Model Predicted Head, Feet MSL	Residual Head (= Simulated - Measured), Feet MSL
B38W02D	57.69	54.18	-3.51
B38W03B	47.06	47.83	0.77
B38W04B	54.43	52.41	-2.02
B38W05B	56.65	55.41	-1.24
B38W06B	47.15	48.93	1.78
B38W07B	44.07	44.22	0.15
B38W12B	42.57	41.85	-0.72
B38W14D	39.76	39.03	-0.73
B38W15D	41.34	39.59	-1.75
B38W17B	43.06	42.67	-0.39
B38W18D	52.91	50.87	-2.04
B38W19D	43.24	43.74	0.50
B38W24D	44.56	45.62	1.06
B38W25D	49.06	46.40	-2.66
BRMW1	42.52	44.03	1.51
BRMW10	50.56	49.78	-0.78
BRMW11	44.19	46.70	2.51
BRMW12	41.42	40.48	-0.94
BRMW13	42.43	43.50	1.07
BRMW14	40.89	43.08	2.19
BRMW15	57.01	55.60	-1.41
BRMW16	56.04	54.41	-1.63
BRMW17	54.3	52.87	-1.43
BRMW3	41.72	41.55	-0.17
BRMW6	44.12	44.69	0.57
BRMW8	39.47	39.71	0.24
BRMW9	37.5	38.33	0.83
BRPZ-2RE	45.08	44.83	-0.25
BRPZ-3RE	45.1	44.58	-0.52
BRPZ-4	44.4	44.86	0.46
BRPZ-5RE	44.97	44.71	-0.26
BRPZ-9	44.22	44.81	0.59
MISS01B	45.18	44.74	-0.44
MISS02B	48.86	49.59	0.73
MISS03B	46.61	47.22	0.61
MISS04B	44.32	46.06	1.74
MISS05B	43.16	43.76	0.60
MISS07B	44.05	43.84	-0.21
MW-10D	52.9	52.91	0.01
MW-12D	41.12	41.52	0.40
MW-13D	39.92	39.55	-0.37
MW-19D	45.6	43.05	-2.55
MW-1D	41.38	40.32	-1.06
MW-20D	49.08	49.11	0.03
MW-23D	44.97	45.75	0.78
MW-24D	43.73	43.90	0.17
MW-2D	40.01	39.10	-0.91
MW-3D	46.57	47.52	0.95
MW-4D	38.31	37.63	-0.68
MW-5D	36.45	35.82	-0.63
MW-6D	35.79	34.48	-1.31
MW-8D	46.02	45.21	-0.81
MW-9D	54.95	55.01	0.06
PT-1DA	45.29	48.84	3.55

Table 6-3
Analysis of Calibrated Flow Model Sensitivity to Horizontal Anisotropy

Horizontal Anisotropy Value			Mean Error		Absolute Mean Error		Root Mean Square Error		Model Run No.	Comments
Overburden	Till	Bedrock	ft	%	ft	%	ft	%		
1.0	1.0	1.0	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to changes in horizontal anisotropy in the overburden. The least amount of calibration error is associated with overburden horizontal anisotropy of 1.0.
1.5			-0.30	-1.1%	0.94	3.4%	1.21	4.4%	Flow_147	
2.0			-0.44	-1.6%	0.98	3.5%	1.28	4.6%	Flow_148	
2.5			-0.57	-2.1%	1.02	3.7%	1.35	4.9%	Flow_149	
3.0			-0.68	-2.5%	1.06	3.8%	1.42	5.1%	Flow_150	
1.0	**1.0**	1.0	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is not sensitive to changes in horizontal anisotropy in the till layer.
	1.5		-0.15	-0.5%	0.90	3.2%	1.17	4.2%	Flow_151	
	2.0		-0.17	-0.6%	0.91	3.3%	1.18	4.3%	Flow_152	
	2.5		-0.19	-0.7%	0.92	3.3%	1.18	4.3%	Flow_153	
	3.0		-0.22	-0.8%	0.93	3.4%	1.20	4.3%	Flow_154	
1.0	1.0	**1.0**	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to changes in horizontal anisotropy in the shallow bedrock. Model is more sensitive to horizontal anisotropy in shallow bedrock as compared to the overburden. Model prediction error is least when horizontal anisotropy values for the shallow bedrock is 1.0.
		1.5	-0.60	-2.2%	1.09	3.9%	1.46	5.3%	Flow_155	
		2.0	-1.03	-3.7%	1.36	4.9%	1.80	6.5%	Flow_156	
		2.5	-1.40	-5.1%	1.65	6.0%	2.16	7.8%	Flow_157	
		3.0	-1.73	-6.2%	1.92	6.9%	2.49	9.0%	Flow_158	

Note:
Model Run Flow_137 represents the best fit model with the least calibration error.

Table 6-4
Analysis of Calibrated Flow Model Sensitivity to Groundwater Recharge

Recharge Rate (inches/year)				Mean Error		Absolute Mean Error		Root Mean Square Error		Model Run No.	Comments
Zone I	Zone II	Zone III	Zone IV	ft	%	ft	%	ft	%		
0.8				-0.14	-0.5%	0.90	3.2%	1.16	4.2%	Flow_159	Model is not sensitive to the variation in recharge rate in Zone I.
1.0	24.0	4.0	0.1	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
1.2				-0.12	-0.4%	0.90	3.2%	1.16	4.2%	Flow_160	
	19.2			-0.66	-2.4%	1.04	3.7%	1.42	5.1%	Flow_161	Model is sensitive to the variation in recharge rate in Zone II. Best fit to observed head data is obtained using a recharge rate of 24 inches/year in Zone II.
1.0	24.0	4.0	0.1	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
	28.8			0.32	1.2%	0.95	3.4%	1.30	4.7%	Flow_162	
		3.2		-0.15	-0.5%	0.90	3.3%	1.16	4.2%	Flow_163	Model is not sensitive to the variation in recharge rate in Zone III.
1.0	24.0	4.0	0.1	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
		4.8		-0.11	-0.4%	0.90	3.2%	1.16	4.2%	Flow_164	
			0.08	-0.11	-0.4%	0.90	3.2%	1.16	4.2%	Flow_165	Model is not sensitive to the variation in recharge rate in Zone IV.
1.0	24.0	4.0	0.10	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
			0.12	-0.11	-0.4%	0.90	3.2%	1.16	4.2%	Flow_166	

Notes:

1. Model Run Flow_137 represents the best fit model with the least calibration error.
2. Model domain was divided into recharge zones as follows:
   - Zone I Area to east of Westerly Brook culvert
   - Zone II Area in the middle of AOCs
   - Zone II Area to the east of AOCs
   - Zone I' Remainder of model domain
3. Model was tested for sensitivity to recharge by varying the recharge rate by +/- 20% from the best fit flow model (run # Flow_137).

Table 6-5
Analysis of Calibrated Flow Model Sensitivity to Hydraulic Conductivity

Hydraulic Conductivity (ft/day)			Mean Error		Absolute Mean Error		Root Mean Square Error		Model Run No.	Comments
Overburden	Till	Shallow Bedrock	ft	%	ft	%	ft	%		
3.92	2.67	2.94	0.26	1.0%	0.96	3.5%	1.32	4.8%	Flow_167	Model is slightly sensitive to the variation in overburden hydraulic conductivity.
7.83			**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
11.75			-0.48	-1.7%	0.96	3.5%	1.27	4.6%	Flow_168	
7.83	1.34	2.94	-0.08	-0.3%	0.89	3.2%	1.16	4.2%	Flow_169	Model is not sensitive to hydraulic conductivity of till layer.
	2.67		**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
	4.01		-0.17	-0.6%	0.91	3.3%	1.17	4.2%	Flow_170	
7.83	2.67	1.47	1.23	4.4%	1.53	5.5%	1.93	7.0%	Flow_171	Model is very sensitive to the variation in shallow bedrock hydraulic conductivity.
		2.94	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	
		4.41	-0.96	-3.5%	1.20	4.3%	1.66	6.0%	Flow_172	

Note:
Model Run Flow_137 represents the best fit model with the least calibration error.

Table 6-6
Analysis of Calibrated Flow Model Sensitivity to Flow Between Shallow and Deep Bedrock

Aerial Water Removal Rate (in/year)		Mean Error		Absolute Mean Error		Root Mean Square Error		Model Run No.	Comments
Shallow Bedrock to Deep Bedrock Flow	Deep Bedrock to Shallow Bedrock Flow	ft	%	ft	%	ft	%		
0.0	0.0	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to the variation in flow from deep to shallow bedrock. The least error is associated with the flow rate equal to zero.
0.1		-1.54	-5.6%	1.62	5.8%	2.08	7.5%	Flow_173	
1.0		-10.29	-37.1%	2.60	9.4%	5.47	19.7%	Flow_174	
0.0	0.0	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to the variation in flow from shallow to deep bedrock. The least error is associated with the flow rate equal to zero.
	0.1	0.75	2.7%	1.11	4.0%	1.50	5.4%	Flow_175	
	1.0	6.58	23.7%	6.59	23.8%	7.29	26.3%	Flow_176	

Note:
Model Run Flow_137 represents the best fit model with the least calibration error.

Table 6-7
Analysis of Calibrated Flow Model Sensitivity to Boundary Conditions

Boundary Location	Boundary Type	Mean Error		Absolute Mean Error		Root Mean Square Error		Model Run No.	Comments
		ft	%	ft	%	ft	%		
Saddle River (all three layers)	Constant Head	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to Saddle River boundary condition.
	No Flow	0.62	2.2%	1.10	4.0%	1.57	5.7%	Flow_117	
South (shallow bedrock layer)	Specified head	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Quantitatively, the overall model is not very sensitive to this boundary condition. However, local groundwater patterns in vicinity of this boundary are impacted.
	No Flow	-0.11	-0.4%	0.91	3.3%	1.17	4.2%	Flow_118	
East - Southern Half (shallow bedrock layer)	Specified head	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is slightly sensitive to this boundary condition.
	No Flow	-0.35	-1.3%	1.00	3.6%	1.29	4.7%	Flow_119	
Model Bottom	No Flow	**-0.13**	**-0.5%**	**0.90**	**3.2%**	**1.16**	**4.2%**	**Flow_137**	Model is sensitive to the variation in flow in or out of the model bottom. The least error is associated with the flow rate equal to zero.
	Downward flow out of the model domain to Deep Bedrock at 0.1 in/year	-1.54	-5.6%	1.62	5.8%	2.08	7.5%	Flow_173	
	Downward flow out of the model domain to Deep Bedrock at 1 in/year	-10.29	-37.1%	2.60	9.4%	5.47	19.7%	Flow_174	
	Upward flow into the model domain from Deep Bedrock at 0.1 in/year	0.75	2.7%	1.11	4.0%	1.50	5.4%	Flow_175	
	Upward flow into the model domain from Deep Bedrock at 0.1 in/year	6.58	23.7%	6.59	23.8%	7.29	26.3%	Flow_176	

Note:
Model Run Flow_137 represents the best fit model with the least calibration error.

Table 7-1
Particle Tracking Results

Aquifer	Porosity	Calibrated Model Hydraulic Conductivity, Feet/Day	Particle Tracking Results		GWRI [1] Estimates		
			Average Hydraulic Gradient, Feet/Feet	Average Groundwater Velocity, Feet/Day	Average Hydraulic Gradient, Feet/Day	Groundwater Velocity, Feet/Day	Average Groundwater Velocity, Feet/Day
Overburden	0.2	7.83	0.010	0.40	0.009	0.11 to 0.72	0.42
Shallow Bedrock	0.05	2.94	0.009	0.52	0.011	0.44 to 0.68	0.56

Notes:
(1) Final Groundwater Remedial Investigation Report (GWRI) prepared by Shaw Environmental, Inc. for the U.S. Army Corps of Engineers (USACE, 2005).

Table 8-1
Feasibility Study Alternative Analysis Modeling Input Parameters

Media Specific (Non-chemical) Input Parameters

	Overburden Aquifer	Shallow Bedrock Aquifer
Porosity	0.20	0.05
Bulk Density (g/cc)	1.65	2.6

Chemical Specific Input Parameters

COC	Limit	No. Wells Above Limit	Aquifer	Distribution Coefficient Kd, mL/g	Longitudinal Dispersivity, Feet	Transverse to Longitudinal Dispersivity Ratio	Vertical to Longitudinal Dispersivity Ratio	Retardation Factor, Rf	Mobility [1] Class	Degradation Half-Life, Years
Lithium	730 ug/L	32	Overburden	0.64	195	0.1	0.01	6	High	NA
			Shallow Bedrock	0.46	195	0.1	0.01	25	Medium	
Benzene	1 µg/L	15	Overburden	1.82	195	0.1	0.01	16	Medium	1
			Shallow Bedrock	1.25	195	0.1	0.01	66	Medium	
Arsenic	3 µg/L	10	Overburden	29	60	0.1	0.01	240	Low	NA
			Shallow Bedrock	1.4	60	0.1	0.01	74	Medium	

Notes:
[1] Rf - Mobility Class
Low: Rf = 101 or higher
Medium: Rf = 11 to 100
High: Rf = 1 to 10

NA - Not Applicable. Constituent does not degrade due to biological activity.

Table 8-2
Feasibility Study Alternative Analysis Results

COC	Limit	No. Wells Above Limit	Aquifer	Expected Travel Distance For No Action Scenario (1), Feet	Expected Duration Above Limit (2), Years		
					No Action / Natural Attenuation	Groundwater Extraction	In-Situ Treatment
Lithium	730 ug/L	32	Overburden	2,550	280	275	NT
			Shallow Bedrock	2,150	280	275	NT
Benzene	1 µg/L	15	Overburden	640	6.5	7.5 (3)	NT
			Shallow Bedrock	30	9.5	7.5	NT
Arsenic	3 µg/L	10	Overburden	1,100	3,850	2,480	<1
			Shallow Bedrock	350	3,400	2,080	180(4)

Notes:

(1) Solute travel distance for concentrations before decreasing below Limits by Natural Attenuation processes.

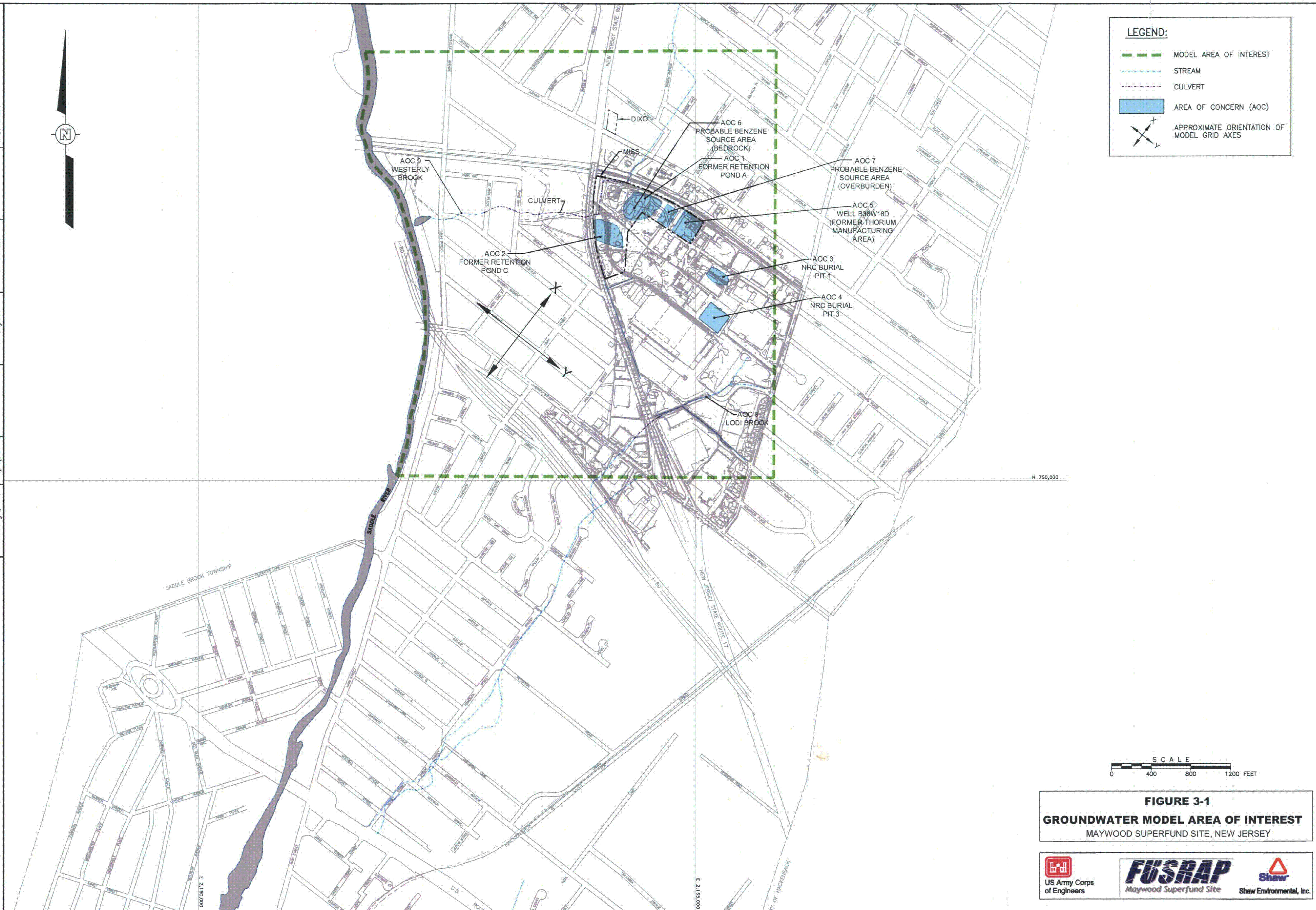
(2) Time for chemical concentrations in groundwater on MISS to be reduced below Limits. Long durations associated with certain COCs are due to low groundwater velocities and high adsorption coefficients.

(3) Groundwater extraction duration is longer than natural attenuation duration. This may be due to a modeling anomaly as discussed in section 8.3.

(4) Arsenic in shallow bedrock will not be treated. In-situ treatment of arsenic will be performed in the overburden only. The untreated shallow bedrock arsenic plume will attenuate in approximately 180 years after the arsenic in the overburden is treated.

NT: Not Treated

FIGURES



OFFICE	DATE	DESIGNED BY	DRAWN BY	CHECKED BY	APPROVED BY	DRAWING NUMBER
Pittsburgh, PA	1/5/05	--	W. Snyder	G. Gaillot	--	108783-E1

Xref: site
Image: FMSS

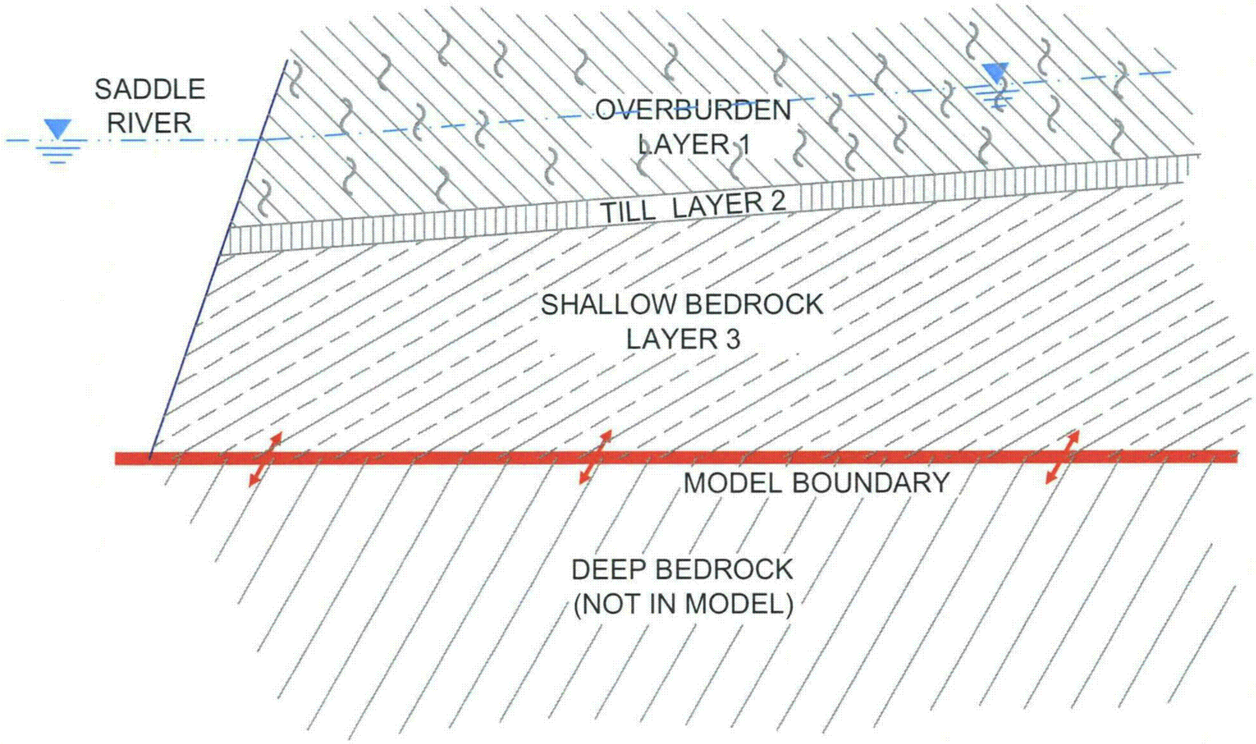
O:\Project\108783\108783E1.dwg
Plot Date/Time: 01/23/06 01:21pm
Plotted by: arthur.smith

FIGURE 3-1

GROUNDWATER MODEL AREA OF INTEREST

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers
FUSRAP Maywood Superfund Site
Shaw Shaw Environmental, Inc.



NOT TO SCALE

OFFICE	DATE	DESIGNED BY	DRAWN BY	CHECKED BY	APPROVED BY	DRAWING NUMBER
Pittsburgh, PA	1/5/05	--	W. Snyder	G. Gaillot	--	108783-A1

O:\Project\108783\108783A1.dwg
Plot Date/Time: 05/23/05 04:16pm
Plotted by: arthur.smith

Xref: .
Image: FMSS

FIGURE 3-2

VERTICAL MODEL DOMAIN

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP
Maywood Superfund Site

Shaw Environmental, Inc.

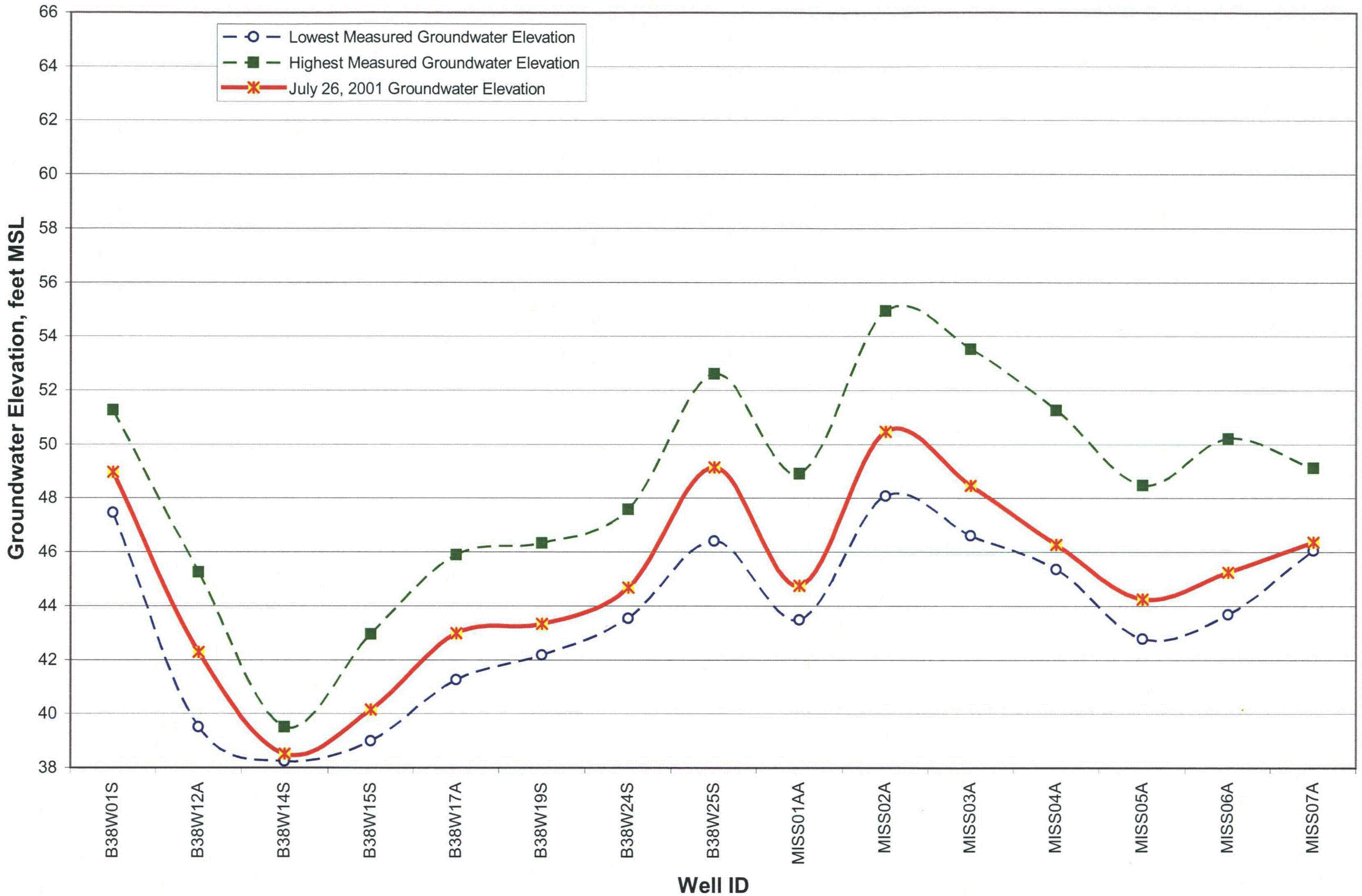


FIGURE 5-1

GROUNDWATER ELEVATION RANGE IN OVERBURDEN WELLS

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.

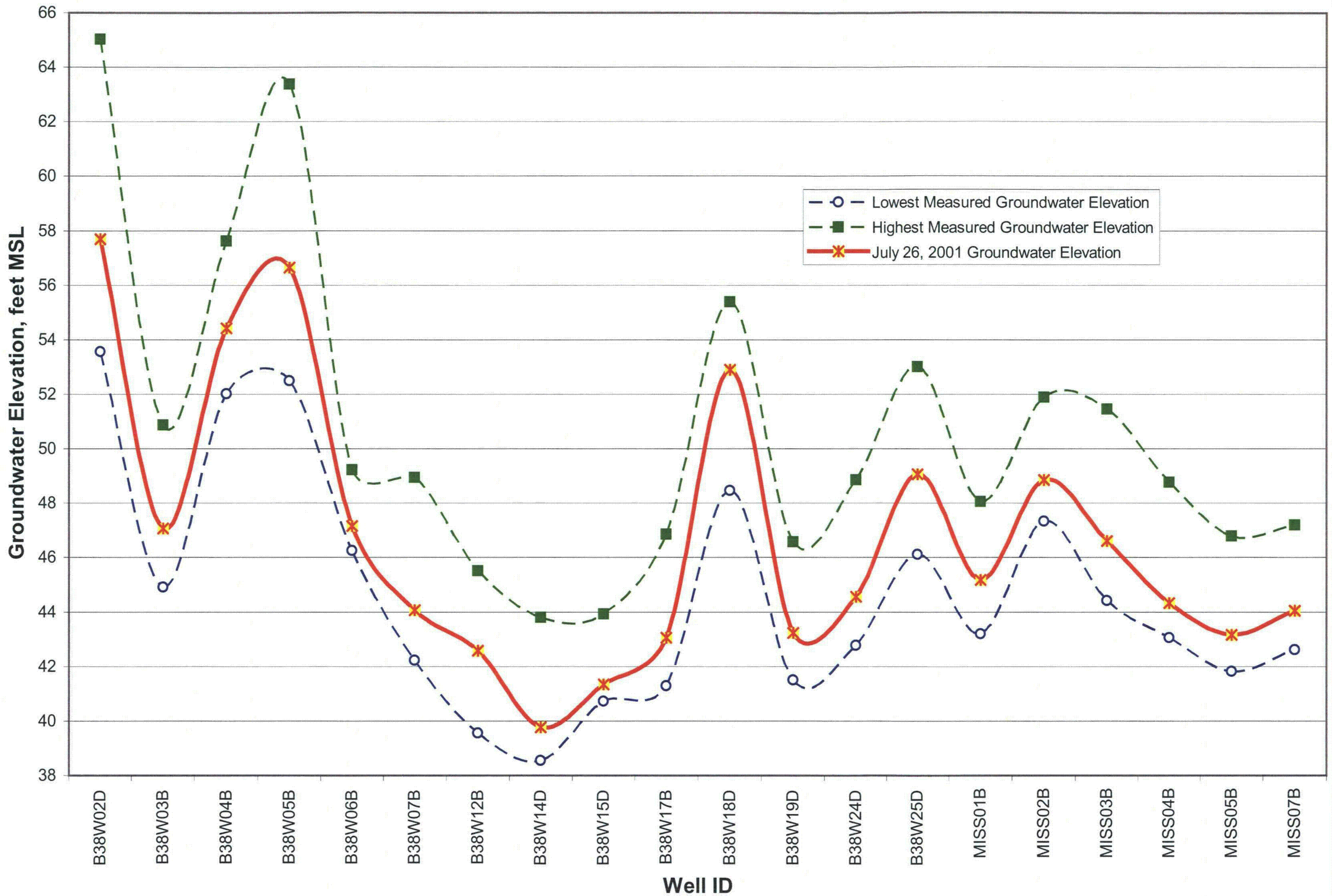


FIGURE 5-2

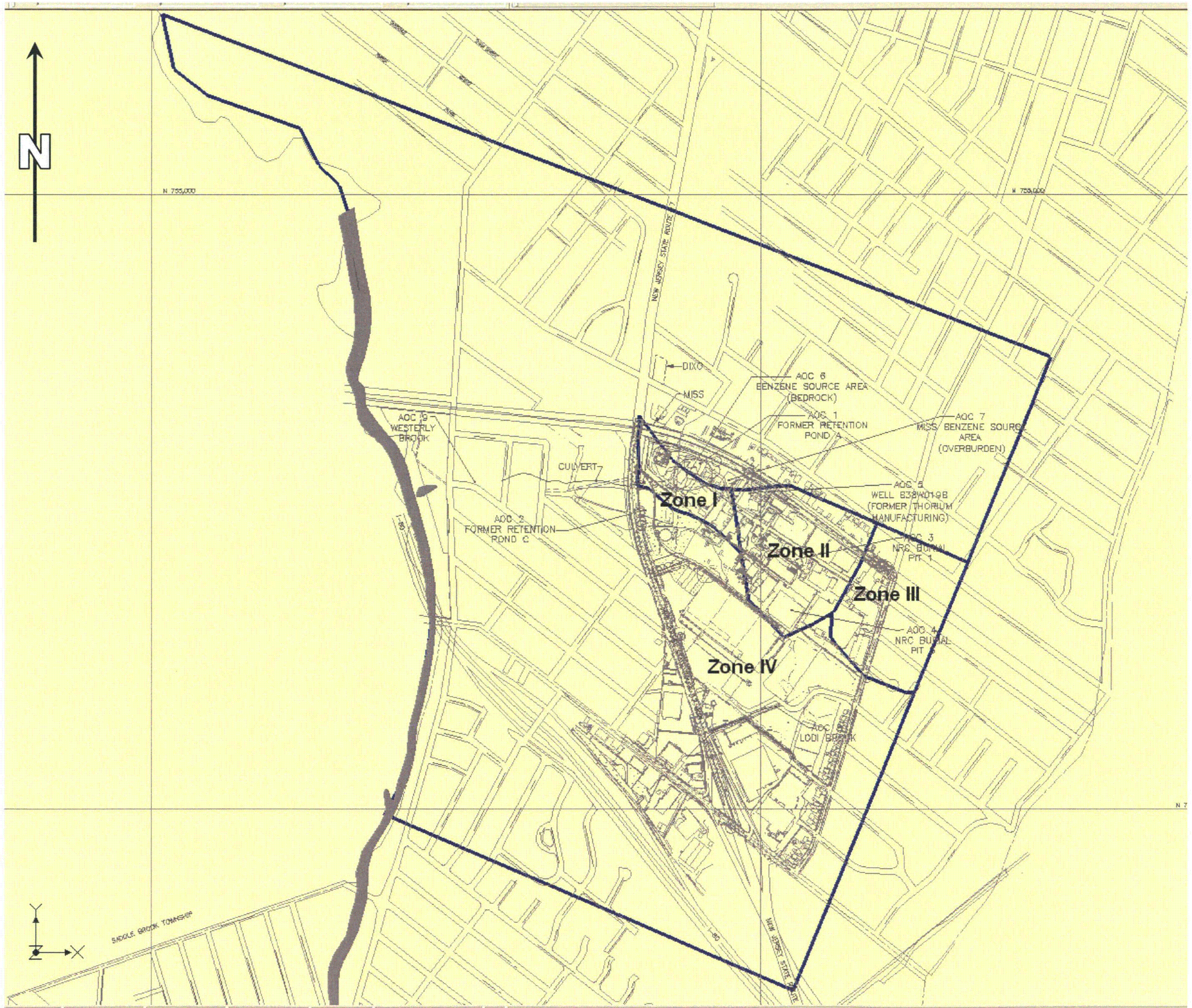
GROUNDWATER ELEVATION RANGE IN SHALLOW BEDROCK WELLS

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Environmental, Inc.



NOTES:

1. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

LEGEND:

ZONE	RECHARGE RATE (INCHES/YEAR)
I	1.0
II	24.0
III	4.0
IV	0.1

SCALE
1 INCH = 1000 FEET

FIGURE 6-1
CALIBRATED GROUNDWATER MODEL RECHARGE ZONES
MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers
FUSRAP
Maywood Superfund Site
Shaw Environmental, Inc.

NOTES:

1. ACTIVE MODEL DOMAIN CELLS ARE SHOWN IN BLACK. PINK CELLS ARE INACTIVE.

2. THE AREA OF INTEREST FOR MODELING AS PROPOSED IN THE MODEL WORK PLAN IS SHOWN WITHIN THE GREEN BOX.

3. THE FOLLOWING BOUNDARY CONDITIONS ARE DISPLAYED ON THE FIGURE:
- DRAIN (GREEN RECTANGLES)
- RIVER (BLUE RECTANGLES)
- CONSTANT HEAD (ORANGE DIAMONDS)

4. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 1176.5 FEET

FIGURE 6-2

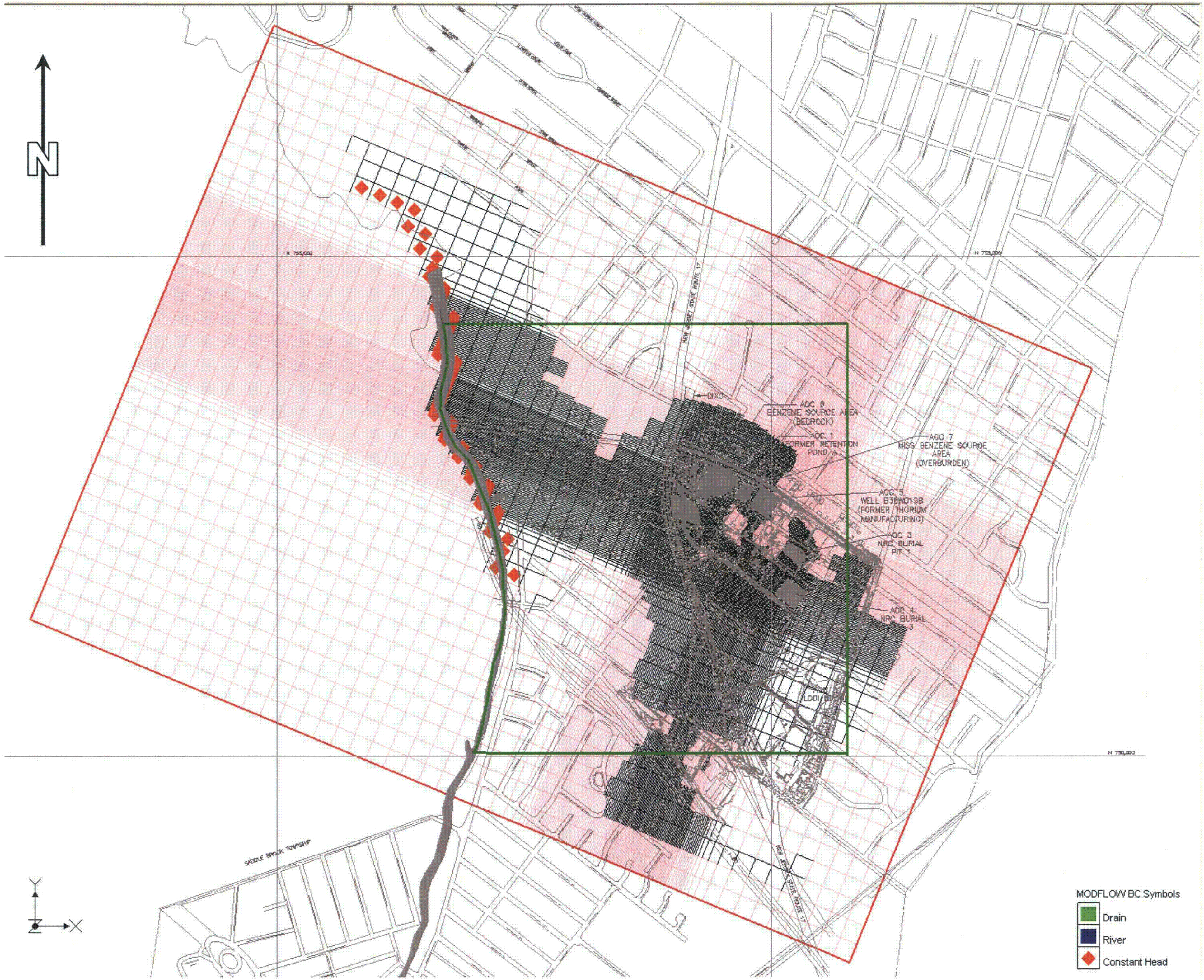
CALIBRATED GROUNDWATER MODEL GRID AND BOUNDARY CONDITIONS FOR OVERBURDEN LAYER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.



NOTES:

1. ACTIVE MODEL DOMAIN CELLS ARE SHOWN IN BLACK. PINK CELLS ARE INACTIVE.

2. THE AREA OF INTEREST FOR MODELING AS PROPOSED IN THE MODEL WORK PLAN IS SHOWN WITHIN THE GREEN BOX.

3. THE FOLLOWING BOUNDARY CONDITIONS ARE DISPLAYED ON THE FIGURE:
   - CONSTANT HEAD (ORANGE DIAMONDS)

4. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 1176.5 FEET

FIGURE 6-3

CALIBRATED GROUNDWATER MODEL GRID AND BOUNDARY CONDITIONS FOR TILL LAYER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.

NOTES:

1. ACTIVE MODEL DOMAIN CELLS ARE SHOWN IN BLACK. PINK CELLS ARE INACTIVE.

2. THE AREA OF INTEREST FOR MODELING AS PROPOSED IN THE MODEL WORK PLAN IS SHOWN WITHIN THE GREEN BOX.

3. THE FOLLOWING BOUNDARY CONDITIONS ARE DISPLAYED ON THE FIGURE:
   - CONSTANT HEAD (ORANGE DIAMONDS)

4. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 1176.5 FEET

FIGURE 6-4

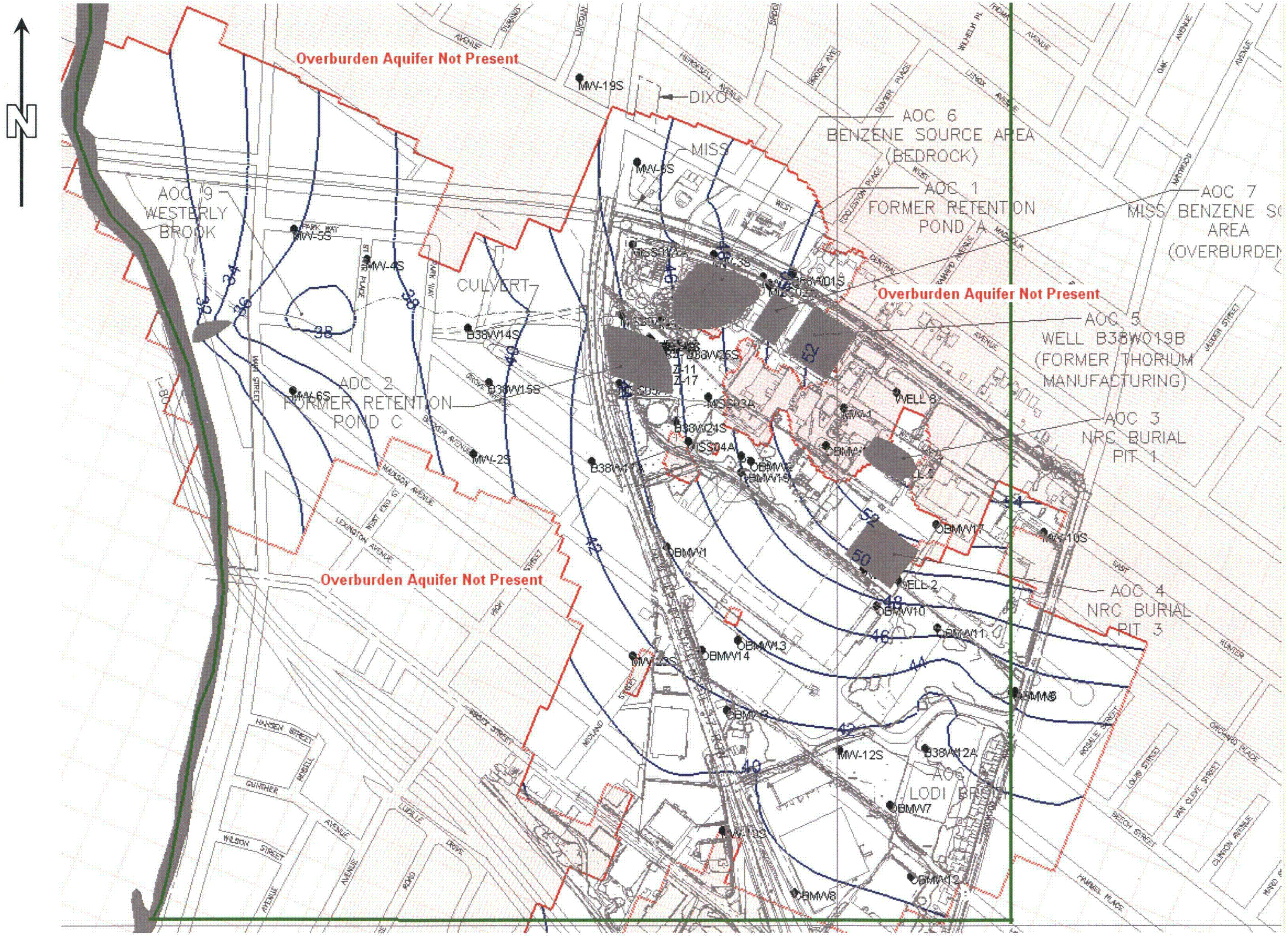
CALIBRATED GROUNDWATER MODEL GRID AND BOUNDARY CONDITIONS FOR SHALLOW BEDROCK LAYER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Environmental, Inc.



NOTES:

1. THE OVERBURDEN AQUIFER WAS CONSIDERED NOT PRESENT IN AREAS WHERE THE JULY 26, 2001 GROUNDWATER ELEVATIONS IN THE OVERBURDEN LAYER WERE LESS THAN THE BOTTOM ELEVATION OF THE MODEL LAYER 1.

2. GROUNDWATER ELEVATIONS ARE IN FEET ABOVE MEAN SEA LEVEL.

3. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 500 FEET

FIGURE 6-5

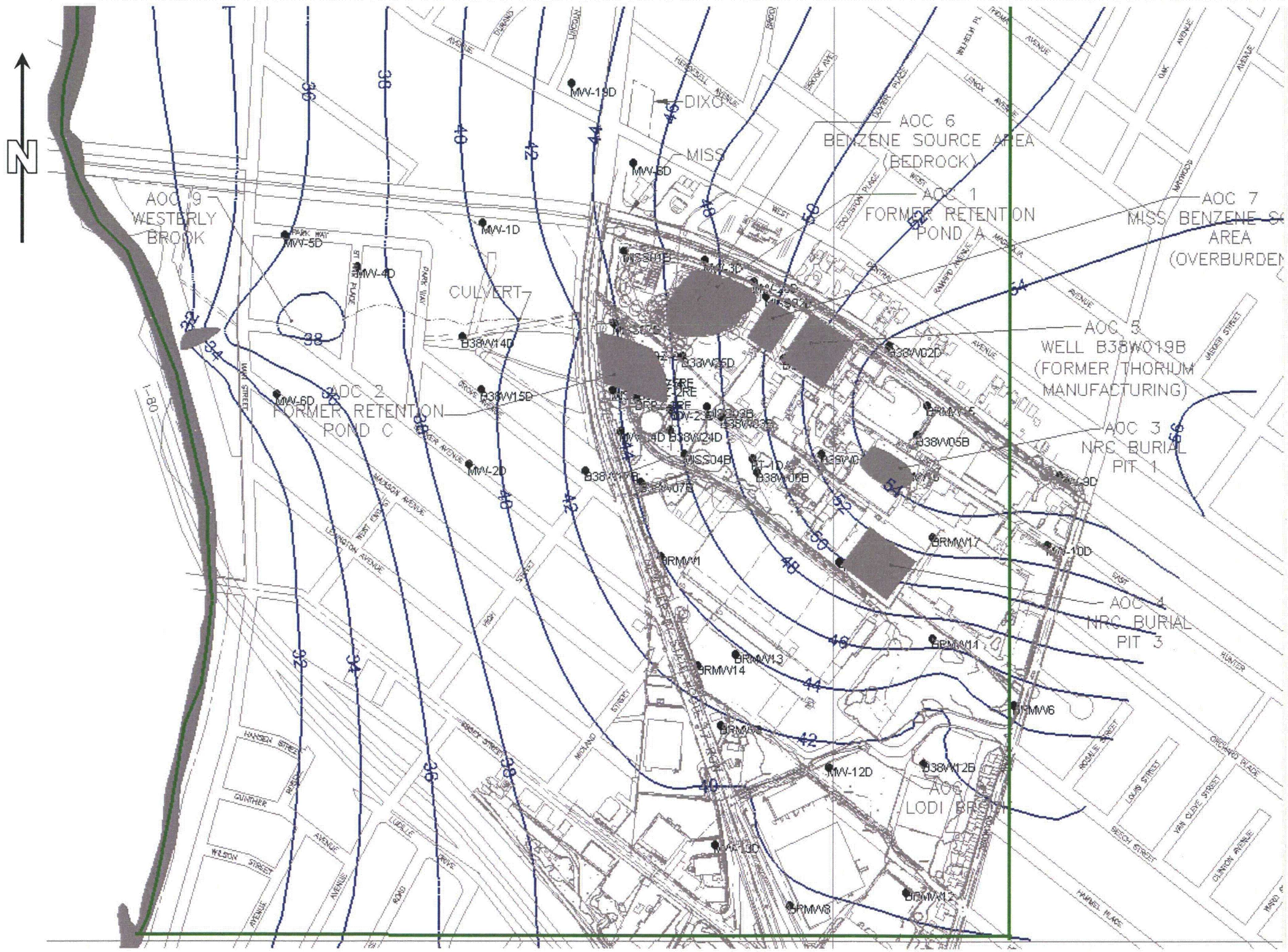
CALIBRATED MODEL GROUNDWATER ELEVATION CONTOURS FOR OVERBURDEN LAYER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers.

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.



NOTES:

1. GROUNDWATER ELEVATIONS ARE IN FEET ABOVE MEAN SEA LEVEL.

2. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 500 FEET

FIGURE 6-6

CALIBRATED MODEL GROUNDWATER ELEVATION CONTOURS FOR SHALLOW BEDROCK LAYER

MAYWOOD SUPERFUND SITE, NEW JERSEY

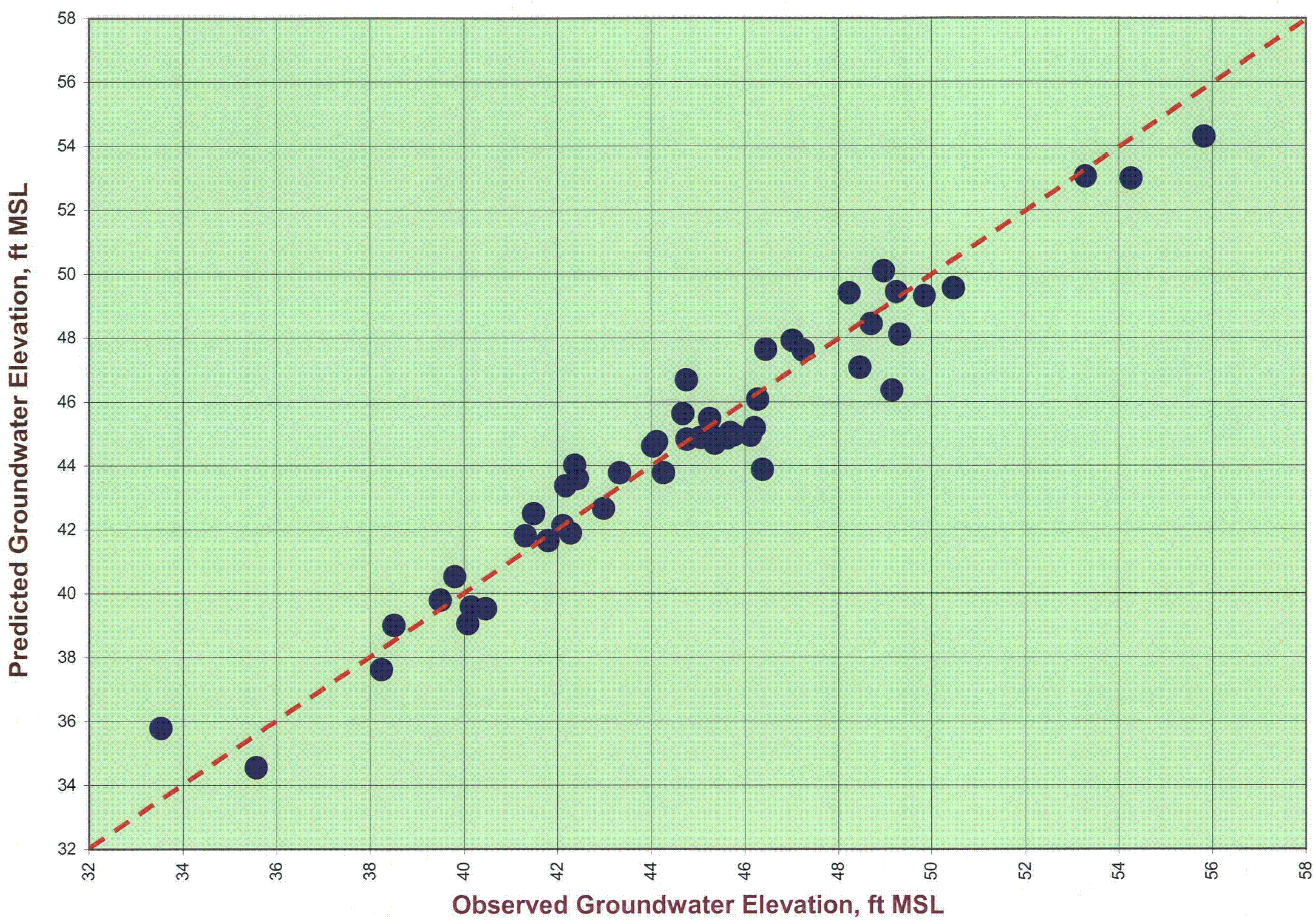
US Army Corps of Engineers

FUSRAP

Maywood Superfund Site

Shaw

Shaw Environmental, Inc.



NOTES:

1. THE OBSERVED GROUNDWATER ELEVATIONS ARE BASED ON MEASUREMENTS CONDUCTED ON JULY 26, 2001 IN WELLS SCREENED WITHIN THE OVERBURDEN AQUIFER.

2. THE PREDICTED GROUNDWATER ELEVATIONS ARE BASED ON THE GROUNDWATER FLOW MODEL THAT WAS CALIBRATED TO JULY 26, 2001 GROUNDWATER ELEVATION MEASUREMENTS.

3. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

FIGURE 6-7

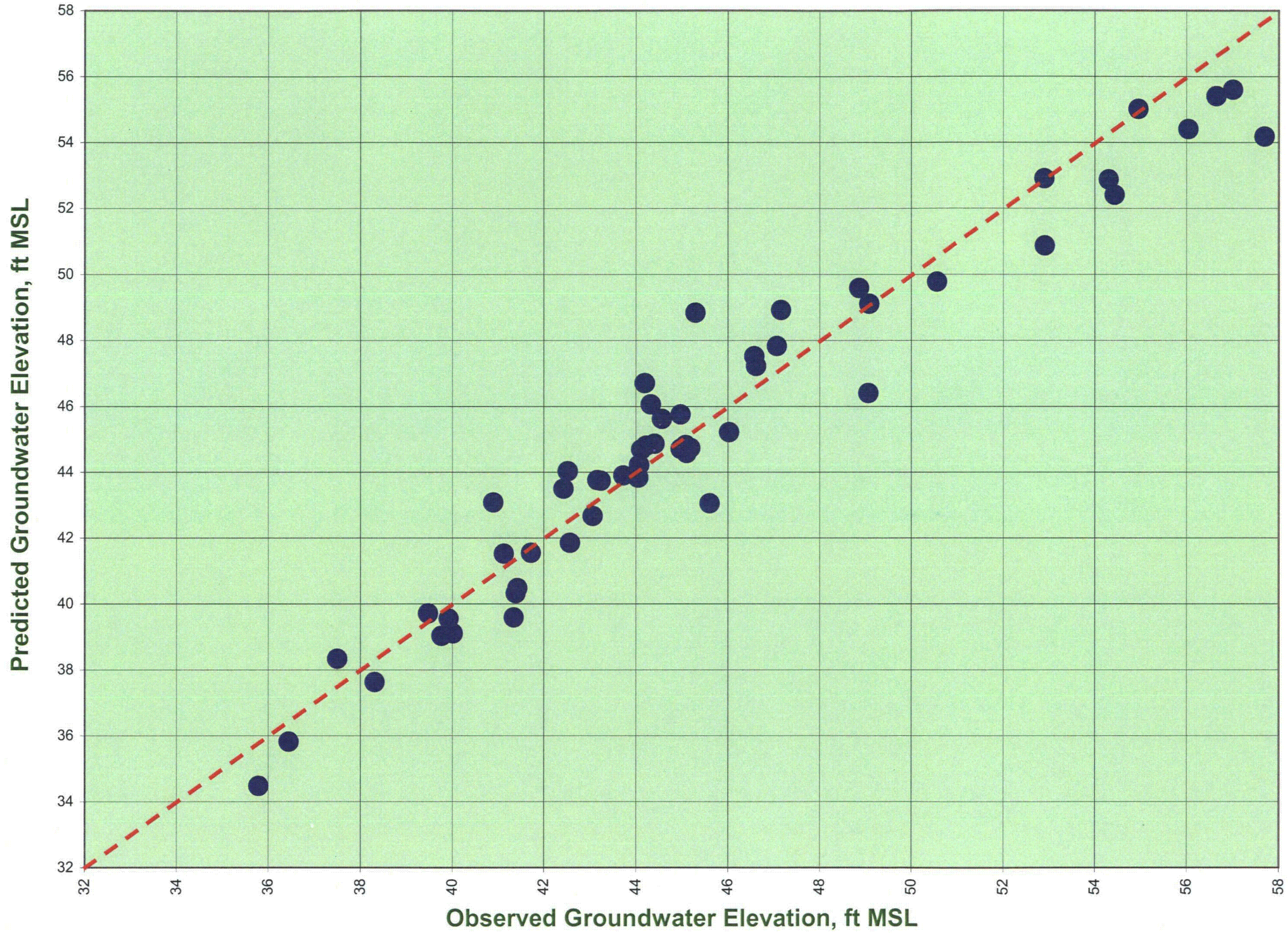
SCATTER PLOT SHOWING RELATIONSHIP BETWEEN OBSERVED AND MODELED GROUNDWATER ELEVATIONS FOR OVERBURDEN OBSERVATION WELLS

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers

FUSRAP Maywood Superfund Site

Shaw Environmental, Inc.



NOTES:

1. THE OBSERVED GROUNDWATER ELEVATIONS ARE BASED ON MEASUREMENTS CONDUCTED ON JULY 26, 2001 IN WELLS SCREENED WITHIN THE SHALLOW BEDROCK AQUIFER.

2. THE PREDICTED GROUNDWATER ELEVATIONS ARE BASED ON THE GROUNDWATER FLOW MODEL THAT WAS CALIBRATED TO JULY 26, 2001 GROUNDWATER ELEVATION MEASUREMENTS.

3. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

FIGURE 6-8

SCATTER PLOT SHOWING RELATIONSHIP BETWEEN OBSERVED AND MODELED GROUNDWATER ELEVATIONS FOR SHALLOW BEDROCK OBSERVATION WELLS

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers.

FUSRAP Maywood Superfund Site

Shaw Environmental, Inc.

LEGEND:

- PARTICLE TRAJECTORY STARTING LOCATION
- PARTICLE TRAJECTORY
- ONE YEAR TRAVEL DISTANCE MARKER

NOTES:

1. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 400 FEET

FIGURE 7-1

PARTICLE TRACKING RESULTS FOR OVERBURDEN AQUIFER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers.

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.

LEGEND:

- PARTICLE TRAJECTORY STARTING LOCATION
- PARTICLE TRAJECTORY
- ONE YEAR TRAVEL DISTANCE MARKER

NOTES:

1. INFORMATION PRESENTED ON THIS FIGURE IS BASED ON FLOW MODEL RUN FLOW_137.

SCALE

1 INCH = 400 FEET

FIGURE 7-2

PARTICLE TRACKING RESULTS FOR SHALLOW BEDROCK AQUIFER

MAYWOOD SUPERFUND SITE, NEW JERSEY

US Army Corps of Engineers.

FUSRAP Maywood Superfund Site

Shaw Shaw Environmental, Inc.