Impact Area Groundwater Study Program

Feasibility Study
Demo 1 Groundwater Operable Unit

Appendix A
Groundwater Modeling

Camp Edwards
Massachusetts Military Reservation
Cape Cod, Massachusetts

August 19, 2005

Prepared for:

U.S. Army Corps of Engineers
New England District
Concord, Massachusetts
for
U.S. Army / National Guard Bureau
Impact Area Groundwater Study Program
Camp Edwards, Massachusetts

Prepared by:

AMEC Earth & Environmental, Inc
Westford, Massachusetts
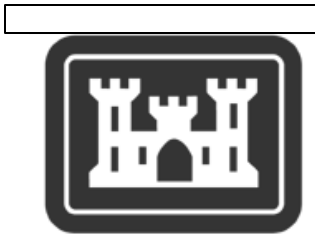Contract No. DAHA92-01-D-0006

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

2,4-DNT	2,4-Dinitrotoluene
2,6-DNT	2,6-Dinitrotoluene
2A-DNT	2-Amino-4,6-dinitrotoluene
4A-DNT	4-Amino-2,6-dinitrotoluene
AEC	U.S. Army Environmental Center
AIRMAG	Airborne magnetometer
AMEC	AMEC Earth and Environmental, Inc.
APC	Armored personnel carrier
bgs	Below ground surface
BIP	Blow-in-place
CIA	Central Impact Area
CLP	Contract Laboratory Program
cm	Centimeter
Comp B	Composition B
CRREL	Cold Regions Research and Engineering Laboratory
CVM	Cesium Vapor Magnetometer
DoD	Department of Defense
ECC	Environmental Chemical Corporation
EM	Electromagnetic
EM61	Geonics Inc. electromagnetic sensor
EOD	Explosive ordnance disposal
GC	Gas chromatograph
GP	Gun position
GPL	GPL Laboratories
GPS	Global positioning system
HE	High explosive
HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
HPLC	High-performance liquid chromatography
HUTA	High use target area
IAGWSP	Impact Area Groundwater Study Program
JE	Jacobs Engineering
LITR	Low-intensity training round
MAARNG	Massachusetts Army National Guard
MADEP	Massachusetts Department of Environmental Protection
MCP	Massachusetts Contingency Plan
MDL	Method Detection Limit
MIDAS	Munitions Items Disposition Action System
m^2	square meters
mg/kg	Milligrams per kilogram
µg/kg	Micrograms per kilogram
µg/l	Micrograms per liter
mm	Millimeter

ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONT'D)

MMR	Massachusetts Military Reservation
MMR-PRG	MMR preliminary remediation goal
MMR-SSL	MMR soil screening level
MP	Mortar position
MS/MSD	Matrix spike/matrix spike duplicate
mV	Millivolt
MW	Monitoring well
NAD 83	North American Datum 1983
NGB	National Guard Bureau
OE	Ordnance and Explosives
o-NT	2-nitrotoluene
PAVE PAWS	Perimeter Acquisition Vehicle Entry Phased Array Warning System
PCBs	Polychlorinated biphenyls
PDA	Photodiode array
p-NT	4-nitrotoluene
PRG	Preliminary Remediation Goal
QA	Quality assurance
QC	Quality control
RCL	Response to Comments Letter
RCS-1	Reportable Concentration, Category S1
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine
RL	Reporting limit
RPD	Relative percent difference
SCAR	Sub-caliber aerial rocket
Schonstedt	Schonstedt Instrument Company hand-held analog magnetometer
SDG	Sample delivery group
SOW	Statement of work
SPLP	Synthetic Precipitation Leaching Procedure
SSL	Soil screening level
SVOC	Semi volatile organic compound
TCLP	Toxicity Characteristic Leaching Procedure
Tetra Tech	Tetra Tech, Inc.
TNB	1,3,5-Trinitrobenzene
TNT	2,4,6-Trinitrotoluene
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
UTM	Universal Transverse Mercator
UXO	Unexploded ordnance
VOC	Volatile organic compound

1.0 INTRODUCTION

In 2001 the Impact Area Groundwater Study Program (IAGWSP) initiated a groundwater modeling program to support groundwater investigations and feasibility studies at the Massachusetts Military Reservation (MMR) required by USEPA Administrative Orders under the Safe Drinking Water Act (SDWA) 1-97-1019 (AO3) and 1-2000-0014 (AO3). Modeling of Cape Cod aquifer systems has been conducted routinely by the United States Geological Survey (USGS) and others for the purpose of understanding flow system dynamics, simulating groundwater contamination fate and transport, designing remedial systems, and siting/permitting water supply wells. Modeling efforts started with the latest version of the USGS regional model of Western Cape Cod (Masterson et al. 2000) that was updated to reflect current data hydrogeologic data. The updated regional model was then used to construct subregional models for simulating local groundwater flow and contaminant transport. This appendix provides documentation of the latest regional model update, Demolition Area 1 (Demo 1) subregional groundwater flow and solute transport model calibration, and the modeling strategy and techniques used to develop and evaluate Demo 1 remedial alternatives.

1.1 Groundwater Modeling Program Objectives

The objectives for saturated zone modeling at MMR include the following: 1) predict future migration paths, rate of movement, and concentrations of contaminants emanating from within the MMR; 2) identify sources of groundwater contamination; 3) provide data for risk analysis; 4) locate monitoring wells using particle path analysis; 5) provide a basis for risk management decisions; and 7) design remedial systems to reduce contaminant concentrations.

1.2 Code Selection

A variety of groundwater modeling codes were selected to perform various phases of required modeling tasks. These tasks include flow modeling, fate and transport modeling and remedial design modeling. In addition, various pre- and post-processors were used to increase efficiency. The following sections summarize the model codes utilized.

1.2.1 Flow Model Code

The USGS modular finite-difference groundwater flow modeling code, MODFLOW96, was selected to simulate groundwater flow at MMR (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988). MODFLOW96 is a public-domain code developed by the USGS, is well documented, and is widely used throughout the environmental industry. In addition, a regional steady-state groundwater flow model encompassing MMR had already been developed by the USGS using MODFLOW96, and had undergone numerous iterative refinements (Masterson et al. 2000, 1998, and 1996).

The USGS particle tracking code, MODPATH, was selected for computing forward and reverse particle tracks (Pollack, 1989 and 1994). MODPATH utilizes the groundwater flow output from MODFLOW96 to predict flow paths and, similar to MODFLOW96, is a well-documented public domain code that is widely used throughout the environmental industry. Particle track analyses have been utilized to select monitoring well locations

and screen depths as well as to calibrate and predict advective contaminant migration paths.

1.2.2   Fate and Transport Model Code

The modular three-dimensional multispecies transport model MT3DMS (Zheng and Wang, 1999) was selected to simulate the fate and transport of contaminants of concern. MT3DMS is designed for use with output from any block-centered finite-difference groundwater flow model (e.g., MODFLOW96). The program utilizes groundwater flow velocities to predict concentrations while considering advection, dispersion, diffusion, and basic chemical reactions (e.g., sorption and decay) of dissolved contaminants and has been widely utilized to evaluate remedial system scenarios such as groundwater extraction and injection.

1.2.3   Additional Codes and Pre/post Processors

A variety of pre- and post-processors were used to implement the modeling codes and display results. Generic tools include text editors, spreadsheets, standard geographic information system (GIS) software, and various graphics and graphing packages such as AUTOCAD, TECPLOT, EVS, and SURFER. The primary pre/post-processing softwares used are Groundwater Modeling System (GMS) Version 3.1 and Groundwater Vistas Version 3.5. In addition, Visual MODFLOW, MODTMR, Flowpath, and Brute Force have been utilized, as well as a number of custom FORTRAN and Visual BASIC programs developed by IAGWSP. Brute Force (a component of Groundwater Vistas) is a particle track-based optimization code designed for groundwater extraction remedial design. This software component is discussed further in Section 4.4.

1.3   Modeling Methodology

IAGWSP's modeling program was established to focus on the northern portion of the MMR where it has conducted environmental investigations since 1997. The methodology has been to continually update the regional flow model by incorporating site-specific lithologic and hydrogeologic information from field investigations, related studies and literature as it becomes available (Figure A1-1). This process is iterative because simulated flow paths from the updated regional model are used to help guide characterization activities. Subregional flow and transport models are developed from the updated regional model using telescopic mesh refinement (TMR) techniques. The USGS MODTMR code (Leake and Claar, 1999) is used to facilitate construction of the subregional models. MODTMR constructs embedded subregional models by extracting boundary conditions and hydraulic parameter distributions from the regional model and projecting those values onto the local grid of the subregional model. Detailed hydrologic information is then input into the subregional models, which are used to more precisely simulate groundwater flow and contaminant migration and to design and evaluate remedial scenarios. Ultimately, post-installation performance data from the selected remedial system design is used to iteratively improve the subregional model and optimize remedial operations.

1.4   Summary of Previous Modeling Work

Since initiation of the modeling program in 2001, the original USGS regional groundwater flow model for western Cape Cod has been continually revised to reflect new site information (e.g., lithologic data) acquired pursuant to MMR investigation activities completed by IAGWSP.   Concurrently with regional model revisions, a variety of subregional models have been developed for Demo 1, the Impact Area, and the Southeast Ranges. Table A1-1 summarizes the important model variants to date. The MMR series models represent the sequential revisions of the regional model. JR-8 series subregional models have been developed for steady-state simulations of the Southeast Ranges area (principally the J-3 Range plumes). The Demo 1-4 series models are the previous Demo 1 subregional models developed for the Draft Feasibility Study (AMEC, 2001). Lastly, TRANS16 and TR_LOC5 represent transient regional and subregional models, respectively, developed specifically for transient simulations of Top-of-Mound wander in the Southeast Ranges area. Documentation of these models and a number of other modeling efforts is presented in the Draft Saturated Zone Modeling Summary Report for Camp Edwards (AMEC, 2003a).

2.0 REGIONAL MODEL UPDATE

In late 2002, a comprehensive update of the MMR regional model was initiated to incorporate new information and improve the model's predictive capabilities. The new model is referred to as MMR-10. The primary objectives of this update were to;

1) refine the model grid spacing from 660 x 660 ft to 330 x 330 ft;
2) calibrate to 2000 groundwater elevations and a revised interpretation of the location of the top-of-mound (TOM) based on 2000 data;
3) incorporate new data on bedrock elevations;
4) update hydraulic conductivity distributions based on pumping tests performed in the Impact Area and elsewhere in the northern portion of MMR;
5) improve the match between predicted and observed Demo 1 plume trajectory;
6) calibrate to a number of other datasets including tritium-helium isotope groundwater ages and streamflow measurements provided by the USGS; and
7) incorporate some recent findings and regional model revisions by the USGS and Jacobs Engineering into the new regional model.

MMR-10 was then used to develop the Demo 1 subregional model of groundwater flow and contaminant transport to support the Demo 1 Feasibility Study. A draft Feasibility Study was conducted previously for Demo 1 (AMEC, 2001) but targeted only RDX reduction. Since that time perchlorate has been identified as an additional contaminant of concern (COC) and plume delineations have changed considerably as summarized in the draft Groundwater Addendum (AMEC, 2003d). Development and calibration of MMR-10 was completed in June 2003.

2.1 Hydrogeologic Framework

The hydrogeologic framework for Western Cape Cod consists of a thick, unconsolidated, highly permeable glacial outwash underlain by relatively impermeable bedrock. Figure A2-1 presents the current surficial geologic map. The groundwater flow system is unconfined and recharges through percolation to the water table and discharges to incised streams and as subsea outflow. The fresh water system is bounded by ocean on three sides, and discharges to Nantucket Sound to the south, Buzzards Bay to the west, and Cape Cod Bay and the Cape Cod Canal to the north. A groundwater high (referred to as the Top-of-Mound) is located to the southeast of the Impact Area with groundwater flow emanating radially away from this point.

The saturated zone (from the water table to bedrock) ranges from 100 to nearly 400 ft thick. The zone is dominantly coarse sand and gravel but also includes discrete zones of silt and clay and is interpreted to exhibit a general coarsening upward, resulting from progradation of lacustrine, bottomset, foreset, and topset sedimentary facies (Masterson et al. 1996). Horizontal hydraulic conductivities are estimated to range from 10 to 350 ft/day based on slug and aquifer test data (AMEC, 2003b and 2003d; Masterson et al. 1996). The ratio of horizontal to vertical hydraulic conductivity ranges from 3:1 to 30:1 (Masterson et al, 1998). A discontinuous layer of till, less than 5 to 20 ft thick, is present on top of bedrock (Masterson et al, 1998). The hydraulic conductivity of the till is

estimated at 1 ft/day (Masterson et al, 1998). Bedrock is encountered at depths of 110 to 365 ft bgs.

Within the outwash deposits geologists have mapped two moraines, the Sandwich Moraine and the Buzzards Bay Moraine, which roughly coincide with the northern and western boundaries of MMR (Figure A2-1). These moraine zones are topographically distinct and generally exhibit more frequent occurrence of discontinuous clay layers and boulders interbedded with the gravel, sand, and silt. Masterson et al. (1996) assumed a hydraulic conductivity range of 30 to 150 ft/day. The ratio of the horizontal to vertical hydraulic conductivity ranges from 10:1 to 100:1.

2.2   Model Discretization

The extent of the model domain and orientation of the 3-D finite difference grid are consistent with previous versions of the regional model developed by USGS and IAGWSP. These earlier models consisted of an 11 layer grid of uniform 660 x 660 ft (horizontal) cells rotated 11.2 degrees counterclockwise (Masterson et al. 2000, 1998, and 1996; AMEC, 2003a). During development of MMR-10, model cells were divided in half resulting in uniform 330 x 330 ft cells and a 288 row by 260 column model grid (Figure A2-2). The finer lateral discretization improves the representation of pumping wells, streams and ponds.

Vertical discretization was not changed and Table A2-1 summarizes layer elevations and thicknesses. Model layers 1 through 8 (to −100 ft NGVD) are typically 20 foot thick. Layers 9 through 11 are variably thick depending on the interpreted elevation of the bedrock surface.

2.3   Boundary Conditions

Although the precursor USGS regional model has been modified several times, the approach to assigning boundary conditions is generally unchanged. Figure A2-2 displays the MMR-10 boundary conditions. Constant heads are used on the eastern side of the model domain coincident with Mystic, Middle, and Hamblin Ponds and the Marston Mills River. Discharge to coastal areas along the northern, southern, and western edges is represented as head-dependent flux boundaries using MODFLOW's General Head Boundary (GHB) package. At GHB boundaries, free water surface elevations were assigned based on mean tide level (as determined by USGS) and conductances were varied proportional to the length of intersection between the GIS mapping of the shoreline and individual model cells. Streams incised into the outwash deposits were also represented as head-dependent flux boundaries using MODFLOW's Drain package.

The top of bedrock defines the bottom of the flow system and is represented by no-flow conditions. In some areas the elevation of the top of bedrock was modified during the development of MMR-10 to incorporate new depth to bedrock information. These data, along with control points introduced to constrain the interpolation where data were absent, are presented in Table A2-2 and were used to construct the bedrock surface contours presented in Figure A2-3. These bedrock contours were generated using Surfer® software, enabling a conventional kriging process. Bedrock elevation data was collected by and shared between USGS, Jacobs Engineering, and AMEC.

The upper surface of the model (layers 1 through 3) receives recharge from precipitation. Figure A2-4 presents a map of recharge specified in the final calibrated regional model. The baseline recharge rate is estimated to be 27 inches per year, approximately 60 percent of the average annual precipitation (Masterson, 1998). Direct recharge to large ponds is estimated to be 16 in/yr due to greater runoff and evaporation potentials. In addition to recharge from precipitation, populated areas receive recharge via wastewater return flows from septic systems and the MMR sewage-treatment facility. This additional recharge rate is approximately 85 percent of the water withdrawn for public water supply and assumed to be distributed proportional to population density (Masterson, 1998).

Ponds within the regional model are simulated using isotropic uniform hydraulic conductivity zones of 50,000 ft/d. Model layer bottom elevations were adjusted to mimic the actual pond depths. High hydraulic conductivity zones in the model allow simulation of kettle pond flow dynamics in which groundwater discharges to the upgradient side of the pond and pond-water recharges groundwater from the downgradient portions of the pond.

Public water is supplied via 26 pumping wells. These wells are simulated in MMR-10 (as in previous regional model variants) at reported average daily 2000 pumping rates.

2.4   Calibration

MMR-10 calibration criteria were prioritized with respect to their inherent quality and relationship to the project objectives (Table A2-3). Plume trajectories were considered the "best" calibration targets as the plumes are representative of long-term groundwater flow directions and velocities. Typically, regional synoptic groundwater elevation surveys are used to define "average" watertable conditions. However, it should be acknowledged that they may never truly represent the long-term (steady-state) conditions being modeled, as the aquifer is always in a dynamic state of change to seasonal and/or long-term climatic trends. For this reason, calibration to monitoring well water levels was considered of secondary priority, followed by pumping test drawdown response curves, groundwater age estimates, and streamflows.

Calibration was achieved through iterative trial-and-error modification of input parameters. The primary calibration parameters were horizontal hydraulic conductivities and vertical anisotropy ratios. Secondary calibration parameters were recharge and MODFLOW Drain and General Head Boundary conductance terms.

2.4.1   Plume Trajectories

Contaminant plumes that have evolved over decades are by definition the best indicators of long-term groundwater flow velocity and direction. At MMR there are field-interpreted extents of more than 20 documented groundwater plumes available for this purpose. Attention was focused on the northern portion of MMR and the Demo 1 and Impact Area perchlorate and RDX plumes, but also considered plumes to the south and west including LF-1, CS-4, CS-10, CS-20, CS-21, CS-29, SD-5, FS-1, FS-12 and Ashumet Valley plumes which have been delineated under the AFCEE program. Southeast Ranges plumes, whose extents and trajectories are still being determined, were excluded from this analysis.

While recognizing that plume trajectories are the primary calibration targets, calibration to water levels and plume trajectories were evaluated conjunctively. At the conclusion of each trial-and-error calibration model run, water level correlation statistics were evaluated and, if a satisfactory correspondence was obtained, forward particle tracking was performed from the head of each plume and allowed to migrate with the ambient groundwater flow field. The resultant particle traces were then compared to known plume geometries and if reasonable matches were obtained (defined as the particle path reasonably corresponding to the center line of plume trajectory) the simulation was deemed to have satisfied plume trajectory target criteria. Figure A2-5 is a comparison of particle trajectories relative to all plume extents for the final calibrated model.

Matching the Demo 1 plume proved uniquely challenging because in initial runs particle tracks from the source area deviated significantly from the interpreted perchlorate center-of-mass trajectory by veering too far northwest downgradient of Frank Perkins Road. Examination of groundwater elevation targets revealed an area to the northwest, corresponding to the so-called "far-field" wells (MW-80 through MW-84 located roughly 4000 feet north of the Demo1 perchlorate plume toe), where observed water levels were consistently being under-predicted. By introducing an elliptical zone of lower hydraulic conductivity in the vicinity of these wells, modeled water levels increased and, as a consequence, improved both the match to groundwater elevations at the far-field wells and correspondence with the interpreted perchlorate center-of-mass trajectory (Figure A2-6). Note that due to the greater uncertainty in source area relative to Demo 1, reverse particle tracking from leading edge detections was used to evaluate the predicted Impact Area plume trajectory.

The final calibrated hydraulic conductivity distribution for each layer in MMR-10 is presented in Figures A2-7a through z.

2.4.2   Groundwater Elevation Targets

2.4.2.1   2000 Well Water Levels

Prior to the development of MMR-10, IAGWSP utilized 1993 water level data (developed by USGS) at 177 wells in calibration of the regional flow model. While these data are considered to adequately represent long-term average water levels, relatively few wells existed in the northern portion of MMR at the time. Since 1993, investigations at Demo 1, the Impact Area, Western Boundary Area, SE Ranges, and the Northwest Corner have provided many additional wells and water levels have been measured during both routine sampling events and periodic synoptic rounds. However, long-term records of regional groundwater conditions suggest the period following 1993 was relatively 'wet' and water levels rose to a historical maximum in 1998. These conditions were followed by an extended period of very low recharge resulting in a steady decline to near historical minimums by late 2002. As a consequence, water levels during the midpoint of this decline (late 2000) are interpreted to represent the first return to average conditions since 1993, and were therefore selected as new groundwater elevation targets for calibration of MMR-10.

The new set of groundwater elevation targets consisted of water levels measured at 1,474 well screens from June through December 2000 (Figure A2-8). These data are a combination of monitoring well water levels collected by USGS, AFCEE and IAGWSP, with duplicate and anomalous data omitted. Where multiple observation dates within the period were available an average water level was computed. Table A2-4 lists all targets including the final model predicted water levels and computed residuals (differences between computed and predicted values). Figure A2-9 is a graph of the correlation between computed and predicted water levels along with a table of residual statistics. While there are individual outliers and a trend of overpredicting water levels at lower elevations, the average residual is just over 1.5 feet.

To focus calibration on AOCs in the northern portion of MMR, a subset of the 2000 water level data was evaluated separately, including only values north and west of Snake Pond. Figure A2-10 is a graph of the correlation between computed and predicted water levels, along with summary statistics for this subset of the calibration dataset. Correlation to these targets is significantly better compared to the full population, with the average residual slightly above 1 foot.

Figure A2-11 displays the final calibrated water table contours for regional model MMR-10.

2.4.2.2 Pond Levels

Kettle pond levels are groundwater controlled and thus were used as calibration targets. Table A2-5 lists the available target elevations, predicted elevations, and computed residuals for 16 representative ponds as reported by USGS. The average residual is just over 1 foot.

2.4.2.3 Top Of Mound Locations

The 2000 groundwater elevation dataset also provided for an improved estimate of the location of the top-of-mound (TOM) in the J-1 Range area. Previous TOM estimates were based on USGS model predictions and the 1993 data, which lacked sufficient wells in the area. Subsequently, it has been recognized that the TOM likely moves laterally up to a few thousand feet between extreme "wet" and "dry" years and, under average conditions, is farther southeast than previously thought. Figure A2-12 shows the correspondence between various field estimated and model predicted TOM locations and elevations. Recent data from near average conditions in late 2003 has been informally reported (Jacobs Engineering, 2003) to confirm the 2000 interpretation.

2.4.3 Pumping Tests

Because of the necessity to construct individual transient subregional models with finer grid spacing expressly for this purpose, one of the more significant calibration efforts involved matching pumping test drawdown response. For this analysis the following seven long-term pumping tests conducted in the northern portion of MMR were selected (Figure A2-13):

- PW-1 - Conducted by AMEC (June 2003)
- WS-1 - Conducted by EarthTech (June 2000);

- WS-2 - Conducted by EarthTech (July 2000);
- WS-3 - Conducted by EarthTech (May 2000);
- Test Site 1 - Conducted by Stone & Webster (September 1996);
- Test Well 2-88 (4036000-06G) - Conducted by Whitman & Howard (March-April 1990); and
- WS-4 - Conducted by Haley & Ward (May 2002).

Subregional models were developed with lateral model boundaries at least 2,000 feet from the simulated pumping wells and horizontal grid spacing varied from one to two feet in the vicinity of the pumping centers, increased to up to 200 feet at the boundaries. A vertical discretization of ten feet was selected for the majority of the saturated thickness. Boundary conditions were defined from the precursor regional model using MODTMR.

Simulations of transient pumping response were calibrated to observed drawdown by varying local hydraulic conductivity values through a conventional trial-and-error process. Specific yield was assumed to range from 10 to 15% and confined storativity from $1x10^{-5}$ to $5x10^{-4}$ ft^{-1} (Range reported by Jacobs Engineering, 2000 and arrived at through calibration of a transient model for the SE Ranges, AMEC 2003). Only late stage drawdown data, after a minimum of 12 to 24 hours of pumping, was utilized. Calibration results from these subregional models were then transferred into MMR-10.

The details of each pumping test and their implications for calibration of MMR-10 are summarized in Table A2-6. Plots of the final correlation between observed and predicted drawdowns for each test are presented in Figures A2-14 through A2-20.

Cumulative analysis of the pump test data relative to the prevailing conceptual model of the hydrostratigraphic framework suggests that:

- hydraulic conductivity is more uniform with depth in the Mashpee Pitted Plain (MPP), compared with the precursor regional models;
- horizontal hydraulic conductivity of MPP in the Impact Area is lower than in the precursor models;
- moraines (both Buzzards Bay and Sandwich) and Buzzards Bay Outwash (BBO) deposits can have higher permeabilities at depth (i.e. at the elevations below mean sea level) than previously interpreted but these zones may be discontinuous in some areas;
- moraines and BBO deposits can be characterized by higher anisotropy coefficients at depth, compared with the MPP.

Most of these conclusions are consistent with the latest findings of both the USGS and other contractors. Of particular note is that 3 of the 7 pump test sites, representative of the moraines and BBO deposits (and the two tests nearest Demo 1), exhibited a low permeability and strongly anisotropic zone between 0 and –40 ft ngvd. As will be discussed in Section 3, this interval at Demo 1 contains several laterally continuous clay and silt lenses, which are interpreted to significantly impede vertical movement of groundwater.

2.4.4   Other Data

2.4.4.1   Tritium-Helium Isotope Ages

In 2002 the USGS collected groundwater samples at 26 well screens throughout MMR and had them analyzed for ratios of the radioisotope Tritium (^{3}H) and its daughter product Helium (^{3}He). These ratios were then used to estimate the age of the groundwater samples based on the principal that systematic deviation from the initial atmospheric ratio is a function of the half-life of Tritium. USGS provided this dataset in early 2003 for comparison to model predicted groundwater ages.

Table A2-7 presents a comparison of the 21 USGS estimated groundwater ages and model predicted ages, as determined by reverse particle tracking from screen midpoints. The overall match is considered very good with an average difference of less than five years, nearly 60% of samples within three years, and only one sample greater than 10 years. Further analysis of this comparison shows equal number of over predictions and underpredictions, no evidence of systematic bias (i.e. the oldest samples are consistently underpredicted), and no evidence of spatial bias (i.e. regions of overprediction). Though uncertainties related to the analytical methodology are low, the limited number of samples, natural variability, and potential for mixing of water of different ages in the flow system or during sample collection must be considered when quantifying these results.

2.4.4.2   Stream Flows

Stream flow data published by USGS conjunctively with the 1993 groundwater elevation data have also been used to confirm regional model calibration.   USGS has acknowledged that these data may represent a period of above average flows, due to a precipitation event just prior to sampling, and therefore are interpreted to define a reasonable upper limit for simulated discharges under average conditions. Table A2-8 provides a comparison of observed and predicted flows at seven locations previously published and two more recent estimates (2002) reported by USGS.

2.5   Summary of MMR-10 Development

Calibration of the MMR-10 model was achieved through manual trial-and-error adjustment of:
- horizontal hydraulic conductivities;
- anisotropy coefficients; and
- conductances at Drain and General Head Boundary cells.

 In addition to the calibration targets utilized in previous regional model variants:
- major plume trajectories;
- 1993 water levels in the observation wells and ponds; and
- 1993 stream flows,

MMR-10 was calibrated to:
- revised plume trajectories at Demo 1 and the Impact Area;
- 2000 groundwater elevation data;

- a re-interpreted Top-of-Mound location (identified by Jacobs Engineering);
- 7 long-term pumping tests in the northwestern portion of the domain;
- ^{3}H/^{3}He age dating of groundwater (provided by USGS); and
- 2002 stream flow data.

Note that IAGWSP's efforts focused on the Demo 1 and Central Impact Areas and therefore prioritized calibration to field data close to the mound and north of the LF-1 area. In general, MMR-10 better predicts Demo 1 plume trajectory, the Top-of-Mound location, horizontal gradients, etc. relative to previous regional model variants, and is considered highly suitable for determining subregional boundary conditions at Demo 1.

The PCG2 solver employed the Modified Incomplete Cholesky method with a relaxation parameter of 0.95 and a convergence criteria of 0.00001 feet. The model mass balance was less than 1×10^{-6} percent and is considered more than satisfactory.

3.0 DEMO 1 SUBREGIONAL MODEL

3.1   Demo 1 Objectives

The major objectives for groundwater modeling at Demo 1 are to:

- develop and calibrate subregional flow and contaminant transport models to simulate particle flowpaths and fate-and-transport of multiple COCs (RDX, perchlorate, and TNT);
- simulate the baseline remedial design scenario representing no further action beyond the RRA system (presently being constructed);
- conduct optimization modeling to assess individual remedial alternatives under selected time-to-cleanup criteria and determine design information such as; number of extraction and/or reinjection wells, well configurations, pumping rates, well screen lengths, etc;
- utilize fate-and-transport modeling to confirm mass removal effectiveness and assess future plume configurations (e.g. at 30 years) relative to the baseline scenario to allow comparing various alternatives;
- conduct sensitivity analysis to quantify uncertainty in cleanup design predictions by varying aquifer parameters; and
- determine number and location of observation wells needed to assess system performance.

While the subregional model is derived from a calibrated regional flow model (MMR-10), the finer discretization allowed for incorporation of important local scale features, such as small kettle ponds and refined hydrostratigraphic layering, which required additional calibration. In addition, data on local hydraulic conductivities from pneumatic slug testing at Demo 1, not available during regional model revisions, were also considered.

Specific flow calibration objectives for the subregional model were similar to those defined for the regional model but focused on obtaining an optimal match to:

- horizontal and vertical trajectory and advective travel time of the observed Demo 1 explosive and perchlorate plumes and
- groundwater elevations including pond elevations and horizontal hydraulic gradients.

Specific fate-and-transport calibration objectives were to verify that:

- the simulated flow system and current set of assumed transport parameters can reasonably reproduce the observed plume geometry from a source within the kettle depression and
- the apparent relative transport of perchlorate and RDX (which are both considered minimally retarded) can be accounted for by available information on the history of potential source activities.

3.2 Conceptual Hydrostratigraphic Model

The conceptual hydrostratigraphic model for Demo 1 consists of approximately 200 feet of saturated sands and gravels atop bedrock, as discussed in Section 2 Site Background and Section 3 Contaminant Nature and Extent in the main document.   These geologic deposits occur in two distinct zones: the Mashpee Pitted Plain (MPP) and the Buzzards Bay Moraine (BBM) (see Figure A2-1).   Both zones are interpreted to become progressively less permeable with depth. However, relative to the MPP, the BBM is interpreted to have overall lower permeability and greater vertical anisotropy, as evident from the frequent occurrence of stratified silts and clays, steeper hydraulic gradients, and occasional significant vertical gradients observed in this zone.   West of the BBM, the Buzzards Bay Outwash (BBO) which is not well characterized but considered to be similar to the MPP, though generally less permeable.

Within the BBM zone at Demo 1, at least two distinct clay horizons were identified consistently in boring logs in the Pew Road area and later verified during gamma logging performed independently by COE. These lenses are interpreted to be laterally continuous over 1000s of feet and of low permeability relative to the coarse grained outwash that predominates elsewhere in the BBM and throughout the adjacent MPP.   Further, the interpreted geometry of the perchlorate plume indicates these lenses are responsible for restricting vertical flow and deflecting the plume trajectory upward (Figure A3-1).

Figure A3-2 shows the boring locations where clay was encountered, the interpreted lateral extent of the clay deposit, and boundaries of the BBM zone. The interpreted extent is constrained to the east and west by MW-240 and MW-210 where clay is not present and assumed to extend north and south quasi-parallel to the trend of the moraine. Given the available data, delineation of the exact north and south extents remains uncertain, however, because the clay is known to extend at least beyond the plume edge, the impact of this uncertainty on simulation of plume trajectory is expected to be minimal. Note that no boring logs were available for the ASPWELL.   Vertical thickness of the shallower deposit (above –40 ft ngvd) is 20 ft at Pew Road tapering to 10 ft toward the west. The deeper lens (below –70 ft ngvd) was only encountered along Pew Road at a thickness of 10 ft.

3.3 Subregional Model Design

The following sections present the discretization, boundary conditions and aquifer properties used in subregional model development.

3.3.1 Discretization

Groundwater flow and contaminant transport from the Demo 1 source area and along the plume path were simulated using a 17-layer finite-difference model extracted from regional model MMR-10 using MODTMR (Leake and Claar, 1999).   The subregional model grid consists of 153 rows and 445 columns having variable spacing ranging from 50 to 100 feet with the finest grid spacing corresponding to the location of groundwater contamination (Figure A3-3). Grid orientation was the same as that used for the regional model. All model layers have horizontal top and bottom elevations except the bottoms of

layers 16 and 17, which correspond to the interpreted top of bedrock, and where bottom elevations are altered to replicate pond bottom elevations.

The upper 14 model layers are all 10 foot thick with the exception of where the watertable exists below the top elevation. In these cells the thickness is less than 10 feet and becomes progressively thinner in the direction of the coast as watertable elevation declines. Layers 15 and 16 have thicknesses of 20 and 40 feet, respectively. Layer 17 has a maximum thickness of approximately 60 feet where depth to bedrock is greatest and pinches out where bedrock rises above the top of the layer.

3.3.2   Boundary Conditions

Model cells along the upgradient and cross-gradient external boundaries (the model edges) are specified as head-dependent flux boundaries using MODFLOW's General Head Boundary (GHB) package, where the specified head corresponds to calculated values at the same location within the regional model (Figure A3-3). GHB conductances were calculated using regional model hydraulic conductivities from corresponding locations.

Subsea outflow to Buzzards Bay at the downgradient edge of the model is simulated using GHB cells having identical properties and locations as the regional model.

Streams within the Demo 1 subregional model are represented using MODFLOW Drain cells. Drain hydraulic head and conductance values are identical to those used in the regional model and represent expected stream stage at corresponding locations along the length of the drainage feature.

The contact between permeable outwash and bedrock was assigned a no flow boundary condition. The elevation of this surface was specified identical to the regional model.

Baseline recharge was specified at 27 inches/year over the majority of the Demo 1 model domain. However, in order to improve the correspondence to observed vertical plume trajectory, a zone of reduced recharge (19 inches/year) was assigned to the moraine region (Figure A3-4). The zone was added to account for differences in vegetative cover (mature canopy type cover verses grasses) and topography (steep verses relatively flat) expected to result in increased evapotranspiration rates and potential deflection of recharge to flatter areas, respectively.

As in the regional model, ponds within the Demo 1 subregional model are simulated using isotropic uniform hydraulic conductivity zones of 50,000 ft/d. Model layer-elevation bottoms were adjusted to mimic the inferred pond depths. Due to the finer grid spacing, ponds that were too small to be represented in the regional model, such as Opening pond and North Pond in the Demo 1 area, are now actively simulated.

3.3.3   Aquifer Properties

Initial hydraulic conductivities for the subregional model were derived from the regional model and then further adjusted through trial-and-error calibration to improve the correspondence to plume trajectory and water levels. Prior to these adjustments, the

two clay lenses discussed in Section 3.2 were explicity incorporated in model layers 8-10 and 14. The clay zones were simulated with an assumed horizontal hydraulic conductivity of 0.5 ft/day and a vertical anisotropy ratio of 10:1.

Local hydraulic conductivity information was provided by analysis of pneumatic slug tests performed on 33 individual well screens at 13 monitoring well locations. These data were evaluated with respect to the MPP and BBM geologic zones and their vertical position in the aquifer. In general, the following trends were noted:

1) all well tests within the MPP (inclusive of MW-210) yield a geometric mean of 163 ft/day and a range of 81 to 228 ft/day. Five of 10 tests are above 190 ft/day.
2) Tests within the BBM yield a geometric mean of 90 ft/day and a range of 27 to 218 ft/day. Sixteen of 24 tests are below 150 ft/day and nine of 24 are at or below 75 ft/day.
3) Vertically, tests within the MPP show higher permeabilities at depth than have been modeled to date and this appears to persist westward into the BBM and under the clay lens. Within the BBM west of the clay lens, permeabilities rapidly decrease with depth, though no data is available below -60'.

These observations suggest: a) The moraine permeability is generally less than outwash permeability (as modeled) and is also more heterogeneous such that preferential pathways for groundwater flow and contaminant transport likely become more important, b) permeabilities for outwash decline with depth less than postulated by USGS, and c) lower permeability deposits in the moraine may partially overlie deeper layers of more permeable outwash.

In order to further interpret the three dimensional distribution of slug test values and incorporate these data into the model, geometric means were tabulated for three depth intervals within three horizontal zones corresponding to the MPP, the portion of the BBM in which the clay lens has been delineated, and the remainder of the BBM to the west (Table A3-1). This western zone presumably extends to the MMR boundary where the BBM meets the BBO. Based on similarities in the mean values, individual zones were interpreted to represent more permeable MPP outwash, less permeable BBM sands and gravels, or least permeable BBM silts and clays as indicated, and then assigned to the subregional model with initial values of 190, 120, and 40 ft/day, respectively. From this starting point, calibration to water levels, plume trajectories and travel times were evaluated as described below and further adjustments made, where necessary. The final calibrated hydraulic conductivity distributions for each model layer are shown in Figures A3-5a through A3-5q. Vertical anisotropy ratios range from 3:1 to 30:1, consistent with the regional model. Figure A3-6 shows the corresponding hydraulic conductivity distribution in an E-W cross-section.

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3.4 Flow System Calibration

3.4.1 Plume Trajectories and Travel Times

Final calibration of the subregional flow system was achieved by adjustments to hydraulic conductivities within the defined zones to optimize the match between observed plume trajectories and travel times. As will be discussed in detail below, low levels of perchlorate are assumed to have been present in Demo 1 soils as early as 1949 (non-OB/OD activities) and therefore, particle track travel times from the kettle depression to the maximum downgradient perchlorate extent should be approximately 50 years. Of note is the fact that the most downgradient detections of perchlorate are comparatively shallow and would therefore likely originate from the most extreme downgradient edge of the source area while the deepest detections would likely originate from the upgradient edge.

In contrast, RDX was not used at Demo 1 until the 1970s and particle track travel times to the maximum downgradient RDX extent should not exceed 30 years. Further, the nature of the RDX source is primarily OB/OD activities which would tend to produce a concentrated source mainly in the bottom of the kettle depression. Figure A3-7 is a comparison of 30 and 50 year forward particle tracks from the kettle bottom and downgradient flank, respectively, showing excellent correlation to the trajectory and leading edge of both the RDX and perchlorate plumes. When viewed in longitudinal cross-section, particle tracks can be seen to travel along the top of the upper clay lens, consistent with the conceptual model, and reasonably correspond to the interpreted vertical trajectory and extent of contamination (Figure A3-8).

3.4.2 Water Levels and Gradients

Comparison of simulated groundwater elevations with measured Year 2000 groundwater elevation data is presented on Figure A3-9. Also presented on this figure is the summary calibration statistics showing the average residual is less than one foot. The complete list of targets and residuals is presented in Table A3-2.

It should be noted that no monitoring wells existed downgradient of Frank Perkins Road in 2000 and water level data from subsequent Demo 1 well installations largely represents below average conditions associated with the recent drought (which peaked in late 2002 and persisted well into 2003). Rather than integrate water level data representing very different conditions, recent synoptic rounds at Demo 1 were used to estimate horizontal hydraulic gradients for calibration. As presented in Figure A3-10, there is a reasonable correspondence with both the observed magnitude of gradient for each interval and also the systematic increase in gradient toward the west.

Estimates of pond levels in the Demo 1 area provided additional calibration targets, particularly downgradient of the plume where monitoring wells are lacking. Local ponds include Opening Pond just east of Frank Perkins Road (surface elevation estimated at 64 ft ngvd), North Pond immediately downgradient of the plume toe (46 ft ngvd), and Flax Pond within the residential neighborhood west of Rt. 28 (37 ft ngvd). The surface elevation of Opening Pond was determined in early 2003 during installation and survey of

shallow piezometers along the shoreline. Estimates for North Pond and Flax Pond were made using a photogrammetric analysis of high resolution airphotos and review of published topographic maps. Final calibrated water table contours are consistent with these levels as shown in Figure A3-11.

3.5   Fate-and-Transport Calibration

Fate and transport calibration consisted of defining the source area and mass loading rates based on site history and present plume mass, estimating transport parameters such as porosity, dispersivity, retardation factor, and biodegradation rate, and interatively adjusting parameters to optimize the match to observed plume extents.

3.5.1   Source Conceptualization

As discussed in Section 3 Contaminant Nature and Extent in the main document, the Demo 1 perchlorate plume is approximately twice the length of the RDX plume (and also wider) based on detections in monitoring wells through April 2003. Given that perchlorate and RDX are minimally retarded (Speitel et al, 2003), both should migrate at approximately the same rate. Therefore, assuming a common source area (the kettle depression), the logical explanation for the difference in plume lengths is differences in temporal contaminant loading histories. Sampling indicates that perchlorate and RDX were present in the soil along the flanks of the kettle depression and therefore supports this interpretation.

Contaminant loading was divided into two temporal intervals: pre- and post-1975. OB/OD activities within the kettle are documented to have started in the mid-1970s (assumed 1975) which likely represent the highest concentration sources for all COCs. Prior to 1975, activities are not well documented, however, air photo interpretations, field observations, and soil data suggest the Demo 1 area and surroundings were used after WWII for small-arms training (i.e. rifle squad attack course) which may represent the earliest low-level source of perchlorate (possibly associated with pyrotechnics used to simulate battle conditions). Thus, initial contaminant loading at the Demo 1 source area is assumed to start approximately 1950 (allowing a few years for leaching and migration from land surface to the water table) with low-level perchlorate mass entering the aquifer until 1975 when OB/OD activities commenced. After 1975, perchlorate mass loading dramatically increases and RDX enters the flow system for the first time. The concept of a two-stage source is also consistent with the observation that perchlorate concentrations west of Frank Perkins Road are relatively low indicating that the earliest activities responsible for the most downgradient portion of the plume were of low intensity compared to those resulting in the higher concentrated plume east of Frank Perkins Road.

The center of the Demo 1 kettle depression extends 45 feet below the surrounding grade and is where contaminant loading to soils from OB/OD activities is considered to primarily occur. In addition, infiltration would tend to be focused on this area due to diversion of runoff from the steep slopes. In contrast, non-OB/OD sources of perchlorate are interpreted to have a wider footprint, as evident from the greater width of the plume relative to RDX.   Therefore, the simplest source distribution consistent with this conceptual model includes two zones: a high-level source in the kettle bottom and a low-

level source (of perchlorate only) inclusive of the kettle flanks (Figure A3-12). Within these zones contaminant loading was simulated by specifying the concentration of ambient recharge. The final calibrated high-level source footprint for perchlorate is a 2000 square foot area restricted to the kettle bottom. The final calibrated high-level source footprint for RDX is a 1000 square foot area.

3.5.2   Transport Parameters

3.5.2.1   Porosity

A porosity value of 0.39 was used for all flow and transport simulations and was not adjusted during model calibration. This effective porosity value was reported by USGS based on tracer studies at MMR (LeBlanc et al, 1991) and is the value used in prior Demo 1 modeling.

3.5.2.2   Dispersivity

Longitudinal, transverse and vertical dispersivity values of 3.00, 0.06 and 0.005 ft, respectively, were used for all transport simulations. These dispersivity values were based on values published by Garabedian et al. (1988) as utilized in previous modeling efforts at Demo 1 (AMEC, 2001). Dispersivities were not adjusted during transport model calibration.

3.5.2.3   Retardation

Perchlorate is known to be a highly mobile anion and not significantly retarded (Perchlorate in the Environment, Urbansky, 2000). Recent column studies using MMR soils conducted by the University of Texas determined that RDX is not retarded and should migrate at the same velocity as ambient groundwater (Speitel et al, 2003). The same study determined that TNT has a K_d of 1.85 Kg/L, which corresponds to a retardation coefficient of 8.685 given a soil bulk density of 1.61 g/cm^3. This retardation coefficient was used for transport modeling and was not adjusted during transport model calibration.

3.5.2.4   Biodegradation

Biodegradation of RDX and perchlorate is not thought to be significant at MMR based on a comprehensive literature review of published studies. Thus, biodegradation of these compounds was not considered in any of the transport simulations.

In contrast to RDX and perchlorate, literature review indicated TNT biodegradation half-lives for conditions similar to MMR range from 0.125 days to 190 years (Spanggord et al., 1980; Meylan, 1997; Townsend and Myers, 1996; and Pennington et al., 2001). For all TNT transport simulations, a biodegradation half-life of 365 days was selected. Despite the uncertainty indicated by the broad range the selected value is considered conservative.

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3.5.3   Calibration to Observed Plume Extents

Transport calibration was accomplished by trial-and-error adjustment of the source footprint and influent concentrations with time, based on the source conceptualization discussed in Section 3.5.1. Adjustments were made to magnitude and duration of peak loading of both RDX and perchlorate in order to best fit the interpreted plume extents and mass distributions within each model layer. Because of its very limited distribution (present in only two wells) TNT was not considered in fate-and-transport calibration.

The final calibrated contaminant loading histories are presented in Figure A3-13. The comparisons between interpreted and predicted perchlorate plume extents within each model layer are shown in Figures A3-14a through A3-14l and Figures A3-15a through A3-15j present the same comparison for RDX plume extents. The match of interpreted to predicted RDX extent is very consistent in terms of plume width, length, depth, and center of mass, however, the leading edge is predicted to be slightly farther downgradient than presently interpreted. Perchlorate also corresponds reasonably well near the source in the majority of layers, however, it was difficult to closely match the observed changes in plume width and the dilute concentrations at the plume toe (in layers 7-9) are predicted to be somewhat deeper than observed (layers 5 and 6). These discrepancies are potentially attributable to either source distribution complexities or uncertainties in the actual lateral extent, vertical position, and connectivity of the shallow and deep clay lenses, both at the upgradient edge where the plume first encounters this low permeability zone and the downgradient edge where the plume leaves this zone.

While an infinite number of complex loading schemes can be specified which would result in equally reasonable or better matches, given the uncertainty in known contaminant distribution (concentrations are only measured at wells and estimated elsewhere) and limited data on actual loading history, it is not expected that exact temporal and spatial contaminant trends will be matched. Further, the objective is not to define an accurate source term to be used in predictive modeling, but rather to verify the simulated flow system and assumed transport parameters are reasonably consistent with the observed plume geometry. Satisfying this objective, the calibrated model is considered appropriate for use as a tool in remedial design. Confidence in flow and transport calibration was further evaluated during the sensitivity analysis discussed in Section 4.6.

3.6   Summary of Demo 1 Subregional Model Development

A subregional model for Demo 1 was extracted from regional model MMR-10 and then modified to incorporate:
- more detailed hydrostratigraphic layering including two discontinuous clay lenses;
- local horizontal hydraulic conductivities from slug testing; and
- representation of small kettle ponds.

Final calibration was achieved through manual trial-and-error adjustment of hydraulic conductivities and recharge to obtain an optimal match to:
- Demo 1 plume trajectory and travel time; as well as

- Demo 1 area groundwater elevations in observation wells, pond elevations, and horizontal hydraulic gradients.

Lastly, fate-and-transport parameters were verified by demonstrating that source loading at the Demo1 kettle depression, consistent with available information on the history of site activities, could produce plumes similar in length, width, and mass distribution to the observed RDX and perchlorate plumes.

4.0 DESIGN SIMULATIONS

The calibrated groundwater flow and contaminant transport subregional model for Demo 1 was used as the basis for performing design simulations to evaluate various remedial scenarios.

4.1   Design Objectives

Administrative Order 1-2000-0014 (AO3) requires the following remedial alternatives be evaluated:

1) Minimal Action Alternative – long-term groundwater monitoring and institutional controls,
2) Baseline Alternative – continuous long-term operation of the current Rapid Response Action Plan,
3) Background Alternative – which reduces contaminant concentrations to background concentrations in a reasonable amount of time,
4) 10 Year Alternative – which reduces contaminant concentrations to relevant regulatory or risk-based standards within ten years,
5) Additional Alternatives – which attain site-specific remediation levels within different restoration time frames.

Through agreement with the USEPA and MADEP, background concentration values are equal to the reporting limit of 0.25 ug/L for both RDX and TNT and the method detection limit of 0.35 ug/L for perchlorate. IAGWSP has designated 30 years as a "reasonable" amount of time to achieve background concentrations for the various COCs. For the 10 Year alternative, standards have been selected from available health advisory and risk-based values as follows: 0.6 ug/L for RDX, 1.0 ug/L for perchlorate, and 2.0 ug/L for TNT.

For additional alternatives, a second risk-based alternative, which achieves target concentrations in less than 20 years, and a second background alternative, which achieves target concentrations in less than 20 years, were developed.

4.2   Minimal Action Alternative

The Rapid Response Action (RRA) for the Demo 1 Groundwater Operable Unit is scheduled to be operational in late 2004 consisting of two separate Extraction, Treatment and Recharge (ETR) systems collectively referred to as the RRA System (Figure A4-1). The Frank Perkins Road (FPR) system includes one extraction well (EW-D1-1) near the center of the plume on FPR with two injection wells (IW-D1-1, IW-D1-2) located on the northern and southern edges of the plume, respectively. The Pew Road system includes one extraction well (EW-D1-2) near the center of the plume on Pew Road with one injection well (IW-D1-3) located south of the plume boundary near the intersection of Pew Road and Estey Road. The design extraction rate for the FPR system is 220 gpm and for the Pew Road system is 100 gpm. Extraction and injection well locations and pumping rates were determined through modeling activities prior to development of the subregional model described in this document, as discussed in the RRA Plan (AMEC, 2003c).

The RRA System will be operational prior to selection of the final remedial alternative and, therefore, the Minimal Action alternative must account for its presence. However, to evaluate an alternative consisting of a limited period of operation followed by system shutdown, a fate-and-transport simulation was developed in which the current interpreted distribution of contaminant mass was run forward in time with RRA System wells pumping for four years only. Since soils containing perchlorate and explosives in the Demo 1 kettle hole will be removed prior to RRA system startup, this simulation assumed complete source removal.

After four years the RRA system captures 17% of RDX mass and 34% of perchlorate mass. Upon system shutdown in 2008, the leading edge of the residual RDX plume reaches the MMR boundary in approximately 35 years (2043). As the plume migrates, attenuation of peak concentrations occurs due to dispersion and dilution and maximum RDX concentrations predicted to cross the boundary are less than 3 ppb at approximately 82 years. The leading edge of the perchlorate plume reaches the MMR boundary in approximately 18 years (2026). Maximum perchlorate concentrations predicted to cross the boundary are less than 2.9 ppb at approximately 78 years. Prior to crossing the MMR boundary both plumes are predicted to impact the Rod & Gun Club pond and, if allowed to migrate indefinitely, ultimately discharge to the Pocasset River, though this requires more than 100 years to occur.

4.3   Baseline Alternative

To provide a baseline against which more aggressive alternatives can be compared an alternative is proposed which consists of long-term operation of the RRA System. Since soils containing perchlorate and explosives in the Demo 1 kettle hole will be removed prior to RRA system startup, this simulation assumed complete source removal.

4.3.1   RDX and Perchlorate Fate-and-Transport Results

Using the final calibrated flow and transport parameters, the current interpreted distribution of contaminant mass was run forward in time with only RRA System wells pumping. The simulation was run for 100 years to enable evaluation of long-term RRA performance. Figure A4-2 shows the simulated long-term mass removal effectiveness of the RRA System for both RDX and perchlorate. Upgradient of Pew Road all mass is effectively contained and perchlorate declines to background concentrations in 35 years while RDX declines to background concentrations in 50 years. Downgradient of Pew Road very dilute concentrations of perchlorate are not captured and require more than 100 years to decline to background through the processes of dispersion and dilution (natural attenuation).

4.3.2   TNT Fate-and-Transport Results

Initial simulations of TNT fate-and-transport under RRA pumping conditions with complete source removal showed concentrations declining to target levels by natural attenuation processes prior to reaching any extraction wells. This result is not unexpected given the low concentrations and limited extent of the observed TNT plume, as well as the fact that, unlike RDX and perchlorate, this COC is both retarded and biodegraded. Figure A4-3 shows that concentrations are predicted to fall below relevant

risk-based levels in approximately three years and below the current reporting limit by 23 years from startup of the RRA system. Based on these results it was determined that no further modeling of TNT cleanup (under more aggressive pumping scenarios) is required, however, the dependence of the above time-to-cleanup predictions on assumed biodegradation rate was evaluated as part of the sensitivity analysis (see Section 4.6).

4.4   Extraction/Injection System Design Optimization

Well fields to remove Demo 1 groundwater contamination were optimized for the range of time-to-cleanup criteria using a particle tracking optimization (PTO) algorithm called Brute Force, commercially available from Environmental Simulations, Inc. The algorithm is based on sequential MODFLOW and MODPATH runs during which pumping locations and rates are systematically varied until the optimal well field configuration required to achieve a specified mass capture percentage within a defined time interval is discerned.

Particle track modeling is inherently faster than transport modeling and Brute Force takes advantage of this difference in execution times to obtain an optimized solution, for both well locations and pumping rates, in the time it would take to perform only a few transport runs. While it is possible to design an extraction system in a limited number of trial-and-error transport model runs, it is unlikely the effort will produce optimal well locations or pumping rates, which ultimately translates to inefficiencies and higher operational costs over the life of the project.

The design methodology utilized is an iterative optimization process that systematically evaluates hundreds of possible extraction well locations, combinations and pumping rates. The pumping designs presented are those that best meet a given set of performance criteria (i.e., 10 years to risk-based levels) and the high extraction rates are required to meet the time criteria for cleanup. An unfortunate consequence is that the plume will collapse faster in some places and extraction efficiency will decline. In practice, during the operation and maintenance phase, the ETR system pumping rates will be optimized based on performance monitoring and individual wells which no longer extract detectable mass will be packed off or shutdown

Three of the four proposed reinjection wells are part of the RRA systems presently being constructed. Those locations were determined prior to development of the subregional model used in the FS design process. In order to balance reinjection along the south side of the plume at Pew Road, a fourth location was identified to the north resulting in two pairs of wells along Frank Perkins Road and Pew Road, respectively. A third pair of candidate injection locations were identified closer to the kettle depression in the event that modeling indicated additional extraction wells were required too distant to make practical use of the Frank Perkins Road treatment system and reinjection locations. No other reinjection scenarios were evaluated however the optimization methodology ensures that extraction rates are balanced by reinjection in each simulation iteration.

4.4.1   Particle Tracking Optimization Methodology

Particle track optimization modeling is initiated by identifying potential extraction and injection well locations within the model domain. For this effort 220 potential extraction well and six potential injection well locations were identified having screen lengths ranging

from 10 to 120 ft (Figure A4-4). At each potential extraction well location, cells representing the well screen are specified across the entire vertical profile of contamination. Brute Force groups well cells having the same horizontal coordinates into individual wells and dynamically partitions flow in each layer proportional to aquifer transmissivity.

Potential injection wells (inclusive of the existing three for the proposed RRA System) were grouped into three pairs along Pew Road, Frank Perkins Road, and near the kettle, respectively, and each was assigned an area from which to receive post-treatment extraction well discharge (Figure A4-4). Cumulative discharge from all extraction wells within these areas is dynamically split and routed to the corresponding pair of injection wells.

Each potential extraction well was assigned initial minimum and maximum pumping rates and also maximum drawdown criteria, based on knowledge of operating extraction and injection systems at the site. Initial minimum pumping rates were specified at 20 gpm for every 10 feet of well screen. Excessive drawdown is rarely a problem in high transmissivity aquifers such as at MMR, however, drawdown constraints of 10 and 25 feet were assigned to extraction and injection wells, respectively.

Next, particles representing contaminated groundwater requiring capture were placed within the model domain and assigned individual capture time criteria (i.e. 10 or 30 years) and weights corresponding to the mass of contamination. Particles weights corresponded to either RDX or perchlorate concentration, whichever is highest at that location. Because fate-and-transport modeling showed that the TNT plume is quickly attenuated to target concentrations, TNT weighting was not considered. Individual particle mass weights were calculated by multiplying the pore volume in the cell by the contaminant concentration and then normalizing by the smallest weight.

Figure A4-5 flowcharts the PTO algorithm. First, single MODFLOW and MODPATH runs are executed to determine if any of the mass weighted particles are captured within the specified capture time criteria by existing wells. Next, sequential runs (the number being equal to the number of potential well locations) are performed during which each potential pumping well location is individually pumped at the prescribed initial pumping rate. The well location that captures the greatest number of mass weighted particles is chosen for further optimization by incrementally increasing pumping until all mass weighted particles are captured within the specified capture time criteria or the prescribed drawdown or maximum pumping rate constraints are exceeded.

If a single well cannot capture all particles without exceeding the specified constraints, those particles that are captured by the well within the specified time criteria are omitted from consideration. The process is then repeated with the first well pumping at the optimized rate, to identify the well location that captures the most remaining mass weighted particles. Wells were continually added in this fashion until a specified mass capture percentage is achieved within the specified capture time or a maximum allowable number of wells is exceeded.

Once the target mass capture percentage is achieved, a polishing routine is executed where the pumping rates of the selected wells are sequentially and incrementally

decreased until capture failure (capturing less than the specified mass percentage) within the specified time criteria occurs. The pumping rates prior to the occurrence of capture failure are the optimal rates for the selected wells.

Because Brute Force uses weighted particles as a surrogate for groundwater contamination (the weights representing the dissolved contaminant mass in the model cell corresponding to the particles initial location) and does not explicitly account for fate-and-transport processes such as dispersion, the methodology was verified against conventional fate-and-transport modeling (using MT3D) prior to conducting design simulations. Figure A4-6 is a comparison of Brute Force and MT3D simulated mass capture over time showing a very good agreement between the two methodologies. The transport parameters used for this comparison are identical to those used for the Demo 1 design effort.

For each design variant generated by the PTO method, mass recovery and future plume configuration were verified with a corresponding fate-and-transport run (using MT3D). The results of this model were then evaluated graphically on plots of declining concentration with time and also depicted in 3-D interactive animation sequences, which allowed for detailed assessment of how long and where concentrations persist within the aquifer system. These animation sequences are provided on CD in Appendix X for all proposed FS designs (discussed below) and the RRA system.

4.4.2   Background Alternative

Using the current proposed RRA System as "existing" wells, the PTO method was implemented to design an alternative that achieves background concentrations in 30 years. Initial conditions for this run were the predicted plume configurations after four years of RRA System operation. Target mass capture was specified at 99%.

The initial PTO run generated a wellfield consisting of three extraction wells: the two existing RRA System wells and one additional well upgradient of Frank Perkins Road. Concurrently, it was recognized that capture efficiency at Pew Road will be improved if an injection well is specified on the north side of the plume to balance the proposed RRA System injection well on the south side and, therefore, a total of four injection wells were simulated. While this initial design achieved capture of 99% of plume mass within the target time, concentrations downgradient of Pew Road and within the low permeability clay zone were predicted to persist above background levels for longer than 30 years. Thus, two additional runs were performed with: 1) an extraction well specified downgradient of the plume toe (4 extraction wells total) to provide containment of the very dilute portion of the plume, and 2) a toe well and an additional well between Pew Road and Frank Perkins Road (5 extraction wells total) to intercept mass predicted to propagate under or stagnate within the clay zone. For these runs the PTO method was used only to determine optimal pumping rates at the given locations. The results of the four well run were considered satisfactory and this is the proposed Background Alternative presented below. The five well variant actually exacerbated the stagnation of mass within the clay zone and provided little improvement of capture efficiency and, therefore, was not selected for presentation.

The final Background Alternative design consists of four extraction wells (including the two existing RRA System wells) pumping at a cumulative rate of 472 gpm. Well locations and individual pumping rates are shown in Figure A4-7 along with the predicted steady-state capture zones. This figure shows the combined capture zone reaches a maximum width of approximately 1,700 feet and the plume upgradient of Pew Road is fully contained. Additional extraction wells are proposed upgradient of Frank Perkins Road along Pocasset-Forestdale Road (EW-D1-401) and downgradient of the perchlorate Plume toe along Fredrickson Road (EW-D1-402). Background levels are achieved in 27 years for RDX and 23 years for perchlorate. A total of four injection wells are specified north and south of the plume extent along Pew Road and Frank Perkins Road including one new proposed injection well (IW-D1-4). The table below summarizes screen elevations for all four injection wells.

Well ID	Location	Model Layers	Top-of-Screen Elevation (ft ngvd)	Bottom-of-Screen Elevation (ft ngvd)	Screen Length (ft)
IW-D1-1	Frank Perkins Rd.	15-17	-80	-177	97
IW-D1-2	Frank Perkins Rd.	15-17	-80	-173	93
IW-D1-3	Pew Rd.	11-12	-40	-60	20
IW-D1-4	Pew Rd.	11-12	-40	-60	20

Note the cumulative capture zone of the system widens upgradient as individual capture zones nest within one another. As a result, the capture zone extends well outside and upgradient of the plume extent near the source area. While this implies that after some period of operation the well will extract only clean water, the specified pumping rates are required to reach the time-to-cleanup objectives. It is anticipated that during system maintenance and operation actual pumping rates will be tailored to minimize excess pumping based on system performance data.

4.4.3   10 Year Alternative

For the most aggressive cleanup scenario, the PTO method was implemented to design an alternative that achieves the relevant regulatory or risk-based standards (0.6 ug/L for RDX, 1.0 ug/L for perchlorate) in 10 years. Initial conditions for this run were the predicted plume configurations after four years of RRA System operation. Target mass capture was specified at 99.9%.

The resulting design consists of five extraction wells (including the two existing RRA System wells) pumping at a cumulative rate of 1417 gpm. Well locations and individual pumping rates are shown in Figure A4-8 along with the predicted steady-state capture zones. This figure shows the combined capture zone reaches a maximum width of approximately 3,000 feet and the plume upgradient of Pew Road is fully contained. Additional extraction wells are proposed upgradient of Pocasset-Forestdale Road (EW-D1-501), upgradient of Frank Perkins Road (EW-D1-502), and between Pew Road and Frank Perkins Road near monitoring well MW-210 (EW-D1-503). For perchlorate, target concentrations are achieved in less than 10 years. For RDX, target concentrations are achieved in just over 10 years, however, at 10 years 99.7% of the mass has been

captured. A total of four injection wells are specified along Pew Road and Frank Perkins Road.

As with the Background Alternative, a number of PTO runs were performed to reach a final design by varying the specified target mass capture percentage and also imposing extraction wells at locations where concentrations persisted beyond time-to-cleanup objectives. In each case, the resulting design proved less effective than the final 10 Year Alternative presented above.

4.4.4   Additional Alternatives

4.4.4.1   Alternative A

To provide an additional risk-based cleanup scenario that would potentially have reduced capital costs (relative to the 10 Year alternative), the PTO method was implemented to design an alternative that achieves the relevant regulatory or risk-based standards in a time between 10 and 20 years. Initial conditions for this run were the predicted plume configurations after four years of RRA System operation. Target mass capture was specified at 99%.

The resulting design consists of five extraction wells (including the two existing RRA System wells) pumping at a cumulative rate of 906 gpm. Well locations and individual pumping rates are shown in Figure A4-9 along with the predicted steady-state capture zones. This figure shows the combined capture zone reaches a maximum width of approximately 2,400 feet and the plume upgradient of Pew Road is fully contained. Additional extraction wells are proposed upgradient of Pocasset-Forestdale Road (EW-D1-501), upgradient of Frank Perkins Road (EW-D1-502), and between Pew Road and Frank Perkins Road near monitoring well MW-210 (EW-D1-503). Target concentrations are achieved in less than 14 years for RDX and 13 years for perchlorate. A total of four injection wells are specified along Pew Road and Frank Perkins Road This design is referred to as Additional Alternative A.

4.4.4.2   Alternative B

Analysis of the risk-based 10 Year and Additional Alternative A design simulations indicated that these designs met background conditions in less than 20 years in all areas except the toe of the plume. Therefore, augmenting these designs with a well at the toe of the plume (as in the Background Alternative) could potentially achieve background conditions in less than 20 years. While the PTO methodology was not utilized, to provide an additional background cleanup scenario, an alternative was developed which consists of the well locations and pumping rates comprising Additional Alternative A amended to include an extraction well at the toe identical in location to the Background Alternative. This well was specified with a pumping rate of 75 gpm.

The resulting design consists of 6 extraction wells (including the two existing RRA System wells) pumping at a cumulative rate of 981 gpm. Well locations and individual pumping rates are shown in Figure A4-10 along with the predicted steady-state capture zones.   This figure shows the combined capture zone reaches a maximum width of approximately 2,400 feet and plume concentrations greater than 1 ppb are fully

contained. Additional extraction wells are proposed upgradient of Pocasset-Forestdale Road (EW-D1-601), upgradient of Frank Perkins Road (EW-D1-602), between Pew Road and Frank Perkins Road near monitoring well MW-210 (EW-D1-603), and downgradient of the perchlorate Plume toe along Fredrickson Road (EW-D1-604). Background levels are achieved in 16 years for RDX and 17 years for perchlorate. A total of four injection wells are specified along Pew Road and Frank Perkins Road. This design is referred to as Additional Alternative B.

4.5   Summary of Design Alternatives

A summary comparison of all proposed alternatives, their design details, remediation objectives, and results are compiled in Table A4-1. Individual extraction well pumping rates and screen elevations are tabulated in Table A4-2. Mass removal effectiveness with time is plotted for RDX and perchlorate in Figures A4-11 and A4-12. As expected the design with the highest cumulative pumping rate produces the most rapid decline in mass and concentration.

However, rigorous comparison of mass removal vs. time curves shows that each design eventually reaches a point of diminishing returns, generally by 20 years, where the differences in mass removal are negligible. For example, with respect to both RDX and perchlorate, after 10 years there is less than one percent performance difference between the 10-Year Alternative, Additional Alternative A, and Additional Alternative B. Despite the significantly lower pumping rates in the Background Alternative, after 20 years this alternative is as effective with respect to mass removal as the three designs with higher pumping rates.

4.6   Sensitivity Analysis

To define the confidence in these model predictions, and thereby better interpret and utilize the results, a sensitivity analysis was performed. Though many approaches are possible, this is typically accomplished by varying selected simulation parameters across a range representative of their expected uncertainty, and then assessing the response of a selected output variable relative to the baseline calibrated model. During the trial-and-error calibration process, the most sensitive calibration parameters become apparent, usually hydraulic conductivity and recharge, and these should always be included in the final sensitivity analysis.

A sensitivity analysis can be designed to evaluate uncertainties in input parameters for either the flow or fate-and-transport components of the model or some aspect of model design (i.e. grid spacing). For the Demo 1 subregional fate-and-transport model, the sensitivity analysis was designed to define the impact of selected hydraulic and transport parameter uncertainties on the predicted performance (mass capture percentage) of the remedial designs. Hydraulic parameters selected for evaluation were:

1. aquifer hydraulic conductivity,
2. ambient recharge rate, and
3. assumed hydraulic conductivity of the clay confining layers.

For each sensitivity analysis model run, uniform changes were made to like parameter types. For example, all hydraulic conductivity values in the model were increased and

decreased by 30%, keeping all other parameters at the calibrated values. This range was considered reasonable based on the observed range of measured hydraulic conductivities (from site-wide slug tests and pump tests) for each sediment type and modest variations observed in lithology. For the run involving changes to the clay confining layers, only this unit's hydraulic conductivity was increased by an order of magnitude, while all other aquifer hydraulic conductivities were held constant.

For the flow portion of the model, two sensitivity metrics were selected: water level calibration statistics and predicted horizontal plume trajectory. Both metrics were evaluated relative to the calibrated steady-state model of ambient conditions. For the remedial design simulations the metric was mass capture percentage, consisting of perchlorate capture relative to an arbitrarily selected design: in this case Additional Alternative A. The water level and trajectory metrics were evaluated initially to ensure the parameter change could still generally replicate observed conditions.

Listed in Table A4-3 are the six sensitivity analysis runs performed, including the calibrated and adjusted parameter values and corresponding water level calibration statistics. The observed differences in statistics are small and indicate that the perturbed flow system is similar to the calibrated flow system. The perturbed horizontal plume trajectories support this contention by being nearly identical to the calibrated trajectory (Figure A4-13). Lastly, the mass capture performance for the various perturbations is very similar to the original design performance (Figure A4-14). All sensitivity runs appear less effective than the baseline in the long-term yet the maximum differences are only a few percent, which represents the best quantitative measure of confidence in model predicted system performance. In conclusion, similarities in calibration statistics, horizontal plume trajectories and mass capture performance indicate that the proposed Demo 1 remedial design alternatives will be robust and likely effective for the expected range of site hydraulic parameter uncertainty.

In addition, the effects of uncertainty in the assumed biodegradation half-life of TNT (365 days) were evaluated. This evaluation was deemed necessary because simulation of TNT showed that the compound rapidly degraded below the relevant standards such that remedial designs specific for its removal were not warranted. To support this assumption fate-and-transport modeling was performed with the biodegradation half-life increased by an order of magnitude. This simulation showed that while it took longer for TNT to degrade (Figure A4-15), the relevant risk-based standard is achieved in approximately 5 years, still well within the 10-year objective. However, more than 20 years are required for TNT to decline below background concentrations.

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