TETRA TECH EC, INC.

May 19, 2009

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SUBJECT: US NAVY CONTRACT NO. N62472-99-D-0032
CONTRACT TASK ORDER NO. 96
NAVAL WEAPONS INDUSTRIAL RESERVE PLANT, BETHPAGE, NY
TECHNICAL MEMORANDUM FOR GROUNDWATER FLOW AND PARTICLE TRACKING ANALYSIS CONCLUSIONS AND RECOMMENDATIONS REGARDING EXTRACTION WELL RW-3 AND OTHER ASSOCIATED WELLS

Dear Ms. Fly and Mr. Scharf:

Tetra Tech EC, Inc. (TtEC) has prepared this Technical Memorandum to present our preliminary conclusions and recommendations from the groundwater modeling related to the groundwater contamination at the GM-38 area. TtEC completed a groundwater flow and particle tracking analysis to evaluate the design and capture zone influence of proposed extraction well RW-3 and associated remedial system wells. The groundwater flow and particle tracking analysis is based on the approach detailed in the Technical Memorandum, dated March 27, 2009, and as presented in Attachment 1. The technical approach is also summarized below.

TtEC has developed a groundwater flow model using similar technical approaches and assumptions used in the development of regional groundwater flow and transport models by the USGS in 1987, 1992, 1995, and 1999, as well as a groundwater flow model developed in 1997 and updated in 2003 by Arcadis. An updated numerical code of the USGS MODFLOW 2000 was utilized for simulation of steady-state groundwater flow conditions. The groundwater flow model was first manually calibrated for the steady-state hydrogeologic conditions which occurred between 2001 and 2007 using the uniform aquifer properties documented in the USGS

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and Arcadis modeling reports as initial values. By adjusting initial values of boundary conditions, hydrology and aquifer properties, reasonable matches were obtained for the regional flow conditions, including both horizontal and vertical flow components. TtEC further calibrated the groundwater flow model for non-uniform spatial distribution of hydraulic conductivity using a model-independent parameter estimation code (PEST) developed by Watermark Numerical Computing (Fifth Edition, 2004). The further calibrated flow model provided more detailed understanding of the site-specific flow conditions in the study area, especially in and surrounding the GM-38 area. A particle tracking code, MODPATH (Version 4), was then used to evaluate the remedial system capture zones and screen interval depths. The particles are tracked both forward and backward through time assuming they are transported by advection within the calibrated flow field.

The site-specific objectives of the analysis were refined from the March 2009 Technical Memorandum and are as follows:

1. Evaluate capture zones in GM-38 area, including extraction wells RW-1 and RW-3, and the Bethpage Water District (BWD) wells (6915/6916);
2. Reduce potential impact to BWD wells;
3. Determine RW-3 screen interval depth at proposed location; and
4. Determine screen interval depths for the proposed monitoring wells locations,TP-1, RW1-MW3, RW1-MW1, RW1-MW2, RW1-MW3, and RW1-MW4.

Attachment 1 also presents the conclusions from the analysis with graphical and animated representations of the flow study, as well as recommendations for well design and additional evaluation by advanced transport modeling. The conclusions and recommendations are also presented below.

<u>Conclusions from Groundwater Flow and Particle Tracking Analysis</u>

- The RW-3 screen interval depth was evaluated and placed at -310 to -400 ft mean sea level (msl), approximately thirty feet above the Arcadis proposed screen depth of -350 to -430 ft msl. The length of the screen was increased from 80 ft to 90 ft.

- Particle tracking analyses, with the refined screen interval depth of RW-3, shows no potential impact to BWD Plant 4 wells. The refined screen depth provides positive benefits to the BWD by shifting the Plant 4 wells' capture zones to the northeast, away from the GM-38 hot-spot.

- Particle tracking analysis indicates that the refined screen depth of RW-3 (at the Arcadis proposed location) will capture the current 1000 ug/L tetrachloroethene (TCE) plume detected at the GM-38 hot-spot.

- Vertical profile boring (VPB) investigation data (Arcadis, 2006/08) indicates elevated volatile organic compound (VOC) concentrations were detected upgradient of the GM-38 area at approximate depths of at least -450 to -500 ft msl. This deep contamination may impact the GM-38 area during remedial system operation.

- Current plume conditions are unknown, but particle tracking analysis indicates pumping of RW-3 (with the refined screen interval depth) and RW-1 will most likely capture the deep VOC contamination if it impacts the GM-38 area.

- The location and screen interval depth, as proposed for well TP-1, is appropriate to meet the objective of assessing hydraulic effects caused by operation of the remedial system. TP-1 will be used to monitor the background hydraulic effects caused by pumping of the BWD wells.

- The locations and screen interval depths proposed for RW1-MW3 and the RW-3 associated monitoring wells (RW3-MW1, 2, 3, and 4) are appropriate for the purpose of monitoring hydraulic conditions caused by the operation of the remedial system.

- As stated previously, current plume conditions are unknown. The monitoring wells at their proposed screen depths may not accurately monitor water quality at the GM-38 area. In addition, the wells may not be appropriate to monitor potential impacts on the remedial system from the deep VOC contamination.

Recommendations for Proposed Well Design and Additional Evaluation

- Based on particle tracking analysis, TtEC recommends the RW-3 screen interval depth be raised thirty feet from Arcadis proposed depth of -350 to -430 ft msl to a depth of -310 to -400 ft msl. The length of the screen should also be increased from 80 ft to 90 ft. Field geophysical testing and lithological logging will confirm or further refine the screen interval depth most appropriate at RW-3.

- TtEC recommends installation of TP-1, as proposed by Arcadis, for the purpose of monitoring hydraulic conditions related to background conditions and the remedial system operation.

- Current plume conditions are unknown and elevated concentrations of contaminants upgradient of the GM-38 area have been detected during the VPB investigation by Arcadis. Advanced transport modeling, with 3-D plume visualization, is proposed to evaluate and predict the current plume front and configuration.

- TtEC recommends evaluation of the screen interval depths for the proposed monitoring wells associated with RW-1 and RW-3. Due to the unknown or potentially changed conditions, the proposed screen interval depths may no longer be appropriate for the purpose of monitoring water quality and potential impacts to the remedial system in the GM-38 area. Advanced transport modeling is recommended to refine the screen interval depths of the monitoring wells. Field lithology will also be used to confirm the screen interval depths are most appropriate.

- In addition to evaluating and refining the screen interval depths of the proposed monitoring wells, TtEC proposes advanced transport modeling to help meet the objectives of understanding the current and future contaminant plume configuration, predicting the remedial system effectiveness, and optimizing the remedial system operation and monitoring.

Advanced transport modeling, using transport processes in addition to advective transport, combined with the newly acquired data, will provide a more accurate model of the current and future conditions of the contaminant plume in the GM-38 area. A brief summary of the objectives for the proposed advance transport modeling are presented in Attachment 1. TtEC will provide a follow-up Technical Memorandum detailing the rationale and approach for the proposed advanced transport modeling.

We plan to install extraction well RW-3 and monitoring well TP-1 as soon as we obtain approval for the refined screen interval depth as proposed for RW-3. The five remaining monitoring wells will be installed after completion of advanced transport modeling, if approved.

We are providing this Technical Memo to you via email, as well as hardcopy and electronic (CD) format. The electronic version of Attachment 1 allows viewing of the model animations. However, the email only contains a PDF version of Attachment 1 as the electronic file containing the animations is too large to transmit via email.

Please do not hesitate to call me at (215) 702-4099 or email at stavros.patselas@tteci.com if you have comments or questions.

Sincerely,

Stavros Patselas
Project Manager

Attachments:

- Attachment 1 Groundwater Flow and Particle Analysis Preliminary Conclusions and Recommendations
- CD Electronic File

cc: David Li, PH, TtEC
Christine Joblon, PG, TtEC
File

ATTACHMENT 1

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NWIRP Bethpage
GM-38 Area
Groundwater Flow & Particle Tracking Analysis
Preliminary Conclusions and Recommendations

Bethpage, Long Island, New York

by
Tetra Tech EC
May 14, 2009

Outline of Slide Presentation

- Objectives
- Approach
- Modeling Strategies
- Numerical Model Domain
- Model Boundary Conditions
- Evaluation of Hydraulic Scenarios
- Development of Numerical Model
  - Lithology
  - Calibration Target Distribution
  - Calibrated Regional Flow
  - Calibrated Site-Specific Flow
- Particle Tracking Analysis
  - Capture Zone Assessment
  - Refinement of RW-3 Screen Depth
  - Conclusions
- Evaluation of Monitoring Wells
  - Conclusions
- Recommendations
- Objectives for Advanced Transport Modeling

Objectives of Flow Study

- Steady State Groundwater flow simulation
  - Understand flow systems
  - Regional & site-specific conditions
  - Lateral and vertical flow components

- Site-specific goals
  - Determine RW-3 screen depth interval
  - Determine proposed monitoring well screen depth intervals
  - Evaluate capture zones in GM-38 area
  - Reduce potential impact to Bethpage Water District (BWD) wells

Approach for Flow Study

- Review references & data
  - USGS water resource investigation reports
  - USGS models, 1987, 1991, 1997, 1999, etc.
  - Arcadis models (1997 to 2006)
- Develop a site-specific conceptual model (SCM)
  - Vertical profile borings
  - TCE concentration profiles
- Build and calibrate
  - Steady-state flow model
  - And/or transient flow model (optional)
  - Calibrated to average hydrogeologic conditions from 2000-2007
- Evaluate capture zones
  - RW-3, RW-1, and/or RW-2
  - BWD's wells 6915/6916

Modeling Strategies

Similarity with USGS & Arcadis

- Use the same technical approach (accepted by NYSDEC)
  - Same numerical codes
  - MODFLOW & MODPATH

- Model domain & boundary conditions
- Lithology & aquifer hydraulic properties
- Vertical discretization
- Hydrogeologic data (averaged)
  - Regional supply wells
  - On-site & off-site monitoring wells data
  - Precipitation data
  - Recharge basins data

- Calibration targets
  - Heads from on-site & off-site monitoring wells
  - Flow patterns (horizontal & vertical)

Modeling Strategies (con't)

Difference from USGS & Arcadis

- Calibration methods
  - trial-and-error; and
  - PEST code (parameter estimation)
- Variable layer thickness
- Refined grid spacing (50x50 ft cell) for study area
- Sloping Raritan clay surface
- Long-term averaged hydrogeologic data
- Regional supply wells with actual screen intervals (ft, msl)
- Particle tracking may be performed with transient flow field
- Transport processes
  - Advective, dispersive, reactive, etc.
  - Sequential degradation of chlorinated hydrocarbons

Numerical Model Domain (Study Area)

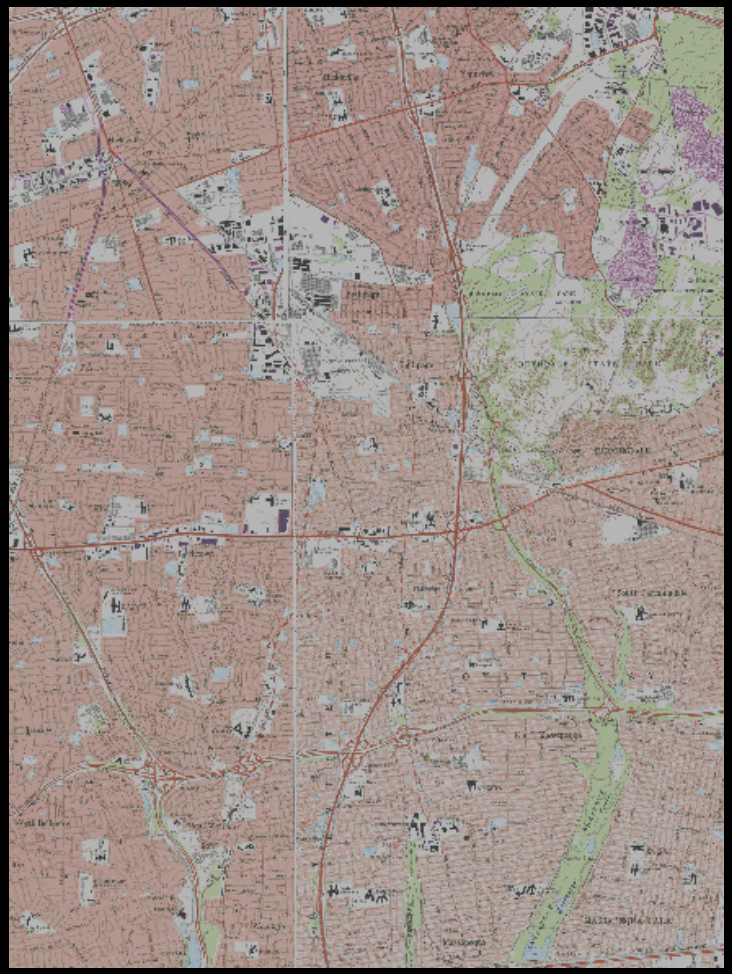


Figure 1

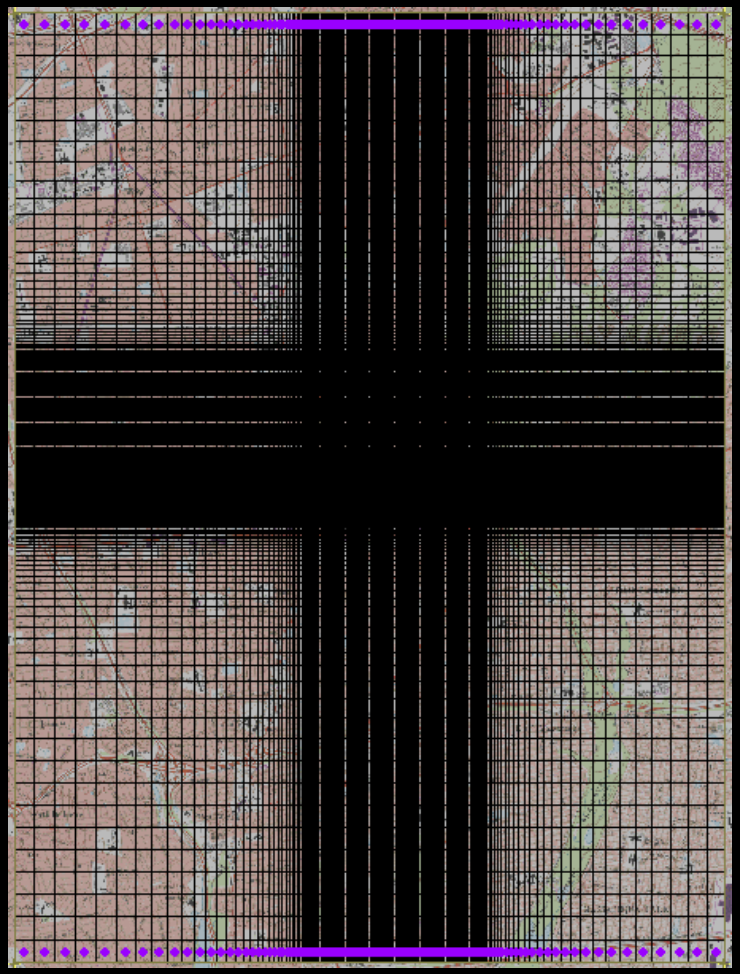


Figure 2

Numerical Domain Details

- Adopted the similar model domain used by USGS and Arcadis
  - With dimensions of
  - North to South = 40,000 ft;
  - East to West = 30,000 ft; and
  - Ground surface to approximately -800 ft, msl

- NWIRP industrial area is located approximately in the northern center of Figures 1 and 2.

Model Boundary Conditions

Mathematical Boundary Conditions

Based on USGS model:

- Dirichlet (specific head): northern and/or southern (approximate regional groundwater divide in north, or known head in the south);
- Neumann (specific flow) ~ water table (areal recharge); along flow lines; at the top of Raritan clay (assuming zero vertical flux); and at saltwater interface (zero lateral flux);
- Mixed ~ both Dirichlet and Neumann (southern)

Recharge

- MacArthur Airport precipitation records (1984 - 2001)
- Recharge ~ 49% of precipitation (USGS study, 1995)
- Avg. areal recharge ~ 0.00588 ft/day (25.75 inches/yr)
- Variable areal recharge may be assigned across study area
- Various recharge (infiltration) basins

Boundary Conditions - USGS Study (1997 to 2006, etc.)

Upper Glacial Aquifer

- USGS water table contour map (1997 to 2006)

Magothy Aquifer

- USGS saturated thickness maps (1997)
- USGS potentiometric maps (1997 to 2006)

Top of Raritan Confining Unit

- USGS Raritan structure contour maps (1997)
- USGS potentiometric maps (1997 to 2006)

Evaluation of Hydraulic Scenarios

Hydraulic Capture Scenarios-Values

- RW-3 and RW-1
- BWD's wells 6915 and 6916

Evaluation Criteria

- Water level drawdown (cone of depression)
  - Steady-state & transient
- Capture zone analyses
  - Particle tracking method
  - RW-3 screen interval
  - RW-3 related monitoring well locations

Development of Numerical Model (Vertical Discretization)

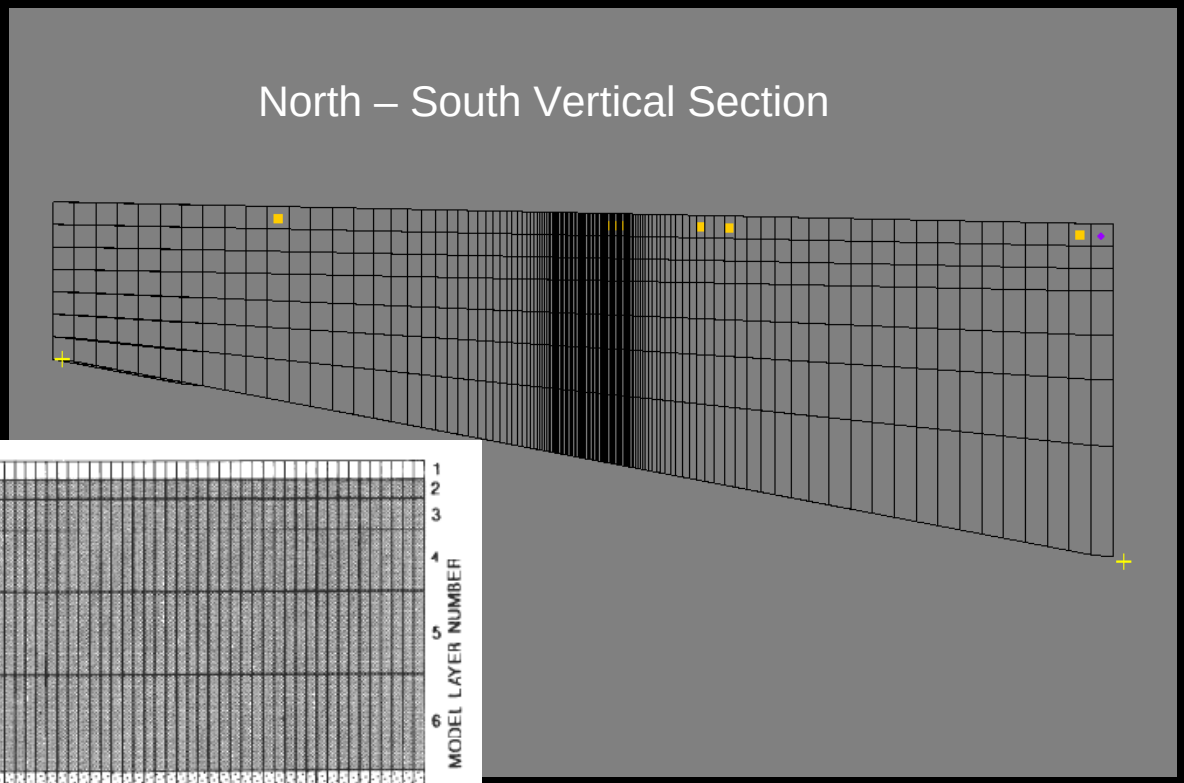


Figure 3

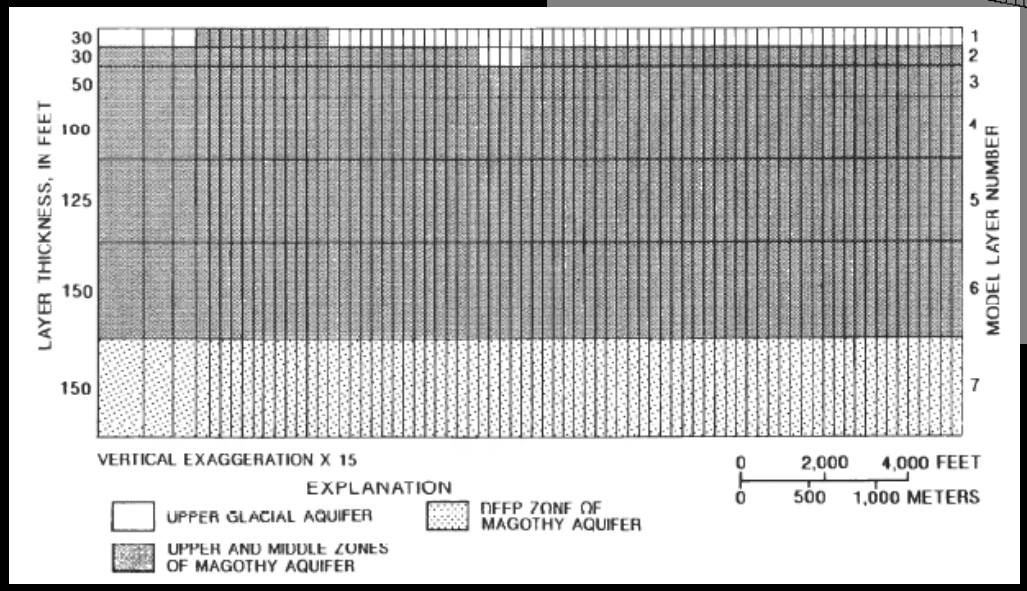


Figure 4
not to scale

Numerical Model (Vertical Discretization) Details

- USGS (Smolensky, 1995) performed an advective transport study for chlorinated hydrocarbons (PCE, TCE, DCE, and VC) beneath an industrial/residential area of Nassau County.

- Figure 3 is a north-south vertical section of the USGS advective transport model developed for this area. USGS used a total of 7 layers: Layer 1-upper glacial aquifer; Layer 2-mix of lower glacial and Magothy aquifers; Layers 3 to 7 represented the upper, middle and basal Magothy aquifer.

- TtEC model adopted USGS lithology; site-specific data incorporates variable spacing ranges from 50 ft to 1000 ft, and variable layer thicknesses.

- Figure 4 approximates the TtEC refined grid spacing along the plume in the area of GM-38 and the RW-1, 2, and 3 area. Total vertical thickness ranges from 450 ft in the northeast to approximately 800 ft in the southeast.

Regional Lithology from USGS Model

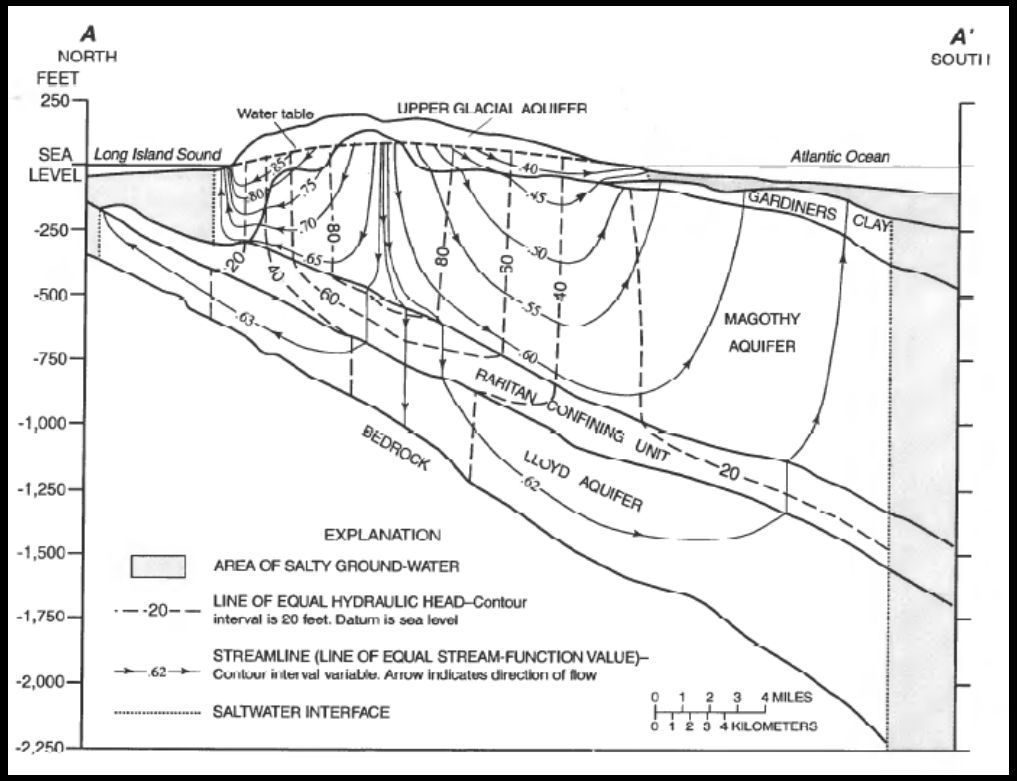


Figure 5

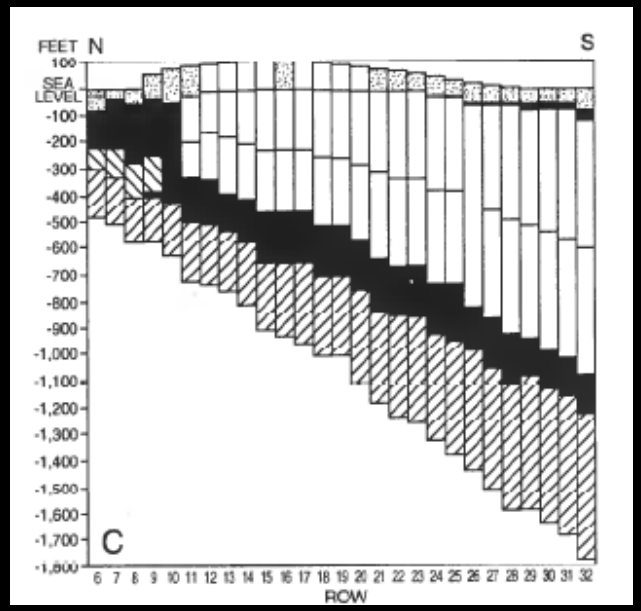
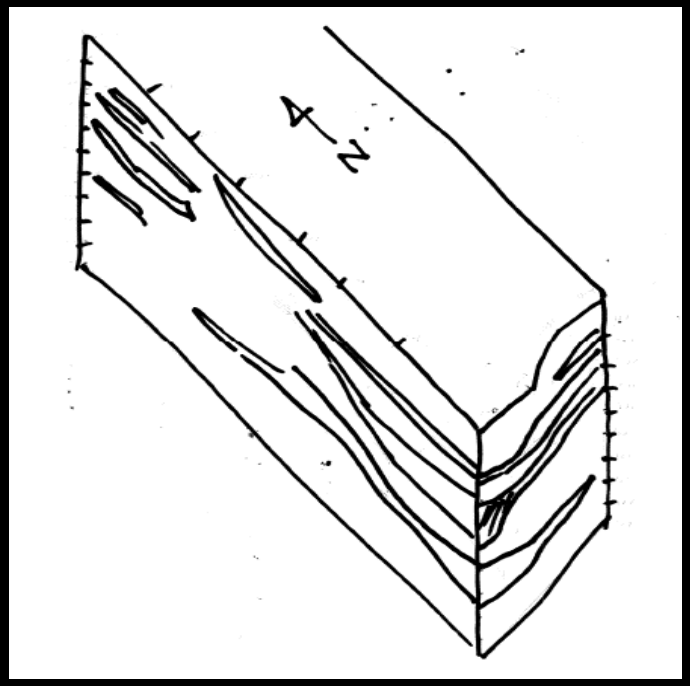
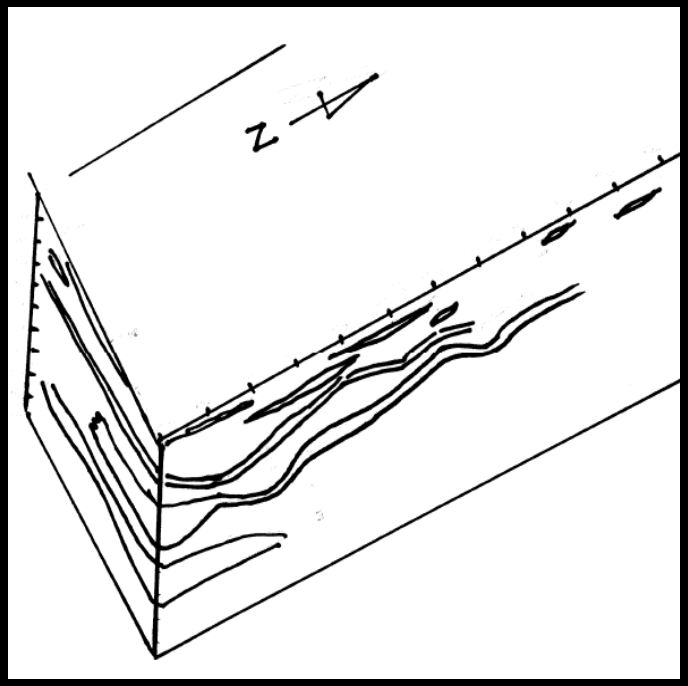


Figure 6

Lithology used in USGS model (Figure 3) and USGS report (Buxton & Smolensky, 1999) (Figure 4)

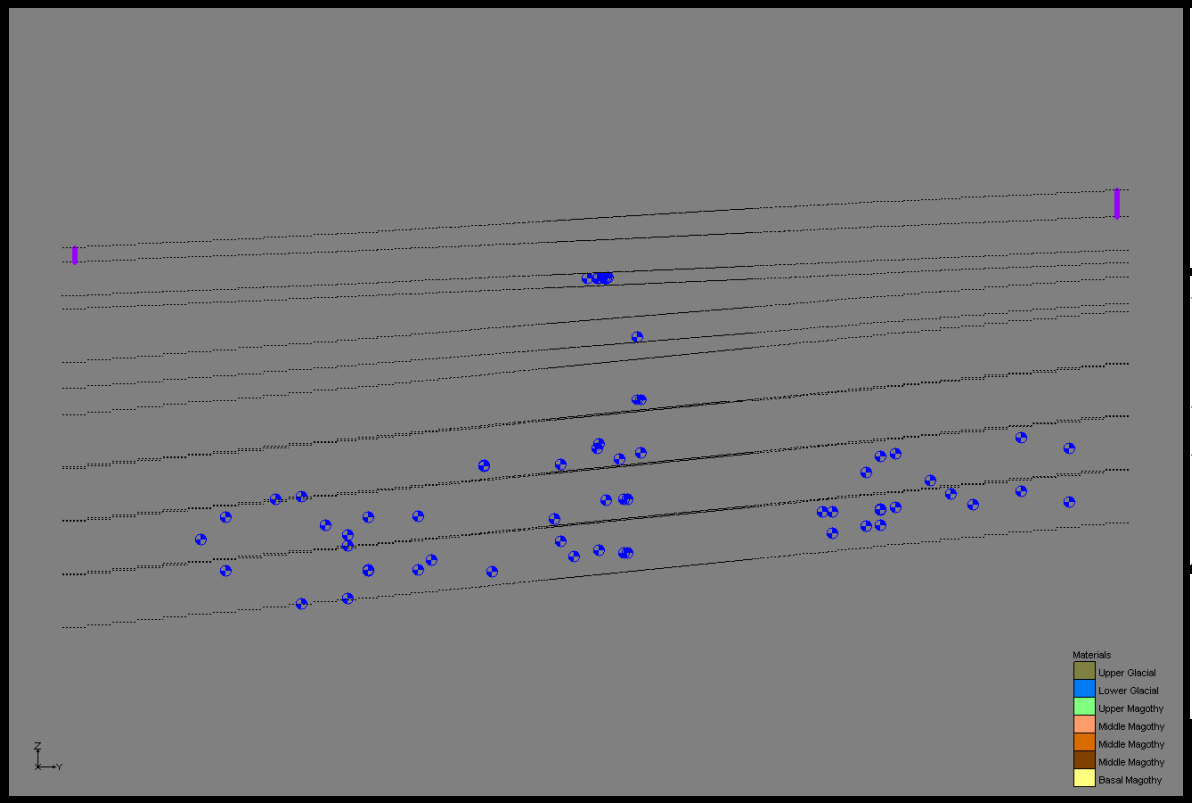
Site-Specific Lithology Details



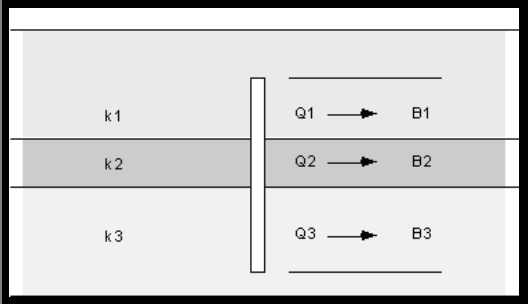


Lithology based on site-specific data represents site-specific conceptual model (SCM), developed based on interpolation from 24 boring logs, including Vertical Profile Borings (VPBs.)

Regional Supply Well Distribution (actual screen depth interval)



$$Q_i = \frac{T_i}{T} = \frac{(k_h)_i B_i}{\sum_{j=1}^{n} (k_h)_j B_j}$$



$$Q_1 = \frac{K_1 B_1}{K_1 B_1 + K_2 B_2 + K_3 B_3}$$

View is to west from the site. Regional water supply wells are spatially distributed in the numerical model with well-specific screen depth interval (ft, msl); the equation (lower right) is used to partition the flow to different layers; where Qi = The flow rate for layer i ; (kh)i = The horizontal hydraulic conductivity for layer I; Bi = The length of the well screen intercepted by the layer.

Observed Regional Groundwater Levels (USGS, 2006)

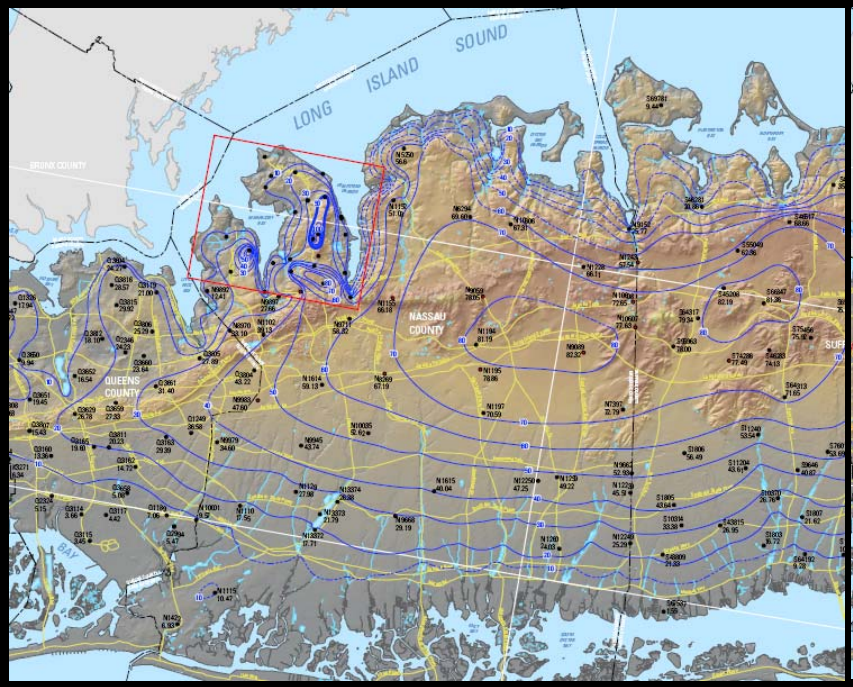


Figure 7 Upper glacial aquifer

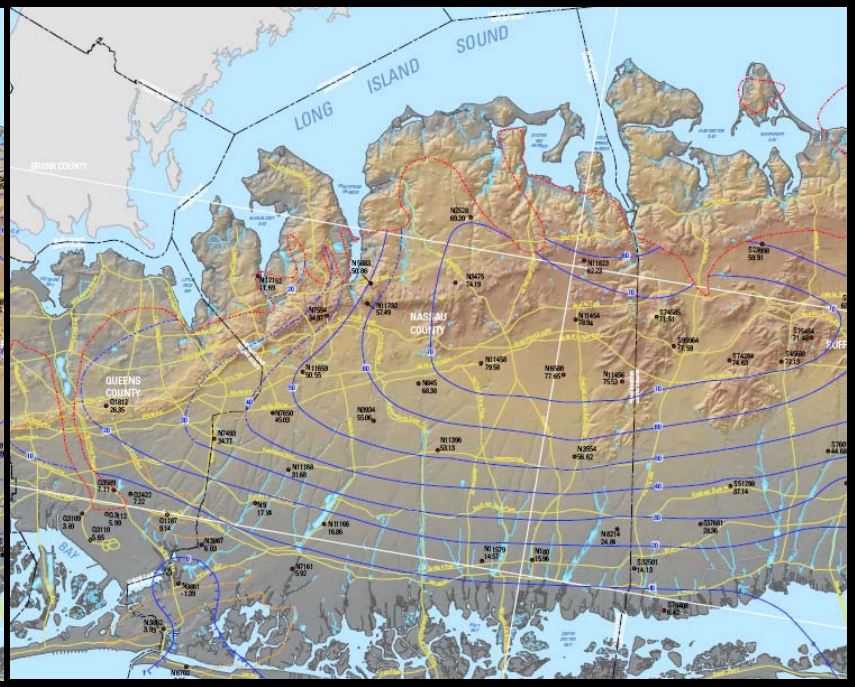
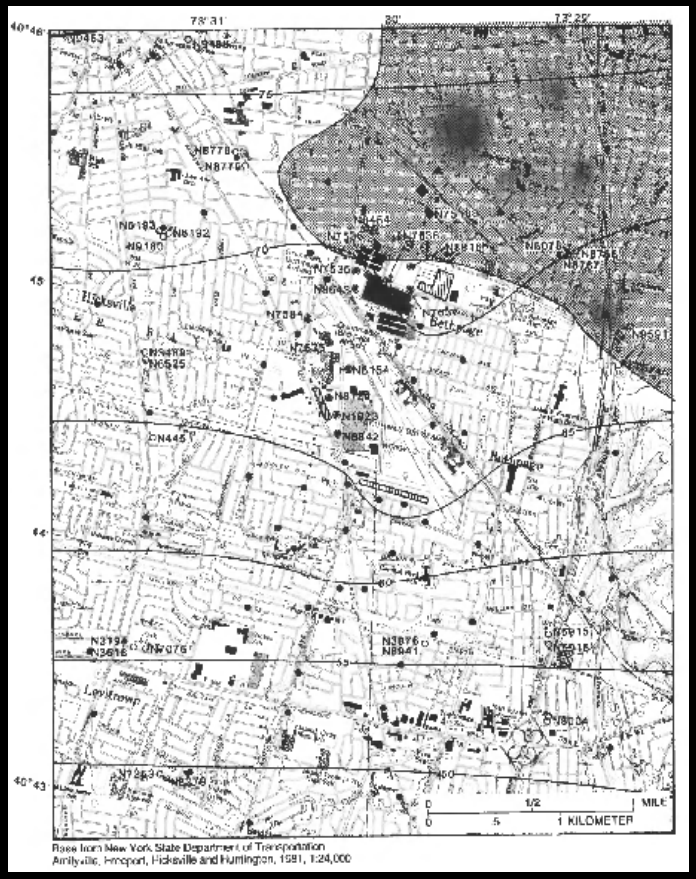
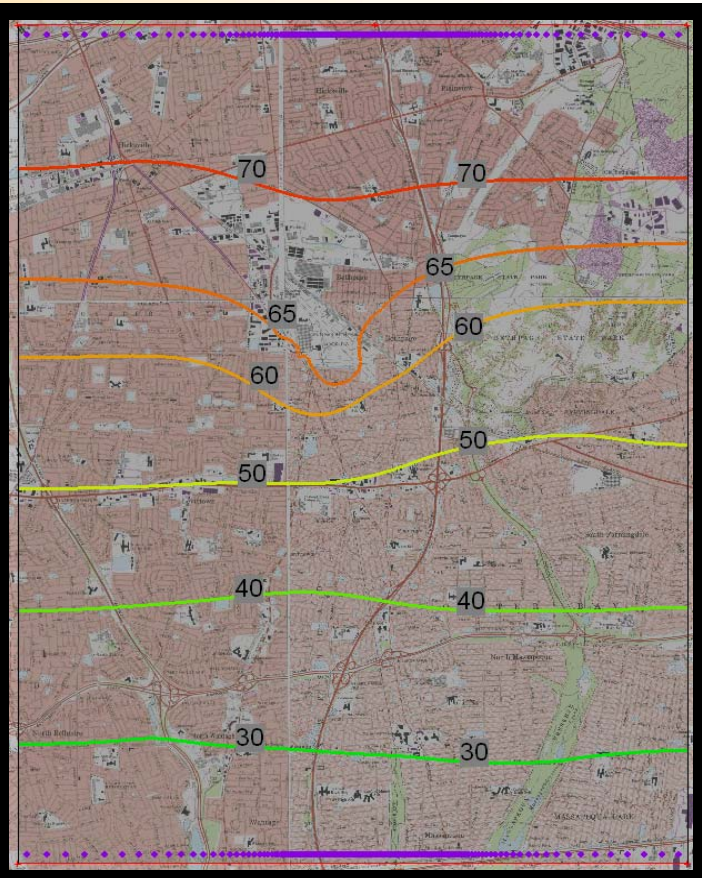


Figure 8 Magothy aquifer

Adopted USGS regional groundwater levels for upper glacial aquifer and Magothy aquifer for (regional) calibration targets.

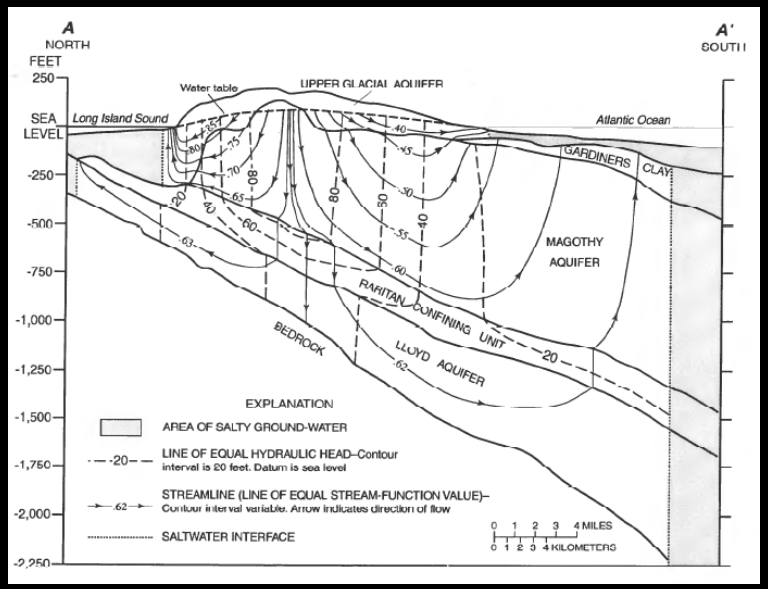
Calibrated Regional (Horizontal Flow Component)

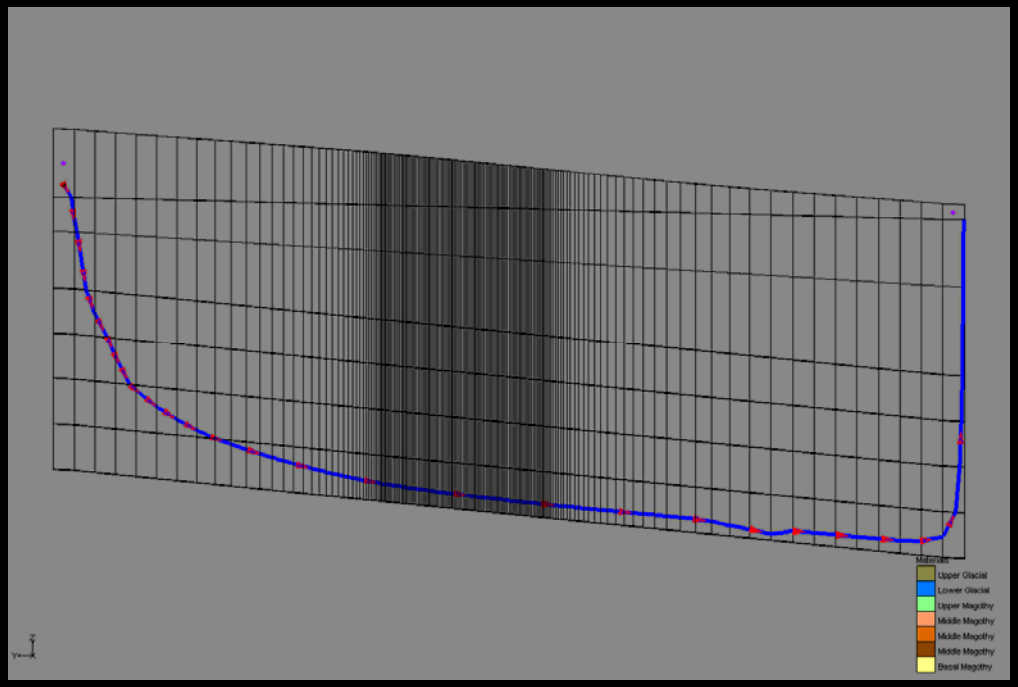




The horizontal component of regional flow was calibrated. The evaluation criteria are flow patterns and groundwater travel time (represented by particle tracking).

Calibrated Regional Flow (Travel Time)





The view is looking to the east from the site. The vertical component of the regional flow was calibrated. It takes approximately 260 to 280 years for water to travel from the regional groundwater divide to the southern bay and streams (in which salt water interface is located). The red arrows represent 10 year particle travel intervals (originated from the industrial area.)

Calibrated Regional (Vertical Flow Component)

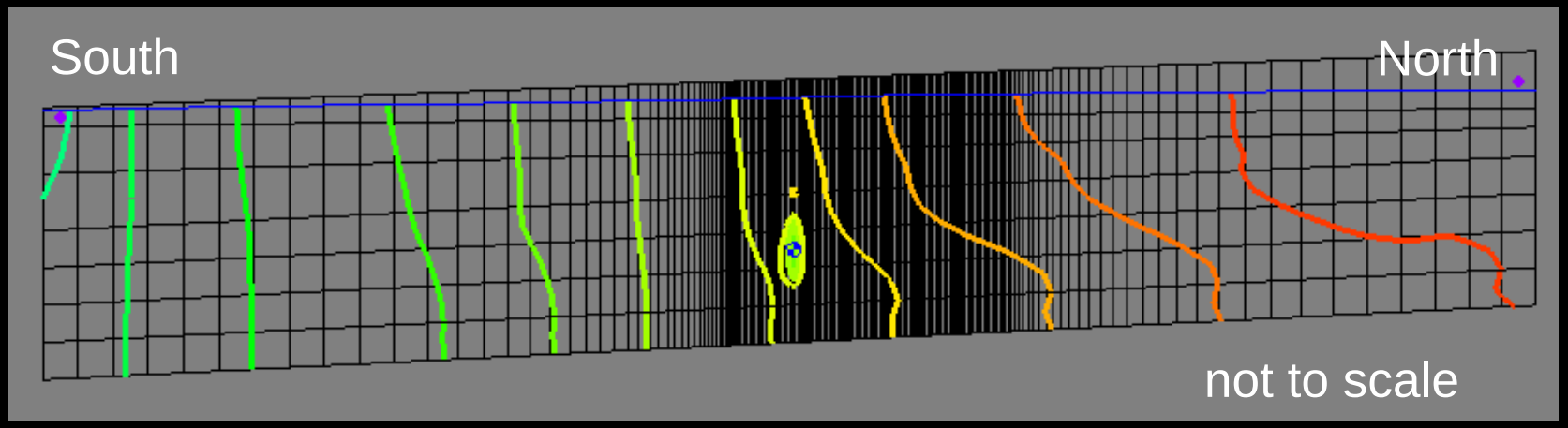


Figure 9

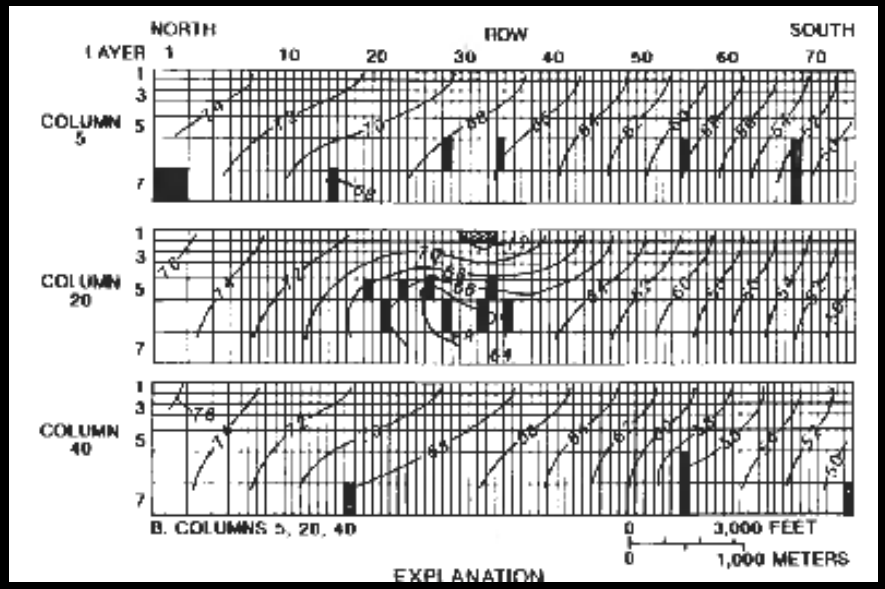
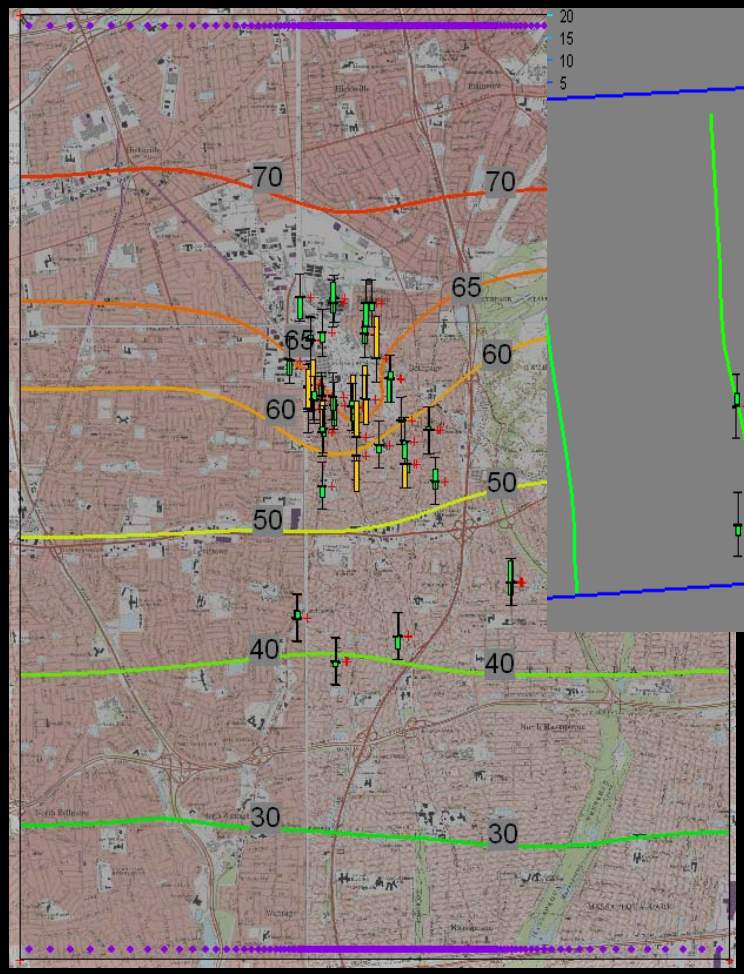


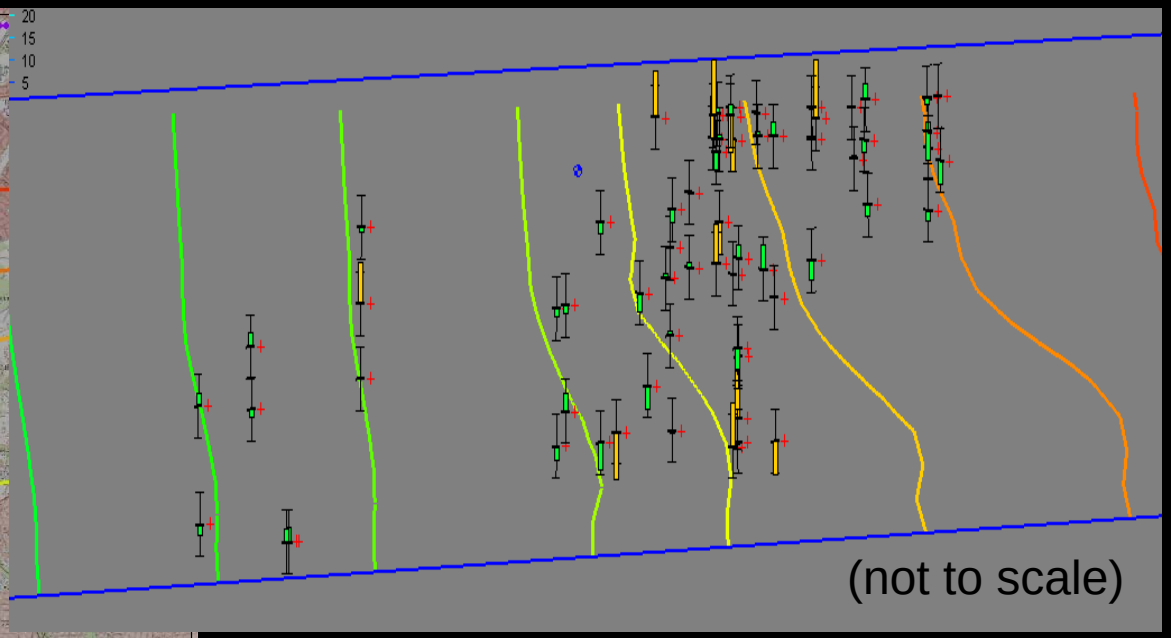
Figure 91 is calibrated vertical flow pattern (and view is looking to the west from the site).

Figure 10 is the USGS simulated vertical flow pattern (and the view is looking to the east from the site).

Figure 10

Calibrated Site-Specific Flow

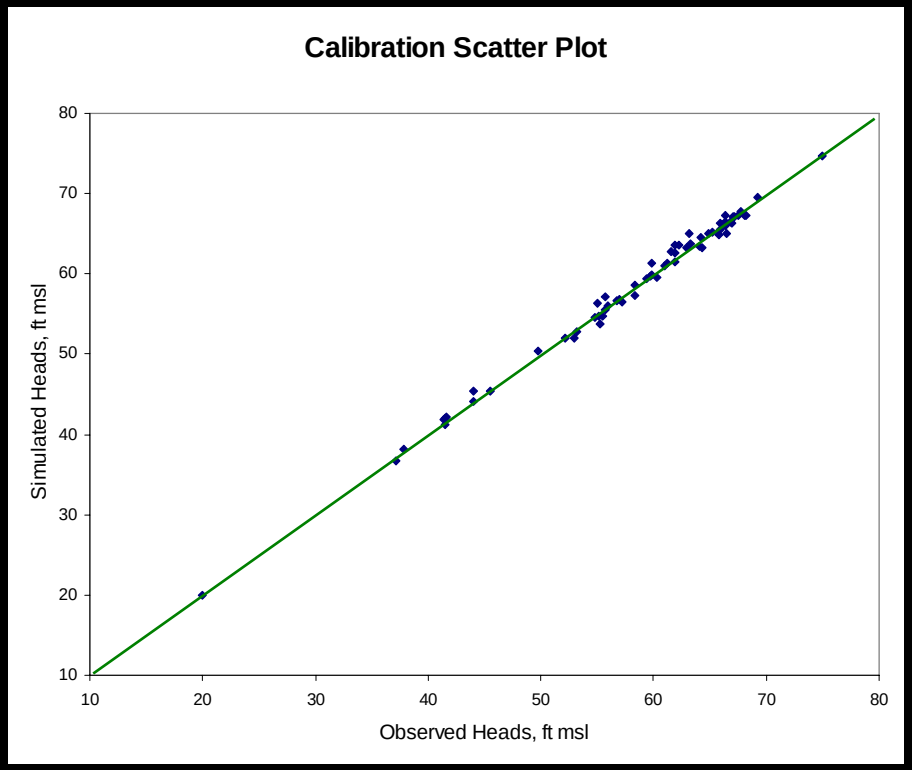




Both horizontal and vertical flow components were calibrated. The green and yellow bars represent calibrated targets, which are within 95% confidence interval. The calibration targets provide feedback on the magnitude, direction (high, low), and spatial distribution of the calibration error.

Calibration Statistics & Scatter Plot

- Mean error (ME) ~ mean difference between observed and simulated heads
- Root mean squared (RMS) error or the *standard deviation* (*std. dev.*) is the average of the squared differences in measured and simulated heads
- ME = 0.017
- RMS = 0.711



RMS of 0.711 is about 77% reduction in *std. dev.* compared to Arcadis 11-layers model (RMS ~ 3.05).

RMS of 0.711 is about 38% reduction in *std. dev*. compared to USGS model (RMS=1.15).

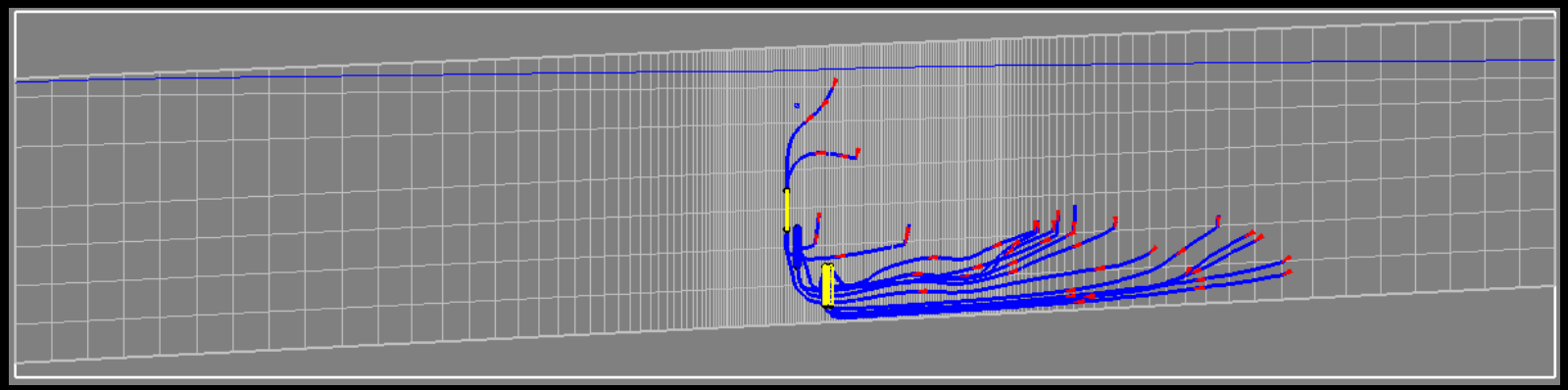
Particle Tracking Analysis Approach

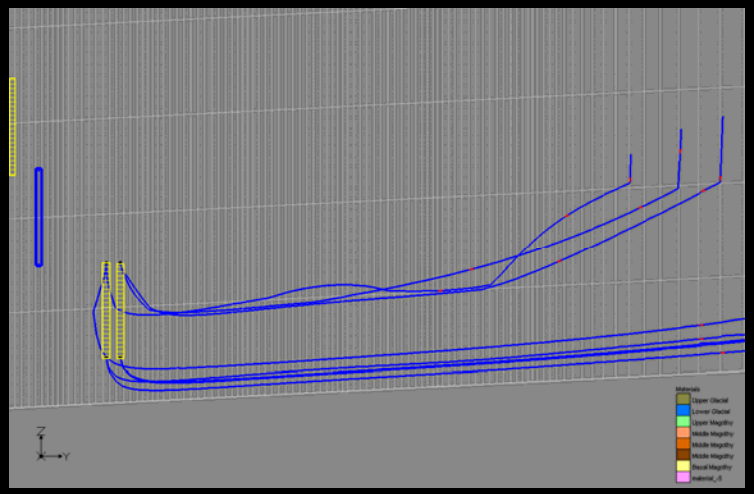
- Particle tracking method (Anderson, 1992)
  - Visualize flow field
  - Track contaminant paths
  - Backward tracking
    - BWD wells 6915/6916
    - RW-1, RW-3 (or RW-2)
  - Forward tracking
    - Horizontal plume profile
    - Vertical plume profile

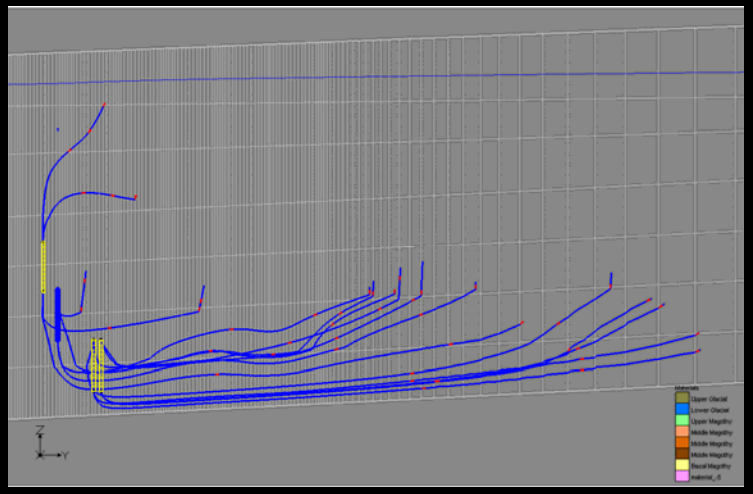
- TtEC evaluated Arcadis's proposed screen depth for RW-3 and RW-1 (existing) to evaluate their capture zones and impacts on BWD wells, and then refined the screen depth of RW-3 to optimize the capture zones and to reduce potential impacts to the BWD wells.

RW-3 Screen Depth Interval

South RW-3 screen interval North

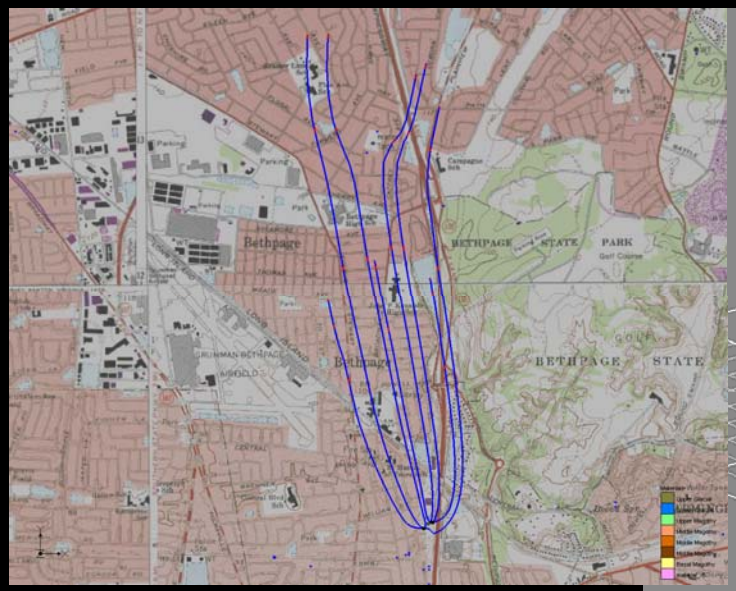


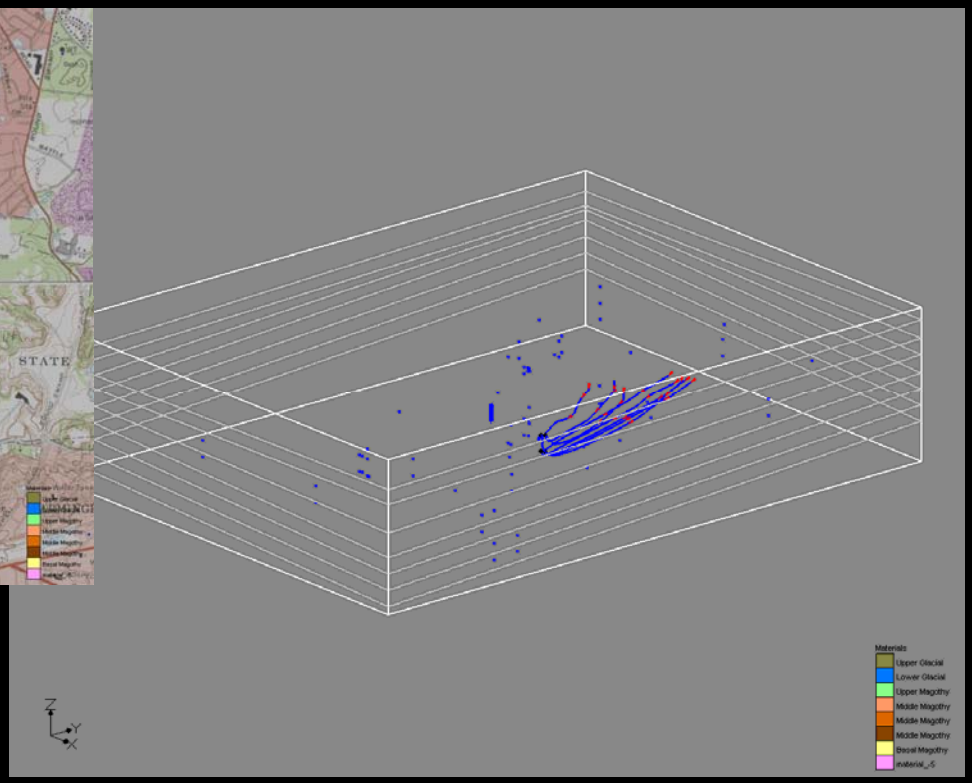




Backward particle tracking result for RW-3. The red arrows indicate 10 year particle travel time.

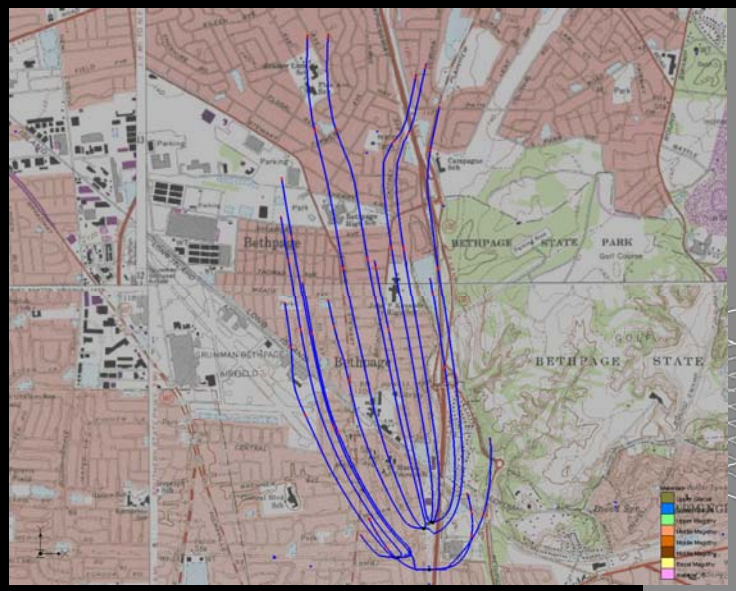
Capture Zone Assessment ~ BWD (30 yrs.)

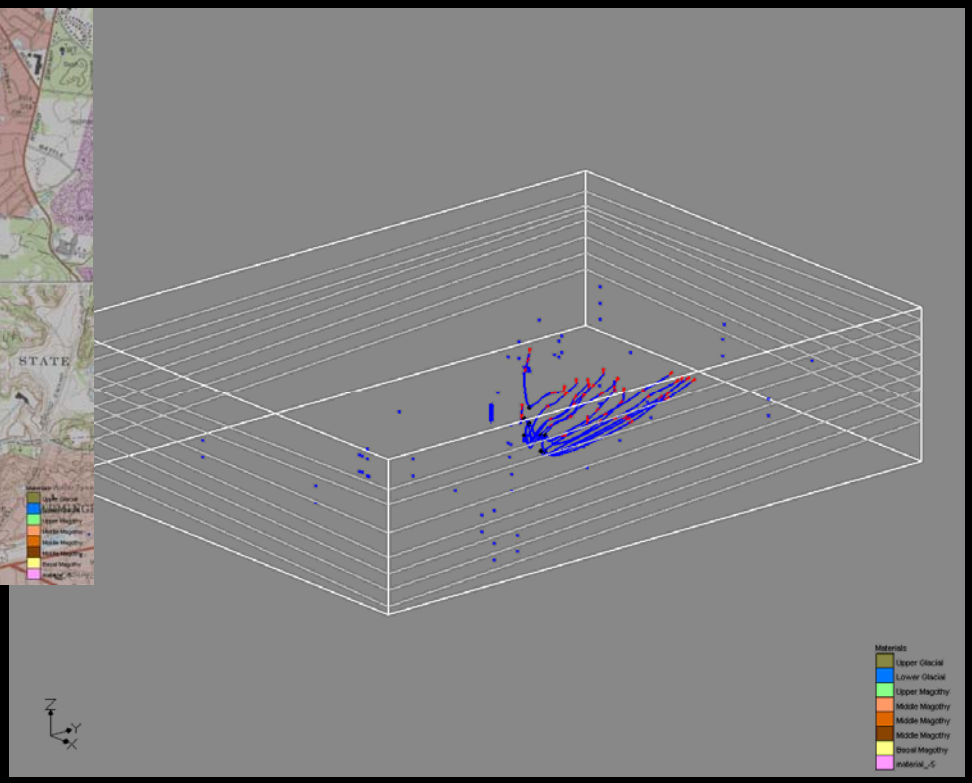




Capture zones resulting from pumping of BWD wells 6915 and 6916.

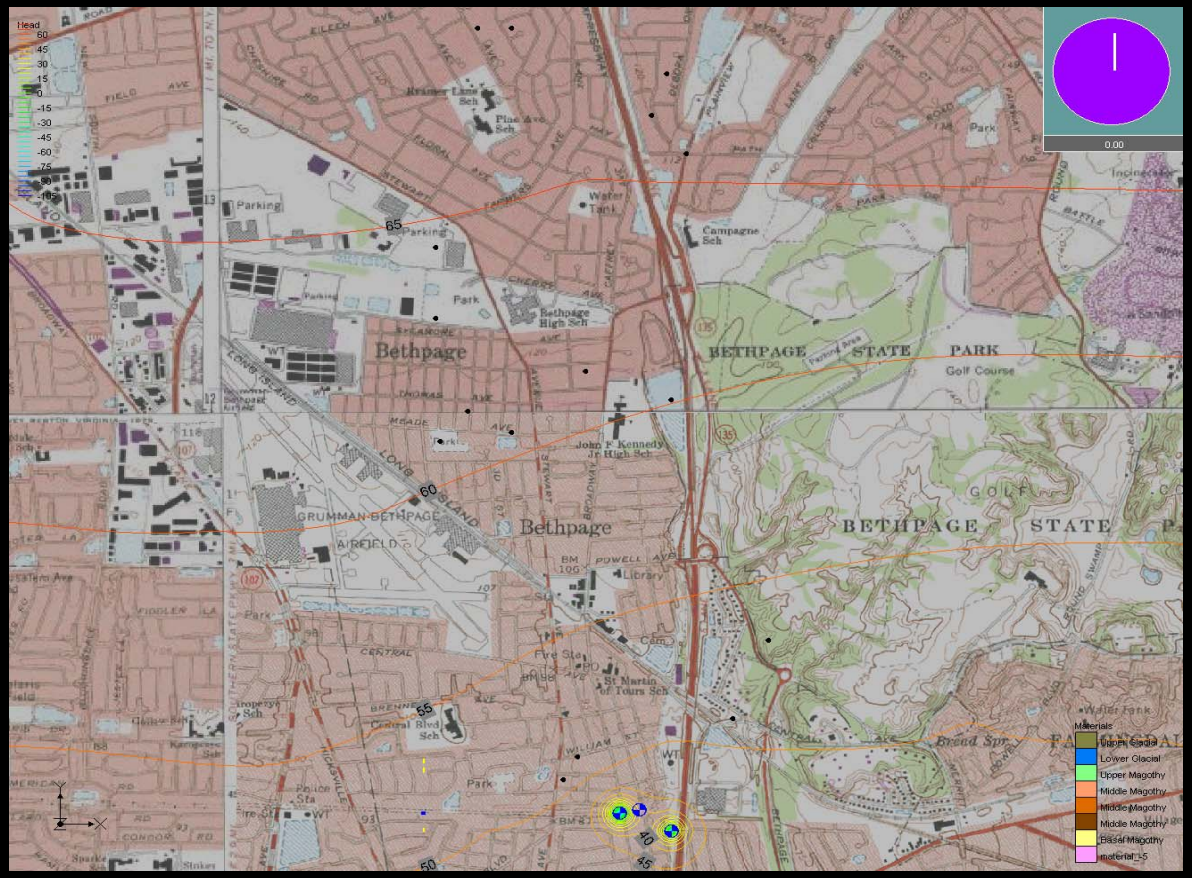
Capture Zone Assessment ~ BWD, RW-1 & RW-3 (30 yrs.)





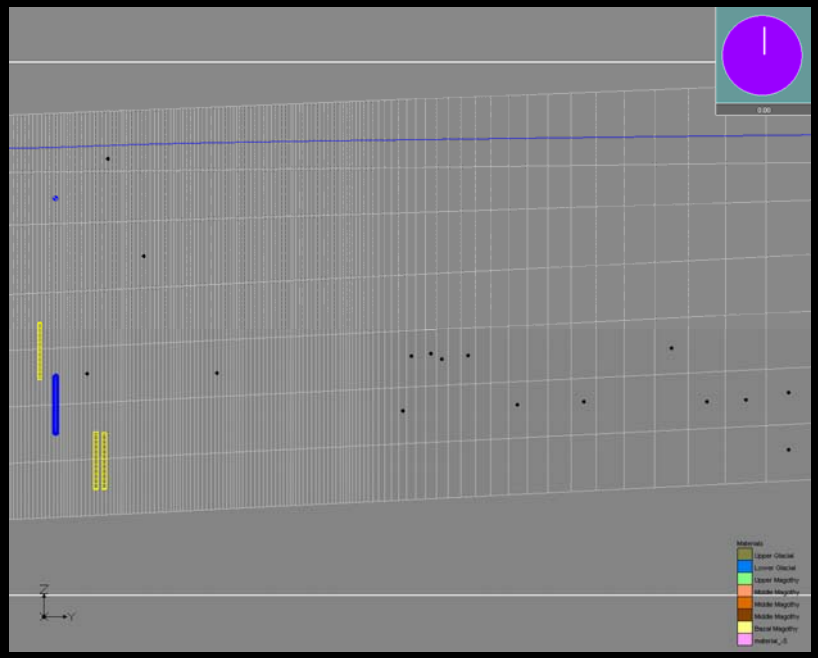
Capture zones resulting from pumping of BWD wells 6915 and 6916 as well as extraction wells RW-1 and RW-3.

Animation 1 (Forward Particle Tracking)

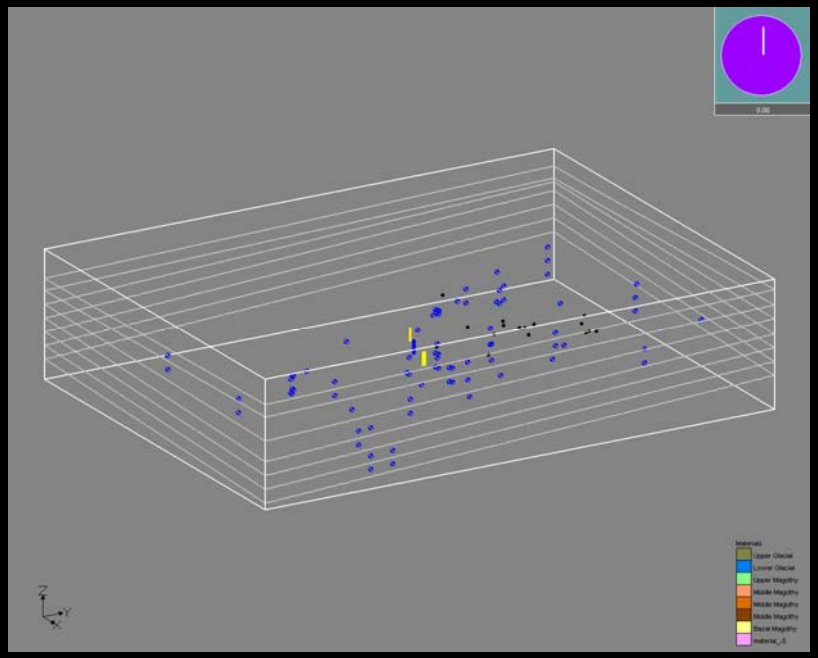


Animation 1 shows forward particle tracking; where particles were released from the flow lines (or contaminant path lines) and captured by BWD wells 6915/6916 as well as RW-1 and RW-3 at different depths. The drawdown cones were developed at RW-1 and RW-3 above the BWD's screen interval. Click on the Icon in the right hand corner to begin.

Animation 2 and 3 (Cross-section & 3D)



Animation 2



Animation 3

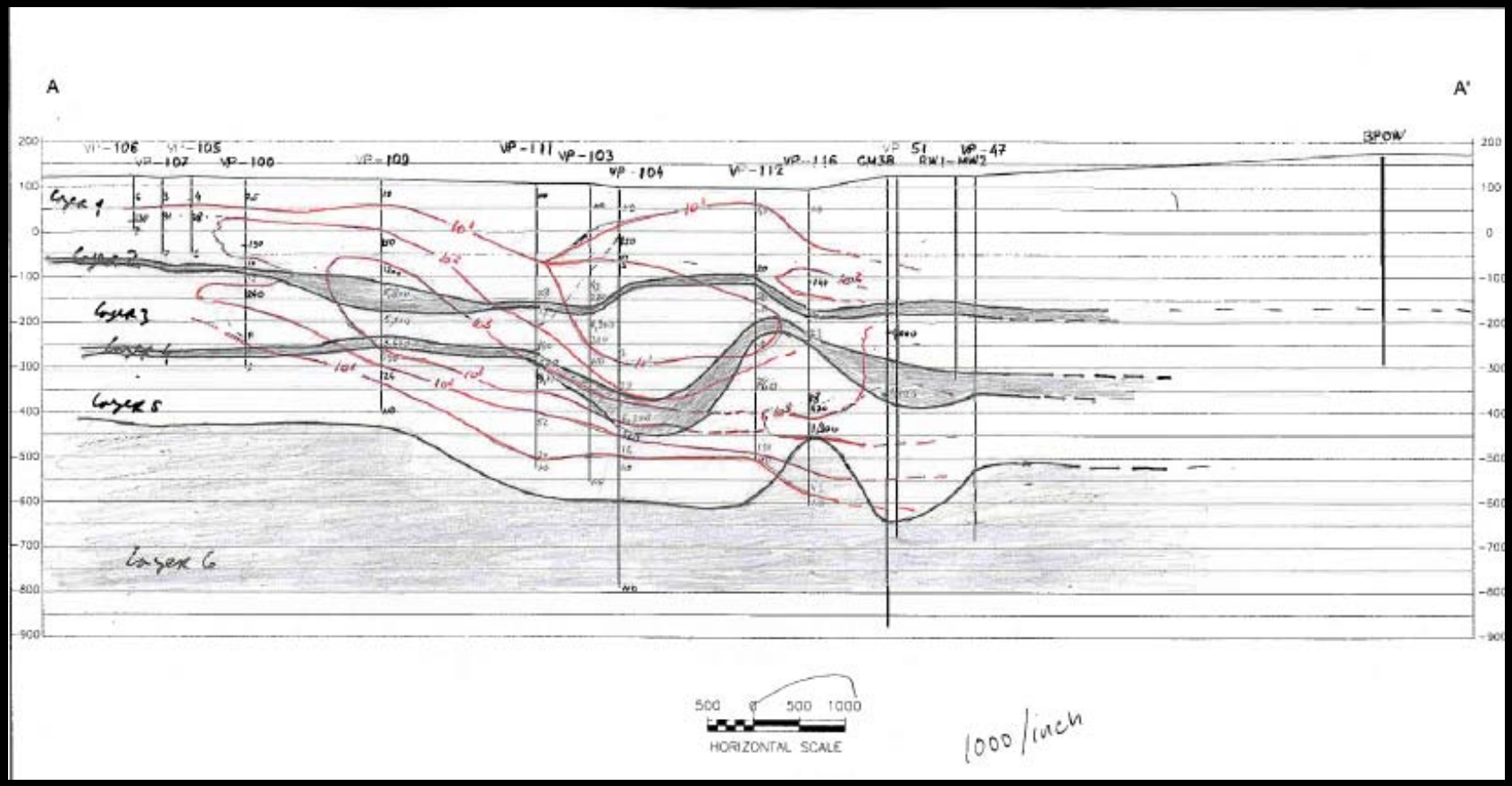
Animation 2 is cross-section view (looking to the west) of particles forward tracking to 6915/6916 and RW-1 and RW-3. Animation 3 shows 3D particle tracking where particles are forward tracked to the extraction wells. Click on the Icon in the right hand corner to begin.

Refinement of RW-3 Screen Depth Interval with Site-Specific Data

- Rational
  - Based on site-specific vertical plume profile (next slide)
  - Further reduce potential impact to BWD wells
    - Screen depth interval of BWD wells is about -450 to -516 ft msl.

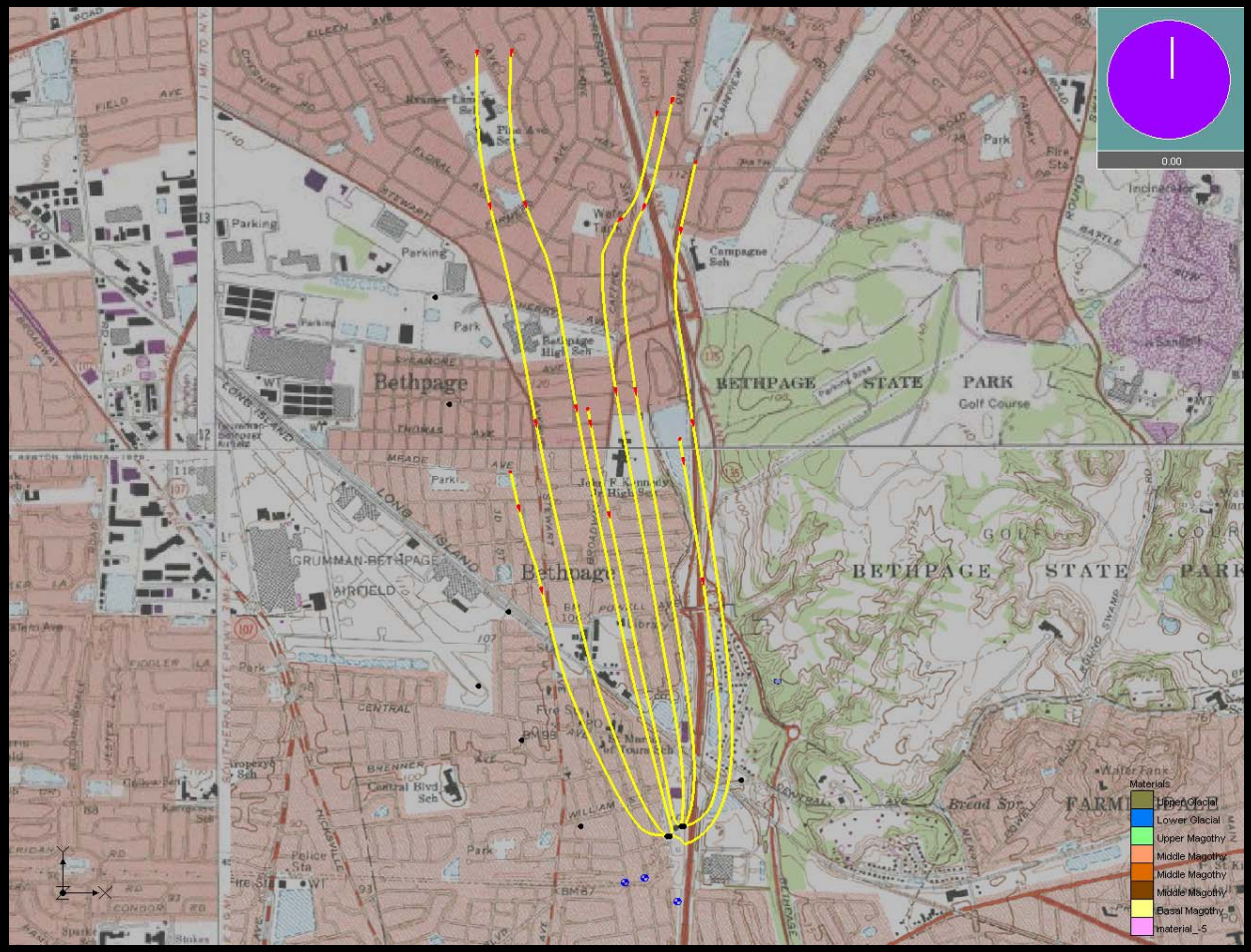
- RW-3 screen interval & capture zone
  - Approximately -310 to -400 ft msl
  - Updated capture zone (30 yrs.)
    - Horizontal
    - Vertical

TCE Plume Vertical Profile



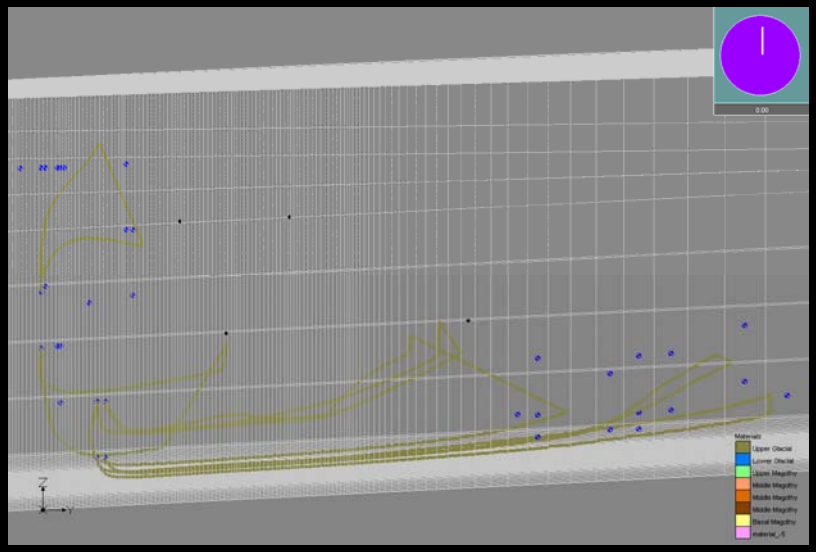
Shaded (predominately fines) and white layers (predominately sands) approximate lithologic layers. Red contour lines approximate TCE concentrations and plume thickness. The TCE concentration of over 1000 ug/L is between -300 to -430 ft msl. The TCE concentration of 100 ug/L is between -250 to -550 ft msl. (not to scale)

Animation 4 for Refinement of RW-3 Screen Depth

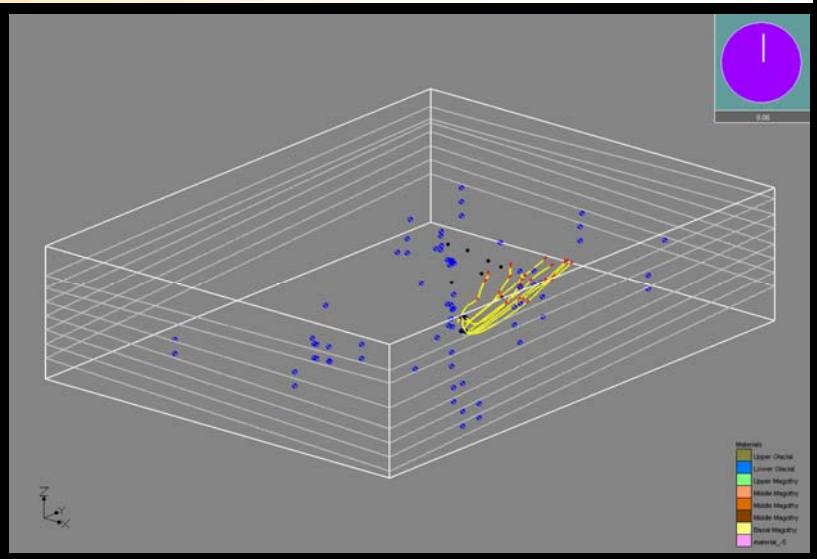


As shown, initial capture zones created by the BWD's wells 6915/6915. Animation 4 shows plan view of the new capture zones created by RW-1 and RW-3 (with refined screen interval). Click on the Icon in the right hand corner to begin.

Refined RW-3 Screen Depth (Cross-section & 3D)



Animation 5 Vertical Component



Animation 6 3-D View

As shown, the initial capture zones created by the BWD's wells 6915/6915. Animations 5 and 6 show the vertical component and 3-D view of the new capture zones created by RW-1 and RW-3 (with refined screen interval), respectively. Click on the Icon in the right hand corner to begin.

Conclusions from Refinement of RW-3 Screen Depth

- The RW-3 screen interval depth was evaluated and placed at -310 to -400 ft mean sea level (msl), approximately thirty feet above the Arcadis proposed screen depth of -350 to -430 ft msl. The length of the screen was increased from 80 ft to 90 ft.

- Particle tracking analyses, with the refined screen interval depth of RW-3, indicates no potential impact to BWD Plant 4 wells. The refined screen depth provides positive benefits to the BWD by shifting the Plant 4 wells' capture zones to the northeast, away from the GM-38 hot-spot.

- Different screen interval depths were evaluated and the particle tracking analysis indicates that the refined screen depth of RW-3 (at the Arcadis proposed location) will capture the current 1000 ug/L TCE plume detected at the GM-38 hot-spot.

- VPB boring data (Arcadis, 2006/08) indicates elevated VOC concentrations were detected upgradient of the GM-38 area at approximate depths of at least -450 to -500 ft msl. This deep contamination may impact the GM-38 area during remedial system operation. Current plume conditions are unknown but particle tracking analyses indicate pumping of RW-3 (with the refined screen interval depth) and RW-1 will most likely capture the deep VOC contamination if it impacts the GM-38 area.

Evaluation of Monitoring wells (H & WQ)

- The monitoring well locations and screen interval depths used in the TtEC evaluation were adopted from Arcadis' modeling prediction based on their particle tracking analyses.

- Purpose of Wells
  - Hydraulic monitoring (H)
  - Water quality monitoring (WQ)

- RW-3 Proposed Related Wells (H&WQ)
  - RW3-MW1
  - RW3-MW2
  - RW3-MW3
  - RW3-MW4

- RW-3 Proposed Related Wells (H&WQ)
  - RW1-MW3

- BWD Proposed Related Wells (H)
  - TP-1 (screen may be set at the same depth with BWD Plant 4 wells if the same lithology is confirmed during drilling)

RW-3 & RW-1 Capture Zones (5 yrs.)

Particle tracking analysis indicates that the proposed monitoring wells are within the 5 year capture zones. This is acceptable for the purpose of monitoring the hydraulic conditions of groundwater.

Note: Monitoring wells are not marked on figure but were shown to be within capture zone.

Conclusions from Evaluation of Monitoring Wells

- The location and screen interval depth, as proposed for well TP-1, is appropriate to meet the objective of assessing hydraulic effects caused by operation of the remedial system. TP-1 will be used to monitor the background hydraulic effects caused by pumping of the BWD wells.

- The locations and screen interval depths proposed for RW1-MW3 and the RW-3 associated monitoring wells (RW3-MW1, 2, 3, and 4) are appropriate for the purpose of monitoring hydraulic conditions caused by the operation of the remedial system; however, based on unknown current conditions of the contaminant plume in the GM-38 area, the screen interval depths may not be appropriate for the purpose of water quality monitoring.

- VPB boring data (Arcadis, 2006/08) indicates that elevated VOC concentrations were detected upgradient of the GM-38 area at approximate depths of at least -450 to -500 ft msl. This deep contamination may impact the GM-38 area during system operation. Current plume conditions are unknown. The monitoring wells at their proposed screen depths may not accurately monitor water quality at the GM-38 area. In addition, the wells may not be appropriate to monitor potential impacts on the remedial system from the deep VOC contamination.

Recommendations

- Based on particle tracking analysis, TtEC recommends that the RW-3 screen depth interval be raised thirty feet up from Arcadis proposed depth of -350 to -430 ft msl to a depth of -310 to -400 ft msl. The length of the screen should also be increased from 80 ft to 90 ft. Field geophysical testing and lithologic logging will confirm or further refine the screen depth interval most appropriate at RW-3.

- TtEC recommends installation of TP-1, as proposed by Arcadis, for the purpose of monitoring hydraulic conditions related to background conditions and the remedial system operation.

- Current plume conditions are unknown and elevated concentrations of contaminants upgradient of the GM-38 area have been detected during the VPB investigation, advanced transport modeling, with 3-D plume visualization, is proposed to evaluate and predict the current plume front and configuration.

- TtEC recommends evaluation of the screen interval depths for the proposed monitoring wells associated with RW-1 and RW-3. Because of unknown or potentially changed conditions, the proposed screen interval depths may no longer be appropriate for the purpose of monitoring water quality and potential impacts to the remedial system in the GM-38 area. Advanced transport modeling is recommended to refine the screen interval depths of the monitoring wells. Field lithology will also be used to confirm the screen interval depths are most appropriate.

Recommendations (con't)

- In addition to evaluating and refining the screen interval depths of the proposed monitoring wells, TtEC proposes advanced transport modeling to help meet the objectives of understanding the current and future contaminant plume configuration, predicting the remedial system effectiveness, and optimizing the remedial system operation and monitoring.

- Advanced transport modeling, with transport processes in addition to advection and with the addition of new and current data, will provide a more accurate model of the current and future conditions of the contaminant plume in the GM-38 area.

- A brief summary of the objectives for advanced transport modeling are shown on the following slide. TtEC will provide a follow-up Technical Memorandum detailing the rationale and approach for advanced transport modeling.

Objectives for Advanced Transport Modeling (with 3-D Plume Visualization)

- Understand plume configuration (site-specific)
  - Spatial and temporal distributions
  - Estimate current plume volume and mass
  - Refine screen interval depths of monitoring wells
- Predict effectiveness of remedial system under current and future plume conditions (distributions)
  - Evaluate GM38 hydraulic containment
  - Simulate GM38 area mass removal
  - Determine influent concentrations
- Optimize remedial system operation & monitoring
  - Pumping schedules
  - Pumping rates vs. concentrations
  - Operational timeframe (schedule)