



DEPARTMENT OF THE AIR FORCE  
377TH AIR BASE WING (AFGSC)

Colonel Dawn A. Nickell, USAF  
Vice Commander  
377th Air Base Wing  
2000 Wyoming Blvd SE  
Kirtland AFB NM 87117

APR 05 2018

Mr. John Kieling, Bureau Chief  
Hazardous Waste Bureau (HWB)  
New Mexico Environment Department (NMED)  
2905 Rodeo Park Drive East, Building 1  
Santa Fe NM 87505-6303



Dear Mr. Kieling

This letter is being provided to communicate the Air Force's (AFs) preference on selection of a groundwater model. The AF has selected the FEFLOW finite element model for groundwater modeling at the Bulk Fuels Facility, Solid Waste Management Unit ST-106/SS-111 at Kirtland Air Force Base (AFB), New Mexico due to the robustness and widely accepted use as an industry standard. The AF took special care in the groundwater model selection process and below details many of the factors that were considered.

**Overview**

Different types of simulation models, which range from analytical to numerical, may be applied to calculate hydraulic heads and subsequently evaluate capture zones based upon particle tracking. As stated in the January 2008 guidance entitled "A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems" (EPA 600/R-08/003), EPA encourages the use of groundwater modeling followed by field monitoring at more complex sites like the Bulk Fuels Facility (BFF) ethylene dibromide plume (EDB) for evaluating and improving the conceptual site model, predicting plume capture zones and evaluating alternative remedial scenarios.

In the 16 November 2017 Notice of Deficiency, the New Mexico Environment Department (NMED) required the AF to perform the six-step plume capture analysis, which includes a numerical or analytical model, in accordance with the EPA guidance. The proof of concept (POC) submitted by the AF on 29 March 2018 proposed the use of FEFLOW, a finite element model, with the understanding that the selection of the appropriate model(s) would be further considered at an upcoming Technical Working Group (TWG) meeting. The referenced submittal was intended to demonstrate the POC and should not be considered a rigorous plume capture analysis.

The POC model assumes that the EDB plume is located along the west/southwest limb of the primary cone of depression surrounding extraction from the Albuquerque Bernalillo County Water Utility Authority (ABCWUA) Ridgecrest and Kirtland AFB production wells. The numerical flow model assumes a homogeneous and isotropic horizontal hydraulic conductivity (Kh) and a uniform vertical anisotropy (VANI) across the model domain. The POC figures (Attachment 1) illustrate the set-up and results of this numerical model under Quarter 2 2017 conditions. Image 1 shows the general gradient field, defined from head measurements, across the plume area for this time period, and Image 2 shows a close up view of how the



model's finite element mesh has been refined around Interim Remedy extraction wells KAFB-106228 and KAFB-106233 in order to produce accurate drawdown estimates associated with the time period extraction rates. Images 3 and 4 show the simulated capture zones for each Interim Remedy well under the two end members of five Kh and VANI scenario runs. Image 5 shows a comparison between the capture zones from the best-fit scenario and the capture zones defined by analysis of measured head data.

The following discussion summarizes the basis for the AFs selection of FEFLOW.

On a global scale, there are mainly two specialized tools for groundwater simulation: MODFLOW with its different variants, graphic user interfaces and packages, and FEFLOW. FEFLOW is typically used in the more complex applications (complex geology, reactive transport, Karst flow and transport, mining applications, etc.). Common applications of FEFLOW include, but are not limited to, the following:

- Determining the spatial and temporal distribution of groundwater heads and contaminants;
- Estimating the duration and travel times of a pollutant in aquifers; and
- Evaluating remediation alternatives, planning remediation strategies, and optimizing groundwater remediation system designs.

FEFLOW is the model of choice on a number of complex groundwater contamination sites, including:

- Puente Valley Operable Unit, San Gabriel Superfund Site, California (EPA Region 9)
- Whittier Narrows Operable Unit, San Gabriel Superfund Site, California (EPA Region 9)
- South El Monte Operable Unit, San Gabriel Superfund Site, California (EPA Region 9)
- Buckhorn Mountain Gold Mine, Washington

FEFLOW was reviewed in Groundwater, Volume 45, Issue 5 (September-October 2007) Software Spotlight (Attachment 2).

FEFLOW is a finite element numerical groundwater flow model. Finite elements allow infinite flexibility with defining model domain, complex stratigraphy (both continuous and pinching out), and simulation of drawdown near a pumping well. FEFLOW is also capable of fully integrating partially saturated units (vadose zone) with saturated flow units.

Unlike finite difference models such as MODFLOW, FEFLOW allows tight discretization of elements around pumping wells, as well as the ability to add a well in the future, and re-discretize tight elements in the location of a future well with ease. Tightening the grid in finite difference models like MODFLOW requires considerably more effort. With FEFLOW, changes may be swiftly made and scenarios evaluated all within the time constraint of the semiannual report schedule.

FEFLOW can cover a wide range of physical processes and can handle an equally wide range of spatial discretization options (2d vertical/horizontal/axisymmetric models, layered 3D models using prisms, layered 3D models with pinch-outs in layers, full tetrahedral discretization). It's easy to use via the GUI covering the whole model setup, simulation and post processing workflow, provides programming interfaces for C++ and Python, and interfaces too many common data formats (ranging from ASCII to spatial databases). These features will allow flexibility over time for the purpose of capture analysis.

### **The use of FEFLOW to achieve the EPA's 6-step capture zone analysis**

Modeling is part of Step 4 "Perform Calculations" in EPA's six-step capture analysis. EPA's recommended calculations include:

- Estimated flow rate calculations
- Capture zone width calculation (can include drawdown calculation)
- Modeling (analytical or numerical) to simulate water levels, in conjunction with particle tracking and/or transport modeling

With its tightly discretized element field, FEFLOW can accurately simulate and facilitate detailed contouring of drawdown at the pumping wells (Bullet 2). It can accurately simulate water levels according

to governing equations for groundwater flow (Bullet 3), and via particle tracking, it can simulate particle trajectories and estimate flow rates along the trajectories (Bullet 3). In concert, these elements will define the capture zone of a well at steady state, and all wells in aggregate, and fulfill the EPA's Step 4 (Performance Calculations) as a second line of evidence. Transient conditions can also be simulated. Stratigraphy may also be added.

In contrast, finite difference models such as MODFLOW withdraw groundwater from a "cell" that the pumping well is placed in. So rather than being a "point withdrawal" near an extraction well it is an area withdrawal. FEFLOW greatly exceeds MODFLOW's ability to simulate drawdown near the pumping well, and therefore allows direct comparison of predicted values to actual field observations. The ability of FEFLOW to simulate "drawdown" at the well will allow the model to be compared directly with measured water levels near the pumping well, and in turn, allow evaluation of bulk hydraulic conductivity in the area of the pumping well in response to long-term pumping.

To address concerns regarding the shifting hydraulic gradient caused by the rising water table, the FEFLOW model is designed to quickly accommodate and test a number of gradient scenarios each semiannual performance assessment period. The FEFLOW model, as currently designed for performance assessment, will evaluate current conditions, including current supply well and groundwater extraction wells within the interim measure domain and the performance of the Ground Water Treatment System extraction wells with respect to capture. Although it is not currently designed as a predictive tool to calibrate to regional groundwater flow or anticipated future pumping rates at public supply wells the FEFLOW model could be expanded to become a predictive tool including the ABCWUA well fields in the future.

Although FEFLOW is a proprietary model, the FEFLOW software download from the DHI website includes a FEFLOW viewer. In viewer mode, FEFLOW does not need a license, Supermesh files, models, and results files can be loaded and inspected. Results evaluation such as done in the Budget or Content panels, and export of images, animations, and data files is also possible. In addition, the '.fem' file, model build file, and the '.dac' file, simulation results file, can be exported in ASCII format. This allows a reviewer the ability to open the model files in any text reader and identify the full suite of assigned aquifer property, recharge, layer elevation, and boundary condition values. Each assigned model perimeter as well as simulated heads and Darcy velocities can be exported as 2D (per layer) or fully 3D point (nodes) or area (elements) files compatible with either Geographic Information System or Excel software for further analysis.

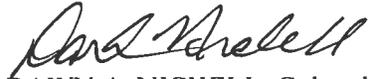
Link to FEFLOW viewer information:

<https://na01.safelinks.protection.outlook.com/?url=http%3A%2F%2Fwww.feflow.info%2Fhtml%2Fhelp%2Fdefault.htm%3Fturl%3DHTMLDocuments%252Fpackage%252Fviewer.htm&data=01%7C01%7Cb Meyer%40eaest.com%7Cea8205f960194435510f08d598ed360b%7C037230a09aa24474a7fd1ffe5d8e4bfc%7C1&sdata=wTjB4l03NNJrSTPv%2BLOUIKhAwN3BFs8RKWMUIdwlsDY%3D&reserved=0>

The AF is committed to continue working with the multi-agency TWG currently scheduled for 12 April 2018. The six-step capture zone analysis and modeling will be the main topic of discussion at the TWG. The AF is committed to complying with the Kirtland Air Force Base's Resource Conservation and Recovery Act Permit and appreciates NMEDs understanding and willingness to help achieve this goal.

If you have any questions or concerns, please contact Mr. Scott Clark at (505) 846-9017 or at [scott.clark@us.af.mil](mailto:scott.clark@us.af.mil).

Sincerely



DAWN A. NICKELL, Colonel, USAF  
Vice Commander

2 Attachments:

1. Proof of Concept Figures
2. FEFLOW Groundwater Software Spotlight

cc:

NMED (Borrego) letter only

NMED-OOTS (McQuillan)

NMED-GWQB (Hunter, Pullen)

SAF-IEE (Lynnes) electronic only

AFCEC/CZ (Renaghan, Segura, Clark, O'Grady) electronic only

USACE-ABQ District Office (Simpler, Phaneuf, Dreeland; Cordova; Salazar) electronic only

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**40 CFR 270.11  
DOCUMENT CERTIFICATION**

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DAWN A. NICKELL, Colonel, U.S. Air Force  
Vice Commander, 377th Air Base Wing

5 Apr 18

Date

This document has been approved for public release.



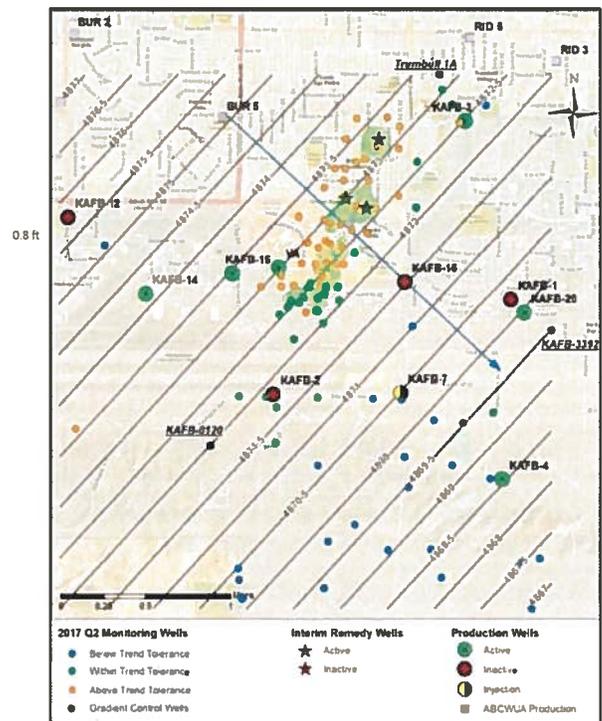
KIRTLAND AIR FORCE BASE  
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Date

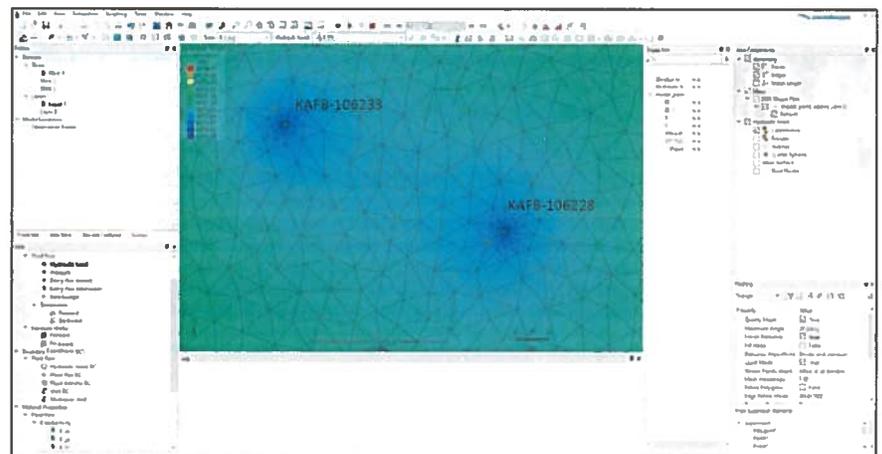
## 2017 Q2 Gradient Input to Model

- Extraction from KAFB and interim remedy water-table aquifer wells has equaled or exceeded extraction from Ridgecrest wells resulting in a shift in flow direction across the AOI
- Only when Ridgecrest extraction greatly exceeds KAFB extraction does flow at Trumbull 1A shift towards Ridgecrest wells
  - Periodic shift
- Combined drawdown associated with KAFB-3, 4, and 20 extraction has become the controlling factor for AOI gradient
- Linear Gradient Model
  - Gradient = 0.00047
  - Flow Direction = S47°E (317°)
  - Goodness of Fit
    - Measure head range (difference)
      - 4,869.3 to 4,875.9 NAVD88 (6.7 ft)
      - Trend fit = residual -0.67 to 0.67 ft
    - NRMSE = 21%
      - The poor fit of the linear trend model to measured head data across the AOI is due to interim remedy extraction.
      - Poor model fit in south of AOI due to gradient across this area is towards the east and the combined KAFB-4 / KAFB-20 drawdown.



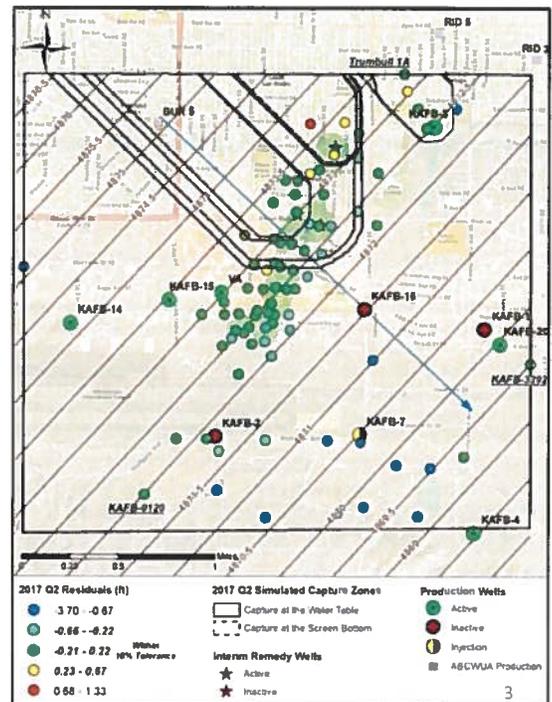
# Gradient Flow Model Design

- Purpose: supporting line of evidence for Interim Remedy Capture Analysis
- Incorporates:
  - Aquifer properties:
    - Horizontal hydraulic conductivity
    - Vertical anisotropy
  - Magnitude and direction of the local gradient
  - Interim Remedy extraction rates
- Design:
  - Finite element numerical flow simulation using FEFLOW
  - 3D, 2-layer, phreatic, steady-state model
    - Top of model elevation set at 4,885 ft amsl
      - Top of KAFB-3 screen
    - Top of layer two set at bottom of Interim Remedy extraction well screen elevations
      - Assures extraction wells are fully penetrating with respect to layer one
    - Bottom of model equals top of A2 confining unit elevation
      - Extracted from CB&I flow model
  - Mesh refined down to less than 3 feet at three Interim Remedy extraction wells and KAFB-3
  - Well screen casing radius assigned to well boundary
  - Approximate node spacing equals 50 ft
    - 74,530 nodes per layer (223,590 total)
    - 148,034 elements per layer (296,068 total)



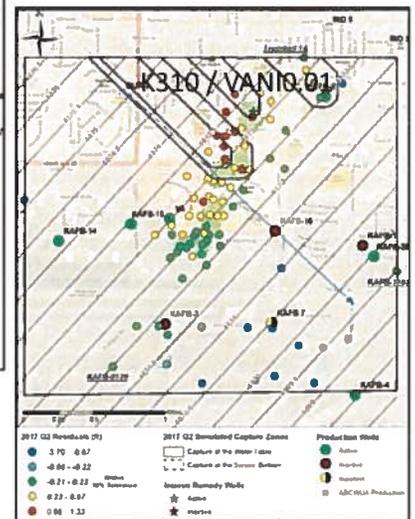
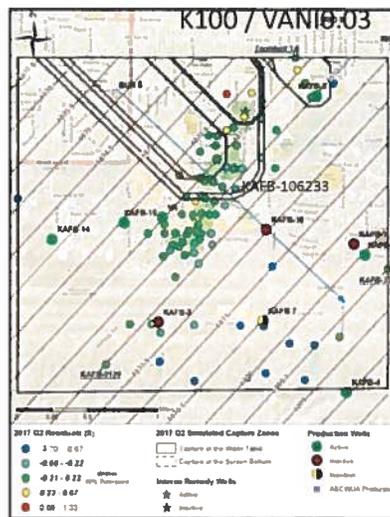
## Gradient Flow Model Calibration

- Five KAFB-106228 aquifer test scenarios simulated to determine aquifer parameters resulting in best-fit to measured head data
  - Homogeneous hydraulic conductivity (K)
  - Homogeneous vertical anisotropy (VANI)
  - Model boundary assigned as constant head
    - Boundary head extracted from 2017 Q2 linear gradient model
  - Starting heads assigned by extracting the heads from the gradient model at each flow model node
- Scenario Assignments:
  - KAFB-106035 (shallow obs. well)
    - K = 170 ft/day; VANI = 0.003; KAFB-3 = 400 gpm
    - K = 180 ft/day; VANI = 0.001; KAFB-3 = 450 gpm
  - KAFB-106022 (shallow obs. well)
    - K = 310 ft/day; VANI = 0.01; KAFB-3 = 650 gpm
  - KAFB-106036 (intermediate obs. well)
    - K = 150 ft/day; VANI = 0.04; KAFB-3 = 375 gpm
  - KAFB-106037 (deep obs. well)
    - K = 100 ft/day; VANI = 0.03; KAFB-3 = 225 gpm
- Scenario Calibration
  - KAFB-106228 = 145 gpm (fixed)
  - KAFB-106233 = 177 gpm (fixed)
  - KAFB-106234 = 161 gpm (fixed)
  - KAFB-3 extraction rate was modified to give a best-fit to monitoring well KAFB-106201 for each scenario (see above)
    - All scenarios but K=310 simulated measured head at 201 within 0.05 ft
    - Simulated head at 201 off by +0.14 ft using max KAFB-3 pump rate



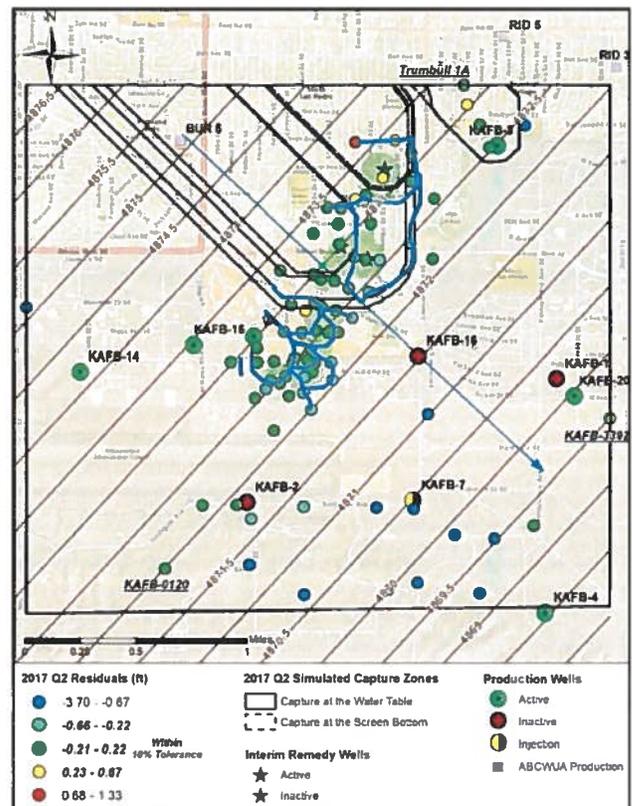
## Scenarios Simulations VS Measured

- Goodness-of-fit was analyzed using standard Normalized Root-Mean-Squared Deviation (NRMSD) method
  - Generally acceptable NRMSD is <10%
  - NRMSD was calculated for the 60 REI 4857 dissolved EDB plume monitoring wells
- Scenario NRMSD
  - K310/VANI0.01 = 26%
  - K180/VANI0.001 = 16%
  - K170/VANI0.003 = 16%
  - K150/VANI0.04 = 17%
  - **K100/VANI0.03 = 13% (Includes southern wells [blue] outside of AOI)**
    - Best Fit
    - Most Reasonable KAFB-3 extraction rate
      - Since the beginning of 2015
      - Average monthly KAFB-3 extraction rate - 14 to 361 gpm
      - Three-year mean – 213 gpm
      - Three-year median – 204 gpm



## Gradient Flow Model Results

- The K 100; VANI 0.03 Scenario best fits the measured head data
- The K 100; VANI 0.03 Scenario produces the most reasonable KAFB-3 extraction rate
- The K 100; VANI 0.03 compares well with the horizontal capture analysis based on only measured head data



# FEFLOW: A Finite-Element Ground Water Flow and Transport Modeling Tool

reviewed by Mike G. Trefry<sup>1</sup> and Chris Muffels<sup>2</sup>

## Introduction

Ground water modeling requires a wide range of models for different types of problems and applications. FEFLOW is an advanced *Finite-Element* subsurface *FLOW* and transport modeling system with an extensive list of functionalities, including variably saturated flow, variable fluid density mass and heat transport, and multi-species reactive transport. It is a proprietary code and not freely available; it supports an impressive array of features of interest in subsurface flow and transport and is well documented, in terms of both peer-reviewed papers in the scientific literature and a comprehensive set of manuals and white papers. The program has been under development since 1979 by the Institute for Water Resources Planning and Systems Research Inc. (WASY GmbH) of Berlin, Germany, which has recently become a part of DHI Group. For more information, see <http://www.wasy.de/english/products/feflow/index.html>.

## How We Tested

FEFLOW v 5.3 (patch 1) was reviewed and tested by two reviewers. One reviewer used two Windows XP computers (a desktop P4 3.2 GHz and a laptop Dual Core 2.33 GHz) each with 2 GB RAM; the other reviewer used a laptop P4 3.0 GHz with 1.5 GB RAM. One of the reviewers has also had experience executing FEFLOW on Linux platforms.

FEFLOW was downloaded and installed directly from the WASY Web site in Germany—a process that took approximately 10 to 30 min depending on Internet connection speed. A handsomely packaged box is also available as the delivery method. After installing the full package, the contents of the WASY folder containing

FEFLOW amounted to 450 MB of disk space, including demo and help folders. FEFLOW requires a license key and is capable of running in licensed stand-alone mode or by connection to a remote license server. FEFLOW's graphics are X-Windows based, so the installation provided the user with an X server (Hummingbird Exceed). Other important tools installed were FEFLOW Explorer 2.0, an OpenGL-based data explorer, and WGEO 5.0, an image georeferencing tool. FEFLOW can be modified and removed using a standard Windows installation manager interface. Stability of the Windows computers was not affected by the presence of FEFLOW. Execution can lead to significant resource demands on the computer host and concomitant slowdowns of other applications, but terminations are uncommon even during execution times of 8 to 12 h or more.

## What We Found

### Software Performance

The software performance was good. It was able to solve a range of classical benchmark problems readily. Both triangular and rectangular finite elements are supported, with a range of direct and indirect solver options, including algebraic multigrid techniques (Stüben 2001). FEFLOW autodetects the number of available processors and invokes a multithreaded parallel mode accordingly, but the user can specify the number of threads to use if desired. Numerical stability is usually good, but complex problems involving strong density coupling and unsaturated flow can present convergence problems. The graphical user interface (GUI) contains many features of use to the modeler, including mouse-driven mesh construction, boundary condition specification, and property editing. It is literally possible to build a georeferenced flow and transport simulation from existing spatial data sets without having to use a text editor.

One reviewer, who is an experienced ground water modeler but new to FEFLOW, tested a portion of FEFLOW's functionality related to ground water flow and contaminant transport. Throughout the testing, the program performed as advertised. While the reviewer found

<sup>1</sup>CSIRO Land and Water, Private Bag 5, Wembley 6913, Australia; [mike.trefry@csiro.au](mailto:mike.trefry@csiro.au)

<sup>2</sup>S.S. Papadopoulos Et Associates Inc., 7944 Wisconsin Avenue, Bethesda, MD 21771; [cmuffels@sspa.com](mailto:cmuffels@sspa.com)

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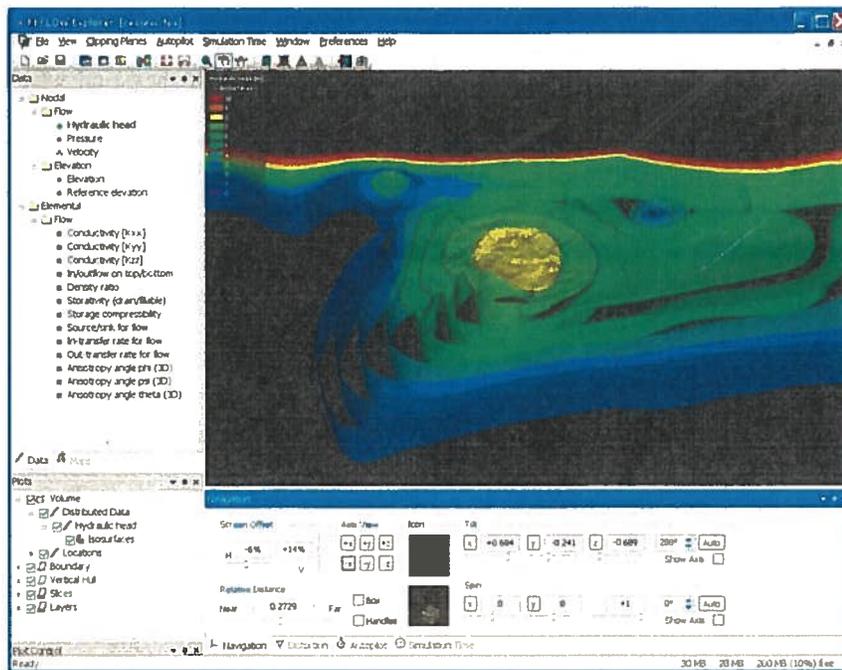


Figure 2. Advanced visualization with FEFLOW Explorer 2.0 showing contours of a simulated 3D head distribution.

### Software Support

The support staff are friendly and expert. WASY maintains a public bug list and issues documented patches frequently. These are available for download and installation directly. One reviewer corresponded with an experienced FEFLOW user who commented that “support from WASY is very good... The manual and the online help are great, but they do not answer all questions or replace the knowledge of their staff.”

### What We Liked

The reviewers were most impressed by FEFLOW's capability to handle saturated/unsaturated flow, and transport and reaction simultaneously in the one mouse-driven GUI package. The fully-3D finite-element nature of FEFLOW is a significant advantage for complex ground water modeling applications. This is all backed up by credible peer-reviewed journal papers on the various methods and solvers, so that users can have confidence in density-coupled simulations, dispersion modeling, unsaturated flows, and in reaction and sorption kinetics. FEFLOW handles multiple free surfaces, discrete fractures and has convenient tools for mapping material properties and boundary condition constraints based on spatial domains. FEFLOW contains the excellent triangulation algorithm by Shewchuk (2002) for fast and optimal gridding, plus has PEST (Doherty 2002) support built-in, and includes fluid age and thermal conduction calculations. There is also a full developer application programming interface that allows users to add custom code modules directly into the FEFLOW simulator.

Being able to work on other tasks while FEFLOW was solving a CPU-intensive transport simulation was helpful as the users could run FEFLOW on one PC with-

out having to switch to another one to do other tasks. Well-documented file formats are important because in the event that the users cannot do something they would like in FEFLOW or FEFLOW Explorer or with the interface manager, they can still write their own utilities for pre- and postprocessing. One reviewer particularly liked that he could tackle his own flow and transport simulation using FEFLOW after only a few days of use. The program is stable and gives users the ability to “play” with the program and push buttons to learn about it without fear of crashing the program. The error handling in the program is excellent and is so often lacking in other programs.

### What We Did Not Like

There are several things that could be better in FEFLOW. First, the GUI, while perfectly functional, is starting to show its age. The reviewer who is new to FEFLOW does not like the “look” of the GUI because it has an outdated blocky feel and does not follow the standard Windows “look.” This does not affect the ability of FEFLOW to carry out the user's wishes, but it can make some things more obscure or laborious than need be. The definition of local grid coordinates, coordinate origin, and problem measure is confusing. Interruption of simulation time-stepping can be difficult, especially for large complex problems where the mouse status is not polled for long periods during matrix inversions. Color representation in the solver window sometimes collapses to a dithered mode, unnecessarily. By default, FEFLOW renders contour maps over the whole domain for each time step. On some platforms, this can slow down time-stepping performance. It is possible to run FEFLOW in “batch mode,” thereby avoiding repetitive renderings, but

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doi: 10.1111/j.1745-6584.2007.00358.x

the GUI not particularly intuitive, the software appeared stable (the program did not crash once)—with warning messages appearing anytime the reviewer did something that might otherwise crash the program. While running FEFLOW to set up and review simulations and results, there were no apparent hiccups in any other programs running concurrently. It took the reviewer about 2 d to complete the demonstration exercise, after which, the reviewer felt confident that he could dive in and set up his own ground water flow and contaminant transport models.

#### Input and Output

FEFLOW supports an array of data import and export filters. It has its own internal formats for mesh and “Finite Element Problem” data, but it can also read and reconstruct simulation files from SWS (Surface Water Modeling System) and GMS (Groundwater Modeling System) produced by Environmental Modeling Systems Inc. For spatial meshing and gridding, FEFLOW can import a range of formats including AutoCAD DXF, ESRI shapefiles plus a variety of simple ASCII formats, and many bitmap formats for gridding and georeferencing operations. This makes it easy to construct complex grids aligned and shaped with geographic data sets (Figure 1); the combination of FEFLOW and a GIS package (e.g., ArcMap) forms a powerful tool for spatial analysis of ground water problems. Extracting data can be tricky sometimes, especially when trying to export nodal values of material properties or fluid velocities in formats that can be read into other packages. However, one reviewer succeeded in extracting a vertical slice through a conductivity distribution from a three-dimensional (3D) FEFLOW model and inserting this into a MODFLOW model without too much effort. The native FEFLOW file format for problem definitions supports both ASCII and binary forms; the ASCII format is larger but allows

FEFLOW files to be generated and/or modified programmatically by external applications.

FEFLOW has three graphical output tools: an internal viewer, FFPLOT, and FEFLOW Explorer. The internal viewer is functional and performs a range of two-dimensional (2D) contouring and particle tracking functions, plus data export as points, ESRI shapefiles and time series, and Golden Software’s GRD files. The internal viewer also supports a 3D mode, but the quality and flexibility of the graphics in this mode are not high. FEPLOT is a routine tool for constructing annotated map-style graphics from FEFLOW runs—but an advanced user may prefer to use GIS and drafting tools for this task instead. The graphics tool that really impressed the reviewers is FEFLOW Explorer—it is here that the user can really see into the simulation results. Explorer allows the user to construct complex 3D animations, fly-throughs, and renderings of the FEFLOW grid and solution data together with superimposed GIS data and georeferenced bitmaps—the output is presentation quality (Figure 2).

#### Software Documentation and On-Line Help

FEFLOW comes with a variety of documents available on-line and as part of the installation package. As well, there is a Web forum to discuss FEFLOW modeling topics with other users. A demonstration exercise and associated tutorial are provided to familiarize new users with the most commonly used features of FEFLOW. The demonstration exercise guides the user through a typical simulation problem: from importing base maps, mesh generation, and boundary condition assignment to solvers and processing of results. The documentation is easy to follow with plenty of screenshots to keep users on the right track. Help is readily accessible throughout a simulation exercise with convenient “Help” buttons available on most GUI forms (F1 can be pressed at anytime as well).

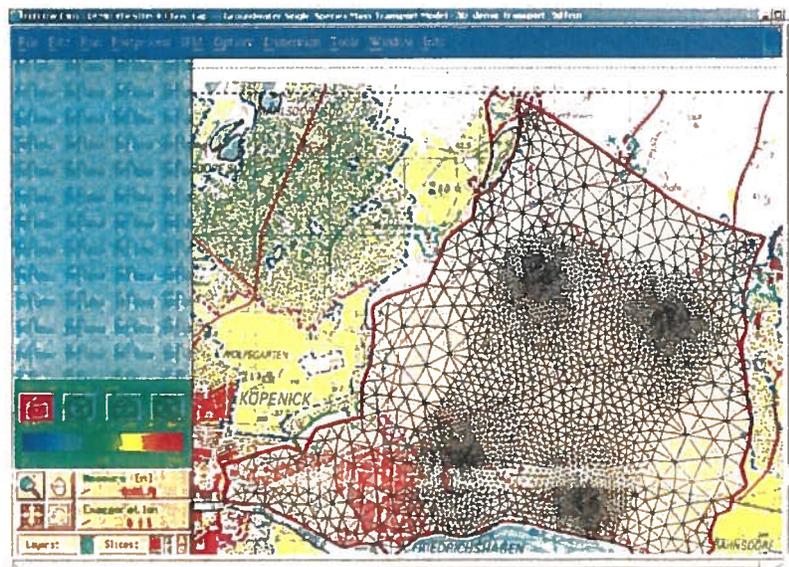


Figure 1. A screen capture of a program window for FEFLOW showing grid refinement around four wells on a base map.

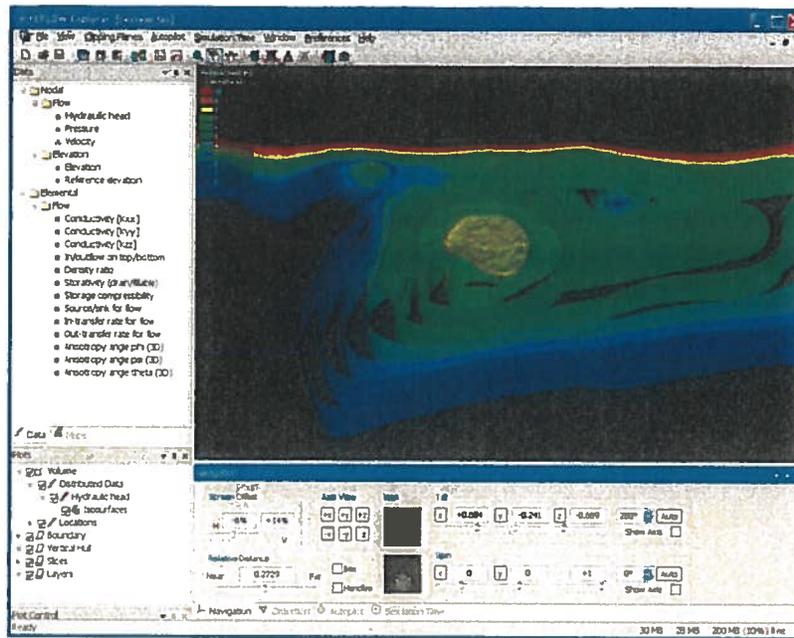


Figure 2. Advanced visualization with FEFLOW Explorer 2.0 showing contours of a simulated 3D head distribution.

### Software Support

The support staff are friendly and expert. WASY maintains a public bug list and issues documented patches frequently. These are available for download and installation directly. One reviewer corresponded with an experienced FEFLOW user who commented that “support from WASY is very good... The manual and the on-line help are great, but they do not answer all questions or replace the knowledge of their staff.”

### What We Liked

The reviewers were most impressed by FEFLOW’s capability to handle saturated/unsaturated flow, and transport and reaction simultaneously in the one mouse-driven GUI package. The fully-3D finite-element nature of FEFLOW is a significant advantage for complex ground water modeling applications. This is all backed up by credible peer-reviewed journal papers on the various methods and solvers, so that users can have confidence in density-coupled simulations, dispersion modeling, unsaturated flows, and in reaction and sorption kinetics. FEFLOW handles multiple free surfaces, discrete fractures and has convenient tools for mapping material properties and boundary condition constraints based on spatial domains. FEFLOW contains the excellent triangulation algorithm by Shewchuk (2002) for fast and optimal gridding, plus has PEST (Doherty 2002) support built-in, and includes fluid age and thermal conduction calculations. There is also a full developer application programming interface that allows users to add custom code modules directly into the FEFLOW simulator.

Being able to work on other tasks while FEFLOW was solving a CPU-intensive transport simulation was helpful as the users could run FEFLOW on one PC with-

out having to switch to another one to do other tasks. Well-documented file formats are important because in the event that the users cannot do something they would like in FEFLOW or FEFLOW Explorer or with the interface manager, they can still write their own utilities for pre- and postprocessing. One reviewer particularly liked that he could tackle his own flow and transport simulation using FEFLOW after only a few days of use. The program is stable and gives users the ability to “play” with the program and push buttons to learn about it without fear of crashing the program. The error handling in the program is excellent and is so often lacking in other programs.

### What We Did Not Like

There are several things that could be better in FEFLOW. First, the GUI, while perfectly functional, is starting to show its age. The reviewer who is new to FEFLOW does not like the “look” of the GUI because it has an outdated blocky feel and does not follow the standard Windows “look.” This does not affect the ability of FEFLOW to carry out the user’s wishes, but it can make some things more obscure or laborious than need be. The definition of local grid coordinates, coordinate origin, and problem measure is confusing. Interruption of simulation time-stepping can be difficult, especially for large complex problems where the mouse status is not polled for long periods during matrix inversions. Color representation in the solver window sometimes collapses to a dithered mode, unnecessarily. By default, FEFLOW renders contour maps over the whole domain for each time step. On some platforms, this can slow down time-stepping performance. It is possible to run FEFLOW in “batch mode,” thereby avoiding repetitive renderings, but

it is not clear how to start batch mode on some platforms. Importing/exporting data for 3D models can be laborious since these operations need to be done for each layer at a time.

Second, while the FEFLOW multispecies reaction model is more than useful, it would be nice to have a greater range of example applications to choose from so that users could see how to relate the example problem settings to the complicated reaction formalism discussed in the FEFLOW white papers. Without this, the reaction model will likely be underused.

Third, FEFLOW incorporates an adaptive layering technique that allows slices between layers in a 3D model to move up and down to minimize solution error. While the user is able to fix slices at will (e.g., to stratigraphic interfaces), it is often useful to include extra "moveable" slices for improved vertical resolution for head gradients, tracer fronts, and so on. The difficulty is that knowledge of the vertical location of a moveable slice as a function of time and space throughout the simulation is not easily accessible. This can complicate the process of model calibration and solution interpretation.

Finally, a comprehensive search option is not available in the help documentation but would be useful as the help buttons did not always connect the user with the information sought. The help documentation is structured or layered in the same manner as the GUI, which may cause some difficulty for novice users who are still getting used to the GUI. For example, while working on the demonstration exercise, one reviewer added too many constant-head boundary condition cells along one edge. The documentation did not instruct him on what to do in this eventuality, nor did the help associated with the form tell him how to delete a boundary node. Deleting such a node is trivial in the end, and it took only a little time to figure out through trial and error, but the lack of help was a little frustrating.

## Overall

Our impression of FEFLOW is that it is a stable and credible ground water simulation code well suited for sophisticated users. The support is excellent and conscientious. The demonstration exercise and tutorials are clear and easy to follow with plenty of screenshots, making it easy to learn the basics of the interface in a short time. FEFLOW could provide better 2D charting and plotting support, but the 3D Explorer is first class. While a search

feature would be helpful for the help documentation, the program is stable enough that users can click around and work with the GUI until they find what they need. All in all, FEFLOW is a well-documented and powerful GUI-based tool for professional subsurface hydrology simulations.

## Rankings

The reviewers ranked the software's capability, reliability, ease of use, and technical support on a scale of 1 (worst) to 5 (best). The following rankings are the average of three sets of scores from both reviewers and the editor:

Capability: 4.7  
Reliability: 4  
Ease of use: 4  
Technical support: 5

## How to Obtain the Software

For software download and pricing information, visit the Web site of WASY GmbH in Berlin, Germany: <http://www.wasy.de/english/produkte/FEFLOW/download.html>.

## Our Mission

The goal of Software Spotlight is to help readers identify well-written, intuitive, and useful software. Independent reviewers from government, industry, and academia try out full working versions of software packages and provide readers with a concise summary of their experiences and opinions regarding the capability, stability, and ease of use of these packages.

Chunmiao Zheng can be reached at the University of Alabama, Department of Geological Sciences, Box 870338, Tuscaloosa, AL 35487; [czheng@ua.edu](mailto:czheng@ua.edu).

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