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3/12

Editorial

FEFLOW's metamorphosis completed

Prof. Hans-Jörg G. Diersch
Director of GMC

This is a special FEFLOW issue supplementing the 3rd International FEFLOW User Conference held at Berlin, Germany in September 2012. Let us remember: Three years ago at the preceding 2nd FEFLOW user conference 2009, the major FEFLOW release 6.0 introduced a completely new working environment that began to replace the classic motif-style GUI, which had been present over a period of about 20 years.

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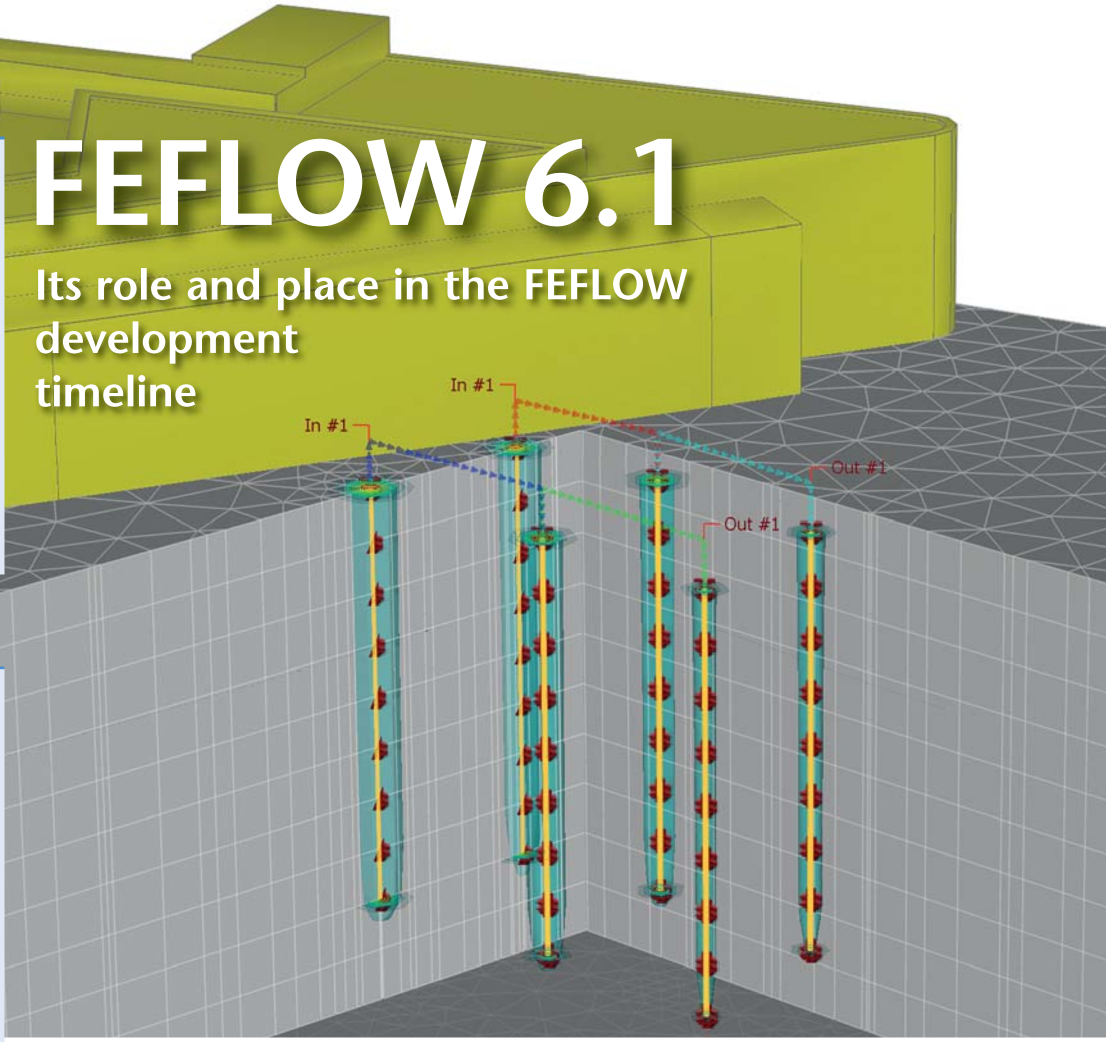
Content

FEFLOW 6.1

Its role and place in the FEFLOW development timeline



Cover Fig.: Geothermal modeling (Detail)

Rainer Gründler & Volker Clausnitzer

With the release of FEFLOW 6.0 in 2010, the long-established *Motif* user interface was joined by a modern *Qt*-based GUI that reflects the technological advances in both GUI toolkit and graphics technology. In particular, the new user interface integrated the capabilities of the previously separate *FEFLOW Explorer* visualization software and employs OpenGL to make full use of the broad availability of hardware-accelerated graphics processing.

Offering several model-view types (3D, 2D slice, and 2D cross section) that can be used simultaneously in multiple view windows, FEFLOW 6.0 brought a new visual quality in interactive groundwater modeling. The efficiency of many typical workflows was greatly enhanced by the conceptual distinction between selection and assignment operations, combined with generous *Undo/Redo* support.

At the same time, the complete separation of simulation kernel and user interface provided the foundation for the development of alternative, possibly purpose-tailored graphical or command-line-based FEFLOW user interfaces – such as the FEFLOW console application that has already been made available with FEFLOW 6.0, or the FEFLOW-PEST interface application presented with the 6.1 release.

Replacing the *Motif*-GUI

At the release of version 6.0 most FEFLOW functions were accessible via the new *Qt*-GUI. However, some essential features still required using the traditional *Motif*-GUI. face pioneered the practical applicability of graphically interactive groundwater modeling. It will now be completely replaced by the *Qt*-GUI whose flexibility is an essential prerequisite for the future FEFLOW development. The release of version 6.1 thus concludes a transition period that was marked by the twin GUI (*Qt* and *Motif*) of FEFLOW 6.0.

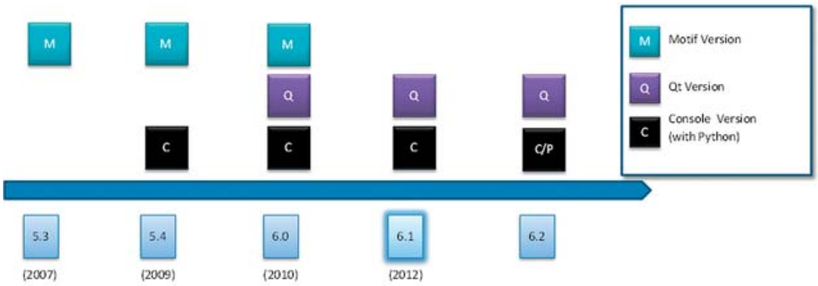


Fig. 1: FEFLOW development timeline

Declared ambition for the next release was thus the complete representation of all FEFLOW features in the new interface.

FEFLOW 6.1 delivers on this promise. The remaining gaps have been closed and as a result the 6.1 *Qt*-interface supports creating, editing, assigning, and visualizing of

- Transient material parameters,
- Material parameters for unsaturated flow,
- Anisotropic conductivity distributions,
- Discrete features (fractured, pipes, channels, ...),
- Budget node groups,
- Borehole-heat exchangers.

Familiar to many users for over two decades, the classic FEFLOW *Motif* user inter-

As a side benefit, FEFLOW no longer requires any *X*-server software which simplifies the installation, removes the potential for *X*-server-related technical complications and reduces third-party dependency.

There are significant improvements and new features in FEFLOW 6.1 that distinctly go beyond the urgently awaited completion of the *Qt*-GUI – they are the subject of separate articles in this issue.

Looking ahead

Prompted by numerous requests from the user community, a second, Python-scripting console application is currently under development.

Currently in prototype stage is the coupling of the FEFLOW engine with other simulators, which will be facilitated via an OpenMI wrapper around the new *Open FEFLOW* API.

A key long-term goal (6.3 or 6.4) is the handling of fully unstructured (tetrahedral) FE meshes. It is expected that a typical tet-mesh workflow will involve the import of (possibly CAD-generated) mesh geometry and topology directly associated with an elemental material index. The necessary introduction of a "material" concept to handle predefined parameter groups is conceivable with version 6.2. First steps beyond a prismatic mesh with strictly vertical edges are also planned for 6.2, specifically the ability to completely deactivate mesh elements (with respect to both computation and visibility) and a relaxation of the mesh geometry where slice-connecting element edges will no longer need to be strictly vertical while maintaining the general prismatic mesh topology.

Users strongly call for a user-friendly application to control PEST automated calibration, technical optimization (well position, etc.), and uncertainty analysis of FEFLOW models. Medium-term, it is intended to develop the new-generation FEFLOW/PEST interface into a convenient GUI-equipped scenario manager/batch processor with remote-execution control via TCP/IP for platform independence and potential cloud-computing capability.

As of version 6.2, the FEFLOW map interface will extend beyond file-based data and also include compatibility with ESRI ArcGIS as well as GIS map services such as Google Maps, OpenGIS, etc. This implies capability development for on-the-fly projection and data processing of maps.

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However, at that time the new interface did not fully cover the entire FEFLOW functionality and a resort to the classic GUI was still required in cases involving, for example, unsaturated conditions, fracture modeling, transient material data, or certain specific boundary conditions.

Now, with the release of FEFLOW 6.1 the work is complete and the classic GUI disappears forever(!). The software architecture has been modernized and generalized to attain a much higher extensibility and efficiency. Indeed, release 6.1 marks a new era in the FEFLOW development and paves the way for scientific and technological extensions which have been deferred so far.

We thank all users for their understanding and patience related to the long-term change of the GUI and software architecture: it was the ongoing support of our user community that allowed for the necessary steps to be taken in a very careful and rigorous manner. In fact, it was an 'open-heart surgery'. But finally and fortunately, the patient lives (survives) – even better, it got a drastic rejuvenation to keep running over the next decades, surely in the leading group.

FEFLOW 6.1 for geothermal modeling

Alexander Renz

With the rapid growth of the geothermal energy market, simulation models for heat transport have emerged from an exotic exercise to a standard application of FEFLOW during the last decade. With its ability to consider all relevant processes (advective, conductive and dispersive heat transport, temperature-related fluid density and viscosity) and providing the flexible mesh geometry needed for the implementation of complex structures for deep or near-surface geothermal models, FEFLOW has become an industry standard in many countries.

Motivated by this development, DHI-WASY has put a special focus on geothermal energy whenever extending FEFLOW's functionality. Consequently also the development of the new user interface was taken as an opportunity to incorporate the latest experiences in this sector; new features were added and some historical shortcomings could be overcome. As a result, FEFLOW 6.1 provides more features, higher accuracy and more productivity for geothermal projects than ever before.

Closed-loop systems

The incorporation of Borehole Heat Exchangers (BHE) including their internal heat transport is a unique feature in commercial groundwater modeling systems.

The BHE are now fully accessible in the new user interface, including the possibility to import large numbers of BHE and their properties directly from map files.

The new BHE boundary condition allows a direct prescription of power or temperature differentials without the previously necessary application of a plug-in.

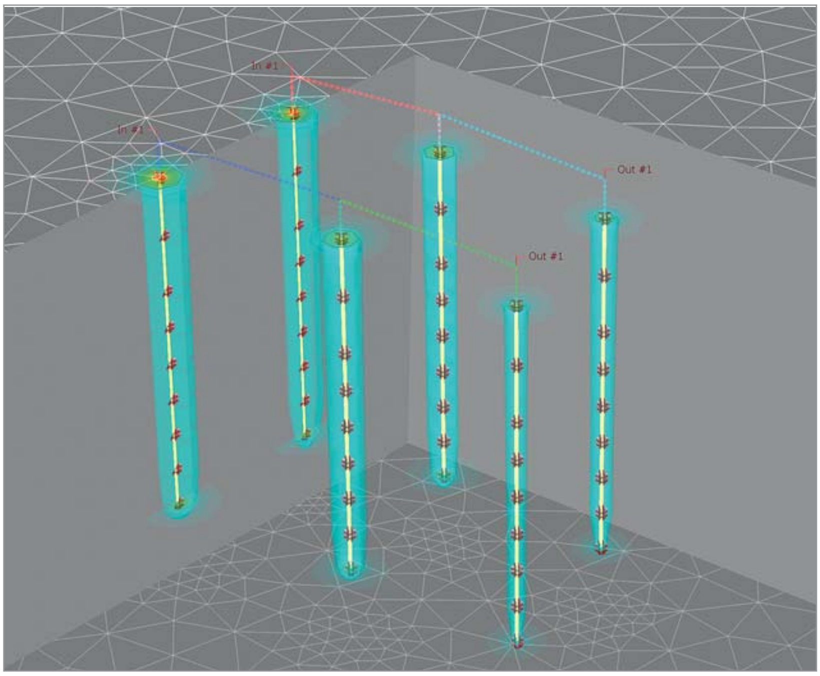


Fig. 1: BHE Array

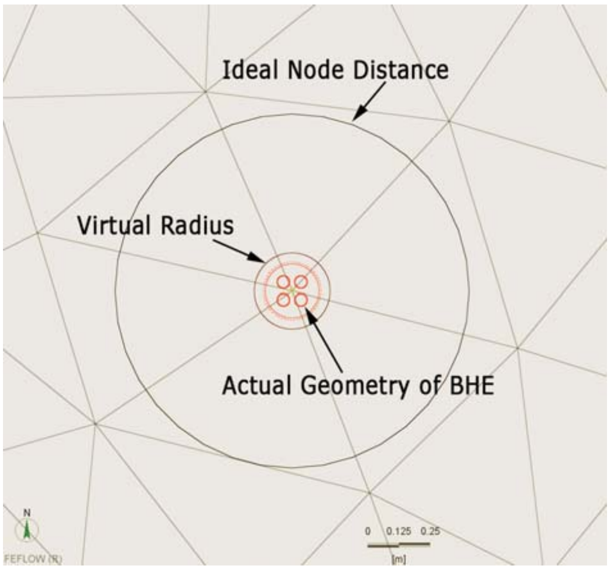


Fig. 2: Virtual radius

Parallel or serial connections of BHE can be implemented to allow the correct description of BHE arrays.

To assist the user in choosing the correct mesh geometry around the BHE, additional visualization styles are available to show the real and virtual well radii as well as the ideal distance to neighboring nodes. This is of critical importance for the accurate calculation of BHE and ground temperatures.

The temperature development of the individual BHE elements can be monitored in a new chart.

Open-loop systems

With its new Multilayer Well boundary condition, FEFLOW 6.1 uses a different and more physical approach to calculate heat transport in wells screened in multiple model layers. More precise temperature values can be obtained for extraction wells of open-loop systems by using this approach.

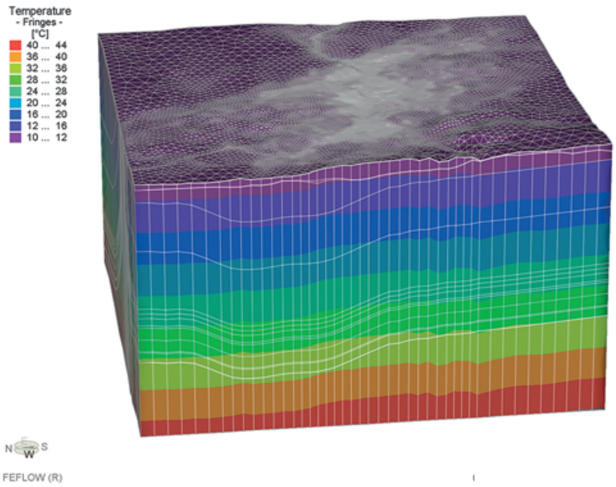


Fig. 3: Geothermal gradient applied

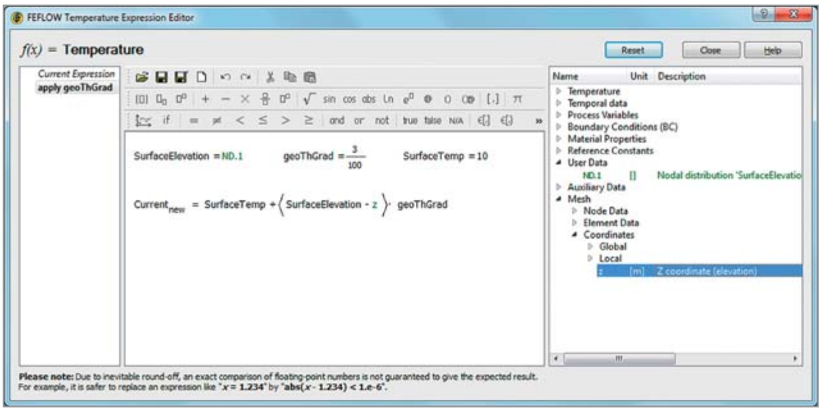


Fig. 4: Geothermal gradient expression

General improvements

Modelers of geothermal energy projects will significantly profit from a number of more general improvements in FEFLOW 6.1. Good examples are the possibilities to apply the geothermal gradient directly as initial temperature distribution using the new expression-based assignment tool, or to assign temperature boundary conditions from a calculated temperature field using the copy & paste functions.

Advances in visualization and user interface

Volker Clausnitzer & Julia Mayer

The much anticipated completion of the *Qt* user interface goes distinctly beyond reproducing the features of the now-legacy *Classic* interface. FEFLOW 6.1 brings powerful new GUI tools for model editing as well as advanced new visualization capabilities.

Model editing

Full GUI control of transient material properties: For many, this was perhaps the most critical feature still missing in FEFLOW 6.0. Version 6.1 provides convenient options for manual assignment and the use of time series as well as powerful map import. Similarly, FEFLOW 6.1 not only closes the gap regarding the editing of multilayer wells, borehole heat exchangers, and variably-saturated flow models, but in each case provides more

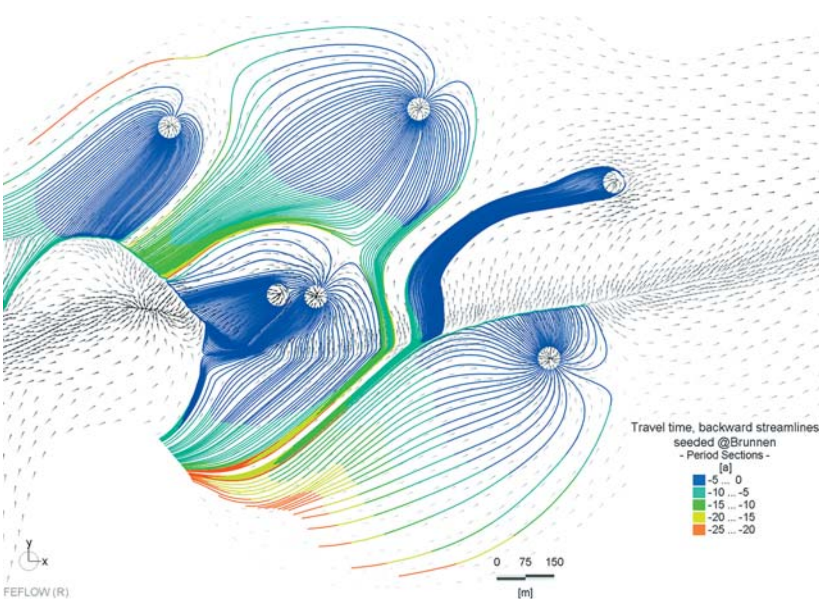


Fig. 1: Backward pathlines shown with period sections

comfortable and intuitive editing than has been available in the *Classic* interface.

The concept of selections for parameter assignment introduced in version 6.0 has been employed to extend discrete-feature modeling capability: Arbitrary mesh nodes on different slices can now be connected to one-dimensional discrete features. This provides, for example, an easy way to model inclined wells or boreholes.

Data plotting

FEFLOW 6.1 significantly extends the plotting capabilities of the previous version. Notably, forward and backward pathlines and/ or streamlines can now be displayed simultaneously while colored period sections facilitate quantitative travel-time analysis (Figure 1).

A new isoline implementation includes flexible, editable in-line labels and also provides more convenience: Based on the current (user-specified or automatic) value range, the interface automatically suggests appropriate "round" isoline levels and allows the definition of major and minor levels (Figure 2).

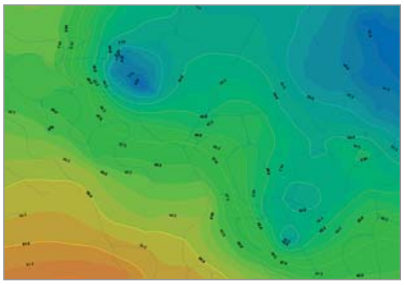


Fig. 2: Major and minor isolines with in-line labels

To facilitate a quick display of the water table, FEFLOW 6.1 provides predefined zero-pressure isoline and isosurface plot styles. Appearance settings can be easily copied not only between entire views but also for individual parameters or plot styles.

The visualization extensions also include an option for displaying calendar time instead of elapsed simulation time, and new annotations such as embedded polyline labels or title, header and footer text for each view window.

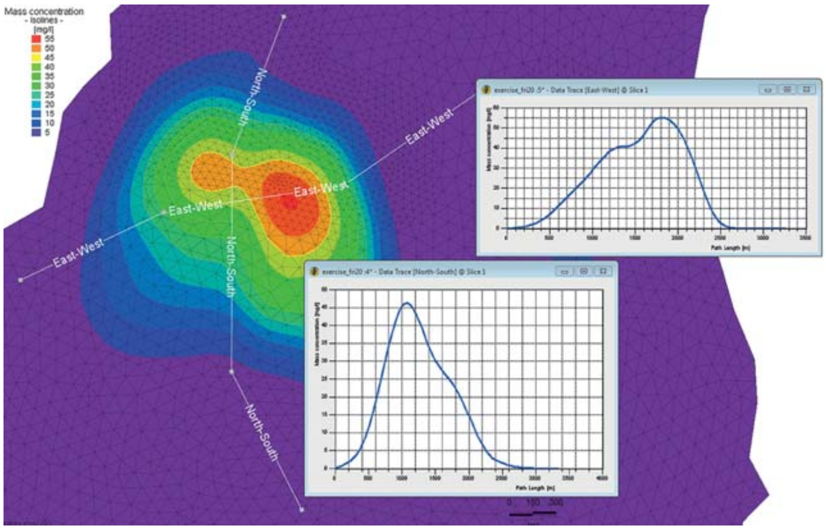


Fig. 3: Labeled cross-sectional lines and associated chart views

View windows

FEFLOW 6.1 complements the existing cross-section, slice and 3D view-window types by a new chart-like view that allows the monitoring of data plots along user-defined 2D polylines on a mesh slice, or along an arbitrary 3D polyline (Figure 3).

In any slice or 3D window, the default navigation reference (full object view) can now be replaced by a mesh-item selection (such as an element or node group) to obtain, for example, a user-defined center of rotation. Also, multiple view windows may be temporarily defined as slaves of a positioning-master view and will then automatically follow the navigation of the master.

Floating view windows for the positioning of views outside the FEFLOW application window and a full-screen mode offer more flexibility for presentation purposes as well as for the interactive work with multiple screens. The full-screen mode can be easily activated for any view window and allows the display of the model view at the maximum possible resolution for the given screen. All tools (navigation, selection, etc.) remain accessible and fully functional.

Stereoscopic visualization

Lastly, a technological trend merits mentioning that could become more prevalent in the near future: It appears increasingly likely that soon set-up and editing of three-dimensional spatial models may be assisted by stereoscopic visualization and direct three-dimensional manipulation. FEFLOW 6.1 takes a first concrete step in this direction by offering a variety of visualization options that, together with suitable hardware, can give a "real" sense of 3D. Specifically, two video signals (one for each eye) are provided simultaneously and separated via special glasses that make use of either shutter technology or polarized light. With FEFLOW 6.1 it is possible to export model snapshots and movies in various 3D stereoscopic formats. Given a 3D-capable monitor or projector, FEFLOW 6.1 also allows the interactive stereoscopic display in the familiar FEFLOW 3D view windows.

Compared to conventional 3D visualization, the difference in perception is particularly evident in models with complex structures. While traditional 3D displays typically require a rotation of the object to obtain an adequate depth perception for such structures, a stereoscopic display provides natural depth much more directly and easily.

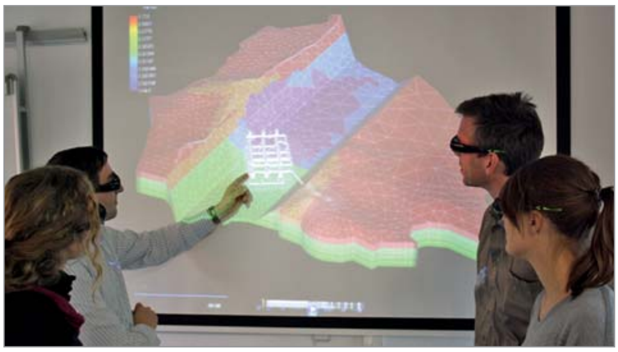


Fig. 4: Stereoscopic projection can improve the perception of complex spatial structures

Powerful features for a new level of workflow efficiency

Olaf Arndt & Rainer Gründler

Map usage

FEFLOW 6.1 introduces embedded supermesh and POW files as new map types. Several features were added to the map handling:

- Filtering map records via SQL (Structured Query Language) statements
- Joining of multiple maps using common key attributes
- Integrated map table data viewer

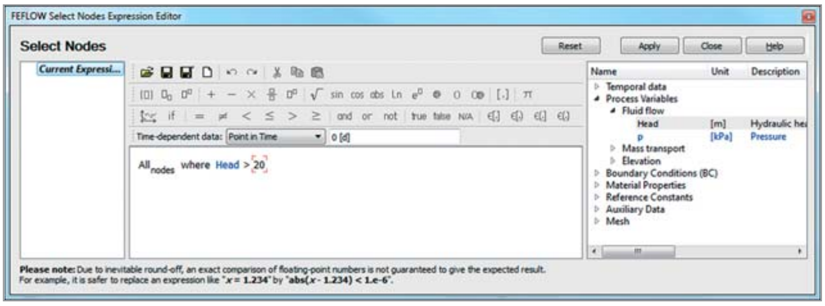


Fig. 2: Expression based selections

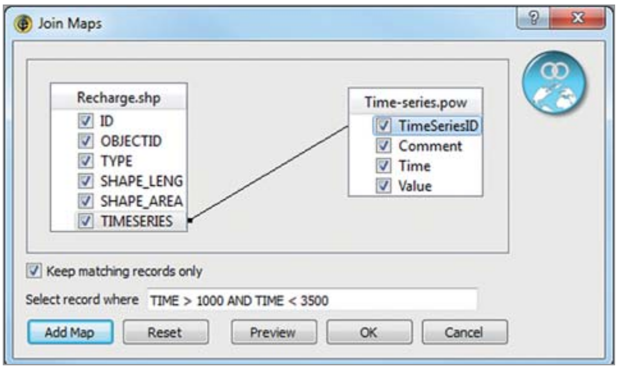


Fig. 1: Joining maps with SQL filtering

In addition, expression-based manipulation can be performed on map attributes during data assignment and 3D map selection was added for 3D maps.

Selections

In FEFLOW 6.1 the capability of selecting mesh items has been extended: New topology types (slice edges, join edges, slice faces, and join faces) are now supported and the selections were separated from the current model data. Each topology type has its own selection state which makes it possible to switch between nodal and elemental selection without losing the corresponding current selection. Additional features of selections are:

- Undo/redo operations are aware of mesh operations (refinement, de-refinement, etc.), hence, there is no need to drop in during such operations
- Expression-based selection (see *Expressions* section below)

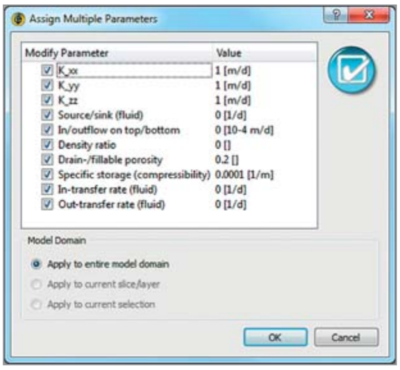


Fig. 3: Editing group of parameter values

Data assignment

FEFLOW 6.1 provides new tools to simplify the assignment of parameter data. In particular, two new features are remarkable:

- Assignment of discrete values to multiple parameters in a specific area at once
- Assignment of parameter values by expression (see *Expressions* section below)

Expressions

The FEFLOW *Expression Editor* is a powerful, generalized approach that replaces and far surpasses the *Debug* function for conditional editing of parameter values and process variables in the Classic user

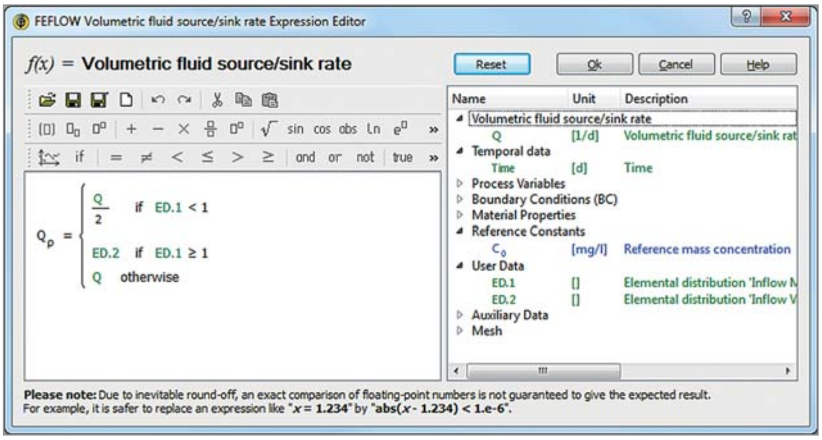


Fig. 4: Expression based value assignment

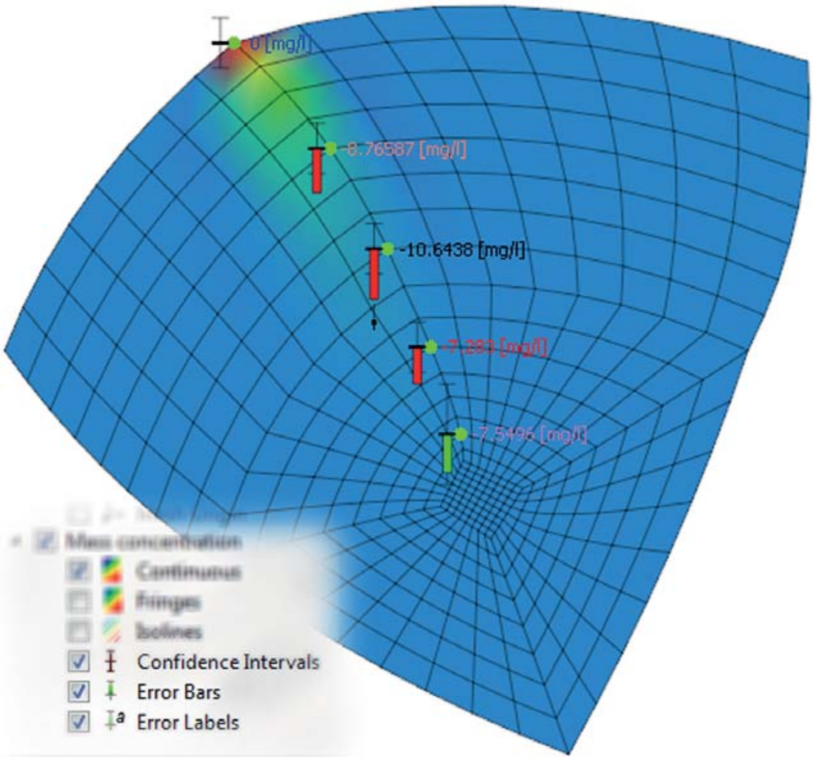


Fig. 5: Error bars and confidence intervals

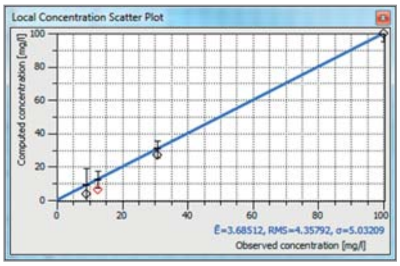


Fig. 6: Scatter plot

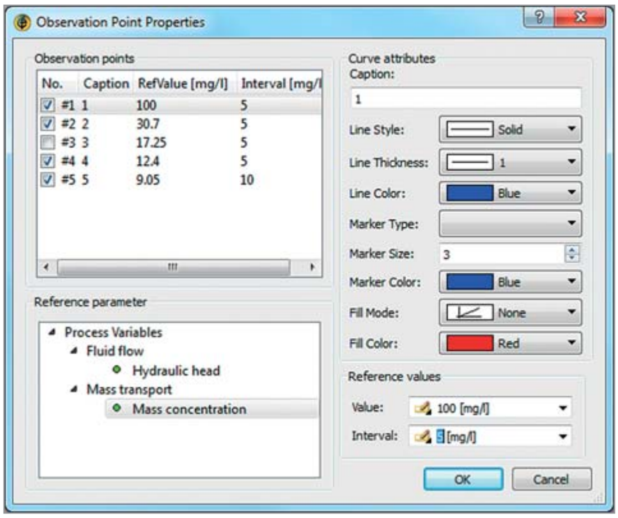


Fig. 7: Observation point property editor

interface. Simple or complex user-defined mathematical expressions can now be used to create element or node selections that are based on current parameter values, process variables or mesh data such as coordinates or node/ element numbers. The *Expression Editor* can further be used to evaluate parameter values based on user-defined expressions and to assign them to an existing selection. Finally, FEFLOW 6.1 provides the means to create new parameter distributions that are defined by mathematical expressions. These are updated dynamically during the computation and can be visualized analogously to other internal FEFLOW parameters. A prominent application example is the dynamic display of groundwater drawdown during a simulation run or while replaying a simulation record.

Data calibration tools

FEFLOW 6.1 offers an extended set of tools for the calibration of FEM models. Reference values can now be used in addition to the regular observation points to visualize the deviation between measured and computed parameters. New visualization options are available for process variables such as hydraulic head or concentration:

- Confidence intervals
- Error bars with qualitative indication
- Error labels displaying the absolute deviation

Mesh geometry

The classic version of FEFLOW provided various tools to check the meshing quality (mesh geometry submenu). In FEFLOW 6.1 most of these tools are represented as *auxiliary parameters*. They include:

- Slice distance (distance between nodes at slice and the slice below)
- Layer thickness (distance between element center points of neighbored layers)
- Maximum interior angle of triangular elements
- Elements violating the Delaunay criterion

These parameters can be used like regular parameters for visualization, export, plotting, and in expressions. Scalar features such as mesh area and volume have their place now in the Summary page of the problem-settings editor.

Geotransformation

The re-implemented geotransformation dialog facilitates the complete transformation of the FEM mesh, superelement mesh, observation points and additional location sets (2D/3D points, polylines, and loops). Besides standard affine and Helmert transformations, FEFLOW 6.1 supports all WGEO transformations as well. By means of a Microsoft-COM-based API it is possible to extend the set of available transformations by custom transformations.

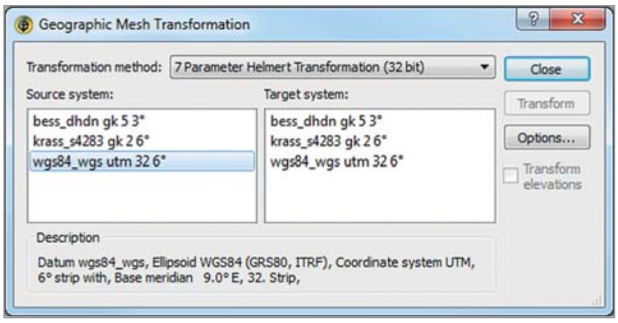


Fig. 8: Geographic transformations

File input and output

As has been customary throughout FEFLOW history, the current version 6.1 is able to read and write the file format of any previous version. New is the ability to write into temporary files rather than overwriting the target files directly. This keeps existing files unaffected until

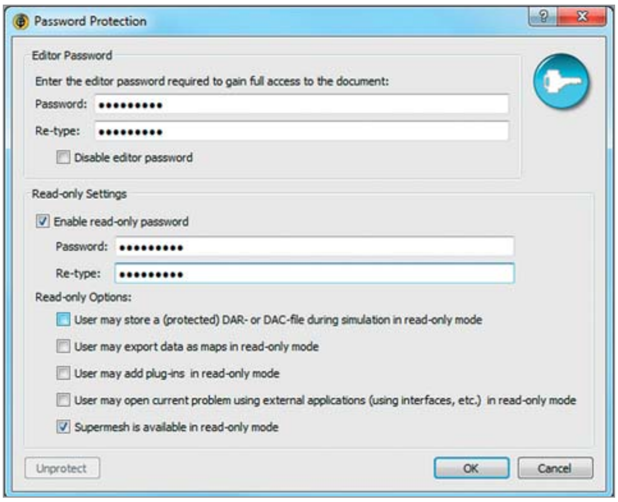


Fig. 9: File protection settings

the write operation concludes successfully. As a positive side effect the previous version can be kept as a backup file (this feature can be user-enabled as a global setting). If a backup file is available the previous version can be restored with the *Revert* command in the *File* menu.

Model protection

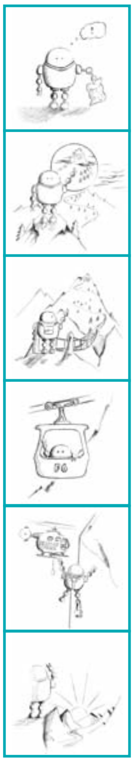
In general, the set-up of a FEFLOW groundwater model requires an enormous investment in terms of expert knowledge and working hours. Nevertheless, during some projects it might be necessary to provide the model to project partners, customers, or even to external staff. In the past, such a necessity always implied a transfer of the knowledge and work effort as well. To protect the investment, FEFLOW 6.1 now supports model protection which can be applied to the finite-element model as well as corresponding DAC result files. It is possible to define an editor and an optional read-only password and several options to enable or disable read-only operations such as:

- Creation of DAR- and DAC-files during simulation
- Export of model data
- Usage of additional plugins (IFM)
- Model access by external applications based on the FEFLOW simulation kernel
- Access to the supermesh

The model protection even provides the ability to block anyone from modifying the model or result file so as to prevent any subsequent manipulations.

Three years since the first ascent of Mount FEFLOW 6 – *where are you?*

Peter Schätzl



When presenting FEFLOW 6 in this newsletter in 2009, we had used the metaphor of FEFLOW users climbing a far and at least at first glance, high and steep mountain while learning how to use the new user interface. At that time, we had done our best to pave the track, to build suspension bridges and funiculars, and to make sure that not too many of you would need a rescue team – but upfront we could only hope that these auxiliary means would be sufficient to enable both experienced and novice climbers to reach the top of FEFLOW 6.

Now, three years later, we can look back on all the encounters we had with you hikers and climbers, and we feel that all who have started the tour have reached the summit. The rescue team had to guide some people back onto the track once in a while, but it didn't have to salvage anyone from free fall, and only minor injuries were reported. At the same time it turned out that for novice hikers starting from the valley bottom without having climbed Mount FEFLOW 5 first, the tour up to Mount FEFLOW 6 was even shorter and much less exhausting than the one up to Mount FEFLOW 5 would have been. And with less effort they got much better views!

During the time of FEFLOW 6.0, many of you were going back and forth over the suspension bridge linking FEFLOW Classic and FEFLOW Standard, and some of you were even staying behind in the comfortable and homely hut on Mount FEFLOW Classic. For these hikers there's somewhat bad news: FEFLOW 6.1 does no longer have the Classic interface, so if you don't want to stay behind the crowd, you'll have to move on to Mount FEFLOW 6.1 soon.

The good news is: There's still a good track paved with an updated and extended help system and a User Manual with many tutorials, and there are many new tutorial screencasts showing the most important user interface features in action. And of course the funicular still operates on schedule and on demand – training courses being organized for open enrollment and as tailored workshops. Contact our new dedicated funicular operator Karen Bossel (FEFLOW Training Coordinator, *sales@dhi-wasy.de*) for any questions and wishes regarding FEFLOW training. And if you get lost, but are not yet ready to call in the rescue team or pay for the cable car – just ask your fellow walkers for the best way to the top via the FEFLOW Web Forum.

We are looking forward to seeing all of you on Mount FEFLOW 6.1 – the summit right next to, but clearly overtopping, Mount FEFLOW 6.0.

Fig. 1–6: © Cryptic 2009

The FEFLOW-PEST interface

Erik McCurdy

What is PEST?

PEST (*by J. Doherty, Watermark Numerical Computing*) is a software tool which can be extremely helpful when calibrating models. It achieves this goal by using modeling software in an inverse way: It attempts to find the combination of input values, which result in a set of known output values. This requires that the model be run many times to test how the output values depend on the input values.

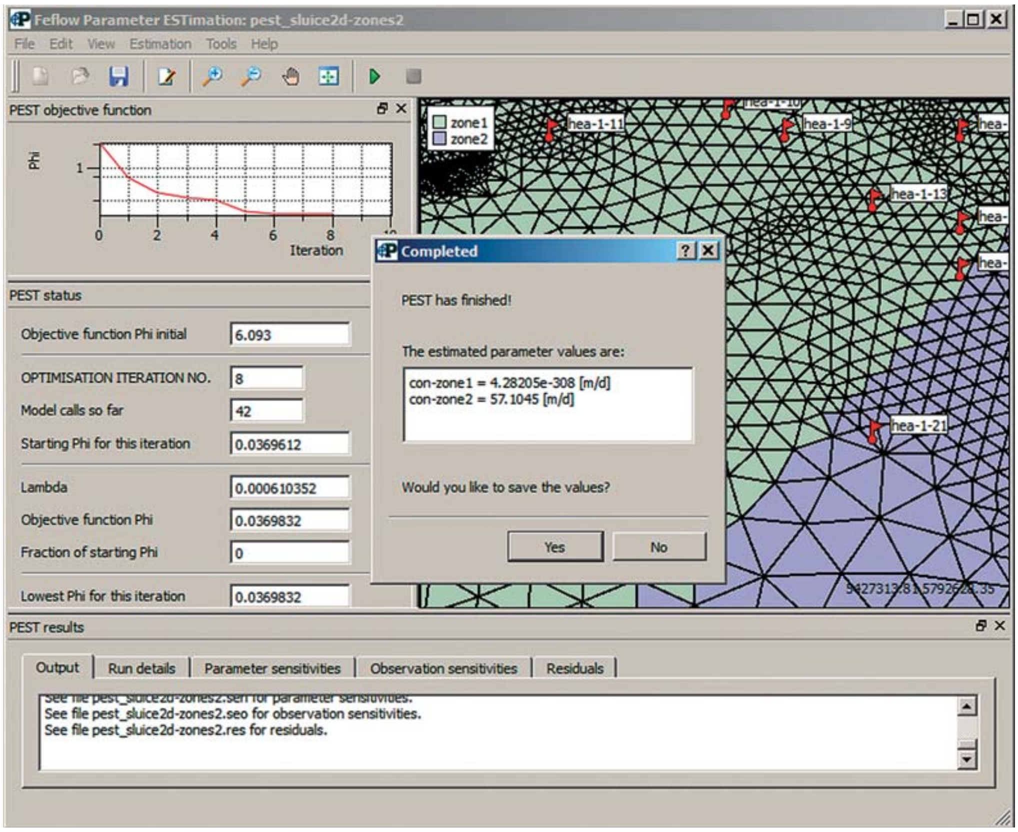


Fig. 1: A screen shot of the new FEFLOW-PEST interface

PEST is model-independent, requiring only that the modeling software is able to read input and write output to text files. Using the text versions of the FEFLOW **fem**- and **dar**-file formats it is possible to use PEST with FEFLOW by constructing PEST configuration files manually. An article describing this procedure is available here: *http://www.feflow.com/uploads/media/pest_feflow.pdf*.

PEST in previous versions of FEFLOW

An IFM module is available which provides a user interface to configure and run PEST with FEFLOW 6.0 in Classic mode. A special recoded version based on PEST version 2.0 was used for this module which enabled it to run from within the FEFLOW process as it is loaded as dynamic link library. Starting with version 6.1 the PEST IFM module will no longer be supported due to the discontinuation of FEFLOW Classic mode.

PEST and FEFLOW 6.1

A new tool for FEFLOW has been developed to replace the legacy IFM module. Like the IFM module it will provide a user interface for configuring and running PEST for a FEFLOW problem but it will use a new approach: the new tool will be a separate executable which will start the standard PEST-executable. It will not be reliant on any particular version of PEST, which was a major disadvantage of the IFM module. Users can therefore now benefit from improvements and newer features as they become available with new PEST versions. The PEST files created by the tool can be edited manually prior to running PEST and thus PEST-functionality not available through the user interface may be activated. Parameter zones are easily defined by creating element sets within FEFLOW and observations by setting reference parameter values at observation points.

Future plans

Aside from performance improvements, new features currently under development include support for pilot points, Parallel PEST, and map services.

DHI-WASY has committed substantial resources for advancing the FEFLOW-PEST interface and suggestions from the FEFLOW community will be very important in deciding what to include in future releases.

http://www.feflow.com/uploads/media/pest_feflow.pdf

Solving large problems in FEFLOW

Vladimir Myrnyy

The performance limit of a single-processor core essentially having been reached several years ago, any increase in the computational power of modern computers is now mainly related to multicore architectures with recent advances including many cores of graphical processors (GPUs), specific processors with many integrated cores (MIC), and the processor vector extensions SSE and AVX.

FEFLOW 6.1 provides basic parallelization capabilities to use multicore shared-memory architectures and accelerate the simulation process. The performance benefit is strongly related to model size and can easily reach several days of computational time for models with millions of nodes.

Each time step of a simulation process can be roughly split into two steps: matrix assembly and solution of the linear equation system based on the assembled matrix. The assembly step is parallelized via an efficient mesh partitioning. A parallelization of the solution step is achieved by the SAMG solver from Fraunhofer Institute for Algorithms and Scientific Computing which implements a hierarchic multi-grid method using OpenMP.

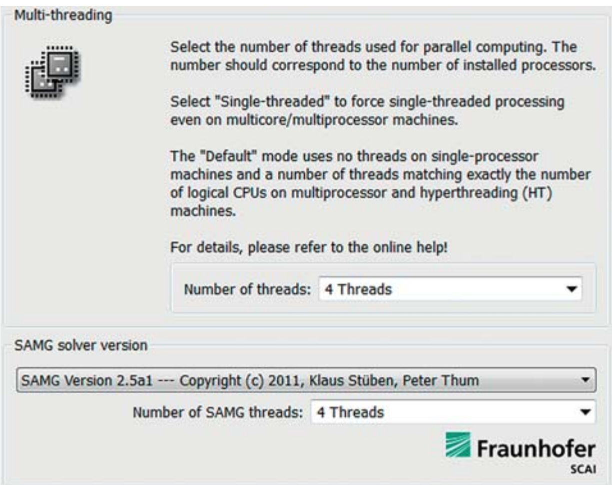


Fig. 1: FEFLOW 6.1 parallel-computing dialog window

SAMG Solver

For several years now SAMG has been a stable and efficient alternative to the default PCG for symmetric and BiCGStab for non-symmetric matrices for large models. In FEFLOW 6.1 the user can select between three versions: 2.3a5, available since FEFLOW 5.4; 2.5a1, the default; 2.6a1, the latest, recently released version. The major improvement of version 2.5a1 was a new automatic solver control for the benefit transient simulations. It attempts to minimize set-up cost by reusing set-ups from previous calls, and also dynamically switches between multi-grid and an alternative (one-level) solver – whichever appears to be more efficient. Version 2.6a1 provides a better OpenMP parallelization as well as additional one-level solvers, including ICCG for symmetric matrices and the direct solver PARDISO.

Table 1: Benchmark models description

Model	Flow	Mass transport	Simulation period	Mesh	Number of elements	Number of nodes
1	√	√	100 d	Triangular	28940	17712
2	√		100 d	Triangular	459155	277158
3	√		steady	Quadrilateral	640000	667521
4	√	√	10 d	Triangular	1852160	1114038

The FEFLOW 6.1 user interface offers controls for selecting the SAMG version as well as the number of SAMG threads (Figure 1). Notably, the number of SAMG threads is completely independent of the separately entered number of threads to be used for matrix assembly parallelization. The selected options persist for future FEFLOW sessions on the same workstation.

When SAMG cannot achieve the targeted accuracy, a warning message will appear in the log window reporting both the actual and target residual values. If that message appears frequently during the simulation, a critical evaluation of the overall accuracy is indicated.

Benchmarks

The performance benefit of parallelization was tested on four models covering different problem classes – one relatively small one for comparative reasons, and three larger ones with hundreds of thousands of mesh elements each (Table 1). All tests were executed on a server with two Xeon X5690@3.47Ghz running the Windows Server 2008 operating system.

Table 2: CPU time in minutes for different solvers in single-threaded mode

Model	PCG/ BiCGStab	SAMG 2.3	SAMG 2.5	SAMG 2.6
1	1.0	3.2	1.3	0.8
2	5.4	12.3	5.7	4.6
3	0.9	1.3	0.6	0.9
4	144.4	190.3	138.5	125.3

Table 3: CPU time in minutes for 1, 2, 4, 8 and 12 threads

Model	1	2	4	8	12
1	1.3	1.1	0.8	0.6	0.6
2	5.7	3.8	2.6	1.9	1.8
3	0.6	0.4	0.4	0.3	0.3
4	138.5	77.1	66.3	52.2	42.6

Single-thread performance of iterative solvers

Table 2 compares single-threaded performance, expressed in CPU-time over all time steps of the simulation. The results clearly show that in terms of single-threaded speed SAMG 2.3 is inferior to the PCG/ BiCGStab solvers in all cases. Moreover, the results illustrate the benefit of adaptive switching to a simple one-level solver introduced with version 2.5, which saves a multi-grid set up: versions 2.5 and 2.6 deliver comparable or better single-threaded performance relative to PCG/ BiCGStab.

SAMG parallel performance

Parallel performance has been tested on the default SAMG version 2.5. The same four simulations were executed using 1, 2, 4, 8 and 12 threads (Table 3). In every test the same number of threads was used for both matrix assembly and SAMG. The general trend shows better speed up (Figure 2) for larger number of mesh nodes with an additional dependency on the problem class. For instance, model 2 has fewer mesh nodes than model 3, but solves flow and transport at every time step and thus derives more benefit from multi-threading.

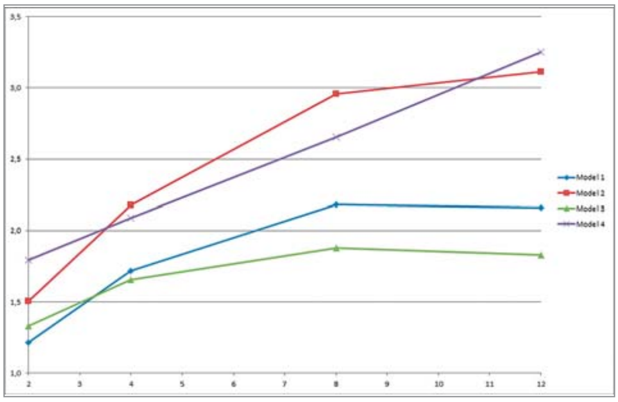


Fig. 2: Speedup with respect to the number of threads

The speedup coefficient is significantly less than the number of used threads, because of inevitable sequential parts in the code and thread-handling overhead. Still the speedup can increase linearly for large models containing more than one million mesh nodes as seen for model 4 in Figure 2.

The FEFLOW book

Hans-Jörg G. Diersch

A new textbook titled ***FEFLOW – Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media*** will be published by Springer next year. This comprehensive book covers on nearly 1000 pages the full spectrum of state-of-the-art modeling from fundamental concepts to problem solutions, extensively and systematically describing FEFLOW's underlying basics and computational capabilities. It fills the gap we recognize in the existing reference materials and various white papers, where the matter has been presented incoherently and parts appeared incomplete. We believe that advanced software such as FEFLOW needs an appropriate fundamental reference work that provides a high transparency of the theoretical and numerical background, makes the available solution methods accessible, reliable and better understandable, and helps users to extend their insight in modeling and to open new fields of application.

The book consists of 15 chapters, which can be formally grouped into two major parts: (I) fundamentals and (II) finite element method (FEM), supplemented by a number of appendices. Part I covers the fundamentals of modeling flow, mass and heat transport processes in porous and fractured media. It starts with preliminaries, where all important notations, definitions and fundamental algebra used throughout the text are explained. Chapters deal with a more general theory for all relevant phenomena on the basis of the continuum approach, develop systematically the basic framework for important classes of problems and derive all relevant constitutive relations based on unified and rigorous principles. The general set of model equations for the multiphase and multispecies, chemically reactive, variable-density, non-Darcy and non-isothermal processes are reduced, in stepwise manner, to important model subclasses in practical modeling applied to variably saturated media, fractured media, and unconfined and confined aquifers. Appropriate boundary, constraint and initial conditions complete the model formulations.

Chapters of part II explain and emphasize the FEM in a number of areas: (1) fundamental concepts (also in relation to other numerical methods such as finite difference, finite volume and spectral methods) including upwind schemes with their pros and cons, numerical stability and accuracy, sparse matrix solution techniques, treatment of nonlinearities, suitable time-integration procedures, proper approaches for flux computation, budget evaluation and property of local conservativity; (2) flow in saturated porous media with free-surface simulation on rigid and moving meshes including multilayer wells; (3) flow in variably saturated porous media with the different forms of Richards' equation, preferred solution techniques and hysteresis; (4) variable-density flow in porous media including sharp interface approximation, convection phenomena, double-diffusive fingering and useful approximation methods; (5) mass transport in porous media with and without chemical reactions; (6) heat transport in porous media involving application of borehole heat exchangers; (7) flow, mass and heat transport occurring in discrete features; and (8) special topics including mesh generation, pathline tracking and others. In all areas a number of prototypical examples and benchmarks are presented to illustrate the capability, usefulness, accuracy and efficiency of FEM.

The book is primarily written for current and future FEFLOW users as a comprehensive theoretical fundament and modeling reference; however, due to its general approach it will also be useful for students and practitioners in engineering, geosciences, and other branches where porous media flow dynamics and computational methods are of specific concern.

Consulting

Case Study Speeding up and improving the conceptual modeling process

Thomas Krom, *ARANZ Geo Limited*

leapfrog

Leapfrog Hydro is a tool for knowledge discovery and numerical analysis within geological systems. The software is based on the implicit modeling approach which results in a **rapid** work flow for the development of geological models. These models are grid free and can then be transferred to grids for use in the FEFLOW flow and transport simulator. To quote a user: "Having worked with geological modeling tools since 1990, I find Leapfrog Hydro to be the most innovative, cost effective, and flexible geological modeling tool I have yet seen. Leapfrog Hydro helped us to quickly solve the most complex geological modeling challenge we've faced in years."

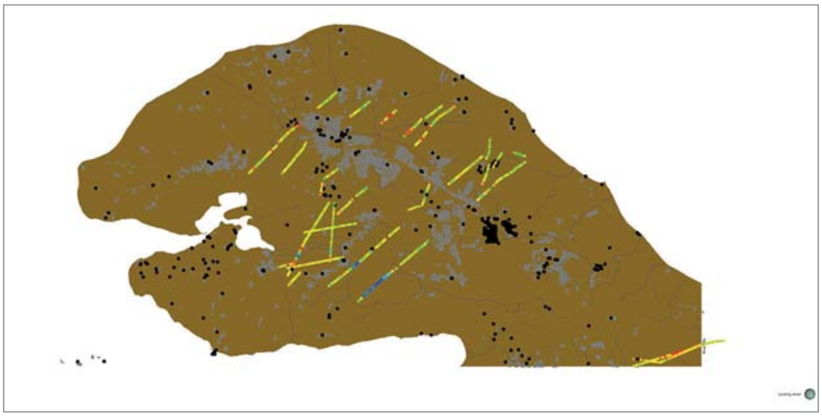


Fig. 1: Data at the site. Borehole logs are black dots while DC-resistivity data is shown as colored lines.

Key tools

Leapfrog Hydro is designed for integration in your business processes and uses data from a wide variety of sources including:

- GIS data in vector and raster format
- Images (georeferencing tools)

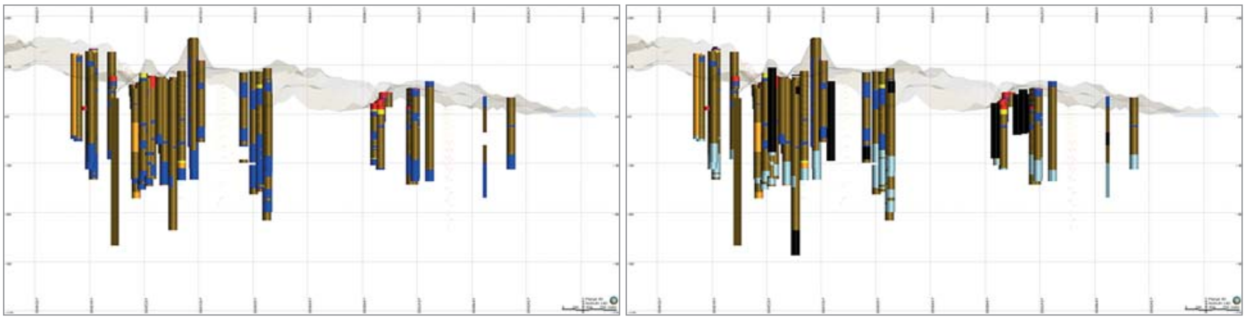


Fig. 2: An E-W same cross-section through the data set, on the left the grouped borehole descriptions and on the right the same borehole data after the main aquifer (light blue) is separated out using the graphical selection tools in Hydro.

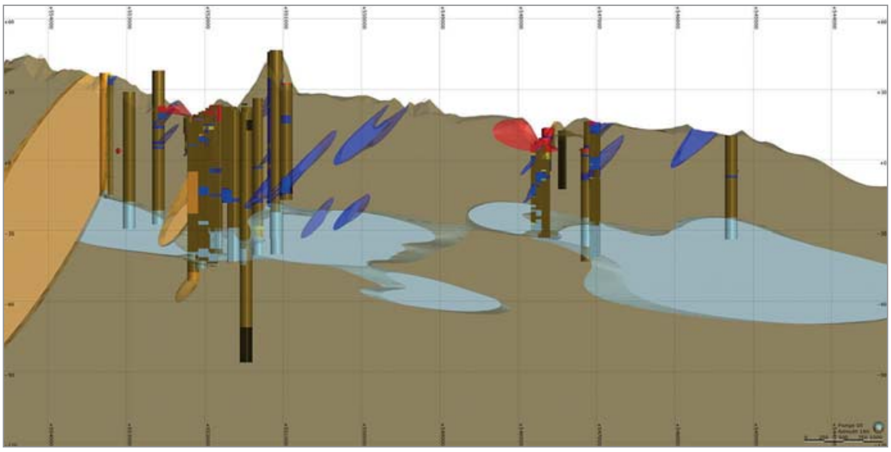


Fig. 3: Cross-section from Figure 2, but with the geological model shown, note that projection width is less than in Figure 2.

The user can model geological units using the most appropriate data. Figure 4 shows a large sand lens modeled directly from DC resistivity data. The geological model can be used to guide the development of the FEFLOW model; and the FEFLOW model including applying geological zonation can be developed literally in minutes once the geological model is developed. Figures 5 and 6 compare the FEFLOW model grid against the geological model, while Figure 7 shows the model in FEFLOW.

- Borehole logs: lithology, wire-line, well screens et al.
- Well screen data (e.g. water levels and concentrations)
- Data from electrical geophysical surveys (resistivity and TEM)
- Point data (e.g. picks from old paper logs)
- Scanned cross-sections
- Other geological modeling packages.

Case study

The following example is motivated by the need to maintain water quality across a peninsula where the water quality is threatened from a number of different contaminant sources. The base data is approximately 350 borehole logs that cover the site (Figure 1) as well as DC resistivity data. Geologically the model is dominated by glacial deposits and lenses which partially cover the modeling area.

The detailed geology can be regrouped using tools in Leapfrog Hydro to provide a more appropriate classification for hydrogeological purposes, for example coarse and fine sands can be grouped together. Tools are also available to split lithologies that are in fact part of multiple structures and need to be modeled separately (Figure 2).

Several geological models can be produced for a site (Figure 3) to explain different geological interpretations and these can then be easily converted to a finite element mesh. It is also possible to explore the effects of alternative meshing solutions on the flow modeling simulations independently of the geological modeling.

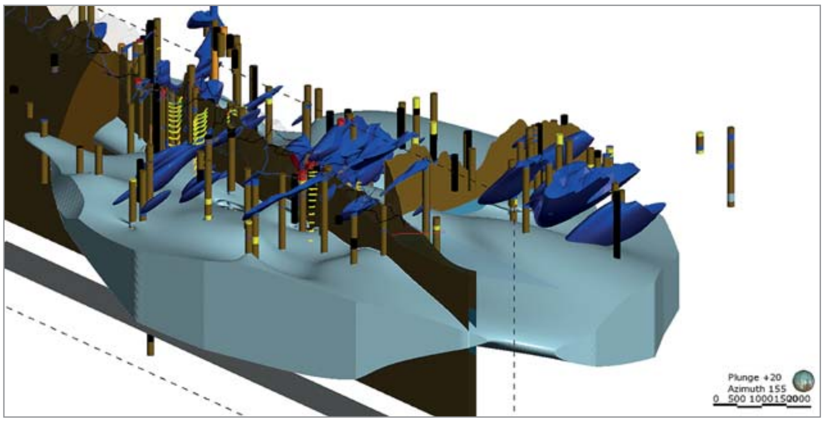


Fig. 4: The main aquifer and gravel lenses, where the cross-sections show the background till, the large sand lens in the middle is modeled directly from DC-resistivity data.

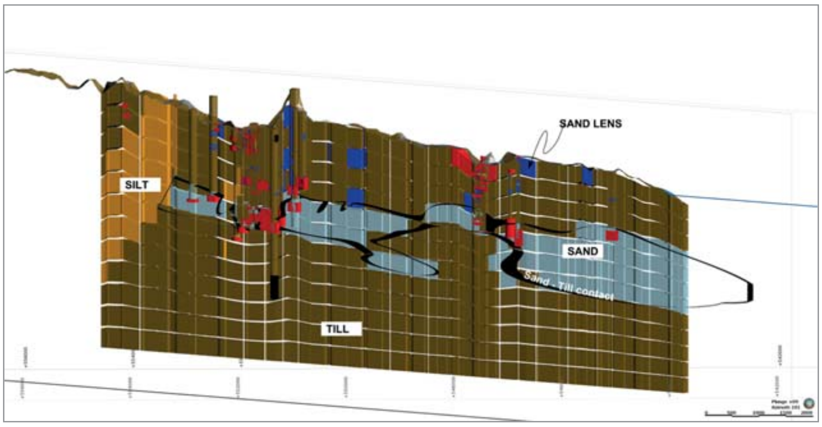


Fig. 5: Cross-section view showing the FEFLOW mesh and the outside of the lower aquifer. Note how Hydro has assigned the correct material property to each element/node.

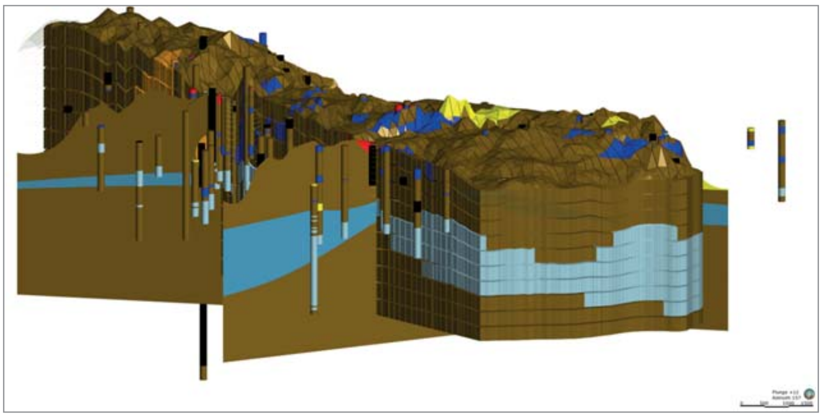


Fig. 6: Along the cross-section line we see the FEFLOW model sliced and the borehole data.

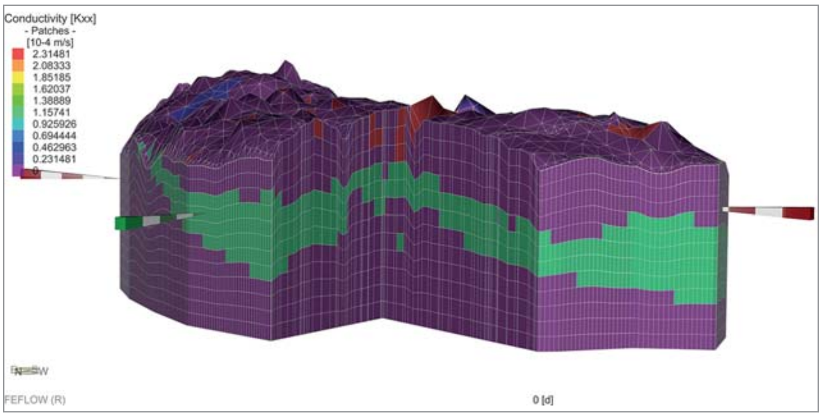


Fig. 7: The exported model in FEFLOW colored by hydraulic conductivity in the X direction.

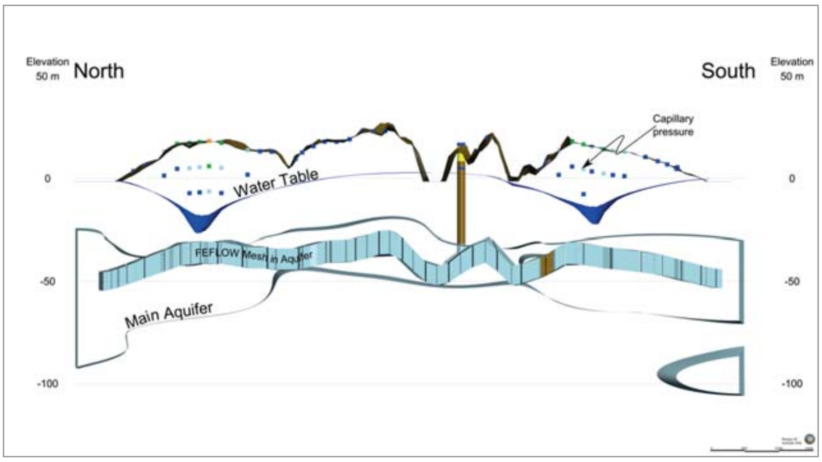


Fig. 8: Results from a FEFLOW simulation in Leapfrog Hydro.

Connection to FEFLOW

The gridding starts by constructing the 2D super mesh in FEFLOW. Once the geological model is built the 3D FEFLOW mesh is constructed in Hydro using that 2D mesh as a guide, and material properties are assigned. The final 3D grid is then exported to FEFLOW as a FEM file. Once the model is set up and calibrated in FEFLOW results can be shown in Hydro. Figure 8 shows the water table and capillary suction for this case study.

Benefits

Leapfrog Hydro software provides an intuitive environment for geological modeling, meaning a more comprehensive model of the geology can be built in less time. The user benefits from gains in:

- Productivity: The software aids staff in carrying out routine tasks more rapidly than in traditional work flows as well as speeding up data cleaning and analysis. Training requirements are lower than for competing products.
- Quality: Since time allotted to routine tasks is reduced, staff can carry out more analysis resulting in better results. Leapfrog Software is designed to aid in QA/QC. These will give you a market advantage over the competition

A user survey shows that a single seat of Leapfrog Hydro on average is used by 3 staff members. If each staff member can save 25 hours of work a year, the software is paid for. Additionally, product quality can be improved for the same resource allocation for project work.

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Prognoses of groundwater influenced flooding of abandoned mining areas in Eastern Germany

Bertram Monninkhoff & Junfeng Luo

Introduction

Since the end of the 19th century, large parts of Southern Brandenburg and Saxony in Eastern Germany have been characterized by large industrial zones, producing lignite and electricity. Although mining carries on to date and three large power stations continue to produce electricity, some of the industrial activities are planned to be phased out by 2015. A number of old pits left by the mining process have already

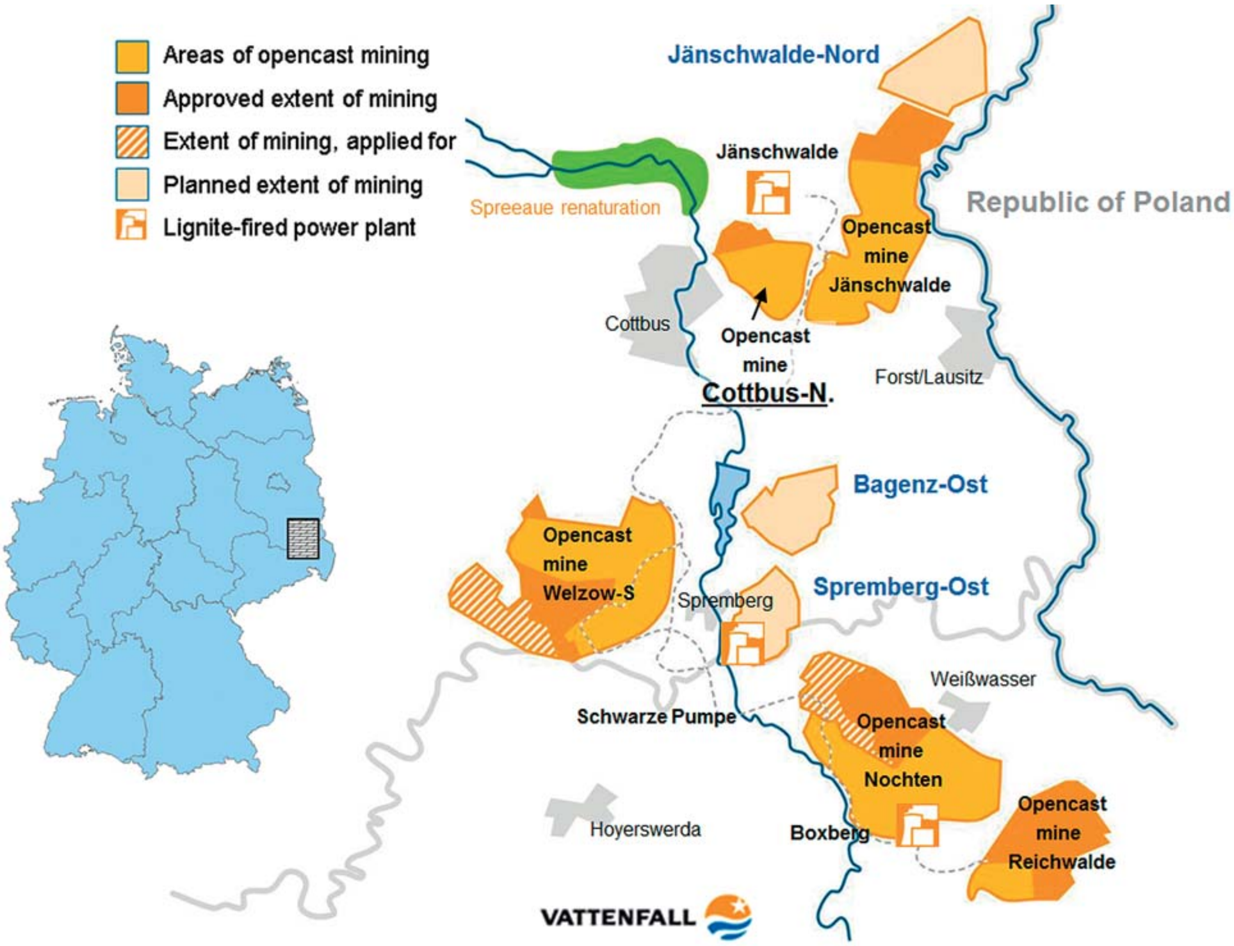

Fig. 1: Location of Cottbus-Nord and the surrounding mining pits

been transformed into a new landscape formerly unknown in this region, creating a huge new lake district. One of the lakes to be developed is the "Cottbuser See" to the East of the city of Cottbus (mining pit Cottbus-Nord).

DHI-WASY was contracted by Vattenfall Europe Mining AG to analyze the flooding process of this lake approximately 19 km² in size.

Methodology and model setup

To identify the optimal flooding strategy to flood and control the lake Cottbuser See the following model components are used:

- a 3D FEFLOW groundwater model
- a FEFLOW plug-in termed IfmLAKE enabling detailed description of the flooding
- a WBalMo water and allocation model to identify long term water needs and optimal allocation strategies
- a MIKE11 surface water model to describe different options for the outflow to the river Spree.

The first two components are completely integrated and are used to simulate the water level development in the lake and for detailed description of the surrounding groundwater levels.

To describe the water level development of the lake, detailed information about the

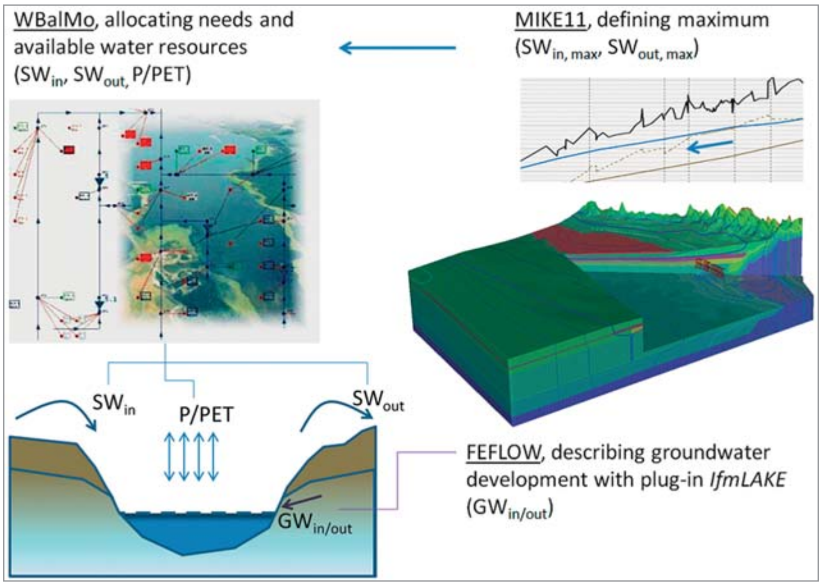

Fig. 2: Model components system

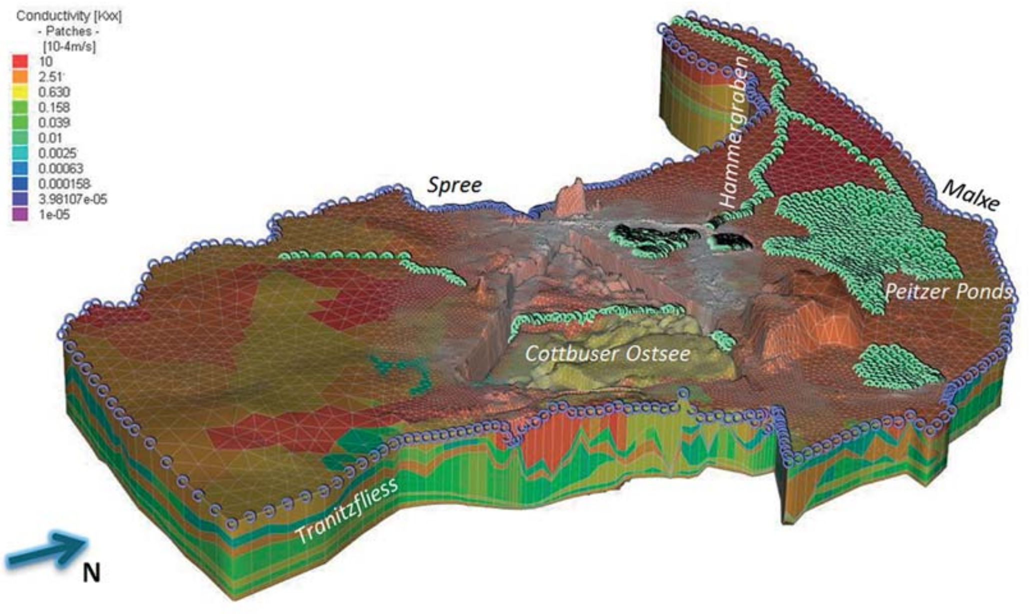

Fig. 3: FEFLOW model with applied conductivities and boundary conditions

inflow into the lake is needed. This inflow consists of three components; (1) groundwater inflow, (2) surface water inflow and (3) rainfall and evaporation at the lake surface. The second component is calculated by the model WBalMo and includes detailed information on the long term water needs and availability of the Spree. It also includes information about the maximum outflow rate of the planned diversion system, which is provided by the fourth model component (MIKE11). This model component system is shown in Figure 2.

The FEFLOW plug-in IfmLAKE has already been described in *DHI-WASY Aktuell 3/2011*. For this project it has been extended to offer the possibility of linking lake series. Within the FEFLOW model linking points can be defined including corresponding weir levels and widths. In case the lakes levels at both sides of a single weir are above the weir crest, both lakes are regarded as a single lake and the corresponding water level – volume curves are integrated. This feature was used to divide the lake Cottbuser See into eight separate parts. This was necessary to describe the flooding of the different basins, especially the basin which was used to fill the lake with additional surface water from the Spree river.

An overview on the 3D FEFLOW groundwater model is shown in Figure 3.

The water management and allocation software WBalMo has already been used in previous analyses for the utilization concept of the mining pit Cottbus-Nord. The model WBalMo Spree/Schwarze Elster was since extended and updated and builds a good basis for long-term management analyses of the area in focus, and the lake Cottbuser See in particular.

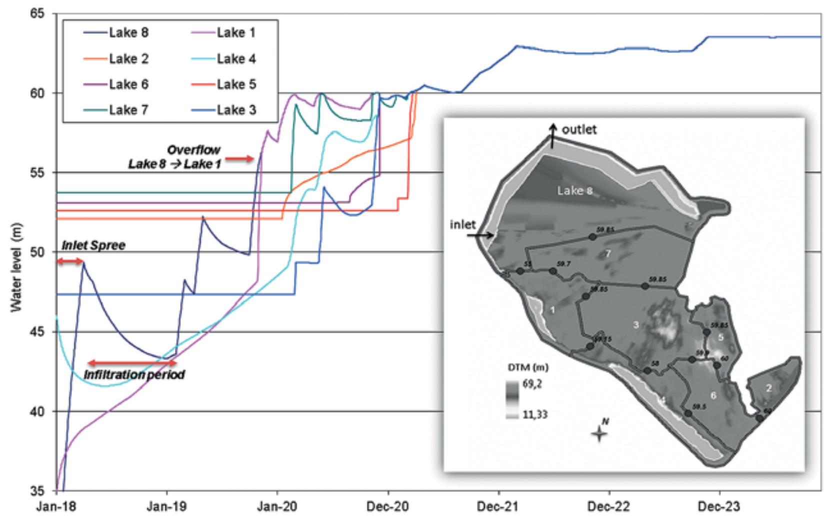

Fig 4: Water level development within single lake basins with additional surface water inlet

Optimization analyses of the WBalMo model had to be restricted with respect to the maximum possible outflow discharge towards the Spree. For this reason, first hydrodynamic analyses using the 1D model MIKE11 were made for routes along the existing branch Schwarzer Graben, as well as for alternative routes directly towards the Spree. For all alternatives, maximum discharges and related costs were analyzed.

Results

Results of the WBalMo simulations were used in FEFLOW (with IfmLAKE) to calculate the water levels in each single sub-lake and to analyze the influence of the proposed control strategy on groundwater levels in the region. An exemplary result of these simulations is shown in Figure 4. The strategy shown in this figure involves an additional surface water inflow from the river Spree under average flow conditions. The maximum withdrawal of surface water is defined according to the management rules currently established by the water authorities in the Spree river basin. The figure shows that in this case the flooding of the lake will take approximately five years (up to a level of 63.5 m). The flooding would then be finished around 2023, which is approximately seven years earlier compared with the flooding period applying a strategy without additional surface water inflow.

Within the project new features of FEFLOW 6.1 could be successfully applied, especially to derive exchange rates between each sub-lake and the different geological horizons. Here, expression-based selections could be used to define observation point groups for each single exchange area. These results could then be used by Vattenfall Europe Mining AG to analyze qualitative aspects of the flooding.

Water regulation measures in the area of Schönebeck

Analysis and evaluation

Sven Seifert, Thomas Koch & Bertram Monninkhoff

The town of Schönebeck is located in the German federal state of Saxony-Anhalt adjacent to the Elbe River between the neighboring communities of Barby and Magdeburg. Previously, the city was mainly supplied with water by local freshwater wells located in the south of the town. Starting around 2004, these wells were consecutively shut down and the water supply was changed to long-distance supply. Consequently an increase of water logging in several parts of the city could be observed in recent years. During winter 2010/11, the highest groundwater levels in recording history were witnessed, accompanied by water damage especially in several basements in the town.

Next to the above-mentioned changes in water supply, the constantly rising water level of the Elbe River, particularly in spring due to the snowmelt, can be seen as one of the main reasons causing the problems mentioned. Additional surface water from within the catchment of Schönebeck could not be dissipated into the Elbe River in time by the existing trenches. This situation led to infiltration of surface water from the trenches into the groundwater, aggravating the matter at hand.

Finally, the sewage system in the city is suspected to interfere with the groundwater. It is assumed that ongoing renovation measures are interrupting this process causing an additional rise of groundwater levels.

The aim of modeling was to investigate to which extent the groundwater level can be affected by passive and active measures in the area. Various measures are conceivable for that case. Besides additional dewatering wells, other measures such as advanced water retention in rural areas or adaption of the existing trench-system should be analyzed. For this the following model system has been set up.

Hydrologic model system

For the analysis of the actual state and the effects of measures, a coupled hydrological model system was built incorporating two models. The first one is a soil water budget model [ArcEGMO, BAH (*www.arcegmo.de*)] to include the influence of inflow from the catchment area of Schönebeck as well as the time dependent groundwater recharge. The second one is a groundwater flow model (FEFLOW) to represent the regional subsurface flow of the groundwater.

The two models are coupled with the FEFLOW plug-in IfmArcEGMO in both directions during runtime. ArcEGMO calculates and provides the groundwater recharge in area and time dependent distribution as input for the groundwater model. FEFLOW uses these data to calculate the groundwater conditions and transfers the groundwater depth back to ArcEGMO as an essential boundary condition for the groundwater influenced parts of the soil water model (Figure 1). Details to the coupling mechanism can also be found in *DHI-WASY Aktuell 3/2011*. The coupling module IfmArcEGMO is now also available for FEFLOW 6.1 and can be conveniently applied to any 3D FEFLOW model.

After transient calibration of the model system a total of seven possible measures were simulated. Some of them include several modifications that culminate in additional sub-scenarios.

http://www.arcegmo.de

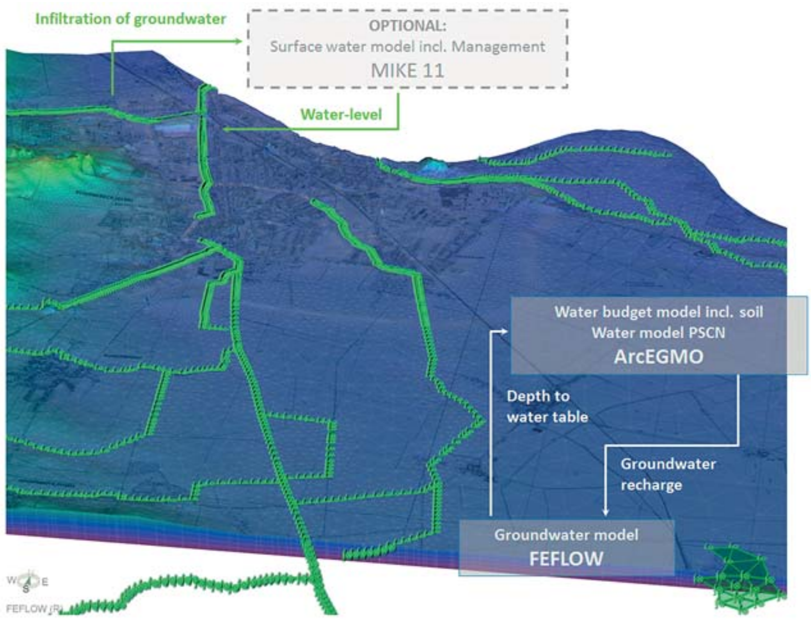

Fig. 1: Coupling between ArcEGMO and FEFLOW

Client:
Prof. Dr. habil. Frido Reinstorf
University of Applied Sciences Magdeburg-Stendal, Department of Water and Waste Management

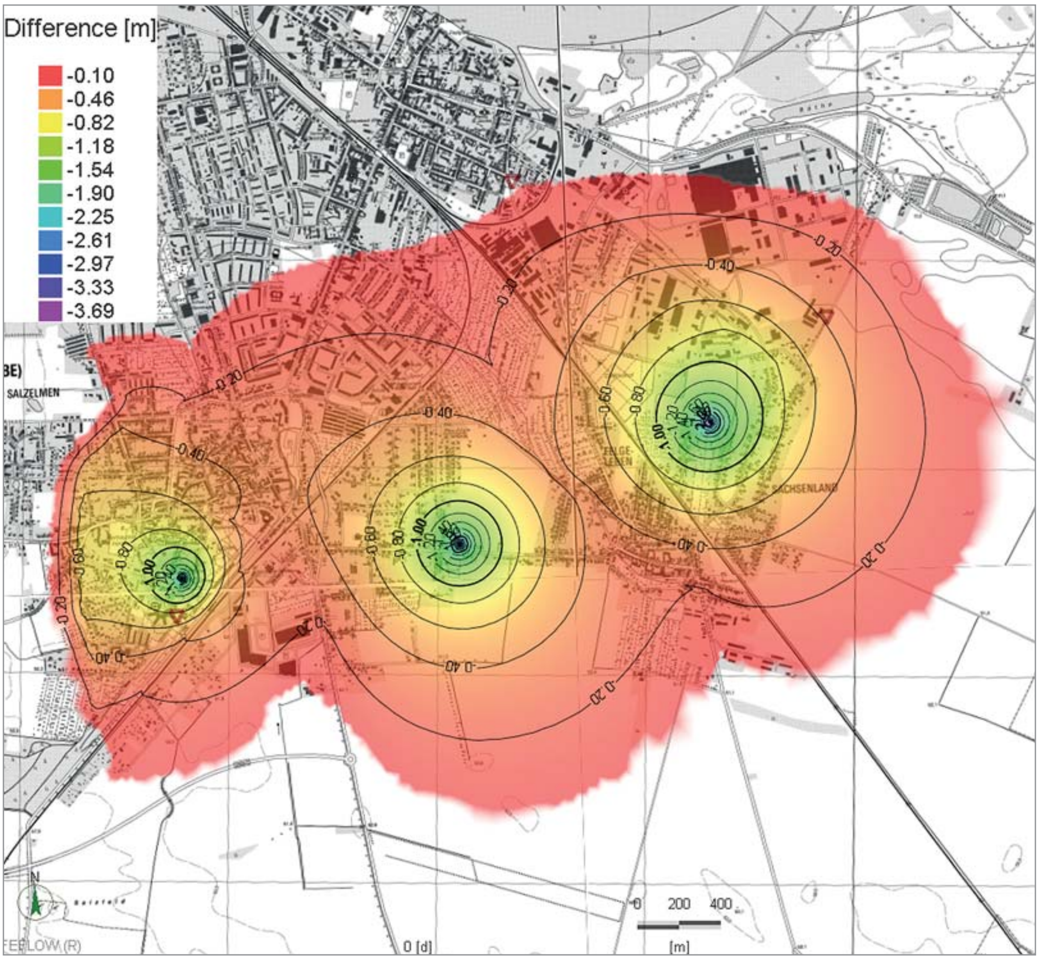

Fig. 2: Achievable drop of groundwater table with dewatering wells

Results

The impact of the measures were calculated and evaluated using the new nodal expression feature available in FEFLOW 6.1. Figure 2 exemplary shows the effect of three groundwater dewatering wells that were placed at strategic points to achieve the maximum result in groundwater reduction in Schönebeck's problem zones. Each well was set with a pumping rate of 5000 m^3/d.

Using the created models and the performed calculations, passive measures such as modifying trenches result only in relatively small improvements in the area of Schönebeck, even in case that these measures are combined. Active measures such as dewatering wells however could attain the best results by far. Additionally, these types of measures can be regulated according to the occurring event. But due to ongoing maintenance and operation costs these measures would be rather expensive. Currently the modeling results are being analyzed by the client and the city of Schönebeck, after which decisions will be made in implementing necessary improvements to the city water system in order to minimize groundwater driven flooding in future times.

News

Modeling software Leapfrog & FEFLOW to combine in dewatering and remediation solution

New Zealand's ARANZ Geo Ltd and German DHI-WASY GmbH plan to combine their flagship Products to create a comprehensive groundwater modeling solution. **Leapfrog** is a fast and dynamic 3D geological modeling software capable of modeling even complicated geologies and was developed specifically for the minerals mining industry, while **FEFLOW** is known as a professional software package for modeling fluid flow and transport of dissolved constituents and/ or heat transport processes in the subsurface.

http://www.feflow.com/leapfroghydro.html

leapfrog

Both programs feature multiple functions for visualization and editing and are flexible, supporting users in all parts of a project cycle. By extending the current linkages between Leapfrog's hydrogeological solution Leapfrog Hydro and the FEFLOW software up to the seamless integration of both products, the previously existing gap between geological modeling packages and hydraulic modeling software will be bridged. The resulting solution, which will incorporate invaluable knowledge gained from current user experiences, is planned to cover the entire groundwater modeling workflow and provide significant benefits for users focusing on mine dewatering and remediation. The novel technology will be available and supported worldwide through DHI offices.

If you would like more information about FEFLOW or Leapfrog software, please visit *http://www.feflow.com/leapfroghydro.html*.

Indian delegation learns about DHI's flood forecast systems in Europe

From **June 4-8 2012**, a delegation from the Water Resources Department of the Government of Maharashtra in western India visited various sites in Europe to learn more about DHI's real-time flood forecasting models.

DHI is currently establishing a real-time flood forecasting system for the Krishna and Bhima river basins in India. These basins are located in western India near the city of Pune, the second largest in the state of Maharashtra after Mumbai. This project, funded by the World Bank and scheduled for the duration of 18 months, will help to protect the local population from floods and ensure – through consideration of dam operations – the irrigation of their fields.

After visiting the DHI head office in Hørsholm (Denmark), the Indian delegation visited the International Forecasting Center in Graz (Province of Styria, Austria) and the Forecasting Center at the Environmental Agency (ARSO) in Slovenia to learn more about the transnational flood forecast systems for the Enns, Mur, Raab and Sava catchments developed and established by DHI during the last years and now operated by these centers.

The Slovenian system has already proven its value and reliability during a flood event in September 2010, when our forecast supported the issuing of early warning messages. Thereby, the Administration of Civil Protection and Disaster Relief was able to coordinate the evacuation of local citizens as well as the coordination of relief workers for flood protection during the flood, saving numerous livelihoods as well as considerable amounts of money.

Fig. 1: The Indian delegation and their Stryrian hosts from visit a gauging station in Austria

The study tour ended with presentations of our German hydropower and discharge forecast, developed and operated at DHI-WASY in Germany.

Fig. 2: The delegation at the forecast center of the Slovenian Environmental Agency

Special thanks for helping with the organization and the very interesting days at the institutions, ensuring that the delegation enjoyed their stay, go to Dr. Robert Schatzl and his team from Land Steiermark in Graz, Austria and to Mr. Janez Polajnar and his team from the Environmental Agency in Slovenia.

New Staff

Dr. Fabien Cornaton

Dr. Fabien Cornaton studied mathematics and physics at the University of Montpellier (France), and obtained a Ph.D. degree in Quantitative Hydrogeology from the University of Neuchatel (Switzerland). His scientific interests focus on coupled surface/subsurface flows, including hydro-thermo-chemical phenomena, density dependent flows, unsaturated flows, reactive multi-species contaminant transport, groundwater age and transit times, with numerous applications to environmental, waste and hydrogeological engineering issues. Particular emphasis is laid upon theoretical and computational developments in mathematical modeling and on the design of simulation methods and tools operational for large, complex hydrogeological systems.

From **February 2012** Fabien Cornaton has joined the Groundwater Modeling Centre (GMC) of DHI-WASY where he mainly will be in charge of the scientific development of the FEFLOW software.

New international trainers

In order to facilitate FEFLOW training courses in native language, the DHI Group has started to extend its network of FEFLOW trainers. FEFLOW trainers have to undergo the trainer certification program of the DHI group, which ensures the high level of professional and didactic qualification.

We are happy to announce that the first trainers outside DHI-WASY have now undergone this process and have been fully approved as FEFLOW trainers. DHI is now able to offer FEFLOW training courses in English, French, Italian and German language.

Marco Bersano Begey

Marco Bersano Begey is a hydrogeologist and groundwater modeling expert at DHI-Italia (Turin, Genova, Italy). Prior with the Hydrodata S.p.A. team, since 1989 he has gained extensive experience in groundwater resources management and quantitative hydrogeology projects, ranging across groundwater research and exploitation, polluted sites recovery, aquifer tests and monitoring, drainage and dewatering systems design.

Prof. Dr. Yvan Rossier and Laurent Galeazzi

Prof. Dr. Yvan Rossier and M.Sc. Laurent Galeazzi are the co-founders of HydroGeAp, an independent Swiss company providing expertise and trainings in Quantitative Hydrogeology. Both are specialists in the application of advanced analytical and numerical groundwater modeling.

Yvan Rossier, part-time Professor of Hydrogeology at the LTHE research laboratory of the University of Grenoble, has over 30 years of experience in groundwater resource assessment and contaminant and heat transport modeling in variably saturated media.

Laurent Galeazzi, who received a master's degree in Hydrogeology from Neuchâtel University (CHYN), has more than 10 years of experience as a professional hydrogeologist specializing in groundwater modeling mainly applied to environmental site investigation and remediation.

FEFLOW Training in 2012

Date	Course Title	Organizer	Location
Sep. 17-21, 2012	Summerschool	DHI-WASY	FU Berlin, GFZ Potsdam, Germany
Sep. 24-26, 2012	FEFLOW – Introduction to Groundwater Modeling	DHI Canada	Toronto, ON
Sep. 27-28, 2012	FEFLOW – Advanced Groundwater Modeling	DHI Canada	Toronto, ON
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http://www.feflow.com/training.html

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Software	Release
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HQ-EX®	3.0
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GeoFES	4.2
WISYS®	3.6
Flood Toolbox	1.1

Latest releases of DHI software

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Imprint

Publisher: **DHI-WASY GmbH**

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Layout: ART+DESIGN · www.ad-ww.de

DHI-WASY *Aktuell* is released four times the year. DHI-WASY *Aktuell* is free of charge.
Release: August 2012 (Set for 18 year, 3rd/12)
Print run: 3.000

Questions or requests should be addressed to: DHI-WASY GmbH, Redaktion DHI-WASY *Aktuell*.

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