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An Overview of Commonly Used Groundwater Modelling Software

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ABSTRACT: A groundwater model is any computational method that represents an approximation of an underground water system. While groundwater models are, by definition, a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process. There are many different ground-water modelling codes available, each with their own capabilities, operational characteristics, and limitations. If modelling is considered for a project, it is important to determine if a particular code is appropriate for that project, or if a code exists that can perform the simulations required in the project. This article presents an overview of most commonly used groundwater modelling codes.

KEY WORDS: Groundwater, Numerical Modelling, MODFLOW, FEFLOW, PEST.

I. INTRODUCTION

Groundwater systems are affected by natural processes and human activity, and require targeted and ongoing management to maintain the condition of groundwater resources within acceptable limits, while providing desired economic and social benefits. Groundwater management and policy decisions must be based on knowledge of the past and present behaviour of the groundwater system, the likely response to future changes and the understanding of the uncertainty in those responses.

The location, timing and magnitude of hydrologic responses to natural or human-induced events depend on a wide range of factors — for example, the nature and duration of the event that is impacting groundwater, the subsurface properties and the connection with surface water features such as rivers and oceans. Through observation of these characteristics a conceptual understanding of the system can be developed, but often observational data is scarce (both in space and time), so our understanding of the system remains limited and uncertain.

Groundwater models provide additional insight into the complex system behaviour and (when appropriately designed) can assist in developing conceptual understanding. Furthermore, once they have been demonstrated to reasonably reproduce past behaviour, they can forecast the outcome of future groundwater behaviour, support decision-making and allow the exploration of alternative management approaches. However, there should be no expectation of a single 'true' model, and model outputs will always be uncertain. As such, all model outputs presented to decision-makers benefit from the inclusion of some estimate of how good or uncertain the modeller considers the results.

II. GROUNDWATER MODELS

A groundwater model is a simplified representation of a groundwater system. Groundwater models can be classified as physical or mathematical. A physical model (e.g. a sand tank) replicates physical processes, usually on a smaller scale than encountered in the field. A mathematical model describes the physical processes and boundaries of a groundwater system using one or more governing equations. An analytical model makes simplifying assumptions (e.g. properties of the aquifer are considered to be constant in space and time) to enable solution of a given problem. Analytical models are usually solved rapidly, sometimes using a computer, but sometimes by hand.

A numerical model divides space and/or time into discrete pieces. Features of the governing equations and boundary conditions (e.g. aquifer geometry, hydrogeologogical properties, pumping rates or sources of solute) can be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a

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groundwater system than could be achieved with an analytical model. Numerical models are usually solved by a computer and are usually more computationally demanding than analytical models.

A groundwater flow model simulates hydraulic heads (and water table elevations in the case of unconfined aquifers) and groundwater flow rates within and across the boundaries of the system under consideration. It can provide estimates of water balance and travel times along flow paths. A solute transport model simulates the concentrations of substances dissolved in groundwater. These models can simulate the migration of solutes (or heat) through the subsurface and the boundaries of the system. Groundwater models can be used to calculate water and solute fluxes between the groundwater system under consideration and connected source and sink features such as surface water bodies (rivers, lakes), pumping bores and adjacent groundwater reservoirs.

An important step in the modelling process is a formal software selection process in which all possible options are considered. This step has often been short-circuited in the past. In many cases, modellers have immediately adopted MODFLOW, developed by the US Geological Survey (USGS) (Harbaugh et al., 2000), with little thought given to the alternatives. However, in recent years, a number of sophisticated and powerful modelling software have become available in easily used commercial software packages that are becoming increasingly popular.

Some software is widely used, but this does not mean that it is more appropriate or accurate than software designed for specific purposes and used by appropriately trained professionals, for example, in universities and research institutions. An overview of commonly used software packages is presented below.

III. GROUNDWATER MODELLING SOFTWARE

A very wide range of computer codes (modeling software) exist for application of different problems. In order to select the best code, a list of demands should be formulated. When choosing a code from the selection available, the following points should be considered:

- What code is best in solving the particular problem?
- What are the data requirements for both code and problem?
- What computer hardware and supporting staff are required?
- How much will the computer code cost?
- How accurate will the code be in representing the real world?

Based on these questions, the modeling code should be selected. Groundwater modelling sometimes requires the use of a number of software types. These include:

- The model code that solves the equations for groundwater flow and/or solute transport, sometimes called simulation software or the computational engine.
- A GUI that facilitates preparation of data files for the model code, runs the model code and allows visualisation and analysis of results (model predictions).
- Software for processing spatial data, such as a geographic information system (GIS), and software for representing hydrogeological conceptual models.
- Software that supports model calibration, sensitivity analysis and uncertainty analysis.
- Programming and scripting software that allows additional calculations to be performed outside or in parallel with any of the above types of software.

Some software is public domain and open source (freely available and able to be modified by the user) and some is commercial and closed (only available in an executable form that cannot be modified by the end user). Some software fits several of the above categories, for example, a model code may be supplied with its own GUI, or a GIS may be supplied with a scripting language. Some GUIs support one model code while others support many. Software packages are increasingly being coupled to other software packages, either tightly or loosely.

While most of the basic functions of each GUI and code are similar, they all have their individual strengths and weaknesses. The final choice depends on project-specific considerations that are related to the modelling objectives and the basic model functionality required to meet these objectives.

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A. MODFLOW

MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions.

Originally developed and released solely as a groundwater-flow simulation code when first published in 1984, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management.

The USGS releases multiple versions of MODFLOW. There is a core MODFLOW version, which is developed and maintained by the USGS Office of Groundwater, and there are advanced versions. The core MODFLOW version is the one that is under active development and is often the most widely used and most thoroughly tested version. MODFLOW 6 is presently the core MODFLOW version distributed by the USGS, but MODFLOW-2005 (the previous core version) is still actively maintained and supported. Advanced MODFLOW versions include specialized MODFLOW variants and versions of MODFLOW that use newer formulations. These advanced MODFLOW versions are also available from the USGS.

There have been six major releases of the core MODFLOW version: MODFLOW-84, MODFLOW-88, MODFLOW-96, MODFLOW-2000, MODFLOW-2005, and MODFLOW 6. MODFLOW 6 is the newest core version and uses a new format of blocks and keywords for input of model data. It was written from scratch using an object-oriented design. MODFLOW 6 presently supports one type of process model — the GWF Model. Other models may be added in the future, such as a groundwater transport model, a surface-water model, and a pipe network model, for example. Underlying MODFLOW 6 is a framework that allows developers to add new models and the interactions between models. A key feature of the new MODFLOW 6 framework is the ability to solve multiple, tightly coupled, numerical models in a single system of equations. These may be multiple models of the same type or of different types. MODFLOW 6 is an entirely new version of MODFLOW.

MODFLOW 6 presently contains one type of hydrologic model, the Groundwater Flow (GWF) Model. The GWF Model for MODFLOW 6 is based on a generalized control-volume finite-difference (CVFD) approach in which a cell can be hydraulically connected to any number of surrounding cells. For complex problems involving water-table conditions, an optional Newton-Raphson formulation, based on the formulations in MODFLOW-NWT and MODFLOW-USG, can be activated. The GWF Model is divided into "packages," as was done in previous MODFLOW versions. A package is the part of the model that deals with a single aspect of simulation. Packages included with the GWF Model include

- those related to internal calculations of groundwater flow (discretization, initial conditions, hydraulic conductance, and storage),
- stress packages (constant heads, wells, recharge, rivers, general head boundaries, drains, and evapotranspiration), and
- advanced stress packages (streamflow routing, lakes, multi-aquifer wells, and unsaturated zone flow).

An additional package is also available for moving water available in one package into the individual features of the advanced stress packages. The GWF Model also has packages for obtaining and controlling output from the model. Table 1 presents other versions of MODFLOW that use new formulations and specialized MODFLOW variants and Table 2 presents the most commonly used USGS MODFLOW utilities.

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Table 1: Other Versions of MODFLOW and Specialized MODFLOW Variants

S. No.	Software	Details
1.	MODFLOW-NWT	A standalone program for solving problems involving drying and rewetting non-linearities of the unconfined groundwater-flow equation.
2.	MODFLOW-USG	An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation.
3.	MODFLOW-LGR	A 3D finite-difference groundwater model with local grid refinement.
4.	GSFLOW	A coupled groundwater and surface-water flow model based on the USGS Precipitation-Runoff Modelling System (PRMS) and MODFLOW-2005.
5.	OWHM	An integrated hydrologic flow model for the analysis of human and natural water movement within a supply-and-demand framework.
6.	GWM	A 3D groundwater-flow simulator with Groundwater Management capability using optimization.
7.	SEAWAT	A computer program for simulation of 3D variable-density groundwater-flow and transport.
8.	CFP	A model for simulating turbulent groundwater-flow conditions.
9.	FMP	A program for simulating dynamically integrated supply-and-demand components of irrigated agriculture.
10.	Surface-Water Routing (SWR)	Simulates surface-water flows and surface-water/groundwater interactions.

Table 2: MODFLOW Utilities, Post Processors, and Graphical User Interfaces (GUIs)

S. No.	Software	Details
1.	FloPy	A Python package to create, run, and post-process MODFLOW-based models.
2.	GW_Chart	A graphing application for MODFLOW, Zonebudget, and other codes. GW_Chart also converts binary cell-by-cell flow files to text files.
3.	ModelMuse	A GUI for MODFLOW-2005, MODFLOW-LGR, MODFLOW-NWT, MT3DMS, PHAST, MODPATH, and ZONEBUDGET.
4.	ModelViewer	A program for 3D visualization of groundwater-model results.
5.	ZONEBUDGET	Program for computing sub-regional water budgets for MODFLOW.

It is recommended that new MODFLOW users begin with MODFLOW 6 and consider other versions only if a capability, not supported in MODFLOW 6, is required for their particular problem. The MODFLOW-2005 guide can be found online but an online guide is not presently available for MODFLOW 6; an up-to-date guide is included in the MODFLOW 6 distribution.

Online Guide to MODFLOW-2005:
https://water.usgs.gov/ogw/modflow/MODFLOW-2005-Guide/

Online Guide to MODFLOW-NWT:

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https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/

Online Guide to MODFLOW-OWHM:
https://ca.water.usgs.gov/modeling-software/one-water-hydrologic-model/users-manual/index.html

Guidance for determining applicability of the USGS GSFLOW and OWHM models for hydrologic simulation and analysis is available at
https://water.usgs.gov/ogw/modflow-owhm/GSFLOW-OWHM-guidance-20170518.pdf

One may also explore other USGS groundwater software at
https://water.usgs.gov/software/lists/groundwater

B. PMWIN (Processing Modflow for WINdows)

PMWIN (Processing Modflow for WINdows) simulates the groundwater flow within the aquifer in MODFLOW using a block-centered finite-difference approach. Layers can be simulated as confined, unconfined, or a combination of both. Flows from external stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can also be simulated.

Freeware version 5.3.1 of PMWIN (Windows 2000, XP and Windows 7) can be downloaded at http://www.pmwin.net/programs/pmwin5/setup_pmwin5.32.exe

Commercial version "Processing Modflow X" (available at https://www.simcore.com/wp/products/) comes with the supported models/codes and a map-based user interface that can display online base maps and shape files along with the grids and results of multiple models. The interface enables users to construct, calibrate, and run models as well as visualize results.

C. mflab (Modflow Laboratory)

Matlab based scripting to set up, run and analyze groundwater model using (different versions of) MODFLOW (+SWI), MODPATH6, MT3DMS and SEAWAT.

It can be downloaded at https://sourceforge.net/projects/mflab/

D. Visual MODFLOW Flex

Visual MODFLOW is a software program developed by Waterloo Hydrogeologic. Originally released in 1994, Visual MODFLOW was the first commercially available graphical interface for the open source groundwater modelling engine called MODFLOW. Later, a newer .NET version of the software was rebranded as Visual MODFLOW Flex. The program also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a three-dimensional model explorer. Visual MODFLOW supports MODFLOW-2000, MODFLOW-2005, MODFLOW-NWT, MODFLOW-LGR, MODFLOW-SURFACT and SEAWAT.

Further details are available at https://www.waterloohydrogeologic.com/visual-modflow-flex/

E. GMS - Groundwater Modelling System

GMS (Groundwater Modelling System) is water modelling application for building and simulating groundwater models. It features 2D and 3D geostatistics, stratigraphic modelling and a unique conceptual model approach. Currently supported models include MODFLOW, MODPATH, MT3DMS, RT3D, FEMWATER, SEEP2D, and UTEXAS.

Further details are available at https://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction

F. Groundwater Vistas

Groundwater Vistas (GV), is a pre- and post-processor for MODFLOW models. GV is a state of the art software package for 3-D groundwater flow and contaminant transport modelling, calibration and optimization using the MODFLOW suite of codes. GV also couples a powerful model design system with comprehensive graphical analysis tools. GV is a model-independent graphical design system for MODFLOW MODPATH (both steady-state and transient versions), MT3DMS, MODFLOWT, MODFLOW-SURFACT, MODFLOW2000, GFLOW, RT3D, PATH3D, SEAWAT and PEST. The advanced versions of Groundwater Vistas add Monte Carlo uncertainty analysis, SWIFT support, Recharge/ET memory compression for large transient models, support for the HUF Package in MODFLOW2000/2005, PEST SVD Assist capabilities, GW3D for 3D Visualization, the sophisticated SAMG Solver etc.

Further details are available at http://www.groundwatermodels.com/

G. MODFLOW-SURFACT

MODFLOW-SURFACT is a powerful 3D finite-difference flow and transport modelling code for analyzing subsurface systems. It offers substantial advancements over public-domain versions of MODFLOW. For example, MODFLOW-SURFACT addresses rewetting of drained cell, handling of pumping wells, solute transport problems, numerical dispersion and oscillations, and impacts of transient flow storage effects on transport. MODFLOW-SURFACT includes advanced computational modules that are based on robust, efficient, mass-conserving algorithms, making it faster and more accurate than its transport modelling counterparts.

Further details are available at https://www.hgl.com/softwareproducts-new/modflow-surfact/

H. MODHMS

MODHMS interfaces seamlessly with the popular MODFLOW code to provide a physically based, spatially distributed, integrated surface/subsurface modelling framework hydrologic system. Developed to meet the growing demand for quantifying available water within a hydrologic system and for numerical simulation of complex hydrological processes, MODHMS extends the MODFLOW-SURFACT subsurface modelling code to include overland/channel flow and transport.

Further details are available at https://www.hgl.com/softwareproducts-new/modhms/

I. FEFLOW

FEFLOW (Finite Element subsurface FLOW system) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media and fractured media. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. FEFLOW 7.0 is the latest version.

Further details are available at https://www.mikepoweredbydhi.com/products/feflow

J. PEST

PEST is the industry standard software package for parameter estimation and uncertainty analysis of complex environmental and other computer models.

Further details are available at http://www.pesthomepage.org/

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IV. GROUNDWATER MODELLING IN FRACTURED ROCKS

A number of approaches can be taken for modelling groundwater flow in fractured rocks. The choice depends on objectives of the modelling and availability of data.

1. *Equivalent porous medium (EPM) approach*: In other words, ignore the fractures and treat the rock as a continuum with average "whole rock" hydraulic properties. If much data on the fractures are not available, then this is probably the best approach and can be done using MODFLOW or FEMWATER within GMS. Drawbacks are that the EPM properties may be scale dependent (larger the area, more large but rare fractures may be encountered). Also, averaging may work for flow, but not for contaminant transport.

2. *Discrete fracture representation*: If we know where the fractures are, then they can be simulated. If we have a regular, orthogonal distribution then MODFLOW can be used, otherwise FEMWATER can be used. The permeability of the fractures can be related to the aperture width. It may have some stability problems due to heterogeneity of the grid.

3. *Stochastic fracture modelling*: If lots of data on fracture distribution are available, then a stochastic approach can be used. We need to build up probability density functions (PDF's) for fracture aperture size, fracture spacing and fracture orientation. Then we can use the same PDF's to stochastically build the fracture grid. The model may be run in a Monte Carlo fashion with many different fracture patterns. Each will provide a different result but will be probabilistically correct. Results can also be presented as PDF's. This will require a specialist software, such as FRACMAN, or others.

V. GROUNDWATER MODELLING OF KARST CONDUIT SYSTEM

Karst systems are characterized by underground drainage systems formed by the dissolution of soluble rocks. The behaviour of these systems is hard to be conceptualized due to the uncertainty in the location and geometry of these underground caves and its connection with the porous media.

In order to be able to model these systems, the Conduit Flow Process (CFP) package (developed by the United States Geological Survey – USGS) can simulate turbulent groundwater flow by coupling the groundwater flow equation with formulations for a discrete network of cylindrical pipes.

VI. NUMERICAL METHODS FOR GROUNDWATER MODELLING

Those who are new to groundwater modelling are often overwhelmed with terms such as finite differences, finite elements, grid discretization and triangulation. Once you gain a basic understanding of the terms and the processes involved in groundwater modelling, you are often faced with the ultimate question "Which numerical method should I use for my project"? The answer is not often so much what you should use but often is based on what method or software package is readily available. Like most people, groundwater modellers want to stick with what they know. There are, however, three main numerical methods that should be considered: Finite Difference, Finite Element and Finite Volume.

Finite Difference

MODFLOW uses the finite differences method to solve the groundwater flow equation. The grid is created using structured, rectilinear (rectangular) grids. This method is widely used and accepted by many governing bodies. It is the most popular groundwater simulator available, open source and well documented. The finite difference solution is easy to understand and calculate, the solutions are mass-conservative and there are several numerical extensions available such as PEST, transport, particle tracking and zone budget. However, the finite difference method is not without weakness. Although grids are easy to create, they cannot be efficiently refined around areas of interest, such as wells and model boundaries. This can be partially addressed by the MODFLOW-LGR (Local Grid Refinement) extension.

Complex geology is difficult to represent particularly if there are discontinuous or pinched out layers; when there are steep gradients in the stratigraphy, this can result in disconnected cells which causes problems with running the model.

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MODFLOW requires model layers to be continuous across the entire model domain, making it a challenge to model smaller formations of materials (lenses) within a larger body, without adding a large number of unnecessary cells. MODFLOW provides an approximate representation of variable anisotropy in model parameters (e.g. it only uses the principal components of the hydraulic conductivity tensor; Kxx, Kyy and Kzz), and therefore limited for modelling faults and fractures.

Finite Element

The finite element method can also be used to solve the groundwater flow equation. There are several codes available; FEFLOW being the most popular. FEFLOW uses a finite element (triangular) mesh to represent the model domain. The use of triangles allows for a more efficient refinement around wells and boundaries. The triangular mesh can more easily adapt to variable stratigraphy such as sloping or pinch outs, and allows for versatile discretization of non-rectangular model domains. Finite element methods provide a better representation of anisotropy (fully represents conductivity tensor – each triangular element is given its own coordinate system, whereas MODFLOW requires conductivity to be perpendicular to the faces of the finite difference cells (horizontally rectangular)).

No method is perfect; with finite elements the local mass conservation is not guaranteed. There can be discontinuous velocities at the element boundaries which can make it difficult to determine unique pathlines. FEFLOW is similar to MODFLOW in the sense that model layers must be continuous across the entire model domain. In order to represent smaller formations within larger bodies, an entire model layer must be inserted with a minimum layer thickness enforced in the discontinuous regions.

Finite Volume

The finite volume method is now being introduced into groundwater modelling through the MODFLOW-USG (UnStructured Grids) code. MODFLOW-USG was released by the USGS in May 2013 and follows a Control Volume Finite Difference (CVFD) formulation in which a cell can be connected to an arbitrary number of adjacent cells. This allows infinite possibilities for the cell geometry. The model domain can be discretized using triangular, rectangular or Voronoi polygons and allows for effective vertical gridding. This means that the grid can be refined locally around areas of interest, such as wells and boundaries, without adding extra cells outside the areas of interest. MODFLOW-USG does not require layers to be continuous across the model domain, allowing for efficient representation of discontinuous layers (lenses, perched aquifers, etc). The CVFD solution remains mass conservative and efficient.

MODFLOW-USG follows the traditional MODFLOW notation for most packages, reducing the learning curve for those who are already familiar with MODFLOW. Many of the packages follow similar formats, with just a few small adjustments to consider the differences in cell geometry and numbering. The code is open source and readily available.

For both Finite Difference and Finite Element methods, the horizontal discretization (number of cells/elements) must be the same in all model layers. This is quite inefficient, because it means that you end up with a large number of cells/elements in layers outside the area of interest. However, with Finite Volume, MODFLOW-USG, each layer can have its own discretization; this means that you can refine upper layers around rivers and streams, and have coarser refinement in lower layers; likewise, you can refine around wells screens in lower layers, and have less refinement in layers above. The result with MODFLOW-USG is fewer cells, faster solutions, while maintaining high accuracy.

VII. REVIEW OF GROUNDWATER MODELLING SOFTWARE

The choice of numerical model depends on the conditions to simulate and conceptual model. First we need to define the objectives of modelling, then we can proceed towards selection of appropriate modelling software. The choice depends upon the modelling task, size, scale and complexity of the modelled groundwater system, project time frame, future use of the model etc. The weakness of many models stays not in the precision of the numerical solving but in a weak conceptual model.

Basically, one needs to select either any MODFLOW-based software package or FEFLOW. So, our discussion revolves around the question which one to use - MODFLOW or FEFLOW? There may not be much difference between these

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codes in accuracy. Generally, the accuracy depends upon the grid resolution. There should be no difference between the two codes and thus, it comes to which code the modeller has more experience with. Experience will generally reduce model generation time and the time it takes to correct mistakes, which is where the experience comes in handy. Salient Pros and Cons of MODFLOW and FEFLOW software have been presented in Table 3.

Table 3: Pros and Cons of MODFLOW and FEFLOW

Software	Pros	Cons
MODFLOW	▪ Easy to set up and pre/post process files ▪ Industry standard ▪ Free to use and GUIs are inexpensive to run/view/process model ▪ Modular (new packages added frequently)	▪ Currently cannot simulate complex geological features, such as angled faults and simulate steep hydraulic gradients such as rewetting/drying cells using the same code ▪ Have to choose either USG or NWT/SURFACT capabilities
FEFLOW	▪ Computational mesh can incorporate complex geologic features ▪ Simulate wetting/drying of cells ▪ FEFLOW Essentials has new groundwater age feature that is similar to ZONEBUDGET	▪ Expensive ▪ Takes longer to learn and setup ▪ Typically need more project budget/schedule to run FEFLOW models because they are more complex than MODFLOW models and take additional time

Bottom line is that a groundwater modeller needs to be able to run both codes. For unstructured grid refinement or simulate drying/re-wetting of cells easily, one needs to use USG or NWT/SURFACT for MODFLOW (not just MODFLOW-2005) but FEFLOW does both. Besides the above, the following aspects may be considered while selecting appropriate groundwater modelling package.

A. Consideration for MODFLOW

MODFLOW is the groundwater modelling software developed by the U.S. Geological Survey (USGS). It appeared in 1984 and has had a constant development till now. Hatari Labs opines that MODFLOW is better than other software for groundwater modelling. MODFLOW's capacities allow the representation of regional or local groundwater flow and its interaction with superficial water bodies. Given that MODFLOW is a free source code (it's distributed without charge), there has been a wrong perception about the program being outdated or having a lesser capacity than its commercial peers.

Every modelling software is a numerical approximation of the complex nature. There's no such thing as the "best" modelling software, and simulation quality depends on the modeller's criteria and input data. A truly open software means having the freedom to download, install, and modify the software without any charge, like MODFLOW. The decision about MODFLOW isn't essentially based on price, although it's a good point to take notice. The main reason of choosing MODFLOW is the information's transfer versatility, simulations transparency, and water resources management dialogue. Main advantages of MODFLOW are given below.

1. It is free and has no charge. MODFLOW, being developed by a public U.S. institution, is distributed freely. There are commercial pre and post interfaces; nevertheless, USGS has developed a high performance pre and post interface called ModelMuse.

2. It is well documented. Each part of MODFLOW has its manual; that is to say, each part of the software that represents a relevant physical process to groundwater flow has its own document about the main considerations taken in the simulation.

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3. MODFLOW is modular and continuously updated. Given its modular structure, different packages can be attached to MODFLOW like the unsaturated flow package (UFZ) or the local refinement package (LGR).

4. MODFLOW is based on finite differences. Given its rectangular cells division, the volumetric control of what enters and exits is pretty accurate and is not a simulation problem. This control is also fulfilled in conditions that vary with time, having an exact control of water coming from storage.

5. MODFLOW represents well the physical processes related to groundwater flow. The evapotranspiration, which is the process that can discharge up to 65% of groundwater, is well configured in MODFLOW and runs without major computational requirements. Lakes and river interaction packages are attached in the code well.

If you don't want to spend money on MODFLOW-SURFACT, then MODFLOW-NWT may be a viable alternative. MODFLOW-NWT essentially handles dry cells in a way similar to MODFLOW-SURFACT's pseudo soil relations and provides improved handling of water table fluctuations over multiple layers in the model. It is fully supported in Visual MODFLOW.

Essentially, MODFLOW-USG contains the best of the Finite Difference and Finite Element codes. The shortcomings of this solution method do not seem to be technical but related to its ‘newness’. Groundwater modellers will need to learn the ‘ins’ and ‘outs’ of this new code to see how it holds up with the tried and true methods. In addition, avid modellers will need to wait for this code to incorporate add-ons such as transport, particle tracking, and the UZF package. At the end of the day, it is a matter of acceptance - will MODFLOW-USG be adopted by the groundwater modelling community as the next great thing?

B. Consideration for FEFLOW

FEFLOW may have a more flexible mesh. There may be some situations when a finite element mesh provides a better solution. FEFLOW is valued for flexibility of a finite-element mesh, direct coupling with solute and heat transport and fracture modelling. FEFLOW also does good job in unsaturated zone modelling. But it definitely takes some time to get acquainted with concepts and applications of the FEFLOW platform.

C. Consideration for MODHMS

For large and complex groundwater modelling projects, and especially when there is spatial complexity, groundwater-surface water interactions, solute transport and/or density affected flow, MODHMS may be a good choice. The main advantages are the time saving and flexibility of using a regular finite difference grid, and the flexibility of processing the data (inputs and outputs) inside or outside of a Graphic User Interface (GUI).

For large and complex models, a modeller needs the flexibility to write custom code for data processing and swapping data between software packages. Being confined to a GUI may be more of a hinderance than an advantage when building large and complex models.

The FORTRAN code of MODHMS (and MODFLOW family) is relatively easy to understand, and the data associated with individual model cells can be readily accessed with ad-hoc changes to the FORTRAN source code (if you have permission from HGL to modify the MODHMS code).

In complex 3D modelling, including extremely dipping 3D strata formations and also in highly complex 3D seawater intrusion with complex land-use patterns, it is the stability and speed of the solvers that really matters in these situations. MODHMS has enormous and amazing capacity to provide fully integrated simulations of surface water flow, solute transport and groundwater flow. MODHMS handles unsaturated flows well, and it is numerically stable and fast in comparison to most other solvers.

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D. Calibration Aspect

Another feature of large complex models is a need for calibration. Model development and calibration may require rebuilding a model 100's or 1000's of times, and it may require pin-pointing problems in very specific cells and locations. Automated calibration of a large model is most flexible and most powerful when managed with PEST (automated parameter estimation) and when setting up the input/output files with some help of a GUI. But ultimately, working with PEST requires very careful insight by the modeller. PEST requires understanding of the conceptual model, the numerical problem and the existence of parameter correlation.

VIII. GUI FOR MODFLOW

A number of the codes have a graphical user interface (GUI) which aids in the creation of input files for the model code to read and for visualizing the model output. As a matter of fact, the basic concept of all models (Visual MODFLOW, Groundwater Vistas, GMS, PMWIN) is the same. There is no significant difference between them except software environment.

ModelMuse is the pre and post-processing platform developed by the USGS that implements MODFLOW. This platform has a high performance due to its "design by objects" that optimizes the conceptualization of boundary conditions and other elements of the model, reducing the time needed to build the model and improving the interpretation of the output data.

Visual MODFLOW is user friendly and easy to learn and the new versions are more or less like GMS. Groundwater Vistas (GWV) is the cheapest GUI to purchase and the interface is easy to use and interacts well with ArcGIS for pre- and post-processing. The GMS model would also be a good commercial package to develop conceptual model, convert the conceptual model into numerical environment, easy interface to input into many cells at a time, and nice GIS interface. It (version 8 and higher) has an unsaturated zone extension which is new in these type of models.

Processing Modflow for Windows (PMWIN) is simplest to learn. Version 5.3 of PMWIN is included in the book "3D-Groundwater Modeling with PMWIN" published by Springer-Verlag. This program is a modelling environment that allows setting the model in a very friendly way and calls the models: MODFLOW, MT3D, MT3DMS, MOC3D, PMPATH for Windows, PEST2000, and UCODE. So you can model groundwater flow, transport, particle tracking and automatic calibration. It includes several tools for data processing and graphical presentations.

Use of such GUI (Visual MODFLOW and others) is convenient mainly because you can modify and apply the produced files by the compiled codes and also with the parameter estimation model WinPEST. You can also investigate the influence of any neighboring physical barrier by, for example, using the inactive grid cells. Also, you can introduce any number of wells and other boundary conditions in the model domain without any limitation. Further, it is also possible to plot and post-process the result of simulation very conveniently.

If Reynolds and Forchheimer numbers suggest that the flow regime is "non-Darcian flow", then you may need to check whether any of the MODLFOW packages can capture its effect or not, and also check if that package is supported by Visual MODLFOW or other GUI. If the non-Darcian flow is due to karst, you may need to use MODFLOW-CFP which is supported by ModelMuse and Groundwater Vistas. It would not be supported in the free version of PMWIN. If the non-Darcian flow is due to turbulence in the vicinity of the well due to high pumping rates, that could be difficult to simulate. You might be able to simulate it with MODFLOW-CFP but it would be a good idea to look into it further. Another possibility to consider is the Multi-Node well package in MODFLOW. It would be appropriate if you are concerned just about skin effects or turbulent flow in the well.

IX. CONCLUDING REMARKS

In practice, it is often difficult to determine the capabilities, operational characteristics, and limitations of a particular ground-water modelling code from the documentation, or even impossible without actual running the code for situations relevant to the project for which a code is to be selected due to incompleteness, poor organization, or incorrectness of a code documentation. Systematic and comprehensive description of a code features based on an

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informative classification provides the necessary basis for efficient selection of a groundwater modelling code for a particular project or for the determination that no such code exists.

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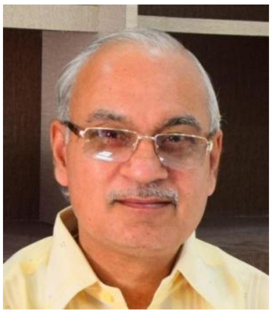

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