ground water

Historical Note/

The History of MODFLOW

by Michael G. McDonald[1] and Arlen W. Harbaugh[2], the original authors of MODFLOW

Motivation for MODFLOW

During the 1970s, the application of computer models of ground water flow grew dramatically within the U.S. Geological Survey (USGS) because they provided improved capability for solving water-resources problems. The only computers capable of running such codes were very expensive and available only to large organizations. Consequently, USGS was a leader in the application of models. Most model codes being used then evolved from codes developed by researchers to establish the feasibility of the technology rather than as tools for routine hydrogeologic studies. Initially, the codes were two dimensional (Pinder 1970 [superseded by Trescott, Pinder, and Larson 1976] and Prickett and Lonnquist 1971); then three-dimensional codes (Trescott 1975) were developed as computers became more powerful.

At that time, USGS hydrologists were accustomed to modifying and adapting existing model codes to their specific needs and preferences, which resulted in substantial duplication of effort. Users would add or modify hydrologic simulation capabilities, e.g., the method of simulating ground water interaction with rivers, or modify the form of model input and output. Most USGS users had their own modified version of a published code. These different versions frequently read data using incompatible formats, and the specific kinds of input data were often different. Furthermore, because the programs used nonstandard versions of Fortran, they were not portable. Programs that ran on one brand of computer would not run without substantial modification on another brand of computer.

In 1981, we estimated that each of the 50 major offices of the USGS had several studies that called for models. We further estimated several hundred USGS employees were using ground water models and as many as 500 distinct versions of USGS ground water flow model programs were on the USGS mainframe computer. USGS policy required complete documentation of all procedures and analytical methods used in studies. This requirement extended to computer programs. Therefore, nearly every report that referred to a computer model needed to include documentation of the specific version of the model code that was used.

Development of MODFLOW

As models became widely used in USGS studies, the benefit obtained from creating one program that combined the best capabilities of all the variations of model programs used in the USGS became apparent. Several individuals in the USGS began developing new programs independently. The USGS Office of Ground Water (which was then called the Ground-Water Branch) formed a committee to revise an existing three-dimensional model program. Realizing that both the "committee" idea and the "revise" idea were untenable, Michael McDonald, who worked in the Office of Ground Water, persuaded the office to disband the effort to revise the existing model and offered to develop an entirely new program. The new code would include all the capabilities commonly used by USGS modelers in early 1981. Arlen Harbaugh, who was in the New Jersey District of USGS, was asked to work with McDonald. Gordon Bennett, who was the chief of the Office of Ground Water, championed the effort.

The resulting model code was originally called the USGS Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Informally, we called the code the Modular Model. The model became known as MODFLOW several years later.

Design

We both had been applying models for several years, and we established several major design criteria based on our experience. The design had to:

- Facilitate a detailed understanding of the model concepts and code among hydrologists with limited mathematical and computer training.
- Facilitate addition of new capabilities.
- Be portable so that it could be run on a wide variety of computers with little or no modification.

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- Optimize usage of the limited amount of computer memory found on most computers of the time.

Input to the model had to be viewed as multiple streams, each related to a specific aspect of the model rather than a single massive input file. Input and output requirements must permit individual users to develop specialized preprocessors and postprocessors, thereby omitting device-dependent code from the model program. The program documentation had to be extensive so users could understand the details of the entire program, and subdivided so users could focus on a single aspect at a time.

The design criteria were met by implementing several strategies: modular structure, creation of comprehensive documentation, flexible and complete output, and strict adherence to the standards of the Fortran '66 programming language. The attribute "modular" was associated with the idea of an improved model design before 1981, but the meaning was not clearly defined. So we devised our own understanding of the term "modular." The modular structure we designed distinguished between "formulators" of terms in the ground water finite-difference equations and "solvers" of the finite-difference equations. The structure then distinguished among specific formulators—e.g., block centered flow, river, evapotranspiration, and recharge—and specific solvers—such as strongly implicit procedure and slice successive overrelaxation. A specific formulator or solver was called a package. Modules were smaller structural components used to construct packages.

This design facilitated ease of understanding by allowing a user or a program developer to focus on specific aspects of the program. For example, the method of representing the interaction of rivers with ground water could be studied without regard to the method of representing recharge or changes in storage. The subdivision of packages into modules with specific tasks facilitated focus on specific details of packages.

It also became clear that user and programmer understanding would be facilitated if the programming style were consistent among packages. Consistent variable naming conventions were used throughout the code. For example, in many packages, the variable "RATOUT" was the rate of flow from the model to an external stress. (Fortran '66 limited variable names to six characters.) The consistency among packages made it so that after users or programmers understood one package, it was easier to understand other packages.

A new capability could commonly be implemented by adding a new package. Existing packages could often be used as a starting point for a new package. New packages could generally be added to the program without affecting existing packages.

The extensive report was organized into chapters, each of which corresponded to a package. The report organization was based on the idea that the user would read only those chapters that corresponded to packages being used. It was also our intent that the chapters would serve as examples for reports describing packages developed by others. Under USGS reporting rules, a new or modified package could be documented alone without having to duplicate documentation for the entire model program.

Chronology

MODFLOW was developed between the spring of 1981 and the winter of 1983. Michael worked nearly full time and Arlen worked about half time on the model. The modular design was the focal point at first. We tried several different schemes before finalizing the modular design. The code was mostly developed before the documentation, but the clarity of documentation was a consideration in code design throughout the project.

At the outset Arlen, in New Jersey, produced and tested prototypes while Michael, in Virginia, worked on the modular design. Arlen tested the code using a grid of seven rows, seven columns, and four layers—the largest grid that his minicomputer could handle. By the fall of 1981, a limited version of the program was available for testing by venturesome hydrologists in the USGS district offices. Between the fall of 1981 and the spring of 1982, we added capabilities, experimented with a variety of solvers, and designed the documentation.

During 1982, we conducted a number of short courses on MODFLOW in the USGS. Experienced modelers learned in three days how to use the model and how to convert data from other models for use in MODFLOW. Thus, many modelers tested MODFLOW by comparing its results to results from other model codes they were using.

Most of 1983 was spent writing the documentation, which was completed except for final USGS processing and printing by the end of 1983. MODFLOW was released as a USGS Open-File Report in the spring of 1984 (McDonald and Harbaugh 1984). The design on the report cover depicted the idea that MODFLOW was similar to a component stereo system. Just as components of a stereo could be plugged into a tuner if the interface followed strict protocols, so new packages could be plugged into MODFLOW. MODFLOW was quickly adopted for use within the USGS and in other organizations that had adequate computer facilities.

Early Experience

The release of MODFLOW coincided with the maturation of minicomputers and the advent of personal computers. Consulting companies and smaller government agencies could afford to apply models. The general availability of computers changed attitudes about use of computers. Most people who used personal computers did not know lower level programming languages such as Fortran. Ironically, as it became practical for greater numbers of hydrologists to use MODFLOW, a smaller and smaller percentage of the users had the programming skills to modify the program. Thus, one of the major design assumptions of MODFLOW, that most hydrologists would be able to modify the program, was no longer valid.

On the other hand, those hydrologists who did know Fortran went to work building new packages. Two packages that provide a more elaborate representation of the relation between streams and an aquifer were developed (Miller 1988; Prudic 1989). Leake and Prudic (1988) developed a package to represent subsidence. Two preconditioned conjugate-gradient packages were developed (Kuiper 1987; Hill 1990).

We were surprised by the development of commercial interactive, character-based programs that prepared input data specifically for MODFLOW. For some people, these programs provided a welcome alternative to general-purpose commercial programs, such as text editors and spreadsheet programs, and user-written Fortran programs for data preparation.

The USGS Office of Ground Water was not formally involved in the development of MODFLOW during the second half of the 1980s. Although we took other assignments in the USGS, we continued working on MODFLOW on our own time, and we taught MODFLOW training classes. We revised the documentation for release in the report series Techniques of Water Resources Investigations (TWRI, McDonald and Harbaugh 1988). The program was largely like that released in 1984, but we made small changes to make the code conform to Fortran '77 rather than Fortran '66. Gordon Bennett provided a thorough editorial review of the TWRI report.

Later Experience

By the early 1990s, MODFLOW had become the most widely used ground water flow model both within and outside USGS. Michael left USGS to start a consulting company, and Arlen transferred to the Office of Ground Water, where he worked (and continues to work) on the support and development of MODFLOW. Continued development of new packages proceeded. An overall update to MODFLOW, called MODFLOW-96, was released in 1996 (Harbaugh and McDonald 1996). MODFLOW-96 was a relatively minor update primarily to improve ease of use.

Increasingly powerful, inexpensive personal computers permitted the routine construction of models containing tens of thousands of cells. As envisioned in the overall plan, external data manipulation capabilities were developed and used rather than incorporating them in MODFLOW. Among these programs were the Zonebudget program for computing subregional water budgets (Harbaugh 1990) and graphical user interfaces (GUIs) such as ModelCad[3] (Geraghty and Miller), Processing MODFLOW (PM, Chiang and Kinzelbach 1993), Modular Integrated Modeling Environment (ModIME)[3] (S.S. Papadopulos & Associates Inc.), Groundwater Vistas (Environmental Simulations Inc.)[3], Visual MODFLOW[3] (Waterloo Hydrogeologic Inc.), Groundwater Modeling System (GMS)[3] (Brigham Young University), and MODFLOW-GUI (Shapiro et al. 1997).

The large models permitted by the new computers made traditional trial-and-error calibration more difficult. Interest in more formal parameter estimation methods increased. Two parameter-estimation programs based on MODFLOW were developed: MODFLOWP (Hill 1992) and MODINV (Doherty 1990); however, MODFLOWP and MODINV were independent programs. PEST[3] (Watermark Numerical Computing) and UCODE (Poeter and Hill 1998) were developed to perform parameter estimation using any model, and were often used with MODFLOW.

Interest in contaminant transport first led to the development of programs to track particles through a model-simulated flow system as a representation of advective transport. Among the first particle-tracking programs were PATH3D[3] (S.S. Papadopulos & Associates Inc.) and MODPATH (Pollock 1989). Shortly thereafter, a full-transport model, MT3D[3] (S.S. Papadopulos & Associates Inc.), was developed. MT3D and the particle-tracking programs are postprocessors. The USGS produced MOC3D (Konikow, Goode, and Hornberger 1996), which incorporates transport directly into MODFLOW-96.

Development of MODFLOW 2000

MODFLOW was originally conceived as a ground water flow model. The addition of transport and parameter estimation was not as straightforward as the addition of new packages. These capabilities require the results of solving the ground water equation, but additional equations must also be solved. Having the separate MODFLOWP and MOC3D versions of MODFLOW for transport and parameter estimation made use and support more difficult. Combining all of these capabilities into a single program promised to make development and use easier; therefore, the decision was made to develop a single program to include ground water flow, transport, and parameter estimation.

To facilitate the integration, an expansion of the modular design was required. The result was MODFLOW-2000 (Harbaugh et al. 2000). Just as the "package" was the highest-level subdivision of MODFLOW, the "process" became the highest-level subdivision of MODFLOW-2000. "Process" is defined as the part of the code that solves a major equation. The part of the code that solves the ground water flow equation became the ground water flow process. Three processes—observation, sensitivity, and parameter estimation—aid calibration and evaluation (Hill et al. 2000). Solution of the transport equation is the ground water transport process.

Conclusion

The original version of MODFLOW was developed in three years; nearly 20 years have passed since MODFLOW was first released. As evidenced by widespread use and the large number of additions that have been made, the modular design was effective in facilitating the design criteria of ease of understanding and expansion. The "process" construct was added to MODFLOW-2000 to extend the benefits of the original modular structure to the solution of multiple equations. As MODFLOW matures and new capabilities expand it beyond its original scope, continued care will be necessary to ensure that the original design criteria are maintained.

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