Forty Years of Evolution of Groundwater Flow and Solute Transport Modelling at And Near Mine Sites

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Abstract

The nature of groundwater flow and solute transport modelling at and near mine sites has evolved because the objectives (the questions) have changed, simulation software has improved, model resolution has increased, graphical interfaces have become very powerful and stakeholders are asking more challenging questions, especially related to prediction uncertainty. Computing performance has increased by a factor of 10^6 or more (cf. Moore's Law and its corollaries), but stakeholder expectations have increased dramatically, so the time required to develop, test and apply a simulation model is not significantly less than it was 40 years ago. High-level modellers still need programming skills to extend available simulation software.

Keywords: Groundwater flow, solute transport, simulation, mining

Introduction

The application of groundwater flow and solute transport models at and near mine sites is not new. Simulation software has been used in the mining sector since it first became available, perhaps starting with PLASM (the Prickett and Lonnquist Aquifer Simulation Model, based on the finite difference method, Prickett and Lonnquist 1971), then with AQUIFEM-1 (Wilson *et al.* 1979, Townley and Wilson 1980), FEFLOW (Diersch 2014, but first released in 1979), MODFLOW (McDonald and Harbaugh 1988), AQUIFEM-N (Townley 1990) and many more.

Objectives of modelling: analysis and design

Working effectively within the mining industry requires an understanding of the types of questions that need to be answered, or problems that need to be solved, and how these questions and problems evolve during the many stages of mining projects, from Conceptual to Order of Magnitude (OoM) to Pre-Feasibility Study (PFS), from Feasibility Study (FS) to Engineering, Procurement and Construction Management (EPCM), from commissioning to operations, and then to expansion and closure studies, each of which involve multiple stages. Another important factor is the nature of the proponent or operator, because startup or "junior" miners are more willing to take risks than "mid-tier" mining companies, with multiple concurrent operations, and "majors", with many concurrent operations and many future projects at different stages of investigation; juniors employ consultants for most tasks while majors often have internal specialist teams. Forty years ago, the project pipeline was not as clear or as well understood, but now it is mature.

Developing a good model requires investment of resources (people, time and money), and every model therefore requires clear objectives. The objectives of a model should be to answer a question, or perhaps several questions. The Australian Groundwater Modelling Guidelines (Barnett *et al.* 2012) emphasise the difference between the objectives of a mining company (e.g. to design a borefield for water supply or mine dewatering, or to gain environmental approvals) and the objectives of a simulation model, which must start with its own conceptual model (conceptualisation of processes), leading to design, construction and execution of that model, with model calibration and often including sensitivity and uncertainty analysis.

An important distinction is between simulation of the past behaviour of a groundwater system and prediction of its future behaviour, without or with human and/or engineered interventions. Simulation of the past is necessary before it is possible to contemplate prediction, which can sometimes be a form of design. Modelling of groundwater near mine sites as part of baseline environmental and Environmental and Social Impact Assessment (ESIA) studies sometimes has the stated objective of developing understanding, but if the effects on environment are considered to be too great, regulators can force the redesign of a proposed mine. Simulation of groundwater flow and solute transport can also be considered in the context of sitewide or integrated water management at mine sites; water management issues can be categorised as being related to having "too little" water, "too much" water or water that is "too dirty".

All the types of studies described in Tab.1 are often described simply as "modelling", but it is useful to emphasise the distinction between analysis and design, partly to elevate our work as "groundwater modellers" to the level of "design engineers". This is not to say that groundwater modelling at or near mine sites is a form of engineering, although sometimes it is, but rather to remind stakeholders that the level of scepticism and criticism sometimes directed at groundwater "modelling" is sometimes much greater than the level of scepticism and criticism directed at all the other types of engineering "design" required to build and operate a mine (e.g. mining, geotechnical, process, civil, mechanical and electrical engineering). All engineering design requires clear design objectives, requires consideration of multiple scenarios and must deal with uncertainties. The use of groundwater simulation software in design is similar to the use of software in all other types of engineering, but with different levels of scrutiny by stakeholders.

Why is groundwater modelling especially challenging in the mining sector?

One of the special features of mining projects is that the geometry of the system is changing every day, through excavation (in either open cut or underground mines) and placement of waste rock in waste rock dumps (WRDs) at the land surface. In many kinds of mining, mineral processing requires crushing and grinding/milling rock, and this leads to construction of Tailings Storage

__Table 1__ Objectives of modelling: analysis versus design

Question/problem	At or near mine site?	Too little, too much, too dirty?	Analysis or design?
1. Groundwater resource assessment and borefield design	Near	Too little for processing	Both
2. Estimation of (passive) mine inflows	At and near	Too much	Analysis
3. Design of (active) dewatering bores	At and near	Too much	Design
4. ESIA of mine inflows and dewatering on regional groundwater (cone of depression, depressurisation)	Near	Too little for environment	Analysis
5. ESIA of mine inflows and dewatering on springs, groundwater dependent ecosystems (GDEs), stygofauna	Near	Too little for environment	Analysis
6. Assessment of pit slope stability and design of depressurisation (both saturated and unsaturated)	At	Too much	Both
7. Evaluation of leakage and migration of (often dense) plumes from water storage ponds, TSFs and WRDs; design of borefields to recover (dense) plumes	At and near	Too dirty	Both
8. Evaluation of the formation and control of acid rock drainage from within mines and WRDs and potential discharge to surface streams and lakes	At	Too dirty	Both
9. Prediction of evolution of mine pit lakes after closure	At and near	-	Analysis

Facilities (TSFs), another kind of constructed landform. When modelling software was first developed, it was based on the concept of a layered system, initially a sequence of sub-horizontal aquifers and aquitards. From the outset, using this available software to simulate mining and later the growth of constructed landforms was a bit like trying to fit the proverbial round peg in a square hole.

Another special feature of mining is the stress that it puts on a regional groundwater system. We use the terms "stress" and "forcing" partly because development of groundwater simulation software followed the development of software for structural engineering in the 1970s. Developing a water supply borefield, in either an unconfined or confined aquifer, leads to lowering of the water table or the piezometric surface over a large area; large borefields are rarely developed in aquifers without some previous history of pumping and without knowledge of aquifer properties. But in mining the opposite is true. Mining nearly always takes place in hydrogeological systems that have not previously been stressed and causes drawdown of the water table or piezometric heads or both by tens and often hundreds of metres. Conducting 72-hour or even 30-day pumping tests hardly stresses the hydrogeological system and rarely provides data to support calibration of a regional scale model. In the same way, three years of monitoring of a quasi-steady regional water table (as required in Australia, for example) is usually insufficient for model calibration.

Because mining leads to so much drawdown, this causes difficulties related to dewatering and draining of cells or elements in a model with a fixed mesh or grid. While this also occurs in borefields, the challenge is greater in mining. MODFLOW, MODFLOW-SURFACT and FEFLOW have similar but different approaches for handling large drawdown, with draining of many cells.

Representation of mines and other infrastructure in modelling software

Since the earliest attempts to estimate mine pit inflows, modellers have been faced with the challenge of how to represent mines in software. Most modellers use software that assumes that Darcy's Law (a linear gradient law, with flow proportional to the gradient in piezometric head) is sufficient to represent flow at a large scale, from tens or hundreds of metres to tens or hundreds of kilometres. Conservation of mass (or volume, if variations in density can be ignored) leads to a diffusion-type partial differential equation (PDE) for piezometric head which can be solved by finite difference, finite element, finite volume or other methods.

The PDE and resulting simulation software only allow three types of boundary conditions: 1st Type, prescribed head or Dirichlet boundary conditions, where piezometric head is known but flux through the boundary at that location is not; 2nd Type, prescribed flux or Neumann boundary conditions (Neumann when the prescribed flux is zero), where flux across the boundary is known but piezometric head at that location is not; and 3rd Type, mixed or Cauchy boundary conditions, where neither piezometric head nor flux across the boundary are known, but a relationship between head and flux is known.

Where do we get guidance on how to use groundwater flow simulation software in the mining sector? The author is not aware of any text or reference book focused on simulation of groundwater near mines. In the Large Open Pit (LOP) project led by CSIRO and supported by many large mining companies (Read and Stacey 2009), Chapter 6 (Hydrogeological Model, by Geoff Beale) introduces a modelling methodology, focused on estimating or predicting pore pressures in pit walls of large open pits, to support assessment of geotechnical stability. Chapter 6 led to a second book (Beale and Read 2013) which was longer than the first. However neither of these books provides detailed advice on how to set boundary conditions in models.

Hamilton and Wilson (1977) used an early version of AQUIFEM-1 to study the effects of strip mining of coal (see also Wilson and Hamilton 1978). Since AQUIFEM-1 was a 2D finite element model, modelling was undertaken in 2D plan and also in 2D vertical section, where it was possible to represent hydrostratigraphic layers with different properties. Typical finite element grids had more than 100 nodes and 200 triangular finite elements. A mine was represented using prescribed head boundary conditions, with head set equal to the elevation of the base of the mine. The AQUIFEM-1 user manual (Townley and Wilson 1980, Section 5.5) includes an example where a mine excavation is represented by only 4 nodes, using a so-called "rising water table" condition (Section 3.4.2), effectively a "seepage face" boundary condition where in this case the ground surface falls in time, and when water table elevation at such a node exceeds the ground elevation, water table elevation is fixed at that elevation until the next time step.

Users of MODFLOW and MODFLOW-SURFACT (HydroGeoLogic Inc. 1998, Panday and Huyakorn 2008) have long used a so-called "drain" boundary condition (DRN package) to represent the base of a mine. This is a mixed boundary condition, and if conductance is very large, this boundary condition is almost equivalent to a prescribed head condition. Some modellers use prescribed pumping first to design dewatering bores and then use drain nodes to check performance.

FEFLOW has an extensive range of special boundary conditions, such as a "seepage face" condition, which is like the rising water table condition in AQUIFEM-1 and AQUIFEM-N and it includes a constraint that the flux through the boundary must be out of the model domain. This, when combined with many other features in FEFLOW such as elements that can be deactivated and reactivated (mined and refilled), and control using the Interface Manager and special data files, makes FEFLOW by far the most powerful and flexible software for representing mines.

Evolution of groundwater modelling software

The last 40 years (or arguably a little more) have seen slow but steady evolution of groundwater modelling software, from PLASM to AQUIFEM-1 and FEFLOW, to MODFLOW, AQUIFEM-N and more (FEFLOW was first released in the former East Germany in 1979, the same year as AQUIFEM-1). These packages are described in two well-known reference books by Anderson and Woessner (1992) and Anderson *et al.* (2015). Other well-known packages are MODFLOW-SURFACT, HydroGeoSphere, HYDRUS and MINEDW (references for the last three are not provided here). MODFLOW-6 is now enormously different from earlier versions, indeed there are so many versions of MODFLOW that even experienced modellers struggle to understand the differences.

In parallel with simulation software itself, there has been evolution of graphical user interfaces (GUIs). In the 1990s the author collaborated with 3G Geotechnica s.r.o. in Prague to develop a GUI for AQUIFEM-N, and this was used for many mining applications by consultants in Australia during the 1990s. At the same time, AQUIFEM-N was embedded within Maptek's Vulcan 3D mining software, and MODFLOW was also embedded within Surpac mining software, but neither were released, largely because it became clear that geological data were collected very close to an orebody, and such data could rarely support the development of a regional scale groundwater flow model suitable for estimating mine inflows. Leapfrog Hydro (now from Seequent) and Geomodeller 4.0 (from Intrepid Geophysics in Melbourne, Australia) provide useful pathways from 3D geological models to 3D hydrogeological models to 3D simulation models, but FEFLOW is evolving rapidly with more and more 3D geological modelling capabilities built in.

MODFLOW and MODFLOW-SURFACT have been supported in many GUIs, such as ModelMuse, Visual MODFLOW, GMS and Groundwater Vistas. For some years the latter was the GUI of choice for users of MODFLOW in the Australian mining sector, but many advanced users are also using FloPy and PyEMU (https://help.pesthomepage.org/pest_and_pestplusplus.html) and Jupyter Notebooks. These methods provide flexibility and transparency, at least for the experts.

FEFLOW is extremely powerful because it is extensible via its Interface Manager (Ifm), with code that can be written in C, Python or other languages. Perhaps one reasonable conclusion is that modellers (users of modelling software) always need capabilities that are not yet available, so high-level modellers still need programming skills

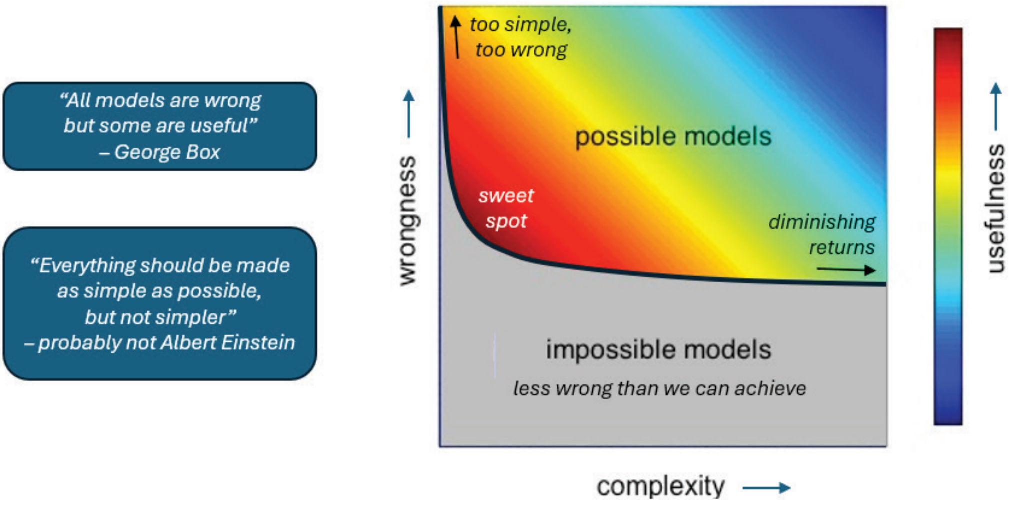

Figure 1 The Box-Einstein surface of mathematical models, after Noble (2016).

to fill the gap. It remains to be seen whether Large Language Models (LLMs), a form of Artificial Intelligence (AI), will reduce barriers to entry and allow non-programmers to achieve results that used to require years of experience.

Model complexity

While simple questions could be answered in the 1980s using 2D models with hundreds of nodes or cells, typical models today have 10^5–10^6 unknowns or more. The number of unknowns affects computation time but this is not the only measure of model complexity. The latter depends also on parameterisation (the way hydrogeological properties and boundary conditions are represented and the number of parameter values required to describe their spatial and temporal distributions). While some modellers subscribe to the philosophy of highly parameterised models, relying on parameter estimation software such as PEST (Doherty 2015) to estimate many parameter values, there may also be good reasons to keep models as simple as possible. Fig. 1 illustrates the possibility that it may be useful to resist the temptation to add complexity.

Expectations are rising

If computing performance is always increasing (see Tab.2), why can't we do much more? Perhaps there are many reasons. Expectations are now much higher than they were 10–20–30 years ago. Government and community stakeholders expect higher resolution in graphics and visualisation, and this implies finer resolution in grids, even though the graphics may then suggest a level of "rightness" that is not achievable.

Table 2 Corollaries to Moore's Law: Evolution in computing power since the 1970s

Performance Measure	Then	Now	Factor of Increase
Transistors (Moore's Law)	2300 in 1971	>20 billion in 2021	$\approx 10^7$
Processor speed	1 SPECint in 1978 (VAX 11/780)	11000 SPEC CPU 2006 in 2017 (Intel Xeon 8180)	$\approx 10^5$
RAM	16 KB in mainframe in 1976	128 TB in Dell T5820 workstation in 2021	$\approx 10^7$
Capacity of disks	360 KB on 5¼ inch floppy in 1978	8 TB in 2021	$\approx 10^7$
Network speed	110 baud on AUSTPAC in 1984	500 mbps in 2023	$\approx 10^7$
Time to develop and run a model	Weeks to months	Weeks to months	1

Stakeholders demand that more processes (e.g. unsaturated flow and reactive transport) should be included in models, even if there are not enough data to support such efforts. Development of models still takes time, even with sophisticated user interfaces, and because modellers need time to communicate with their teams and with other stakeholders. This part of the modelling process is not becoming easier or faster.

Conclusions

The objective of this paper was not to teach modellers how to develop models, but rather to provide context that partly explains why modelling remains difficult and time-consuming. High-level modellers still have needs that are not met by available software, so they often still need programming skills to extend the available capabilities.

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References

Anderson MP, Woessner WW (1992) Applied Groundwater Modeling, Simulation of Flow and Advective Transport, Academic Press Inc., 381 pp.

Anderson MP, Woessner WW, Hunt RJ (2015) Applied Groundwater Modeling, Simulation of Flow and Advective Transport, Second Edition, Academic Press Inc., 564 pp.

Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A, Boronkay A (2012) Australian Groundwater Modelling Guidelines, Waterlines Report Series No. 82, National Water Commission, Canberra, June, 203 pp.

Beale G, Read JRL (Eds) (2013) Guidelines for Evaluating Water in Pit Slope Stability, CSIRO Publishing and CRC Press, 600 pp.

Diersch HJG (2014) FEFLOW: Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media, Springer, 996 pp.

Doherty J (2015) Calibration and Uncertainty Analysis for Complex Environmental Models. Watermark Numerical Computing, Brisbane, Australia. www.pesthomepage.org/pest-book.

Hamilton DA, Wilson JL (1977) A generic study of strip mining impacts on groundwater resources, MIT Energy Laboratory Report No. MIT-EL 77-017, September, 156 pp.

HydroGeoLogic Inc. (1998) MODFLOW-SURFACT v.3.0: A comprehensive MODFLOW-based flow and transport simulator, Code Documentation Report, Reston VA.

McDonald MG, Harbaugh AW (1988) A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Techniques of Water-Resources Investigations 06-A1, USGS, 576 pp.

Noble R (2016) The Box-Einstein surface of mathematical models, www.thesefewlines.wordpress.com/2016/11/20/the-box-einstein-surface-of-mathematical-models.

Panday S, Huyakorn PS (2008) MODFLOW SURFACT: A State-of-the-Art Use of Vadose Zone Flow and Transport Equations and Numerical Techniques for Environmental Evaluations. Vadose Zone Journal, 7(2), 610. doi:10.2136/vzj2007.0052

Prickett TA, Lonnquist CG (1971) Selected Digital Computer Techniques for Groundwater Resource Evaluation, Illinois State Water Survey, Bulletin 55, 62 pp.

Read JRL, Stacey PF (Eds) (2009) Guidelines for Open Pit Slope Design, CSIRO Publishing and CRC Press, 496 pp.

Townley LR (1990) AQUIFEM-N: A Multi-layered Finite Element Aquifer Flow Model, User's Manual and Description, Townley and Associates.

Townley LR, Wilson JL (1980) Description of and User's Manual for a Finite Element Aquifer Flow Model AQUIFEM-1, Technical Report No. 252, Ralph M Parsons Laboratory for Water Resources and Hydrodynamics, MIT, 294 pp.

Wilson JL, Hamilton DA (1978) Influence of strip mines on regional groundwater flow, J.Hyd.Div. ASCE 104, 9, 1004–1011, September.

Wilson JL, Townley LR, Sa da Costa A (1979) Mathematical Development and Verification of a Finite Element Aquifer Flow Model AQUIFEM-1, Technical Report No. 248, Ralph M Parsons Laboratory for Water Resources and Hydrodynamics, MIT, 114 pp.