Benchmarking variable-density groundwater flow and solute transport models: Approaches, Resolutions and Future Challenges

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ABSTRACT

In many groundwater environments, fluid density and viscosity may vary in space or time as a function of changes in concentration, temperature or pressure of the fluid. Examples include, but are not limited to, seawater intrusion in coastal aquifers, high-level radioactive waste disposal, groundwater contamination, and geothermal energy production. Numerical groundwater flow and solute/heat transport models have and will continue to play an important role in understanding such groundwater systems and as such, there has been significant effort put into developing reliable numerical models to simulate these systems. A critical part of this development involves the testing and evaluation of computer codes.

In comparison to the cases involving homogeneous fluid properties, for many complex variable-density problems it is difficult to formulate appropriate analytical solutions that usually provide a basis for testing a numerical model. The numerical codes developed to simulate such variable-density processes e.g., SUTRA [Voss, 1984], MOCDENSE [Sanford and Konikow, 1985] and HST3D [Kipp, 1987] to name just a few, usually employ a set of coupled equations which may include nonlinear relations among parameters and an interdependence of solutions of the individual equations. Evaluation of variable-density numerical modeling codes typically relies on both internal consistency tests including mass balance indicators and external tests typically involving comparison with other numerical models (benchmarking) and against other observational evidence. The demonstration of agreement between observations (laboratory tests, in situ tests and the analysis of natural analogs) and numerical model prediction form part of what Oreskes et al., [1994] term “model confirmation” which is a matter of degree and is inherently partial. This is because for any given numerical model, some predictions will agree with observations and some will not. In practice, few (if any) models are entirely refuted or confirmed by observational data [Oreskes et. al., 1994].

Variable-density transport models are typically tested by comparing model output with the results of three standard benchmarks: (1) the HYDROCOIN Level 1, Case 5 “salt dome” problem [OECD, 1988], (2) the Henry [1964] approximate analytic solution for steady-state saltwater intrusion and (3) the Elder [1967] problem for complex natural convection where fluid flow is driven purely by fluid density differences. These benchmarks have been discussed in previous literature including...
Kolditz et al., [1998], Oldenburg and Pruess [1995] and Voss and Souza [1987]. We review these model benchmarks and discuss the evolution of research and results relating to them. The successes and limitations of each benchmark are described. Since model confirmation is at best only partial, increased trustworthiness in a numerical model can only be gained by the repeated testing of a code and making some judgement on its relative successes and failures. To do this requires a sufficient number of well-defined tests whose results are well known. Given the importance of variable-density flow and transport processes in many field problems, the development of further test cases for variable-density flow and transport codes is considered useful.

We present two new problems that are test cases for benchmarking variable-density flow and transport codes. The first is a numerical simulation of natural convection in porous media based upon work of Horton and Rogers [1945] and Lapwood [1948]. This problem has a well-defined analytical solution for the onset conditions for convection as well as for the geometry of the resultant steady-state convection cells. The second test case, the “Salt Lake Problem” [Simmons et al., 1999], involves a numerical model of an idealised evaporating salt lake produced using the 2-D density-dependent model SUTRA, the results of which are compared with an equivalent laboratory Hele-Shaw cell system developed by Wooding et al., [1997a,b]. Evaporation results in dense brine overlying less dense fluid, which is hydrodynamically unstable, and leads to downward convection of salt fingers or plumes. A comparison of experimental and numerical plume growth shows good spatial and temporal agreement. The numerically generated plume pattern is sensitive to changes in random noise level applied just below the evaporation surface that serves as a trigger for the growth of instabilities. Experimental plume patterns were best matched with a noise level corresponding to 1% of the total salinity difference between boundary layer and background fluid concentrations at saturation. This comparison appears to provide a stringent test for variable-density groundwater flow and solute transport numerical codes.

References


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