Comparison of numerical models using a two-dimensional benchmark of density-driven flow

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ABSTRACT

We compare five numerical models to a physical benchmark of density-driven flow of a freshwater lens. Freshwater flow paths, velocity and salinity distributions as well as the propagation of the saltwater-freshwater interface were observed and analyzed in detail. Steady-state as well as transient results reveal certain differences of the numerical models, even though the model settings and boundary conditions are kept as identical as possible.

INTRODUCTION

Today, a great variety of groundwater modeling software is available. Due to differences in structure, solver types and features implemented in the models, it is assumed that differences in modeling results should occur. We therefore investigate five numerical models capable of solving the partial differential equations of density-driven coupled flow and transport and compare them to a physical benchmark experiment. Describing the capabilities and revealing differences and limitations, as well as advantages of the different models, is the aim of this study.

METHODS

The test case used to compare the different codes is an artificially generated two-dimensional freshwater lens in a homogeneous sandy aquifer with horizontal and vertical extensions of approximately 80 cm and 30 cm, respectively. The benchmark is described in more detail in Stoeckl and Houben (2012), who used an acrylic glass box to simulate such a cross section of an infinite strip island. Salt water with a density of 1021 kg m^{-3} was injected, saturating the sand from bottom to top. Saltwater was continuously displaced by infiltrating freshwater at the top, developing a lens until equilibrium was reached. To visualize the flow pattern of the fresh water with a density of 997 kg m^{-3}, different fluorescent tracer dyes were added.

The models used for comparison are: *d3f* (Fein and Schneider 1999), *Feflow* (Diersch 2005), *HydroGeoSphere* (Therrien et al. 2007)*, OpenGeoSys* (Kolditz et al. 20012), and *Spring* (König et al. 2012). To ensure the highest level of comparability for the numerical groundwater flow models, the setup is defined as similar as possible for all models, with identical temporal and spatial resolution (triangular grid with 241,400 elements and a constant time step size of 8.64 s). Additionally, the same boundary conditions and parameters are used (Fig. 1). The output of each model is then converted into the same format and post-processed using the open-source program ParaView.

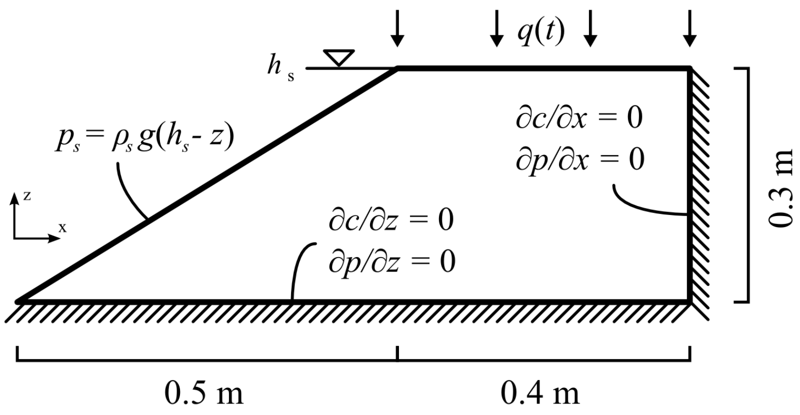

Figure 1: Sketch of model domain and boundary conditions used for the five different numerical models (Walther submitted, after Stoeckl and Houben 2012).

Table 1: Model geometry and parameters (based on Stoeckl and Houben 2012)

	acronym	value	unit
Model geometry			
Half width of island (top)	L	0.4	m
Bottom half width	B	0.9	m
Height of island	H	0.3	m
Number of elements (triangular)	-	241,400	-
Number of nodes	-	121,362	-
Measured parameters			
Hydraulic conductivity	K	$4.5\cdot10^{-3}$	$m\cdot s^{-1}$
Intrinsic permeability = $(K_f\cdot\mu) / (g\cdot\rho_f)$	k	$4.6\cdot10^{-10}$	m2
Effective porosity	n_e	0.39	-
Density saltwater	ρ_s	1021	$kg\cdot m^{-3}$
Density freshwater	ρ_f	997	$kg\cdot m^{-3}$
Saltwater-freshwater ratio	a	0.02407	-
Salt concentration	c	1	-
Recharge rate	R	1.152	$m\cdot d^{-1}$
Estimated parameters			
Longitudinal dispersivity	α_L	$5\cdot10^{-3}$	m
Transversal dispersivity	α_T	$5\cdot10^{-4}$	m
Molecular diffusion	d	10^{-9}	$m^2\cdot s^{-1}$
Specific storage (compressibility)	S_s	$1\cdot10^{-4}$	m^{-1}
Viscosity	μ	$1\cdot10^{-3}$	$Pa\cdot s$

RESULTS

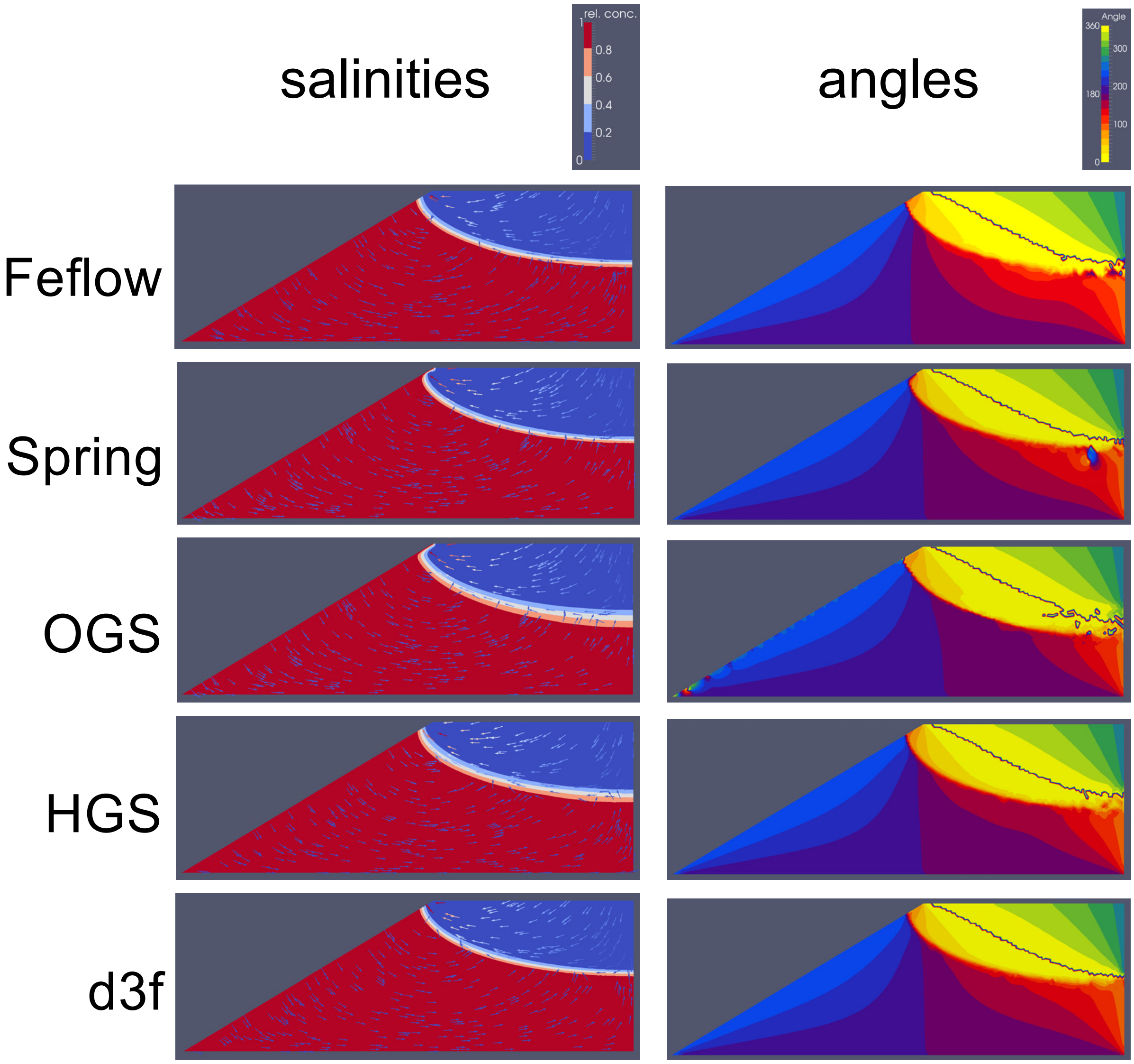

Figure 2: Steady-state simulation results for the five different models showing (left) salinity concentrations normalized to 1 (= seawater) and (right) angles of velocity vectors, clockwise from 0° (horizontal) to 360°.

Figure 2 demonstrates that the thickness of the saltwater-freshwater transition zone shows differences with thinner interfaces for Feflow, Spring and d3f. Spring and OpenGeoSys show an interface bended upwards at the outflow zone where the mass boundary condition at the slope cannot be disabled when water leaves the model domain. This is, however, a graphical artifact, as water is still exiting through this zone. The distribution of the angles of the velocity vectors shows a similar picture for all models (Fig. 2, right side). In Feflow and Spring slight deviations at the right boundary close to the interface are visible (darker spots) indicating a local disturbance. Results obtained for OpenGeoSys show local circulations at the slope.

Transient model results show small differences in the position of the saltwater-freshwater interface over time. Final interface depth positions at steady-state are also very similar at 14.5 cm b.s.w.l. with a deviation of ±0.1 cm.

DISCUSSION AND CONCLUSIONS

Steady-state flow fields and concentration distributions, as well as the transient propagation of the interface at the centre of the island, are compared for five models. All models are capable of representing the benchmark of a developing freshwater lens reasonably well.

As expected, smaller deviations in the results exist as shown for e.g. the thickness of the transition zone or the alignment of the velocity vectors. Reasons for this behavior might be on the one hand program-specific techniques of solving the partial differential equations. On the other hand, the basic conditions are kept as similar as possible but not completely identical due to technical reasons (e.g. the implementation of a constraint turning off the mass-boundary condition).

REFERENCES

Diersch, H.-J.G., 2005. FEFLOW: Finite Element Subsurface Flow and Transport Simulation System WASY GmbH Institute for Water Resources Planning and Systems Research, Berlin, 292p.

Fein, E., Schneider, A. (eds.), 1999: d³f—Ein Programmpaket zur Modellierung von Dichteströmungen. FKZ-02 C 0465 379, final report. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-139, Braunschweig 1999.

König, C., Becker, M., Diehl, A., Rosen, B., Rüber, O., Seidel, T., Werth, B., Zimmermann, C., 2012. SPRING Benutzerhandbuch, Ausgabe 4.1, ISBN 978-3-00-040369-9; delta h Ingenieurgesellschaft mbH; Witten, Germany.

Kolditz, O., Bauer, S., Bilke, L., Böttcher, N., Delfs, J.O., Fischer, T., Görke, U.J., Kalbacher, T., Kosakowski, G., McDermott, C.I., Park, C.H., Radu, F., Rink, K., Shao, H., Shao, H.B., Sun, F., Sun, Y.Y., Singh, A.K., Taron, J., Walther, M., Wang, W., Watanabe, N., Wu, Y., Xie, M., Xu, W., Zehner, B. (2012): OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. Environmental Earth Sciences, 67(2), pp 589-599.

Stoeckl, L., Houben, G. 2012. Flow dynamics and age stratification of freshwater lenses: experiments and modeling. Journal of Hydrology 21 (458-459), pp 9-15.

Therrien, R., McLaren, R.G. and Sudicky, E.A. (2007): HydroGeoSphere - a three-dimensional numerical model describing fully integrated subsurface and surface flow and solute transport (Draft ed.). Groundwater Simulations Group, University of Waterloo. http://www.science.uwaterloo.ca/~mclaren/public/hydrosphere.pdf.

Walther, M. submitted. Variable-Density Flow Processes on Small, Medium and Regional Scales. Technical University Dresden. Dissertation.

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