Simulation of Processes Controlling Migration of Saline Water and Brine above a Flooded Salt Mine in Western New York, USA

Richard M. Yager[1] and *Paul E. Misut*[2]
[1]U.S. Geological Survey, Ithaca, New York, NY, USA
[2]U.S. Geological Survey, Coram, New York, NY, USA

ABSTRACT
Variable-density/vicosity simulations were conducted to investigate processes controlling the migration of brine and saline water in the aftermath of a salt mine collapse, which threatens to contaminate an overlying glacial-drift aquifer. The simulations represent 10.7 years of water-level recovery after mine flooding, followed by a one year of brine pumping. Model results indicate that movement of brine and saline water is controlled by displacement of brine from the mine and mixing of waters from bedrock fracture zones.

INTRODUCTION
The Retsof mine in western New York State, one of the world's largest salt mines, was abandoned after roof collapses in 1994 triggered flooding by water from a confined glacial-drift aquifer. The roof collapses propagated upward through overlying bedrock and formed two rubble zones or chimneys that connected the mine to the aquifer. Inflow rates averaged about 74 m^3 per minute until the mine was completely flooded in January 1996. Flooding of the mine caused dissolution of unmined halite and lowered water levels in the aquifer near the collapse area by as much as 120 m by January 1996 (Yager et al., 2001). By 2005 water levels in the aquifer had nearly recovered to pre-collapse conditions and the mine cavity contained about 60 million m^3 of saturated halite brine.

As the mine cavity closes through continued salt creep, about 80 percent of the brine could be displaced and migrate upward through the rubble chimneys toward the aquifer (L.L. Van Sambeek, RE/SPEC Inc., written commun., July 2007). Saline water flowing through carbonate rocks between the mine and the aquifer could also migrate upward through the rubble chimneys toward the aquifer. A brine mitigation project that includes pumping and desalination of saline water and brine from the rubble chimneys was begun in September 2006 to limit contamination of the glacial-drift aquifer. This study used variable-density simulations to examine the factors that control movement and mixing of waters in the collapse area in support of this project.

HYDROGEOLOGIC SETTING
The flooded Retsof salt mine underlies a bedrock valley that was deepened and widened by ice during the Pleistocene Epoch. The bedrock valley is partly filled with glacial drift deposited during the last deglaciation. The 8-m-thick lower confined aquifer (LCA) is 154 m below land surface in the collapse area and was the principal source of water that flooded the salt mine. About 180 m of nearly flat-lying Devonian and Silurian bedrock separates the aquifer from the mined salt bed in the Salina Group shale. Drilling conducted in 2004 indicated that the rubble chimneys are surrounded by a deformation zone, bedrock that contains numerous bedding fractures created as rock layers sagged toward the mine cavity (Alpha Geoscience, 2005). Borehole geophysical surveys conducted by USGS in 1994 and 2004 detected water-bearing fracture zones at the top and bottom of the Bertie Limestone, 20 m and 50 m below the bedrock surface, respectively. The upper fracture zone is regionally extensive and discharged 4.1 L/s of water in 1986 to a vertical shaft in the salt mine 2 km northwest of the collapse area (Richard F. Langill and Associates, 1990).

VARIABLE-DENSITY/VISCOSITY MODELS

Variable-density/vicosity, transient ground-water-flow models were constructed using SEAWAT-2000 (Langevin and others, 2003) to simulate water-level recovery during the 10.7-yr period following flooding (January 1996 to September 2006), and the subsequent movement of brine, saline and fresh water within the rubble chimneys and surrounding deformation zone. Transport simulations used a migrating tracer to represent halite saturation because the relations between saturation and density, and saturation and viscosity in saline water and brine are relatively linear. The advection-dispersion equation was solved using the total-variation-diminishing (TVD) method with a Courant number of one to minimize numerical dispersion. The flow and transport equations were explicitly coupled and solved alternately; the flow solution was updated whenever the maximum change in density was greater than $5x10^{-3}$ g/cm^3.

The simulation models represented the area within 1 km of the rubble chimneys, coinciding with the location of wells north and south of the collapse area (Fig. 1A). The model grid defined 283,558 active cells with dimensions ranging from 10 m to 300 m; the layer spacing ranged from 0.6 m in the upper half of the domain to 4 m in the lower half. The models simulated flow through the LCA, the two rubble chimneys and surrounding deformation zone, and a portion of the flooded Retsof salt mine (Fig. 1B).

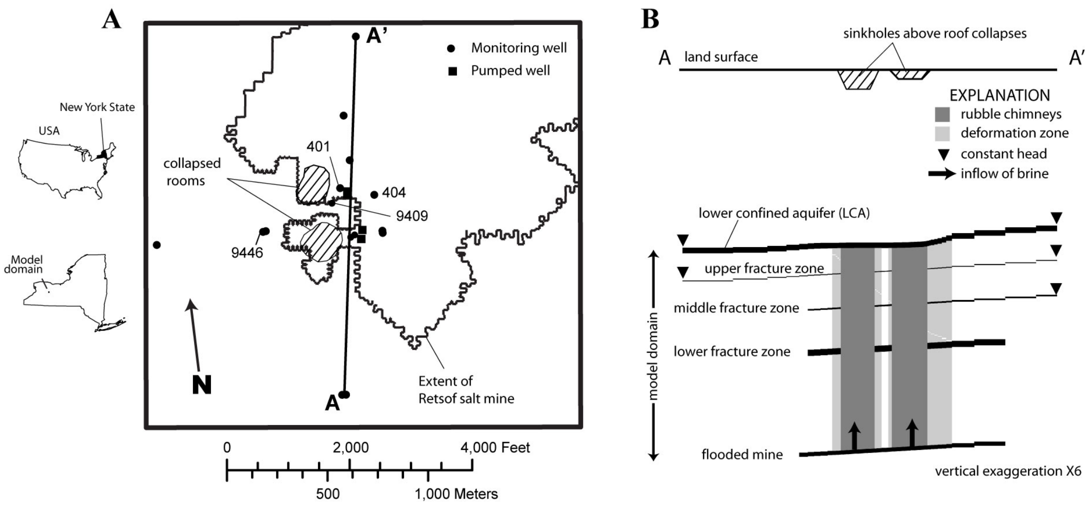

Figure 9. Model domain showing (A) collapse area, mine and well locations, and (B) section with water-bearing units and boundary conditions represented in model.

Three fracture zones in the bedrock were also represented in some models (Fig. 1B). Simulated saturations were compared with a salinity profile constructed from nine discrete-depth samples collected in borehole 9409 in September 2006. Although model parameters were adjusted by trial-and-error to reproduce the measured salinity profile, the resulting models were intended to illustrate the important processes controlling transport, rather than as calibrated representations of the flow system.

Solute at 100 percent saturation was introduced in the bottom model layer to represent brine displaced from the mine at declining rates ranging from 8 to 1.6 L/s, as estimated from subsidence monitoring (RE/SPEC Consulting & Services, 2003). Annually-varying constant heads were specified at the northern and southern boundaries in the top model layer (LCA) based on measured water level recovery in well 9446. Boundaries also represent inflow of saline water through the upper fracture zone and outflow of saline water through the middle fracture zone.

Constant heads computed for the upper and middle fracture zones were based on the measured heads in well 9446 and the assumption that the vertical-pressure gradient was negligible during the 10.7-yr period. The lower fracture zone was assumed to be a cavity developed within the collapse area. Separate 11-month simulations were conducted to represent pumping of brine from the collapse area.

SIMULATION RESULTS

In model A the bedrock fracture zones were omitted and brine migration through the rubble chimneys and deformation zone was controlled only by advection and dispersion. The simulated saturations closely match those observed in the lower 80 percent of the profile, but measured saturations exceed those simulated at the top of the profile (Fig. 2A). Geochemical models constructed previously in this study suggest that saline water at the top of the profile is a mixture of fresh and saline water discharged from the upper fracture zone, and not brine discharged from the mine cavity (D.L. Parkhurst, U.S.G.S., written commun., May 2007), indicating that inflow of saline water has entered the rubble chimney from fracture zones and migrated upward in front of the brine.

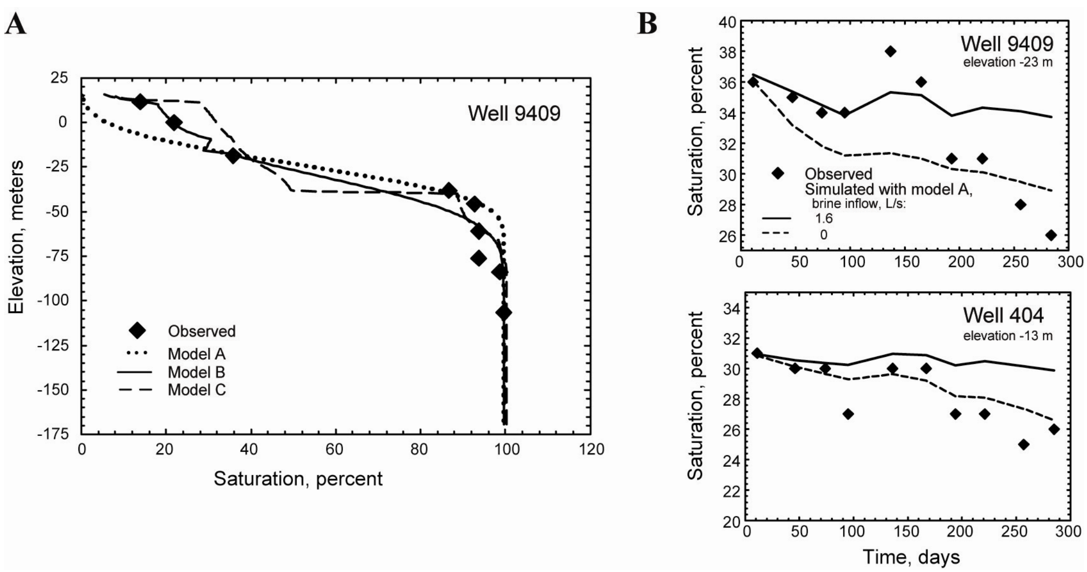

Figure 2. Observed and simulated halite saturations (A) after 10.7-yr water level recovery in borehole 9409, (B) during pumping in wells 9409 and 404.

Mixing of saline and fresh water was simulated in model B, in which saline water was allowed to enter through the upper fracture zone during water level recovery, and the lower and middle fracture zones were not represented. Simulated saturations with this model more closely match the upper part of the profile than results with model A (Fig. 2A). All three fracture zones were represented in model C, in which some of the displaced brine (0.3 L/s) was diverted laterally to the middle fracture zone (elevation -40 m). The resulting salinity profile is affected by mixing where the fracture zones intersect the rubble chimneys (Fig. 2A, elevations -10, -40 and -80 m). Simulation of pumping with model A indicates that the current rate of brine displacement is between 0 and 1.6 L/s (Fig. 2B), and that the salinity is gradually decreasing within the rubble chimneys at elevations above -25 m.

CONCLUSIONS

Pumping of saline water and brine appears to have prevented further contamination of the glacial-drift aquifer. Model simulations indicate that migration of brine and saline water above the flooded salt mine is controlled by advection, dispersion, and mixing of waters where fracture zones intersect the rubble chimneys. Simulations also suggest that some of the displaced brine could be diverted laterally into the middle fracture zone. The constructed models are not unique, however, because the exact geometry and the values of several parameters that affect simulated saturations cannot be estimated from the available data. Continued monitoring of the salinity profile together with borehole flowmeter surveys during pumping could provide additional data for model calibration. Additional boreholes are required to determine whether the displaced brine is migrating through the middle fracture zone.

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Contact Information: Richard M. Yager, U.S. Geological Survey, 30 Brown Road, Ithaca, NY 14850 USA, Phone: 607-266-0217, Fax: 607-266-0521, Email: ryager@usgs.gov