Application of MODFLOW using TMR and discrete-step modification of hydraulic properties to simulate the hydrogeologic impact of longwall mining subsidence on overlying shallow aquifers

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Abstract We apply Groundwater Vistas ® MODFLOW to model hydrologic impacts due to longwall subsidence in the shallow aquifer zone above a 220-m deep mine. Steep spatial and temporal changes are handled using TMR, zooming a transient local model (146,624 cells, 7.3 km^2) from a steady-state regional model (34,200 cells, 53 km^2). Because MODFLOW cannot handle run-time hydraulic property changes, we approximate the mine advance in discrete steps, modifying subsidence-altered property values in discrete stress zones. Simulated potentiometric responses in the demonstration model were similar to observed behavior but further calibration is needed.

Key Words longwall, subsidence, modeling, MODFLOW

Introduction

Subsidence due to longwall underground coal mining significantly affects overlying groundwater systems. The hydrologic mechanisms involved are well understood, but are difficult to model using standard groundwater modeling software. We have developed an approach by which the USGS groundwater flow model MODFLOW (McDonald & Harbaugh 1988; Harbaugh *et al.* 2000) can be applied to simulate the hydrogeologic impact of longwall mining in the upper part of the overburden. We used Groundwater Vistas (ÒEnvironmental Simulations Inc. 2007: ver. 5) (GV), including its TMR (Telescopic Mesh Refinement) conversion and property zone configuration features.

A demonstration model was constructed in GV to simulate the hydrologic behavior over a four-panel section of a longwall mine in Jefferson County, Illinois for which extensive data are available from a field study in 1988—1995 (Mehnert *et al.* 1997; Booth *et al.* 1998). Preliminary stages of this project were reported at the IMWA-2008 meeting (Booth and Breuer 2008). The final project report (Booth & Greer 2010) is available on the US Office of Surface Mining (OSM) website (www.techtransfer.osmre.gov).

Several figures illustrating this paper are in color and are mostly derived from screen-capture of the model. They will be included in the CD-ROM and are cited below as Figure A1 … A4.

Hydrology of Longwall Mining

Longwall mining completely extracts rectangular panels of coal typically 200—400 m wide and several km long, maintaining roof support only in the barrier-pillar zones alongside the panels and with temporary moveable supports in the narrow working face zone that advances as the coal is removed. Consequently, the overburden strata behind the face zone rapidly collapse and subside, producing a subsidence trough over the panel and extensive fracturing and bed separation in the strata. These strains cause substantial changes in secondary porosity and permeability, hydraulic heads, groundwater flow patterns, well water levels, spring flows, and stream-groundwater interaction.

The conceptual model of these hydrologic impacts depends strongly on recognition of the characteristic vertical zones in the overburden that are common to virtually all longwall profiles (Singh and Kendorski 1979; Booth 2002; Kendorski 2006). For hydrologic modeling purposes these are most simply expressed, from the extraction upward, as:

(1) *A lower zone comprising the collapsed roof and overlying intensely fractured strata with major dislocations and bedding separations*. This zone drains to the mine and is characterized by variably saturated flow and probable non-Darcian conditions that restrict application of MODFLOW-type groundwater models, although Merrick (2009) has had some success with MODFLOW-SURFACT applied to an Australian longwall mine.

(2) *An intermediate zone that retains overall low permeability and forms a hydraulic barrier between the lower draining zones and shallower aquifers*. This may be subdivided (Kendorski 2006) into a lower "dilated zone" with increased horizontal permeability along bedding separations, permitting enhanced lateral flow while still restricting vertical flow, and an upper "constrained zone" of low permeability that forms an effective confining layer.

(3) *An upper fractured zone in which the near-surface strata are relatively free to move and frac-*

ture. Substantial hydrological effects (rapid but often temporary head drops in bedrock aquifers) result from in-situ changes in hydraulic properties but are independent of drainage to the mine, which is blocked by the intermediate constrained zone.

For this project, the demonstration model was limited to the upper 60—70 m of overburden above a 220-m-deep longwall mine. This is considered to be well separated from the lower zone by the constrained zone, allowing us to ignore the hydraulic problems associated with the lower fractured zone. The model thus simulates aquifer impact but not inflow to the mine.

Study Site

The Jefferson County (Rend Lake) site, located in south-central Illinois, USA, consists of gently rolling topography with about 15 m of local relief, drained by several small streams that flow into a large man-made reservoir. The study mine extracted the Herrin (No. 6) Coal, about 3 m thick at depths of about 220 m, producing about 2 m of subsidence over the panels. The overburden strata are mostly shales and siltstones, but include the Mount Carmel Sandstone aquifer at depths at the main study site of about 21—23 m, overlain by shale and glacial till. The Mount Carmel varies up to about 23 m thick and consists of lower channel sandstone and upper sheet sandstone separated locally by a shale-siltstone unit 0—6 m thick.

Detailed subsidence and piezometric monitoring was conducted at the site from 1988 to 1995 during and after mining of the last two panels of a four-panel section. Panels were 183 m wide and from 1584 to 1737 m long. Numerous hydraulic tests of the sandstone showed hydraulic conductivities originally around 10^{-6} m/s that increased by one to two orders of magnitude during subsidence. The observed potentiometric levels declined rapidly ahead of the approaching mine face and subsidence zone. The most rapid head drops occurred during the early tensile fracturing phase of subsidence, when water levels fell to about 42 m below ground surface (BGS). Mining ended in 1989; water levels had recovered to 10 m BGS by 1995 and to 6 m BGS in 2008.

Application of TMR

Subsidence effects produce high hydraulic gradients and extreme spatial variation of hydraulic properties in the overburden above the longwall panels. Finely discretized grids are needed to simulate these local areas of complexity embedded within the larger hydrologic domain requiring a coarser mesh. Telescopic Mesh Refinement (TMR) has been used in groundwater modeling for this problem for many years but has not previously been applied to longwall mining. We used the TMR conversion feature in GV that transfers the physical and hydraulic framework from an initial regional model to a more refined local model. Regional and Local Models (RM, LM) were constructed in GV to represent the upper 60—70 m of the 220-m overburden, including the sandstone aquifer, underlying shale and limestone, and overlying shale and glacial till (Figure A1).

Regional Model. The regional model (RM) has 34,200 cells (57 rows × 75 columns × 8 layers) and covers an area about 53 km^2 that encompasses natural boundaries of the sandstone paleochannel and the hydrologic system. The RM was calibrated in steady state against a limited database of groundwater levels, the key calibration targets being water levels in the Panel 4 study area. Final calibration was reached using 10 hydraulic conductivity property zones, constant-head external boundaries in the more permeable aquifer units

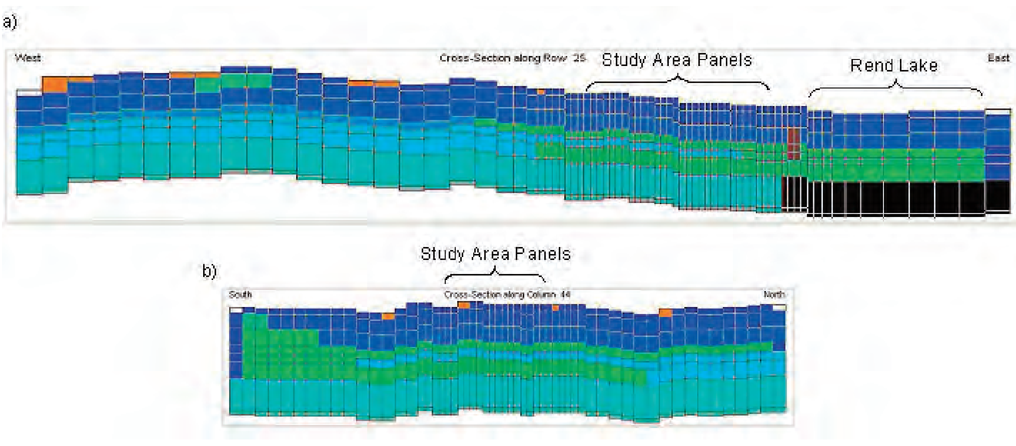

Figure A1 *Regional Model Cross Sections (a) west-east (b) south-north. Low permeability units blue, higher permeability sandstone green, stream drain cells orange, constant heads dark blue.*

and no-flow external boundaries in the low-permeability units, a complex configuration of the Rend Lake Fault System, and stream drains in the surficial layer to permitted discharge of shallow groundwater.

Local Model. The Local Model (LM) was created using the TMR conversion feature in GV, which sets the fine grid and transfers external boundary conditions and starting heads from the RM. It consists of 146,624 cells of uniform size 20 m × 20 m arranged in 158 columns, 116 rows and the same 8-layer configuration and thicknesses as in the RM. The LM covers an area about 7.3 km^2 including the four panels, barrier pillars, subsidence region and an estimated radius of hydrologic influence to about 600 m outside the subsidence area. Base hydraulic conductivity zones were mapped in from the steady-state RM and values modified locally in the subsidence zones as described below. Storage coefficients for transient simulation were specified from field and literature values.

Model Approaches to Hydraulic Property Changes

Longwall subsidence produces complex hydraulic effects because of various changes in hydraulic properties that result from fracturing, bedding separations, and changes in existing joint apertures. MODFLOW has no program mechanism to handle such dynamic changes in hydraulic properties during run-time simulations. Therefore, we approximate the advance of the longwall mine panel in short discrete steps. Between each step, hydraulic stresses are reconfigured manually in spatially discrete zones around the new subsidence front position, a somewhat laborious but ultimately routine process. Our approach recognizes that there are two major mechanisms that must be handled separately.

- *Rapid increase in fracture porosity in the early tensile phase of subsidence.* The initial rapid opening of fractures and bedding separations characteristically causes very rapid head drops, especially in confined bedrock aquifers (Booth 2007), due to loss of water into the new void space. This is a transient effect similar to any other temporary withdrawal of water; we simulate the mechanism indirectly by using well sinks, a standard feature in MODFLOW. A small zone of wells is temporarily specified at the subsidence front at each discrete-step position. Equivalent "pumping" rates were determined from estimates of the total volume of new void space per grid cell divided by the estimated time of rapid subsidence during which they were created. Partial recovery generated during the compressional phase was simulated by source (recharge) wells.
- *Fracture-induced increases in hydraulic conductivity (K) and storage coefficient (S) in the subsidence area over the panel during the initial tensile phase, followed by partial reduction during the compression and settlement phases.* These permanent changes in aquifer properties produce both transient and long-term permanent potentiometric changes. Between each mine-advance step, the hydraulic properties are manually reconfigured at the subsidence front in the discrete spatial zones using the convenient property zones feature of GV. Changes are simulated by a discretely advancing package of three stress zones (see Figure 1 and Figure A2. (A) an advance zone of slight increase; (B) a zone of major increase during the principal subsidence phase; and (C) a compression zone in interior of the panel in which the earlier K and S increases partially relax. The

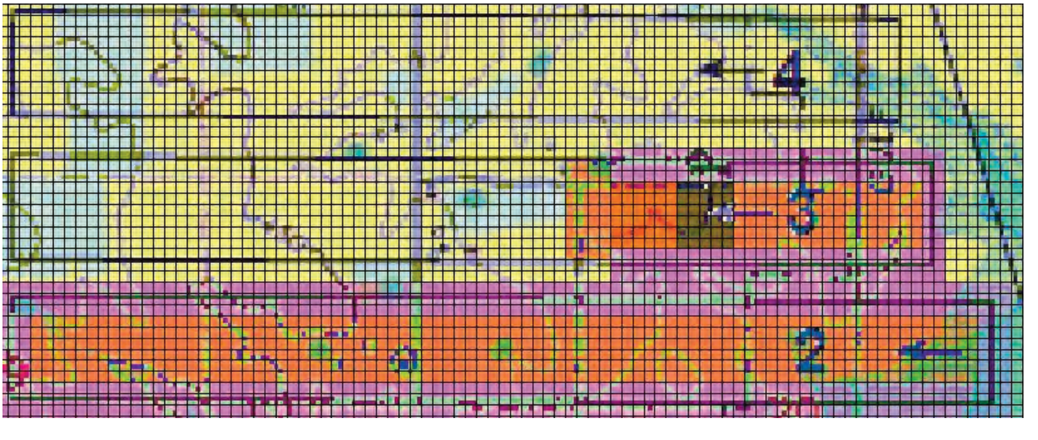

Figure A2 *Position of permeability stress zones in Layer 4 (Upper Sandstone) at example position of Panel 3 (Model MM-1106F). Panel 2 has been completed.*

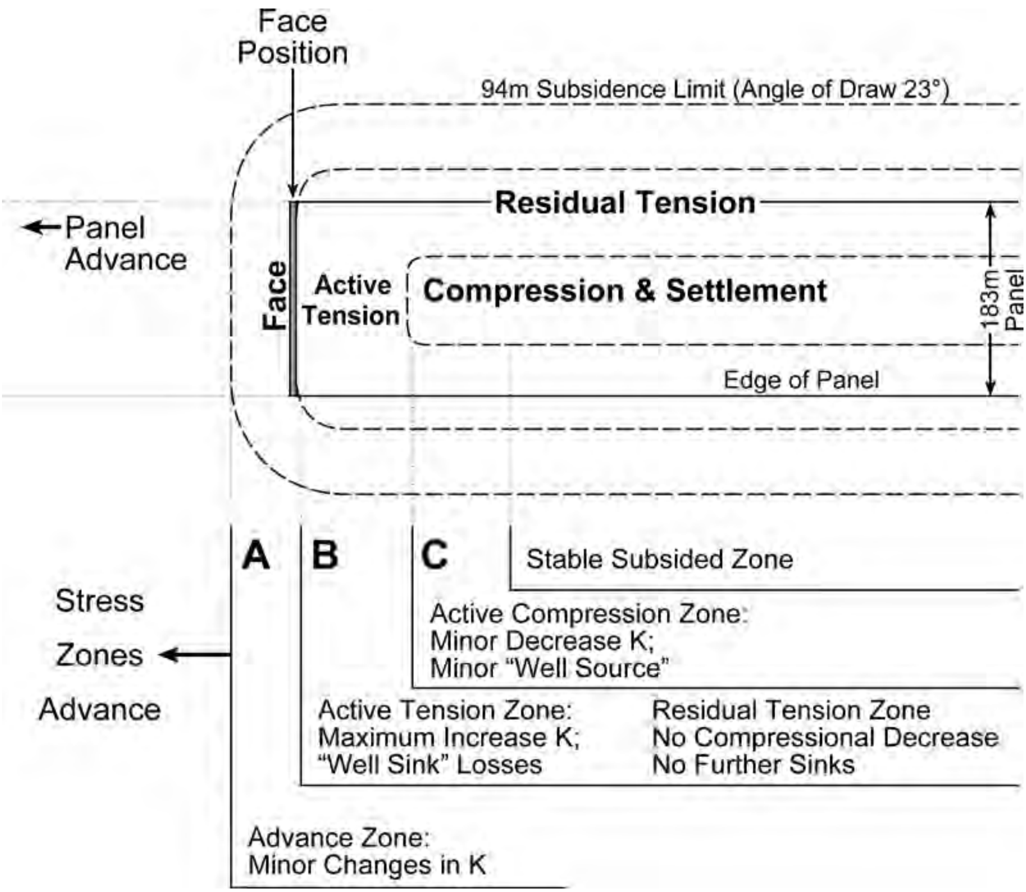

***Figure 1**. Concept of stress zones over and around subsidence trough*

base values of K and S were respectively modified 2×, 10x and 7.5× in zones A, B and C in the final demonstration model.

The initial heads for each successive run are input from the final heads of the previous run (the previous run file must be accessible to the active run file). The starting heads for the whole transient simulation are established in a steady-state LM derived from the original RM. In the demonstration model, a single 200-day transient model coarsely simulated panels 1 and 2 in 10 continuous stress period. Panels 3 and 4, for which more information was available, were then modeled in detail using individual transient runs of 16 or 17 discrete 100-m face advances each taking about 6 days. The sequence was completed with a recovery simulation after the end of mining.

Results

The overall pattern of simulated potentiometric levels in the demonstration model compared well with the behavior pattern observed in 1988—1995. However, precise timing and values of the simulated responses were not quite equivalent and better calibration of the K and S modifications and simulated well-sink values is needed.

The well-sink approach was successful in simulating the transient cone of depression that forms in the subsiding area due to the rapid opening of bedding planes and fractures. This is a simple way to represent a key mechanism that has not previously been modeled in the longwall situation. Simulated drawdowns were less than observed values and still require further calibration adjustments, but were in an appropriate general range of observed drawdown both at the center of the subsiding area and as transmitted to adjacent panels (Figures A3 and A4).

The use of discrete stress zones and discrete mine-advance steps to modify the hydraulic properties as the mine face and subsidence front progress is also new and was successful procedurally as a viable though time-consuming way to

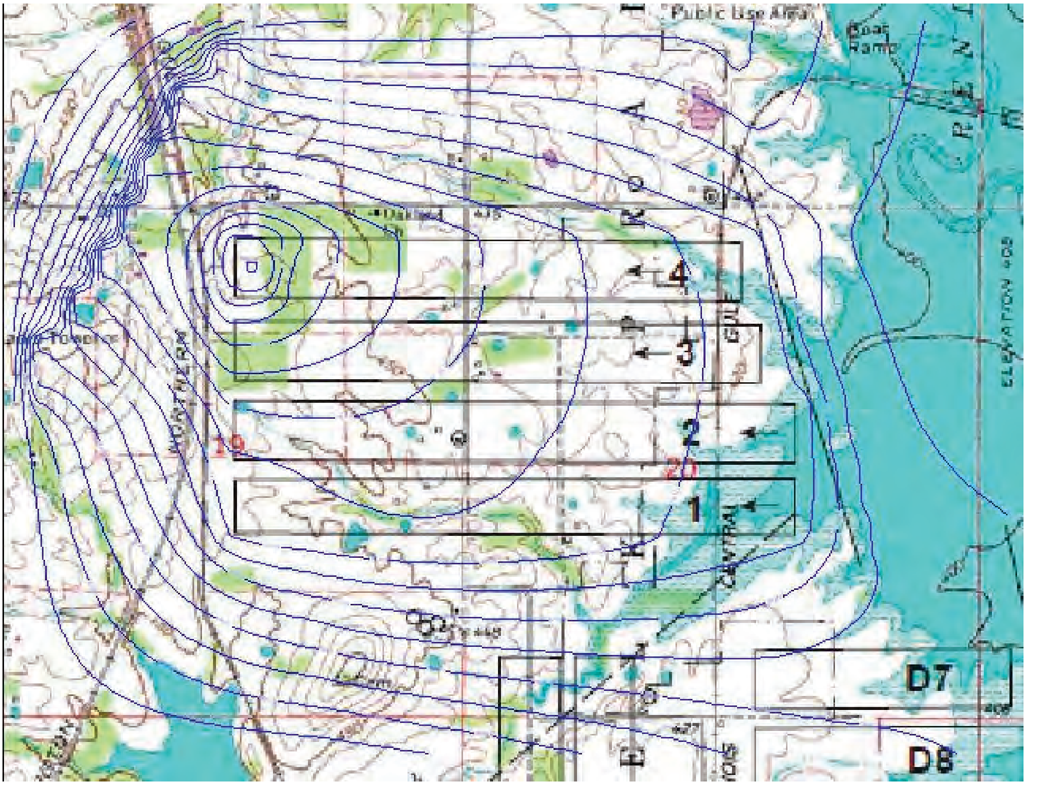

Figure A3 *Simulated head distribution in Layer 6 (lower sandstone) at completion of Panel 4. Contour interval = 1.0 m., lowest contour = 112 m amsl.*

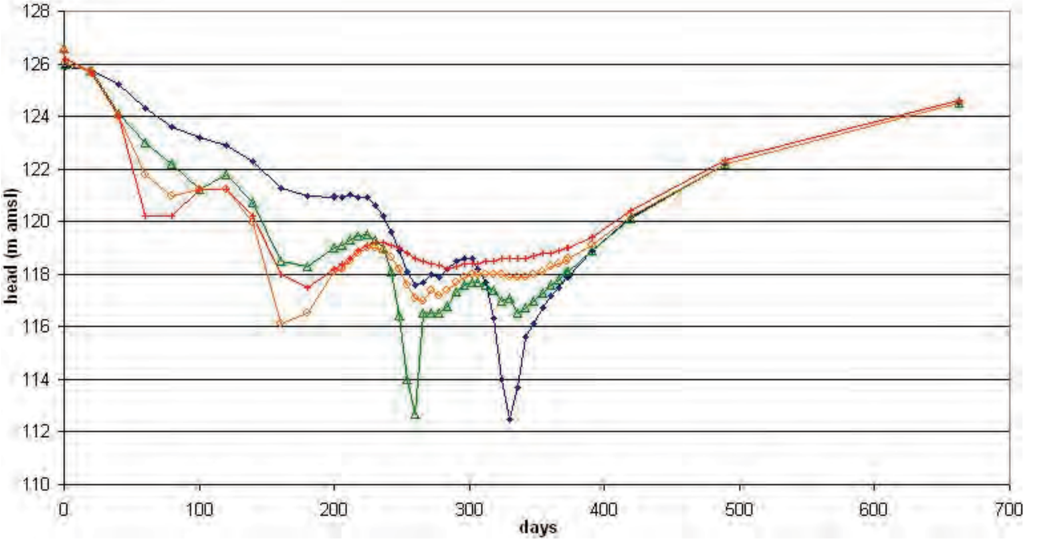

Figure A4 *Hydrographs of simulated heads at mid-panel points for the entire simulation period. Note that adjacent panels also reflect the potentiometric low in the active panel.*

apply MODFLOW to the longwall problem. Again, the general pattern of the simulated heads in the demonstration model was consistent with field observations and expectations but needs further calibration by adjustment of K and S value modifications.

The major mechanism still lacking in the model is the lowering of ground and strata elevations, which was not simulated in the demonstration model. This would require cell-by-cell adjustments in the elevation property matrix for each layer at each discrete advance step, which is possible in GV but would be a major manual task and a likely source of model instability. Further work is needed.

Although this demonstration model would need more complete LM sensitivity analysis and further calibration to be used for specific prediction and analysis of the study site, the general viability of the procedures used to simulate the impact of longwall mining has been successfully demonstrated. The techniques can be applied to other areas. Substantial site information would be needed, but application of TMR and the procedures developed for the LM would be relatively straightforward.

Acknowledgments

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