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Simulation of solute movement through wellbores to characterize public supply well contaminant vulnerability in the High Plains Aquifer, York, Nebraska

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ABSTRACT

A ground-water flow and transport model simulating contaminant movement to public supply wells in the High Plains aquifer near York, Nebraska was developed as part of the U.S. Geological Survey National Water-Quality Assessment Program. Water-quality samples were collected from wells screened in unconfined and confined units. Samples collected from a public supply well and selected monitoring wells completed in the confined aquifer have chemistry and age-tracer concentrations consistent with a mix of young water from unconfined recharge areas combined with relatively older confined aquifer water. These results imply that there are preferential flow paths that permit shallow recharge water and contaminants to move through the confining layer.

The transient ground-water flow and transport model was constructed using the multi-node well package of MODFLOW-2000, which simulates flow between different layers through the wellbore of a well. MODFLOW-GWT (Ground-Water Transport) was used to simulate solute movement through the system, while also assigning ages to the particles. The simulations indicate that summer pumping conditions, which can cause vertical head differences of up to 15 meters between unconfined and confined layers, and wells screened through multiple layers introduce shallow recharge waters and contaminants to lower layers, increasing the vulnerability of public-supply wells completed in the confined system to contamination from unconfined waters.

INTRODUCTION

Contamination of public-supply wells has resulted in public-health threats and has produced negative economic impacts for communities that must treat contaminated water or find alternative water supplies. The concerns about contamination of public-supply wells have lead to widespread interest in understanding the vulnerability of public-supply wells to contamination. To investigate factors controlling vulnerability of public supply wells to anthropogenic and natural contaminants using consistent and systematic data collected in a variety of principal aquifer settings in the United States, several studies of Transport of Anthropogenic and Natural Contaminants (TANC) to public supply wells were begun in 2001 as part of the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) Program (Eberts et al., 2005). Results presented here are from a study near York, Nebraska (fig. 1), within the High Plains Ground Water regional study unit of the NAWQA program (Dennehy, 2000).

The possible sources of contamination and hydrogeology at York are typical of conditions that occur in many communities across the Midwest or other predominantly rural areas of the nation. Movement of contaminants through the aquifer system may be enhanced because of increased ground-water flow velocities caused by intensive ground-water pumping for irrigation and increased recharge because of irrigation return flows. Moreover, the practice of screening wells across large intervals of an aquifer can contribute to faster vertical movement of contaminants to depth than would naturally occur because of penetration of confining units by wellbores and consequent inter-aquifer mixing. The purpose of this paper is to present preliminary findings of an investigation of the influence of flow through wellbores as a primary process affecting solute movement to public-supply wells. Ground-water flow was simulated using a small-area model, which was calibrated for an area within a regional-scale model (M.K. Landon and M.J. Turco, U.S. Geological Survey, written commun., 2004), in a study area near York. Subsequently, solute movement was simulated in a transport model sub-grid within the small-area model (fig. 1).

Description of Study Area

The study area is a rectangular area of 108.4 km^2 and was selected for study of processes influencing contaminant distribution along a ground-water flow path from a regional-scale model to a public-supply well in southeastern York (fig. 1). The small-area model within the study area is nested within a regional-scale model of 388.5 km^2 (M.K. Landon and M.J. Turco, U.S. Geological Survey, written commun., 2004). The study area is in southeastern Nebraska within Quaternary-age alluvial deposits that constitute the High Plains aquifer system in eastern Nebraska and Kansas. Mean annual precipitation is 71.1 centimeters per year (cm/yr) (High Plains Climate Center, 2003). Irrigated agriculture is the primary land use in the study area with corn and soybeans the primary crops. Ground water is the sole source of water for irrigation, domestic, public supply, and commercial supply in the study area (M.K. Landon and M.J. Turco, U.S. Geological Survey, written commun., 2004). Much of the ground-water in the study area is pumped from the unconfined aquifer composed of mostly sand and gravel with an average thickness of 27 meters (m). A clayey silt till confining bed (average thickness of 22 m) separates the unconfined from the underlying upper confined aquifer (average thickness of 10 m), another major source of ground-water. Below the upper confined aquifer, another clayey silt layer separates the lower confined aquifer from the two overlying aquifers. Many irrigation wells, and some commercial and public-supply wells, are screened across unconfined and confined layers of the aquifer to maximize yields. Vertical head differences between the unconfined and confined layers are as much as 15 m in the summer irrigation season and 3 m during other seasons. These large downward head gradients make these multi-screened wells potential pathways for rapid movement of ground-water through the confining units, allowing contaminants to reach the confined layers where most public-supply wells are screened.

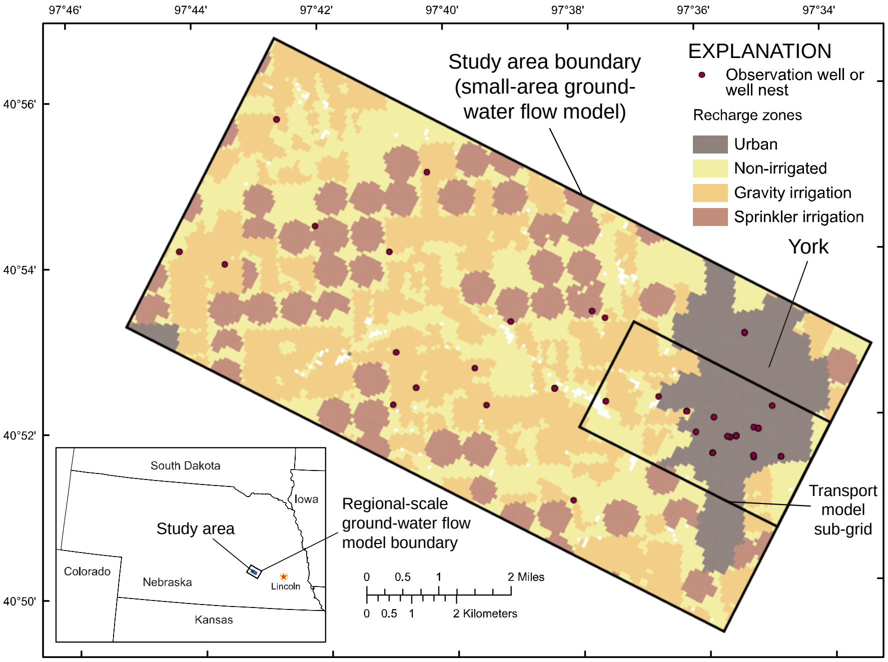

Figure 1. Study area showing recharge zones, location of observation wells or well nests, and transport model sub-grid.

SMALL-AREA GROUND-WATER FLOW MODEL

Model Geometry and Discretization

The USGS modular three-dimensional finite-difference code, MODFLOW-2000 (Harbaugh and others, 2000), was used to simulate flow in the small-area model. The model area is discretized into a finite-difference grid of 180 rows by 372 columns of uniform cells each 40 m on a side. The model is a 14-layer representation of 3 water-bearing units and 2 confining units within the High Plains aquifer. The top layer begins at land surface and represents mostly unsaturated silt (loess) deposits. Layers 2 through 4 represent an unconfined aquifer layer composed of mostly sand and gravel. Layers 5 through 9 represent the upper confining layer, a clayey silt till. Layers 10 through 12 represent the upper confined aquifer, a fine sand. Layer 13 represents a lower confining layer, mostly clayey silt, and layer 14 represents the lowermost confined layer, a heterogeneous mix of sand, silt, and clay. Ground-water flow in the small area model is simulated from September 1, 1944 through August 31, 2004. Steady-state conditions are simulated prior to September 1, 1944 and represent conditions prior to use of ground-water for irrigation. The transient simulation from 1944 to 2004 is divided into 120 stress periods. There are two annual stress periods, one stress period representing fall, winter, and spring (9 months) and one stress period representing the summer irrigation season (3 months).

Boundary Conditions, Recharge, and Pumping Wells

Lateral inflows to and outflows from the model are represented with the flow head boundary (FHB) package (Leake and Lilly, 1997). Specified heads in the FHB were adjusted based on long-term water-level observations distributed throughout the model area in the unconfined and confined aquifers. The FHBs do not represent natural hydrologic boundaries based on structural features; however, they are artificial boundaries that are placed far enough away from primary areas of concern and interest so that boundary effects are minimized. Lateral boundaries of confining units are represented as no-flow boundaries because flow into and out of these units horizontally from surrounding areas is negligible compared to flow in water-bearing aquifer layers. The base of layer 14 is also represented as a no-flow boundary.

Areal recharge is applied throughout the model using the recharge package. Four recharge zones based on land use were assigned in the model consisting of urban areas, non-irrigated areas, sprinkler irrigated areas, and gravity irrigated areas (fig. 1). Recharge rates were modified from conceptual model estimates during calibration of the regional-scale model (M.K. Landon and M.J. Turco, U.S. Geological Survey, written commun., 2004) and the current model; recharge rates were constrained by water and chemical balance calculations.

To test the influence of solute movement through wellbores, irrigation, municipal, and industrial wells are simulated using both the multi-node well (MNW) package (Halford and Hanson, 2002) and the WEL package (Harbaugh and others, 2000). The MNW package allows simulation of wells that are completed in multiple nodes or layers, while the WEL package assumes withdrawal amounts from designated layers without the added complexity of inter-wellbore flow.

Hydraulic Parameters

The model includes 22 hydraulic parameters, including horizontal hydraulic conductivity, specific storage, specific yield, recharge, and the ratio of vertical to horizontal hydraulic conductivity. The preliminary parameter values for the calibrated model are consistent with available data. For the unconfined layer, hydraulic conductivity decreases with depth, from calibrated values of 55 to 12 meters per day (m/d), as was evident from lithology and slug tests in the study area. Calibrated values of hydraulic conductivity in the confined portion of the system ranges from 5 to 15 m/d based on average aquifer and slug test values. Calibrated specific yield values vary from 0.05 in the loess to 0.25 in the unconfined sand. Calibrated specific storage values in the confined layers range from 6.6×10^{-7} to 9.8×10^{-5} per meter. Average simulated recharge (1994-2004) ranges from 7.4 cm/yr in the urban area to 16.3 cm/yr in areas utilizing gravity irrigation (fig. 1).

Ground-Water Chemistry

A network of 36 monitoring wells screened at different depths in the unconfined and confined portions of the aquifer was installed in the study area. The monitoring wells and a single public-supply well were sampled for a wide variety of constituents including chlorofluorocarbon-11 (CFC-11) and other age tracers. Flow measurements and samples also were collected from different depths in the public-supply well under pumping conditions to determine where water and contaminants entered the well screen. The samples from the bottom half of the well screen (which lies below the confining layer) had chemical signatures consistent with water derived from shallow recharge areas recharge in the urban area mixed with relatively older native water from the confined aquifer. Similar mixed unconfined-source water signatures were detected in 4 of 15 monitoring wells screened in the confined layer. This non-uniform distribution of mixed water implies that there are preferential flow paths that permit recharge water and contaminants to move through the confining layer. Interpretations of lithologic and geophysical logs indicate that the confining clay layer is continuous throughout the model area and therefore that natural preferential flow paths through the confining clay are absent. Laboratory tests of vertical hydraulic conductivity on cores of the confining layer resulted in relatively low (10^{-6} m/d) values. These data support a hypothesis of downward leakage of water through wellbores of irrigation wells or supply wells that penetrate the confining unit. To test the geochemical interpretations, a simulation approach using the transport model that included leakage through wellbores was done to test whether this leakage could explain the contaminant distribution in the confined aquifer.

TRANSPORT MODEL SIMULATIONS

Transport simulations were run on a smaller area, called the transport model sub-grid, within the small-area model (fig. 1) to reduce computation time. Transport simulations included use of both the MNW package and the WEL package in separate simulations. Ground-water age and CFC-11 was simulated using the GWT package of MODFLOW (Goode, 1999), which contains algorithms for directly simulating ground-water age in a transport model.

RESULTS

For the purpose of comparing modeled hydraulic heads throughout the simulation period with actual, field-measured head values, 470 water-level observations from 53 wells were used as calibration targets in the small area model. The Root Mean Square Error (RMSE) in 10-year increments achieved after calibration ranges from 1.13 to 1.47 m in comparison with observed hydraulic-head altitudes ranging from 472 to 499 m in 2004 (table 1). RMSE is a statistical representation of variance, and as such, smaller values of RMSE indicate a better model calibration.

Mean	Minimum	Maximum	RMSE	Year
0.08	-2.33	1.54	1.47	1964
-0.07	-2.88	1.42	1.28	1974
0.10	-2.18	2.53	1.42	1984
0.15	-2.60	1.75	1.31	1994
-0.26	-3.12	2.97	1.13	2004

Table 1. Head residuals (simulated minus observed) for the small area model, in meters. [RMSE, Root Mean Square Error]

Transport model simulations utilizing the MNW package indicated that particles with relatively younger ages and elevated CFC concentrations were flowing down wellbores into the upper confined system (fig. 2). Simulated ground-water age was compared to ground-water age tracer data in the unconfined wells. Preliminary simulated mean ages in unconfined wells were mostly within 5 years of interpreted ages (mean error of 4 years), with observed ages ranging from 5 to 45 years and increasing with depth. In the upper confined wells, age-tracer data and water chemistry indicated that the ground water was a mixture of relatively old confined water and relatively young water from the unconfined layer.

The concentration of CFC-11 was simulated directly for comparison with CFC-11 concentrations measured in confined monitoring wells. Simulated CFC-11 concentrations using the MNW package for wells in the upper confined layer showed considerable variability. However, simulated CFC-11 concentrations were in the same range as observed CFC-11 concentrations and had a median residual of -0.04 picomoles per kilogram (pmol/kg), a maximum residual of 0.40 pmol/kg and a minimum residual of -0.53 pmol/kg over the range of observed CFC-11 concentrations (0.02 to 3.6 pmol/kg) in the upper confined layer. Conversely, simulations of CFC-11 using the WEL package show concentrations of zero in most confined monitoring wells, which is not consistent with the observed distribution of young unconfined water signatures in the upper confined layer. This result supports the hypothesis of solute movement through wellbores as the primary mechanism for transport between the unconfined and confined aquifer system.

LIMITATIONS

The accuracy of ground-water models is limited by simplification of complexities within the flow system, boundary conditions, space and time discretization effects, assumptions made in the formulation of the governing flow equations, accuracy and availability of data on hydraulic properties, accuracy of calibration, and accuracy of withdrawal estimates. In the case of this transport model, additional uncertainty exists in the precise location of MNWs and the variability of transmission of water through the wellbores.

CONCLUSIONS

One of the major ground-water quality issues in the study area is that young, potentially contaminated water in the unconfined aquifer can move downward into the confined portion of the ground-water system where public-supply wells are screened. One hypothesis was that leakage of water through the confining unit was induced by withdrawals from the confined aquifer. However, water chemistry results and results of GWT age and tracer simulations indicate that wells screened through multiple aquifer layers can introduce flow through the wellbores, thus providing a rapid path from the unconfined aquifer to the upper confined aquifer. Simulations indicate that “plumes” of higher CFC-11 concentrations in the confined aquifer originate at wells screened through multiple units and are drawn toward other pumping wells. This mechanism for movement of younger water through the wellbores of wells screened through multiple units is thought to be the primary process affecting the existence of contaminants in the confined system and corresponds with independent geochemical data.

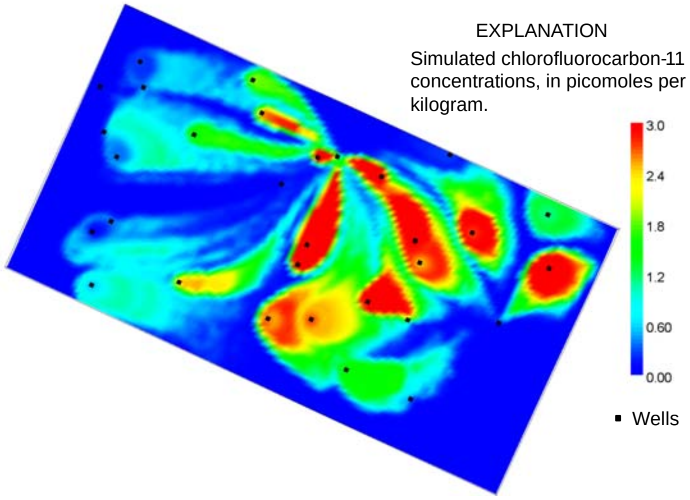

Figure 2. Map view of transport model sub-grid showing preliminary chlorofluorocarbon-11 transport simulation results in the confined system.

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