Modeling multiaquifer wells with MODFLOW

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Modeling Multiaquifer Wells with MODFLOW

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Abstract

Multiaquifer wells, i.e., wells that are open across more than one aquifer, can have a profound effect on the hydraulics of a ground water system. These wells change the physical system by establishing direct hydraulic links between otherwise isolated strata. Several methods are available to simulate multiaquifer wells in the context of comprehensive ground water flow simulators. In this paper, we review four methods to represent multiaquifer wells with the widely used code MODFLOW. These methods include a specialized code developed, but never formally released, by the U.S. Geological Survey (USGS), the Multi-Aquifer Well (MAW1) Package. An expanded implementation of the techniques in the MAW1 Package has been incorporated in the Multi-Node Well Package released recently by the USGS (Halford and Hanson 2002). We examine the performance of the methods in the context of a benchmarking study against the analytical solutions of Papadopulos (1966) and Sokol (1963). Our results demonstrate that results obtained with the MAW1 Package closely match exact solutions for pumping and nonpumping conditions, using both coarse and refined grids.

Introduction

Multiaquifer wells are open across two or more water-bearing strata that have different hydraulic properties and water levels (Figure 1). Multiaquifer wells are encountered in applications involving relatively deep water-supply wells in the western United States. Wells that are open across multiple flow zones in fractured rock settings should also be conceived as multiaquifer wells. These wells can have a profound effect on ground water flow, regardless of pumping. They change the physical system and the equations that describe it by establishing direct hydraulic links between units that are otherwise isolated. The simulation techniques developed for multiaquifer wells can also be applied to represent wells that span multiple model layers, whether the layers involved represent distinct aquifers or arbitrary subdivisions of a single aquifer.

Although the properties and hydraulic head distributions may differ among the units penetrated by a multiaquifer well, a single water level is established within the wellbore. The static water level established in the multiaquifer well is a transmissivity-weighted average of the piezometric levels near the well in the individual units. This is in general not equivalent to the arithmetic average of the hydraulic heads. Under pumping conditions, the total discharge from the well is apportioned among the individual strata, depending upon both the transmissivity and the heads. Under nonpumping conditions, the total discharge is zero, with some strata contributing water to the well and others withdrawing water from it.

In this study, we evaluate methods for representing multiaquifer wells in large-scale analyses of ground water flow that are developed with MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996; Harbaugh et al. 2000). We begin by describing three methods available for representing multiaquifer wells in transient simulations. We evaluate the performance of these methods in the context of two benchmark examples for transient flow. Our evaluations include an examination of a specialized code that was developed, but not formally released, by the U.S. Geological Survey (USGS), known as the Multi-Aquifer Well (MAW1) Package (McDonald 1986). An expanded implementation of the techniques in the MAW1 Package

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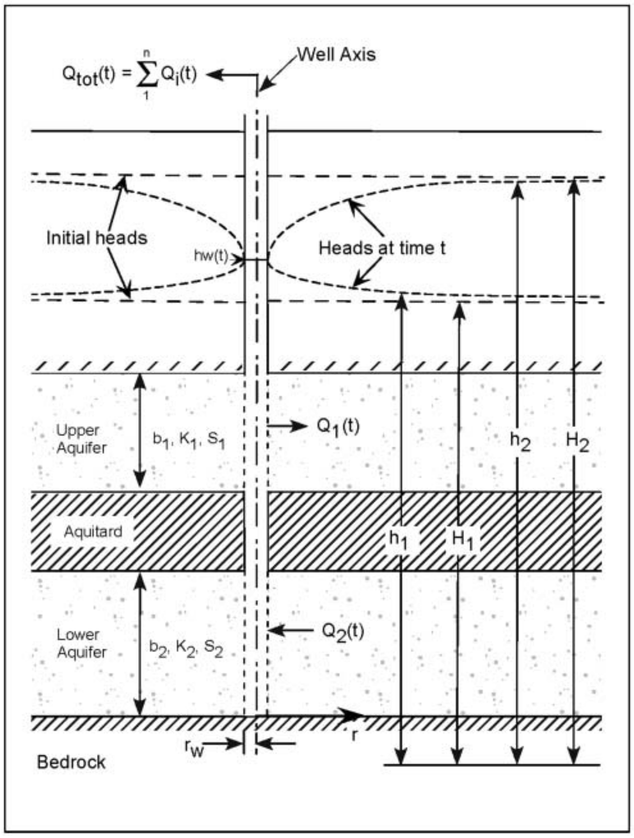

Figure 1. Schematic of a multiaquifer well penetrating two aquifers that have different initial heads.

has been incorporated in the Multi-Node Well (MNW) Package released recently by the USGS (Halford and Hanson 2002). We examine the case of a single well under pumping and nonpumping conditions, using coarse and refined finite-difference grids. In the final section, we describe two methods available for representing multiaquifer wells in steady-state simulations.

Approaches for Modeling Multiaquifer Wells

In this section, we examine three approaches for simulating multiaquifer wells in MODFLOW models:

- Conventional application of the MODFLOW Well Package
- A modified application of the MODFLOW Well Package, which we call the High K_v in the Well Block approach
- The MAW1 Package.

A fourth method, application of the MODFLOW General Head Boundary (GHB) Package, is also evaluated in the context of a steady-state analysis.

Standard Application of the MODFLOW Well Package

The first approach for modeling multiaquifer wells consists of a straightforward application of the MODFLOW Well Package (McDonald and Harbaugh 1988). This approach is shown schematically in Figure 2. The multiaquifer well is represented by conventional discharge-controlled wells in each of the permeable strata penetrated.

With the standard Well Package approach, the total discharge must be allocated a priori among the individual strata. The simplest allocation procedure is transmissivity-weighting, derived by assuming purely radial flow:

$$Q_{j,i,k} = \frac{T_{j,i,k}}{\sum_{k=1}^{NL} T_{j,i,k}} Q_{TOT} \qquad (1)$$

where $Q_{j,i,k}$ is the specified discharge and $T_{j,i,k}$ is the transmissivity of the grid block in each layer k penetrated by the well, and Q_{TOT} is the total discharge.

The standard Well Package approach is strictly correct only if flow is steady and purely radial in each stratum, with no vertical flow along the wellbore. This vertical flow may be important, and there is no guarantee that the discharge allocation of Equation 1 is appropriate. This approach has the further defect that it cannot be used to determine the pumping level in the multiaquifer well. MODFLOW calculates a piezometric level in each well block, and the modeler must correct for head losses associated with converging flow in the well blocks and develop an approach for averaging the individual levels. Several corrections for converging flow have been developed; however, there is no simple method to estimate the transient composite water level in a multiaquifer well based on application of the standard Well Package.

High K_v in the Well Block Approach

The second approach for modeling multiaquifer wells consists of representing the connection along the wellbore of the multiaquifer well by assigning high vertical hydraulic conductivities to the cells it intersects. We call this the High K_v in the Well Block approach, and it is illustrated in Figure 3. To simulate active pumping with this

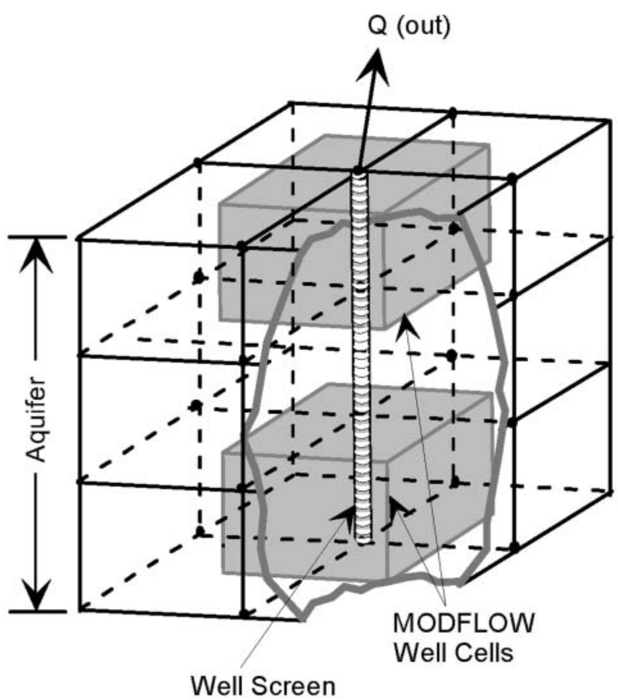

Figure 2. Representation of a multiaquifer well using the MODFLOW Well Package.

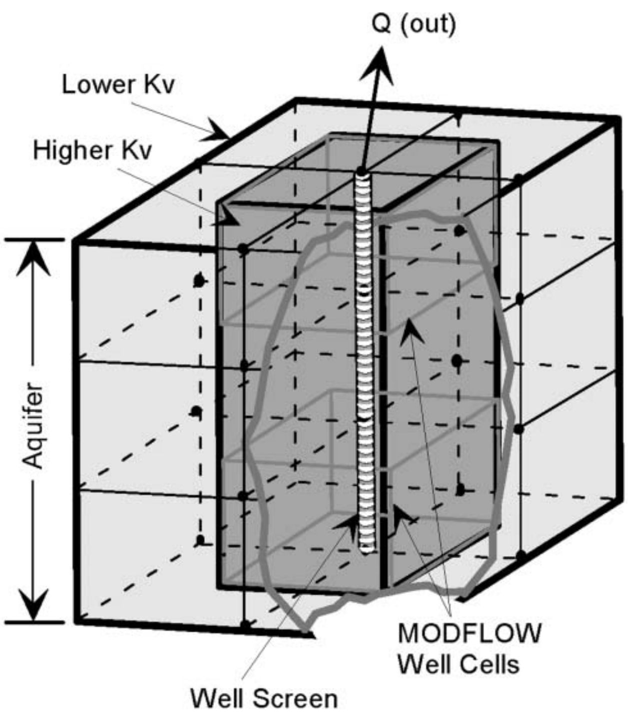

Figure 3. Representation of a multiaquifer well using the High K_v in Well Block approach.

approach, the MODFLOW Well Package is used, and the total discharge is applied to the uppermost or the lowermost aquifer penetrated by the multiaquifer well. For nonpumping conditions, the Well Package is not required; it is sufficient to incorporate the connection along the well with the high vertical conductivities.

The High K_v in the Well Block approach can accommodate vertical flow along the wellbore. Furthermore, this approach does not require assumptions regarding the pumping level in the well or the allocation of the total discharge among the strata penetrated. Both the pumping level and allocation of flow are determined as part of the solution. However, it is not immediately obvious what constitutes a high vertical hydraulic conductivity in this context. The appropriate vertical hydraulic conductivity can be estimated when the size of the well block approaches the physical dimensions of the wellbore, using Hagen-Poiseuille pipe-flow theory (Reilly et al. 1989):

$$K_{pipe} = \frac{\rho g}{\mu} \frac{r_w^2}{8} \tag{2}$$

where ρ and μ designate the density and dynamic viscosity of water, g is the acceleration due to gravity, and r_w is the radius of the well screen. For a 0.3 m diameter well, the effective conductivity of the well is ~28,000 m/s. In practice, it is not generally feasible to specify a vertical hydraulic conductivity of this magnitude, as too great a contrast with respect to the properties of neighboring cells may lead to convergence problems. It is, however, sufficient to specify a vertical conductivity that is adequately high to ensure that the head is nearly uniform along the wellbore.

MAW1 Package

The third approach for modeling multiaquifer wells is the MAW1 Package developed by M.G. McDonald while at the USGS. The MAW1 Package was implemented in MODFLOW, but never released formally by the USGS; as far as we are aware, the only documentation is a preliminary description (McDonald 1986). Our copy of the code included notes prepared by A.W. Harbaugh of the USGS, Reston, Virginia, office. These notes indicate that the MAW1 Package has been used for several project-specific applications within the USGS, including a recent application in the Hueco Bolson, New Mexico (Heywood and Yager 2003).

The USGS has recently released a new package for MODFLOW, the Multi-Node Well (MNW) Package (Halford and Hanson 2002). The MNW Package incorporates the capabilities of the MAW1 Package, as well as additional features. The bases of the simulation approach for multiaquifer wells are similar in the MAW1 and MNW Packages, and the MNW Package documentation cites as benchmark analyses the results presented in a preliminary publication from this study (Neville and Tonkin 2001). The benchmark analyses presented may serve as formal documentation of the testing of the techniques implemented in the MNW Package.

The MAW1 Package is based on the formulation for finite-difference modeling described by Bennett et al. (1982). Bennett and his coresearchers implemented the approach in the direct predecessor to MODFLOW, the three-dimensional simulator of Trescott (1975) and Trescott and Larson (1976). The hydraulics of a multiaquifer well incorporated in the MAW1 Package is shown schematically in Figure 4 (modified after Bennett et al. [1982]).

In the MAW1 Package, the total discharge from a multiaquifer well is evaluated by writing the Thiem solution for a sequence of aquifers that have the same head in the wellbore:

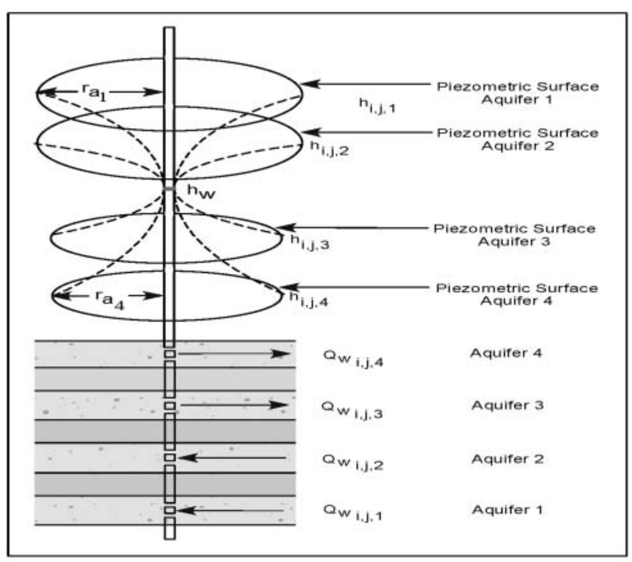

Figure 4. Representation of a multiaquifer well using the MODFLOW MAW1 Package.

$$Q_{TOT} = \sum_{k=m}^{n} 2\pi T_{j,i,k} \frac{(h_{j,i,k} - h_w)}{\ln\left(\frac{r_{eq}}{r_w}\right)} \quad (3)$$

where $h_{j,i,k}$ is the head in the grid block that contains the well, r_w is the radius of the well, and r_{eq} is the equivalent radius of the wellblock.

The equivalent radius of the wellblock is defined as the radial distance from the center of the finite-difference block at which the model-calculated head matches the head from the Thiem solution. Several researchers have presented approximations for the equivalent radius of the wellblock. Prickett (1967) presented the following approximation for square grid blocks with uniform spacing Δx and isotropic horizontal hydraulic conductivity:

$$r_{eq} = 0.208\,\Delta x \quad (4a)$$

Peaceman (1983) developed a more general expression for the case of regular grid spacing that can accommodate uniform rectangular grid blocks and anisotropy of the horizontal hydraulic conductivity:

$$r_{eq} = 0.28 \frac{[(K_y/K_x)^{1/2}(\Delta x)^2 + (K_x/K_y)^{1/2}(\Delta y)^2]^{1/2}}{(K_y/K_x)^{1/4} + (K_x/K_y)^{1/4}} \quad (4b)$$

For the case of a square grid and isotropic conductivity, Peaceman's formula reduces to $0.198\Delta x$, which is 5% smaller than the Prickett approximation.

The MAW1 Package first solves by iteration the head in the multiaquifer well, using an alternative form of Equation 3:

$$h_w = \frac{\sum_{b=m}^{n} T_{j,i,b} h_{j,i,b}}{\sum_{b=m}^{n} T_{j,i,b}} - \frac{Q_{TOT}}{\frac{2\pi}{\ln\left(\frac{r_{eq}}{r_w}\right)} \sum_{b=m}^{n} T_{j,i,b}} \quad (5)$$

The flow in each layer penetrated by the well is then calculated from the Thiem solution for each cell:

$$Q_{j,i,b} = \frac{2\pi T_{j,i,b}}{\ln\left(\frac{r_{eq}}{r_w}\right)} (h_{j,i,b} - h_w) \quad (6)$$

The iteration continues until the total discharge is equal to the sum of the discharges of the individual flows. That is,

$$Q_{TOT} = \sum_{b=m}^{n} Q_{j,i,b} \quad (7)$$

This equality holds whether the total discharge from the well is positive (injection), negative (extraction), or zero (a passive wellbore).

Since the head in the wellbore, h_w, is a function of the heads in every cell penetrated by the well, $h_{j,i,m}$, the structure of the governing equations are altered with respect to the standard MODFLOW 7 point finite-difference structure. To retain the original structure, the wellbore head is approximated using the heads calculated at the end of the previous iteration of the matrix solver. As indicated by McDonald (1986), the advantage of this approach is that it can be applied with all of the solvers available for MODFLOW. The disadvantage of this approach is that the finite-difference equation is more explicit and, therefore, additional iterations are required when using some of the solvers. A direct solution approach can be used with the Sluice-Successive Overrelaxtion solver (Bennett et al. 1982). However, additional iterations are required when using the MAW1 Package in conjunction with the Strongly Implicit Procedure and preconditioned conjugate-gradient solvers. When used with preconditioned conjugate-gradient solvers, outer iterations are required to update the discharge rates during the iterative solution.

The theory of the MAW1 Package is formulated for a single well located at the center of a grid block, in a model with uniform grid spacing where radial symmetry is not disturbed by heterogeneity or hydrologic boundaries. Although the assumptions of the conceptual model are rarely satisfied in practice, deviations from them tend not to limit the applicability of the method. Bennett et al. (1982) indicate that although complex cases may present difficulties, "ignoring the effects of multiaquifer wells in a simulation will inevitably produce erroneous results."

The approach implemented in the MAW1 Package provides an approximate means to account for converging flow in relatively large grid blocks. The approach implemented in the MNW Package is more general and offers flexibility in representing situations that are more complex.

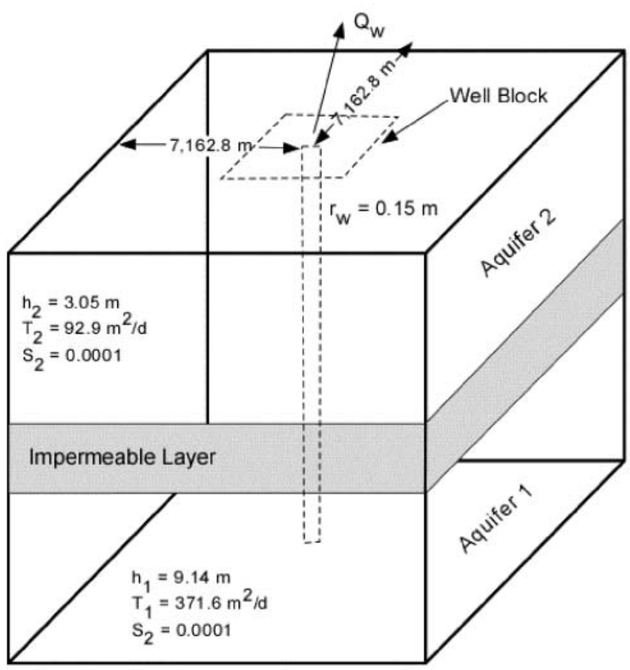

Figure 5. Definition sketch for the benchmark problems.

Benchmark Problems for Transient Flow

The performances of the different approaches for modeling multiaquifer wells are evaluated by comparing simulation results against the analytical solution of Papadopulos (1966). The benchmark problem is adapted from Bennett et al. (1982). As shown in Figure 5, the analytical solution considers a well that is open across two aquifers. The solution assumes that the aquifers are infinite in areal extent, homogeneous and isotropic, and separated by an impermeable layer. In the numerical models, the aquifers are represented by square layers that are 14,325 m on a side. No-flow boundary conditions are imposed along each face of the model. To exclude the effects of the lateral boundaries on the numerical simulations, only results from times before the effect of the well propagates to the model boundaries are considered.

The problem starts with a different uniform head in each aquifer, h_1 = 9.14 m (lower aquifer) and h_2 = 3.05 m (upper aquifer). At time zero, a well is installed that connects the two aquifers. The radius of the well is 0.15 m. In the first problem, we consider a well that pumps at a total rate of 1767 m^3/d. In the second problem, we consider a well that is not actively pumped. Each problem is simulated using both a coarse grid with a uniform spacing and a graded grid that is refined around the well.

Results for Pumping Conditions

The coarse finite-difference grid consists of 101 columns and 101 rows and has a uniform spacing of 142 m. To ensure maximum accuracy for the comparison with the axisymmetric analytical solution, the active area of the finite-difference grid is circular, with the well placed at the center of the grid and the cells deactivated beyond a distance of 7163 m from the well.

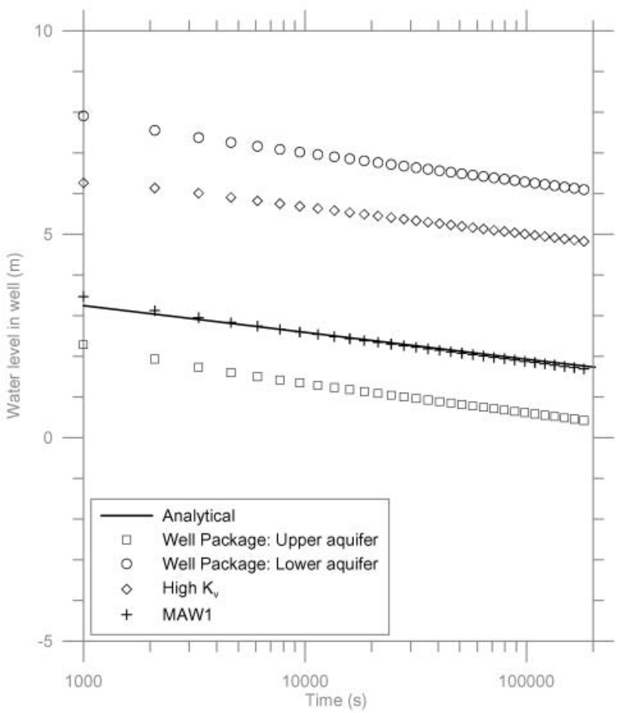

Figure 6. Pumping water levels in the pumping well—coarse grid.

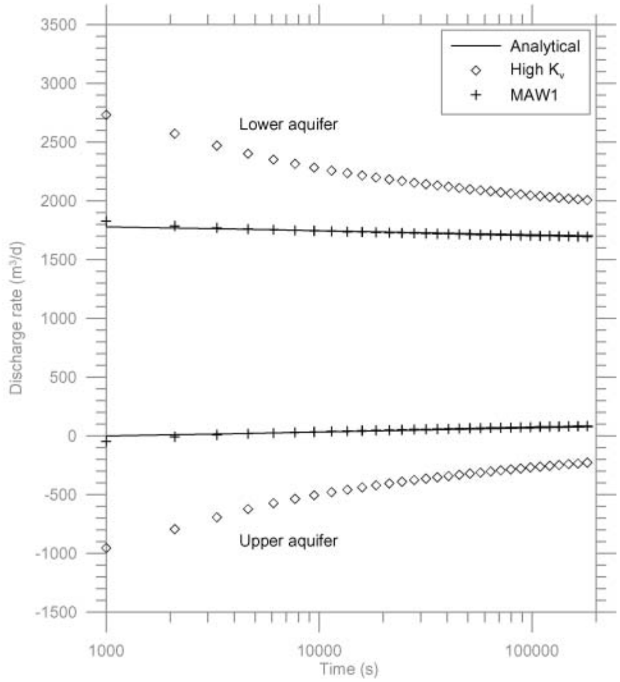

Figure 7. Pumping aquifer discharges—coarse grid.

The results for pumping conditions with the coarse finite-difference grid are shown in Figure 6. The standard application of the MODFLOW Well Package yields two water levels in the multiaquifer well, one for each of the penetrated aquifers. The results for the two aquifers bear little resemblance to the analytical solution. Better results cannot be expected by applying a correction to the individual levels to account for the relatively large size of the well block, because the heads in the upper aquifer become very low. The results obtained with the High K_v in the Well Block approach do not match the exact solution either. In contrast, the results obtained with the MAW1 Package are in excellent agreement with the analytical results, even for this coarse spatial discretization.

The calculated discharges for the two aquifers are plotted in Figure 7. The discharge allocation calculated by the MAW1 Package matches the analytical results closely. It is important to note how different the flow allocation is from the simple transmissivity-weighting adopted for the standard application of the Well Package. Using transmissivity-weighting, 80% of the total well discharge is predicted to come from the more transmissive lower aquifer. The analytical solution predicts that ~95% of the discharge comes from this layer. The flow from the upper aquifer is actually initially negative, indicating that at early time water flows up the wellbore and into the upper aquifer, rather than discharging from it.

The refined finite-difference grid also has 101 rows and 101 columns; however, the grid is graded so that the cell containing the multiaquifer well has dimensions of 1.5 m by 1.5 m. The results for the refined grid are shown in Figure 8. The results shown in Figure 8 confirm that grid refinement has not improved the results from the standard Well Package simulation. The water level in the lower aquifer begins to approach the exact solution, but the water level in the upper aquifer declines drastically. For the

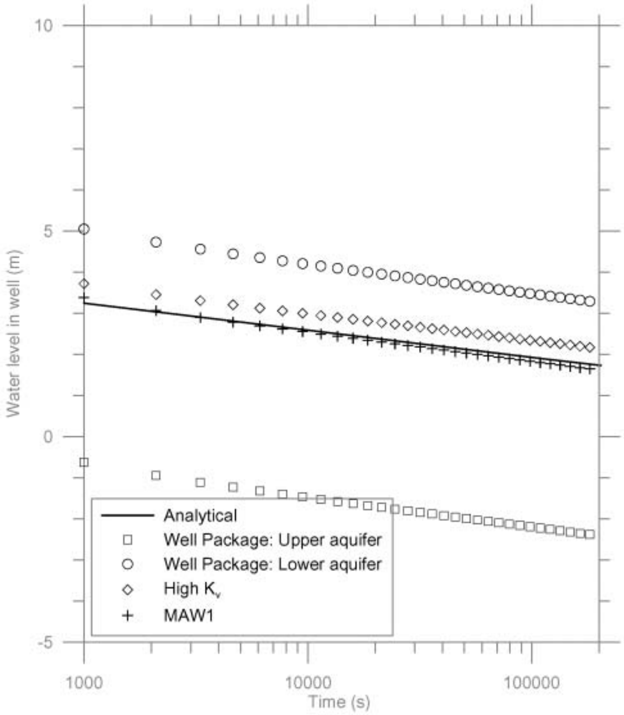

Figure 8. Pumping water levels in the pumping well—fine grid.

refined grid, the results with the High K_v in the Well Block are closer to the analytical results. The MAW1 Package again yields an excellent match to the analytical solution. The calculated discharges for the two aquifers are plotted in Figure 9. Both the MAW1 and the High K_v in the Well Block approaches yield nearly exact flows for the two aquifers.

Results obtained from additional simulations not reported here demonstrate that results obtained with the High K_v in the Well Block approach closely match the analytical solution when the dimensions of the well block are equal to the equivalent radius of the well. In this application, the required well block dimension is 0.77 m (i.e., r_w/0.198). We conclude from this that application of the High K_v in the Well Block approach is appropriate for the analysis of single well pumping tests where the grid is refined to the dimensions of the well.

Results for Nonpumping Conditions

The results of simulations for zero net pumping with the coarse finite-difference grid are shown in Figure 10. The analytical solution predicts a quasi-steady water level in the well of ~7.8 m, or 1.4 m below the initial head in the lower aquifer and 4.7 m above the initial head in the upper aquifer. The MODFLOW Well Package cannot be used to analyze this problem. If the total discharge from a well is zero, the well is excluded altogether from the simulation. The results obtained with the High K_v in the Well Block approach the analytical results only toward late time. The results obtained with the MAW1 Package match the analytical solution. The calculated discharges from the two aquifers are plotted in Figure 11. The MAW1 Package yields nearly exact flows from both aquifers.

The results of simulations for zero net pumping with the refined grid are shown in Figure 12. The MAW1 results agree relatively closely with the analytical results, particularly at later times. The calculated discharges from the two aquifers are plotted in Figure 13. The MAW1 results again match the analytical solution closely. It is important to note the magnitude of the flows between the two aquifers. After more than 1 d, the flow between the aquifers still exceeds 280 m^3/d. These results provide some insight into the important role that multiaquifer wells can play in redistributing water and solutes between strata that are otherwise isolated.

Benchmark Problem for Steady Flow

Two approaches for modeling multiaquifer wells under steady conditions are evaluated by comparing results from MODFLOW with an extended version of an exact solution presented by Sokol (1963). The extended analytical solution for steady-state flow to a multiaquifer well is presented first. The results of MODFLOW simulations with the MAW1 Package are then compared with analytical results. In the final part of this section, an alternative approach for representing a multiaquifer well in steady-state flow conditions is described. This alternative approach sheds additional light on the hydraulics implemented in the MAW1 Package.

Analytical Solution for Steady-State Flow to a Multiaquifer Well

Sokol (1963) presents a solution for steady radial flow to a single well that penetrates multiple horizontal strata. The solution is effectively a generalization of the Thiem solution for a net pumping rate of zero. The water level in the well is calculated from

$$h_w = \frac{\sum_{m=1}^{N} T_m h_m}{\sum_{m=1}^{N} T_m} \tag{8}$$

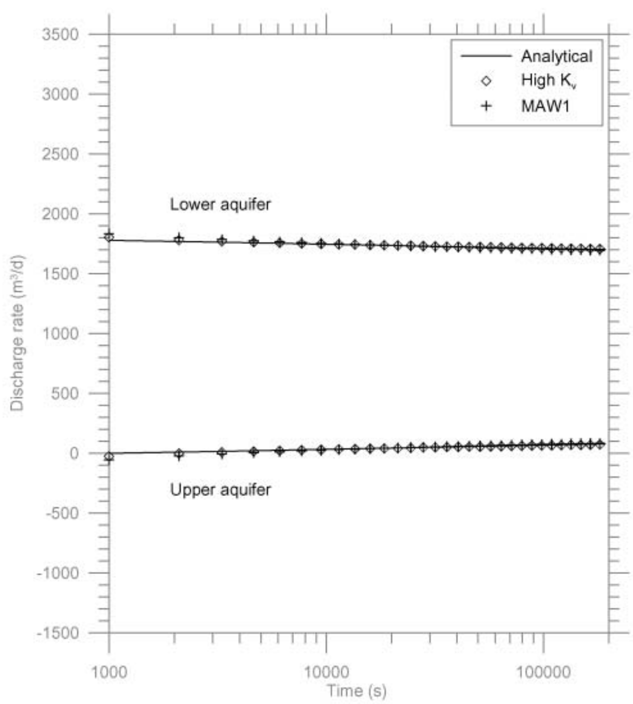

Figure 9. Pumping aquifer discharges—fine grid.

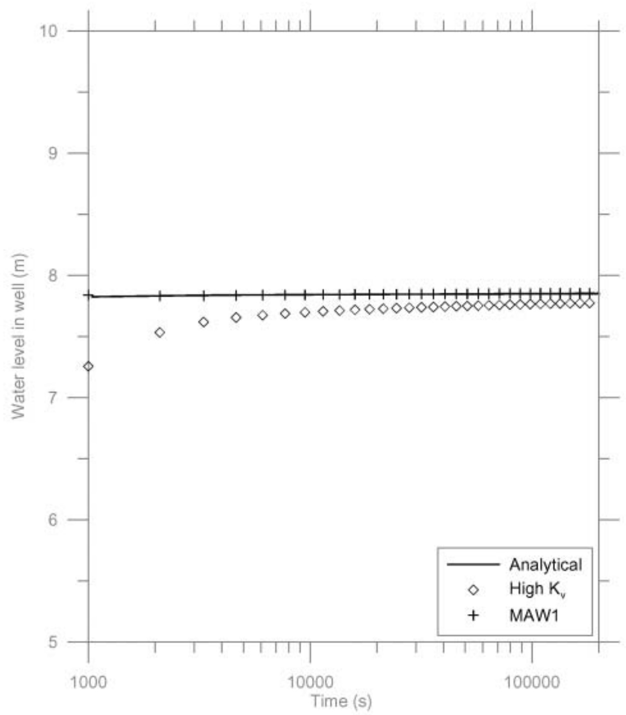

Figure 10. Nonpumping water levels in the pumping well—coarse grid.

where N is the number of aquifers penetrated by the multiaquifer well, T_m is the transmissivity of each aquifer, and h_m is the far-field head in each aquifer.

For this benchmarking exercise, Sokol's solution is extended for a nonzero net pumping rate. For a net pumping rate of Q_{TOT}, the water level in the well is given by

$$h_w = \frac{-\frac{Q_{TOT}}{2\pi}\ln\left\{\frac{R}{r_w}\right\} + \sum_{m=1}^{N} T_m h_m}{\sum_{m=1}^{N} T_m} \qquad (9)$$

where R is the distance to the outer constant-head boundary and r_w is the radius of the well. This form of the solution presumes that the total discharge from the multiaquifer well is known. If the water level in the well is known instead, then the total discharge rate is given by

$$Q_{TOT} = \frac{2\pi}{\ln\left\{\frac{R}{r_w}\right\}}\left[\sum_{m=1}^{N} T_m (h_m - h_w)\right] \qquad (10)$$

Demonstration Problem

The test problem for steady flow is similar to that developed for transient flow by Bennett et al. (1982). An impermeable stratum separates two horizontal, confined aquifers. The transmissivity of the upper aquifer is 92.9 m^2/d, and the transmissivity of the lower aquifer is 371.6 m^2/d. The heads in each aquifer remain fixed at an outside radial boundary that is 7150 m from the multiaquifer well. The boundary head in the upper aquifer is 3.05 m and the head in the lower aquifer is 9.14 m.

The results of a set of simulations obtained using the MAW1 Package are shown in Figure 14. For each simulation, the total discharge rate is specified, and the head in the wellbore is calculated. As shown in the figure, the results obtained with the MAW1 Package match closely the extended Sokol solution for both coarse and fine grid models. The dashed line in Figure 14 designates the solution for zero net pumping. This corresponds to the Sokol solution, Equation 8. For the parameters of the benchmark problem:

$$h_w = \frac{\left(92.9\frac{m^2}{d}\times 3.05\ m\right) + \left(371.6\frac{m^2}{d}\times 9.14\ m\right)}{\left(92.9\frac{m^2}{d}\right) + \left(371.6\frac{m^2}{d}\right)} = 79.2\ m$$

The results from this benchmarking exercise suggest that it is possible to obtain accurate results with the MAW1 Package for steady conditions, even for relatively coarse grids.

Alternative Approach for Steady-State Simulations

The MODFLOW General-Head Boundary (GHB) Package may also be used to model multiaquifer wells, provided that it is understood that in some ways its functionality is a mirror image of the MAW1 Package. The MAW1 Package starts with a specified total discharge from the well and determines the water level in the well and the flow allocation among the penetrated aquifers. In contrast, the GHB Package analysis starts from a specified water level in the multiaquifer well, and the flows from each layer and the cumulative discharge are calculated.

To understand the application of the GHB Package, let us recall the general formula for the flow into or out of a GHB (McDonald and Harbaugh 1988):

$$Q_G = -C_G(h_{jik} - h_G) \qquad (11)$$

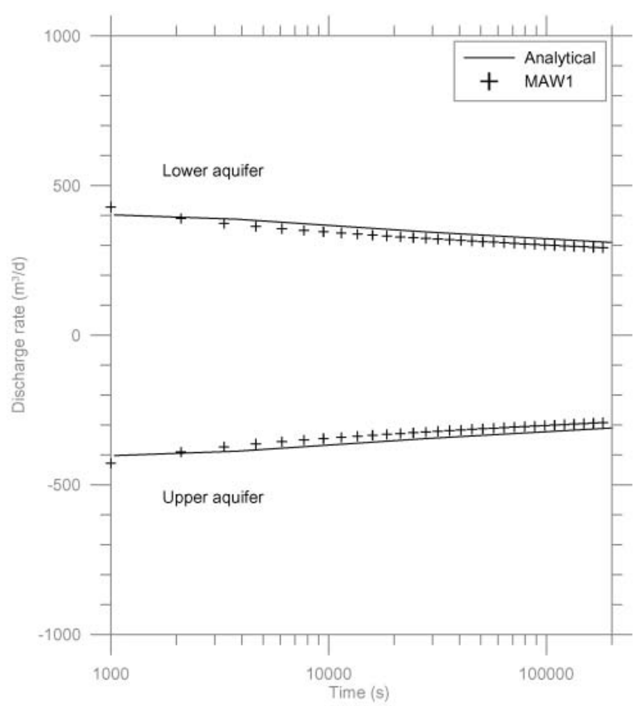

Figure 11. Nonpumping aquifer discharges—coarse grid.

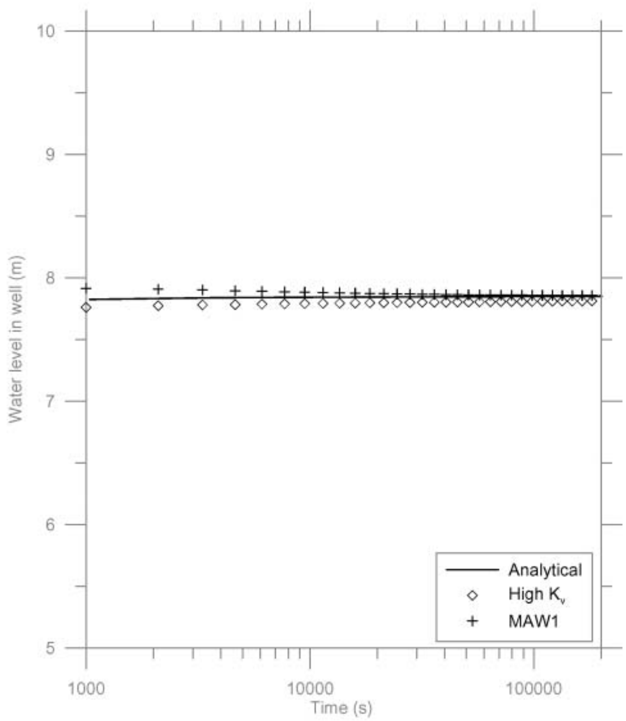

Figure 12. Nonpumping water levels in the pumping well—fine grid.

where C_G is the conductance of the GHB, and h_{jik} and h_G are the head in the grid block and the control level of the GHB, respectively. If we assume that flow is steady and radial in each layer penetrated by the well, then the discharge in each layer can be approximated with the Thiem solution:

$$Q_{Wjik} = -2\pi T_{jik} \frac{(h_{jik} - h_W)}{\ln\left(\frac{r_{eq}}{r_W}\right)} \tag{12}$$

In writing the Thiem solution in the context of a finite-difference model, we again hypothesize that the head in the well block is interpreted as the head that prevails at a distance of r_{eq} from the center of the well.

The general GHB formula can be made equivalent to the Thiem solution by setting the stage as the specified water level within the wellbore and setting the conductance for each model layer penetrated according to

$$C_{Gjik} = \frac{2\pi T_{jik}}{\ln\left(\frac{r_{eq}}{r_w}\right)} \tag{13}$$

The GHB does not impose a constraint on the flow if the stage is below the water level in the aquifer. In general, the use of the GHB Package to represent a drawdown-controlled extraction well is inappropriate, because it does not preclude the possibility of the well injecting water into the aquifer. However, the reversal in flow is a real possibility in the case of a multiaquifer well.

The results of a set of simulations obtained using the GHB Package with coarse and fine grid models are shown in Figure 15. For each simulation, the water level in the well is specified, assigning a common stage for the two aquifers penetrated by the multiaquifer well, and the total discharge is calculated. As shown in the figure, the results obtained with MODFLOW and the GHB Package match the extended Sokol solution. The results from this benchmarking exercise suggest that equivalent results can be obtained with the MAW1 and GHB packages.

In the context of a steady-state simulation, the application of the GHB and MAW1 packages described here are the same. Both are derived from the Thiem solution, and both yield essentially the same weighting of water levels with respect to transmissivity. There is a crucial difference, however. With the GHB approach, the modeler must assume a head in the multiaquifer well, rather than determine it as part of the analysis. The net discharge from the well is determined from the solution as a postprocessing step, by adding the flow from each layer penetrated by the well.

The difference between the use of the MAW1 and GHB packages can be addressed by recognizing that under steady-state conditions there is a unique relationship between the discharge rate and the pumping level. Therefore, only a few additional runs of the steady-state model are required to characterize the performance of the multiaquifer well. For each run, a different water level in the well is assumed, and the resulting total discharge is determined. The resulting pairs of points (pumping level, total discharge) can be plotted as a rule curve for the well. Unfortunately, this method cannot be used for simulations involving multiple multiaquifer wells that are relatively close to each other. If the wells are sufficiently close, they may interfere with each other and the rule curve developed for a single well is not applicable.

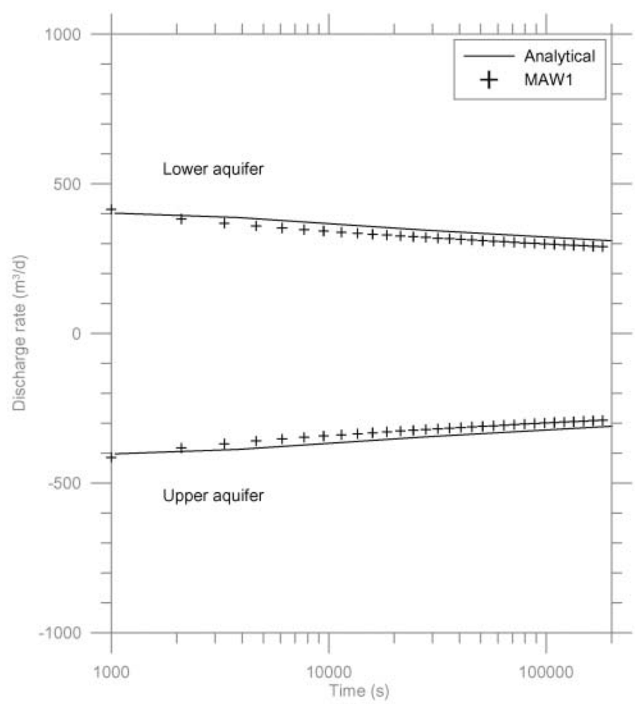

Figure 13. Nonpumping aquifer discharges—fine grid.

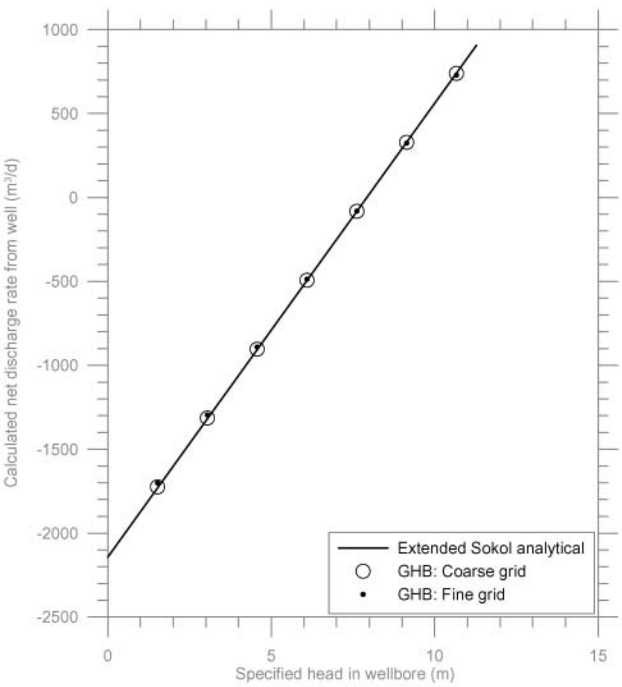

Figure 14. Results of steady-state analyses, MAW1 Package.

Conclusions

Simulating multiaquifer wells by direct application of the MODFLOW Well Package may be inappropriate. The Well Package will in general yield different water levels in each stratum penetrated by the well, none of which will be a good approximation for the water level in the well. The results presented here demonstrate that allocating well flows among the layers penetrated by a multiaquifer well may yield a completely incorrect distribution of discharge. In the case of a multiaquifer well with zero net discharge, the Well Package cannot be used.

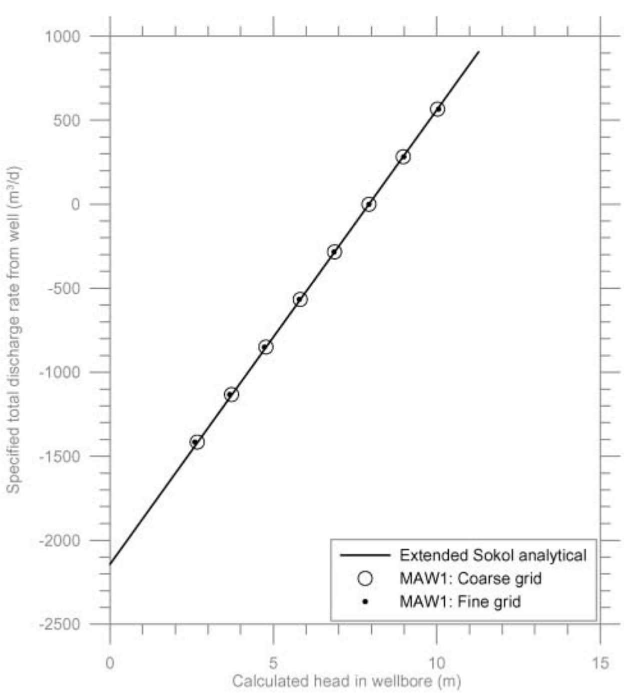

Figure 15. Results of steady-state analyses, GHB Package.

The High K_v in the Well Block approach can be used to model a multiaquifer well provided that two important conditions are met. First, the vertical hydraulic conductivity specified for the well must be sufficiently high that there are effectively no vertical gradients in the well block. Second, the dimension of the well block must be similar to the actual dimensions of the well. Optimal results are obtained when the dimension of the well block is chosen so that its equivalent radius is equal to the radius of the well.

The MAW1 Package yields excellent agreement to analytical solutions for pumping and nonpumping conditions. The benchmarking results suggest that MAW1 correctly implements the theory of the multiaquifer well developed by Bennett et al. (1982). Results obtained with the MAW1 Package appear to be relatively insensitive to grid refinement, suggesting that this is an appropriate method for representing wells in regional models with relatively coarse grids.

The MAW1 Package matches analytical results under steady conditions. For steady-state conditions, the MAW1 Package has similar functionality to the GHB Package. With the MAW1 Package, the modeler specifies the total discharge from the well, and the package calculates the head in the well and the distribution of the discharge. With the GHB Package, the modeler specifies the head in the multiaquifer well, and the net discharge from the well is determined from the solution as a postprocessing step.

Multiaquifer wells can have a profound effect on the hydraulics of the ground water system, regardless of pumping. They change the physical system (and the equations that describe it) by acting as very permeable tubes that establish direct hydraulic links between units that are otherwise isolated. The MAW1 Package is an effective approach to simulate these wells in three-dimensional models. The techniques developed for the MAW1 Package can, and should, be applied to represent wells that span multiple model layers, whether the layers involved represent distinct aquifers or arbitrary subdivisions of a single aquifer.

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