Modeling Axially Symmetric and Nonsymmetric Flow to a Well with MODFLOW, and Application to Goddard2 Well Test, Boise, Idaho

by Warren Barrasha and Martin E. Dougherty

Abstract

Tools for analyzing aquifer test data at the pumping or injection well are limited for aquifer conditions that are not axially symmetric about the pumping well. Accurate simulations of head change at a pumping well can be generated with MODFLOW using a discretization scheme that (1) captures steep gradients adjacent to the cell(s) containing the pumping or injection well and (2) approximates radial flow despite rectangular prism cell(s). This scheme is based on a very small incremental cell width adjacent to the pumping or injection well cell, and then a logarithmic increase in cell width outward with the expansion factor, \( \alpha \), in the range of 1.2 to 1.5. The validity of this scheme has been demonstrated by comparing model results with analytical solutions and RADMOD (axisymmetric adaptation of MODFLOW) for three radially symmetric confined aquifer scenarios, and with the analytical solution for a nonaxisymmetric confined aquifer scenario. Utility of this scheme is demonstrated with simulation of time-drawdown behavior at the Goddard2 pumping well in Boise, Idaho where four observation wells did not respond during a pumping test and where 28.8 m of drawdown occurred in the pumping well during the first 2 min of the test. The hydrogeologic setting for the test is interpreted to be a partially penetrating well pumping from a sand-stringer aquifer that receives leakage from surrounding finer grained sediments, and includes a fault (no-flow boundary) truncating the aquifer.

Introduction

Tools for analyzing aquifer test data at the pumping or injection well (hereafter referenced as pumping well only) are limited for aquifer conditions that are not axially symmetric about the pumping well. Although the exact meaning of aquifer test interpretations from data at a pumping well can be complicated by well construction, well development, well storage, and well efficiency issues, analysis of test data from pumping wells is necessary for single-well tests in nonideal or complex hydrologic settings, and for multiple-well tests where observation wells do not respond. Analysis of data at the pumping well also is valuable where few observation wells are available and where responses in observation wells are ambiguous, or where heterogeneity is known to be significant for the scale of the aquifer test.

Finite-difference models with rectilinear grid geometry such as MODFLOW (McDonald and Harbaugh, 1988) generally have not been used to simulate aquifer test results at a pumping well because they are not designed or expected to closely simulate head changes in pumping wells. Head gradients in the vicinity of the pumping well are large and commonly are underestimated in conventional discretization schemes because distances between adjacent cell centers, or nodes next to the well, are too large to capture the steep and rapidly changing head gradients there. Also, explicit treatment of the well itself is difficult with rectilinear geometry because porous media flow physics do not apply within a well, and numerical instability may result from attempts to treat the well bore as a zone of very high permeability.

Although an axisymmetric node-centered adaptation of MODFLOW exists [RADMOD (Reilly and Harbaugh, 1993)] which is very efficient for modeling axisymmetric scenarios, we are not aware of another finite-difference model or discretization scheme that has accurately simulated transient responses at a pumping well for nonaxisymmetric flow or nonradially symmetric aquifer conditions. However, such flow and aquifer conditions are common in heterogeneous media and in environments with complex boundary and induced-stress configurations. And such a capability with MODFLOW might be extended further in conjunction with other modeling codes that accept MODFLOW results as input, such as contaminant or tracer transport modeling with MT3D (Zheng, 1992) and parameter estimation with MODFLOWP (Hill, 1992).

This paper (1) describes a discretization scheme for the rectilinear grid system of MODFLOW which supports accurate simulation of drawdown behavior at the pumping well, and
(2) uses this discretization scheme in MODFLOW to analyze nonaxisymmetric flow to a well, the Goddard2 well in Boise, Idaho, for a test where four observation wells did not respond, where boundary effects are evident, and where geologic data indicate that the aquifer cannot be treated as laterally extensive in the nonboundary direction.

Discretization Scheme

The discretization scheme presented here (Figure 1a) uses twice the well radius as the X and Y (column and row) dimensions of the cell containing the pumping well (the "well cell"), and then moves outward from the well cell with increasing cell widths starting with a cell width that is a small fraction of the well diameter. The expansion factor, \( \alpha \), used to determine widths for cells outward from the cell adjacent to the well cell (Figure 1a) is the same as that used by Reilly and Harbaugh (1993) in RADMOD: \( \alpha = r_{i+1}/r_i \), where \( r \) is the radial distance to a node, \( i \) is the index number of the "column" or radial shell outward from the well, and \( \alpha \) is generally given a value between 1.2 and 1.5. By having very small cell widths near the well cell, errors associated with finite-differencing of distance between nodes are small. Also, intensity of discretization and symmetry of cell dimensions increase to a maximum at the corners of the well cell, and at outward projections of those corners throughout the grid.

In this geometry, cells with the poorest aspect ratios are located along and near streamlines at 90° intervals where their short dimensions and nodes are aligned or nearly aligned with the direction of flow to best capture steep gradients, and their long dimensions are more nearly "aligned" with head contours where head change along the long dimension (crossing streamlines) is small (Figure 1b). Conversely, with approach to a corner along a row or column, cell dimensions become progressively more equal with the longer dimension decreasing in length as rate of head change increases in the respective column or row direction—until increases in head change relative to X and Y coordinates are nearly equal and maximum at corners where, also, cell dimensions are equal and minimum (Figure 1b). With this geometry, effects of converging flow (e.g., curvature of head contours and steep, rapidly changing head gradients) can be simulated accurately near the pumping well.

Drawdown at the pumping well in this discretization scheme is represented by drawdown not in the actual well cell but in any of the four cells immediately adjacent to the well-cell faces along principal axis directions. Nodes in these adjacent cells are at \( r = r_w + \text{very small increment} \) (Figure 1a). We assume that the head measured in the formation immediately outside the well (i.e., at \( r = r_w \)) is equal to the head in the well; this is a reasonable assumption in well hydraulics where well losses and/or well storage contributions to discharge may be neglected (Hantush, 1964; Papadopoulos and Cooper, 1967). This assumption is based on continuity considerations where the water level in the well equals the head at the well screen and the pumping rate from the well equals the flow rate into the well across the cylindrical surface at \( r_w \) (Figure 2).

In MODFLOW, pumpage is independent of head and is distributed throughout the well cell to which it is assigned. MODFLOW uses a block-centered discretization formulation, so head in the well cell is calculated at the node in the center of the well cell based on the finite-difference form of the continuity equation (using Darcy's law to relate flows with heads) for flows entering and leaving through the six faces of a given cell. In the discretization scheme presented here, the well is not modeled explicitly as a cylindrical pipe, but rather as a rectangular (square) prism filled with aquifer material (Table 1). Hence, drawdown calculated by the model for the well cell itself does not represent drawdown in the real well. However, in a numerical model that accurately represents the transient behavior of a pumped hydrologic system in the region where \( r \geq r_w \) (i.e., flow rates are equal and continuous across cylindrical surfaces inward to \( r_w \)), the head values at \( r_w \) in MODFLOW closely approximate head values in the real well where the same flow rate is removed immediately inward from \( r_w \) in the real well and in MODFLOW (Figure 2b) even if the well is filled with aquifer material in MODFLOW (Table 1).

It should be noted that simulated drawdown is less than theoretical drawdown (i.e., drawdown calculated from an analytical solution) at early time for any given MODFLOW run with the discretization scheme presented here (Figures 3 and 4). This is not unexpected in a numerical model because time is discrete.
Table 1. Comparison of Well Characteristics for Different Well-Aquifer Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Well radius</th>
<th>Well permeability</th>
<th>Well geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real world</td>
<td>$r_w = r_w$</td>
<td>$k_{well} \gg k_{formation}$</td>
<td>Cylinder</td>
</tr>
<tr>
<td>Line sink analytical solution</td>
<td>$r_w = 0$</td>
<td>$k$ at $r &gt; r_w = k_{formation}$</td>
<td>Line</td>
</tr>
<tr>
<td>MODFLOW</td>
<td>$r_w = \frac{1}{2} \Delta X_w = \frac{1}{2} \Delta Y_w$</td>
<td>$k_{well} = k_{formation}$</td>
<td>Rectangular (square) prism</td>
</tr>
</tbody>
</table>

The discretization scheme presented here has been benchmarked against analytical solutions and RADMOD for three axially symmetric confined aquifer scenarios and against the analytical solution for a nonaxisymmetric confined aquifer scenario with multiple no-flow boundaries (Barrash and Dougherty, 1995a, b). Table 2 gives characteristics of the four different scenarios and the models run. For perspective on the performance of the "intense" discretization scheme in MODFLOW presented here, the four benchmarked scenarios also were run with MODFLOW in a more "conventional" discretization scheme where the cells adjacent to the well cell along principal axes have widths determined by $\alpha$ relative to the well-cell radius (rather than relative to a very small-width cell adjacent to the well cell) and where $\alpha$ is 1.3 (rather than 1.5 as is used for the intense scheme).

Examples of benchmarked comparisons of analytical and numerical models are given here for two scenarios: pumping an aquifer overlain by a leaky aquitard with elastic storage (Figure 3), and pumping an aquifer with vertical no-flow boundaries at different distances from the pumping well (Figure 4). These examples are typical in that MODFLOW results using the intense discretization scheme compare well with analytical or numerical models.

Fig. 3. A. Axisymmetric benchmark scenario: Hantush (1960) Case 2 conditions: Confined aquifer receiving leakage from an aquitard bounded by a no-flow boundary. B. Comparison of model results at the pumping well. MODFLOW results with $\alpha$ symbol are generated with intense discretization scheme where cells adjacent to the well cell have very small widths and cell widths expand outward with $\alpha = 1.5$. MODFLOW results with $x$ symbol are generated with conventional discretization scheme where cell widths expand outward from the well cell with $\alpha = 1.3$.
Table 2. Characteristics of Numerical Models Used in Benchmarking (1)

<table>
<thead>
<tr>
<th>Model scenario (All confined systems)</th>
<th>Discretization scheme</th>
<th>Rows (2)</th>
<th>Columns (3)</th>
<th>Layers (4)</th>
<th>Stress periods</th>
<th>Time steps (5)</th>
<th>Time of step 1 (minutes)</th>
<th>Radius of well cell (meters)</th>
<th>Width of cell adjacent to well (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No leakage (Theis, 1935).</td>
<td>MODFLOW intense (6)</td>
<td>40</td>
<td>40</td>
<td>4</td>
<td>90</td>
<td>2.1E-06</td>
<td>0.1</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>2. Leakage from storage in aquitard (Hantush, 1960).</td>
<td>MODFLOW conventional (6)</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>95</td>
<td>5.4E-06</td>
<td>0.15</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>3. Partially penetrating well, anisotropic permeability $K_r &gt; K_z$, similar to Neuman (1974).</td>
<td>MODFLOW intense (6)</td>
<td>45</td>
<td>45</td>
<td>25</td>
<td>95</td>
<td>5.4E-06</td>
<td>0.285</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>4. Intersecting no-flow boundaries, superposed Theis solutions using image well theory.</td>
<td>MODFLOW intense (6)</td>
<td>74</td>
<td>70</td>
<td>1</td>
<td>95</td>
<td>5.4E-06</td>
<td>0.15</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>5. Application: Modeling of a Constant-Rate Pumping Test at the Goddard2 Well, Boise, Idaho</td>
<td>MODFLOW conventional (6)</td>
<td>59</td>
<td>54</td>
<td>1</td>
<td>95</td>
<td>5.4E-06</td>
<td>0.15</td>
<td>0.046</td>
<td></td>
</tr>
</tbody>
</table>

(1) All four scenarios are fully presented in Barrash and Dougherty (1995b).
(2) In RADMOD, rows are model layers.
(3) In RADMOD, columns are radial shells.
(4) In RADMOD, layer is a model feature that does not represent scenario geometry.
(5) TSMULT, the multiplier for successive time steps in a given stress period is 1.2 for all runs.
(6) Model domain is 1/4 of full domain; cell-width expansion factor is increased from 1.5 to 2 in outer regions of the model where gradients are low.

RADMOD solutions, especially at times likely to be measurable in a real aquifer test. Also, MODFLOW results evaluated at a cell adjacent to the well cell on a principal axis using a conventional discretization scheme remain below the analytical solution for the full duration of the tests in axisymmetric scenarios. The lower drawdown values occur because of the greater distance between well-cell and adjacent-cell nodes in the conventional discretization scheme, even with $\alpha = 1.3$. The other two scenarios against which the intense discretization scheme was benchmarked are detailed, along with the two examples given here, in Barrash and Dougherty (1995b).

Application: Modeling of a Constant-Rate Pumping Test at the Goddard2 Well, Boise, Idaho

Consider a case with the following conditions. (1) A large-capacity production well is constructed and tested with a step-test and constant-rate pumping test. (2) The constant-rate test is monitored in four observation wells of convenience (i.e., available wells not constructed or located to serve the test), but none of these observation wells respond during the test. (3) Well losses in the pumping well are minimal based on flow-velocity calculations and step-test data. (4) Engineering analysis of the constant-rate test provides an estimate of transmissivity but data poorly fit the Theis model. (5) Available geologic and geophysical data support a conceptual model of the hydrogeologic system that cannot be simulated at a pumping well with an analytical or axisymmetric numerical model.

The above conditions apply to the Goddard2 well which is a replacement well for the nearby, deeper Goddard1 well in northwest Boise, Idaho (Figure 5). In this case there is value in continuing the analysis of the constant-rate pumping test because the well is located in a region (lower Boise River valley) where the stratigraphic and structural settings of the groundwater system are known to be complex (Wood and Anderson, 1974).
growth, water-level declines in some areas, incipient contaminations, ...), where other single-well tests are common by design or prediction, with quantified interaction of hydrologic data (aquifer parameters, and fundamental changes in the hydrologic system associated with the shift to advanced urban land use from irrigated agriculture.

Hydrogeologic Setting
The study area in northwest Boise, where the Goddard2 well pumping test was conducted (Figure 5), is near the northern boundary of the western Snake River Plain which is a major, NW-trending, late-Cenozoic rift basin that is filled, in the upper portion, primarily with lacustrine, deltaic, and floodplain sediments of the Idaho Group (Malde and Powers, 1962; Malde, 1972; Kimmel, 1982). The study area is underlain by a thin veneer of coarse alluvium which overlies a 450 m to > 600 m thick section of Idaho Group sediments. The water table commonly lies in the coarse alluvium, even where the valley topography is stepped up in terraces south of the Boise River. Two significant NW-trending normal faults (Figure 5) near the Goddard2 well may cut Idaho Group sediments at producing-zone levels in this area (S. H. Wood, unpublished data; Squires et al., 1992; Barrash and Dougherty, 1995b).

Well and Test Conditions
Two types of tests were conducted at the Goddard2 well in 1991 (Mills, 1991): a step-drawdown test and a constant-rate pumping test. Total depth of the Goddard2 well is 168 m with a 30-slot, 0.25 m diameter screen set from 145 to 166 m below land surface (BLS). Casing diameter above the screen is 0.46 m. For both the step-test and the constant-rate test a line-shaft turbine pump was set at 61 m BLS which is about 84 m above the screen. Flow rates were measured through an orifice weir with a lower calibration threshold of 2.3 m$^3$ min$^{-1}$ (Mills, 1991). Schematic diagrams of the Goddard2 well and the four observation wells monitored during the constant-rate test are given in Figure 6.

Minimal Well Losses
It is important to establish that well losses are minimal if the hydraulic behavior of the aquifer is to be interpreted from drawdown responses at the pumping well alone. Two lines of evidence indicate that well losses do not significantly influence drawdown behavior at the Goddard2 well: (1) calculations on construction dimensions predict laminar flow into the well and small head loss with flow up the well, and (2) step-test performance demonstrates that nonlinear well losses are minimal.

Well Construction Analysis
Analysis of well construction and inflow conditions at the well screen support the interpretation of laminar flow in the vicinity of the well screen. For a cylinder of 21.3 m length and 0.25 m diameter, the surface area is 18.25 m$^2$. For a 30-slot screen, 41% of the surface area is open for flow (Driscoll, 1986). Entrance velocity to the well then is $v_e = Q/A$, where $v_e$ is entrance velocity to the well screen, Q is pumping rate, and A is the screen area at the screen surface. For the Goddard2 well the highest $Q$ was 6.5 m$^3$ min$^{-1}$, during the constant-rate test, and $v_e$ is 7.5 m$^2$. So, $v_e = 0.87$ m min$^{-1}$ which is below the design limit (i.e., within the laminar flow range) for relatively permeable aquifers (US EPA, 1975, p. 90; Driscoll, 1986, p. 996).

Similarly, flow up the well from the screen to the pump intake incurred minimal pipe loss. Flow velocity up the casing equals $Q/A$, where Q is 6.5 m$^3$ min$^{-1}$ and A is 0.16 m$^2$, the
cross-sectional area for the well with casing diameter of 0.46 m above the screen. Flow velocity, then, is about 40 m min⁻¹. Head loss in the Goddard2 well is expected to be less than 0.09 m (i.e., < 0.03 m/30 m of pipe x 84 m from screen to pump) during a constant-rate test at 6.5 m³ min⁻¹ based on the nomogram provided by Driscoll (1986, Appendix 13K) to determine head loss knowing pipe diameter or flow rate and flow velocity.

**Step-Test Analysis**

A five-step test (Mills, 1991) was conducted with discharges of 1.3 (?) m³ min⁻¹, 2.3 m³ min⁻¹, 3.8 m³ min⁻¹, 4.9 m³ min⁻¹, and 5.7 m³ min⁻¹ for time periods ranging from 15 min to 73 min with the last four steps lasting more than 50 min each (Table 3). Pumping was continuous across steps for a total pumping period of 255.5 min. In addition, data from the constant-rate pumping test at 6.5 m³ min⁻¹ are used to extend the step-test analysis to the pumping rate of the constant-rate test (Table 3). Specific capacity values range between 0.19 and 0.2 m³ min⁻¹/m of drawdown for the last four steps and the constant-rate test based on a uniform time of pumping per step. That is, specific capacity remained essentially constant with increasing pumping rate, and did not decrease with increasing pumping rate as would be expected if nonlinear well losses were associated with pumping at this well (e.g., Hantush, 1964).

**Constant-Rate Test**

The Goddard2 well was pumped for 8 hr at an average rate of 6.5 m³ min⁻¹ on February 28, 1991. Four observation wells were monitored for drawdown effects during the test, but data

<table>
<thead>
<tr>
<th>Step</th>
<th>Q: Discharge rate, m³ min⁻¹</th>
<th>Time during step, min</th>
<th>s: Drawdown during step, m</th>
<th>Q/s: Specific capacity, m³ min⁻¹/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.3*</td>
<td>50</td>
<td>7.62**</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>2.3</td>
<td>51.5</td>
<td>11.31</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>3.8</td>
<td>48.8</td>
<td>20.32</td>
<td>0.19</td>
</tr>
<tr>
<td>4</td>
<td>4.9</td>
<td>50</td>
<td>25.90</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>5.7</td>
<td>50.5***</td>
<td>30.38***</td>
<td>0.19</td>
</tr>
<tr>
<td>6</td>
<td>6.5</td>
<td>50****</td>
<td>32.16****</td>
<td>0.20</td>
</tr>
</tbody>
</table>

* Estimated rate—discharge was below minimum calibrated rate of flowmeter.
** Extrapolated from trend through 12.5 minutes and 7.55 m drawdown.
*** Interpolated from drawdowns at 47.1 and 54.9 minutes elapsed time in step 5.
**** Interpolated from drawdowns at 47.5 and 57 minutes elapsed time during constant-rate pumping test.
Theis curve 1 is the solution of Mills (1991) for drawdown values, but fits to the data still are poor.

The conceptual model of a nonleaky confined aquifer (Figure 7) is used to attempt a match with measurements at the Goddard2 well during the constant-rate pumping test. Pumping rate is 6.5 m$^3$/min$^{-1}$, which requires an unrealistically low specific storage value of $4.7 \times 10^{-8}$ m$^{-1}$. Theis curves 2 and 3 have more realistic specific storage values, but fits to the data still are poor.

Presented by Mills (1991) indicate that none of these wells responded to pumping. This is not necessarily surprising because three of the monitored wells are about 1.5 km from the Goddard2 well, the screened intervals in three of the wells (including the Goddard1 well 12.2 m from the Goddard2 well) are at significantly different elevations than the screened interval in the Goddard2 well (Figure 6), and the length of the test was only 8 hr.

Analysis of the test at the Goddard2 well for engineering purposes (Mills, 1991) with the semilog straight-line method (Cooper and Jacob, 1946) gave a transmissivity value of 56 cm$^2$/s for drawdown data prior to boundary effects starting at about 180 min. If the aquifer thickness is taken to be 21.3 m, or the screened thickness of sand at the Goddard2 well (Figure 6), then an initial estimate for hydraulic conductivity of the aquifer is 0.026 cm/s. However, log-log plots (Theis curves) with $T = 56$ cm$^2$/s (or similar values) do not compare favorably with the observed pre-boundary data at the Goddard2 well, especially if reasonable specific storage values ($S_s > 3.3 \times 10^{-6}$ m$^{-1}$) are used (Figure 7). The conceptual model of a nonleaky confined aquifer pumped by a fully penetrating well is not sufficient to explain drawdown behavior at the Goddard2 well.

**Conceptual Model for Hydrogeologic System**

A conceptual model for the hydrogeologic system in the vicinity of the Goddard2 well has been developed from available well and seismic reflection data (Barrash and Dougherty, 1995b) which are consistent with previous interpretations of a floodplain environment in the subsurface (Squires et al., 1992). Figure 8 is a highly simplified schematic diagram of sand and fine-grained units in a floodplain environment. In general, sand bodies are relatively thick (commonly > 10 m thick), have limited lateral extent, and are relatively long and linear along the basin-axis direction. Fine-grained sediments surround the sand bodies, although overlap and hydraulic continuity between sand stringers is possible (e.g., Cant, 1982; Fogg, 1989).

Lithologic logs from wells deeper than 700 m elevation in the vicinity of the Goddard2 well (Figure 6) identify sequences with relatively thick intervals of sand and fine-grained sediments below the shallow alluvial aquifer. The sequence as a whole and individual units are difficult to correlate directly because numbers and thicknesses of sands and fine-grained units are not consistent between adjacent wells that are ~ 1.5 km apart (Figure 6). A seismic reflection profile taken 1 km NE of the Goddard2 well (Figure 5) indicates that the portion of the stratigraphic section represented by wells in the vicinity of the Goddard2 well (unit 4 in Figure 9) is consistent with meandering stream deposits in a floodplain where sand bodies have limited lateral extent, and variable dips and dip directions (Barrash and Dougherty, 1995b).

The dimensions of the sand unit tapped by the Goddard2 well, based on drillers' logs and high-resolution seismic reflection data (Figures 6 and 9), likely are limited in width (perhaps < 600 m) and thickness (~ 30 m). Limited width in the cross-basin or NE-SW direction is demonstrated by lack of correlative sand units in a cross section 800 m SE from (up paleoergradient from) the Goddard wells (Figure 6b); structural offset cannot account for this lack of correlation (Barrash and Dougherty, 1995b). Length continuity of several kilometers or more may be inferred from the nature of meandering stream deposits and by tentatively correlating thick sands in wells along the NW-SE (basin-axis) trend of sediment influx (Figure 6a) where the sands collectively have a basinward gradient (0.006-0.007) in the meandering stream range if a sinuosity index in the meandering stream range (> 1.5) is assumed (Morisawa, 1985; Barrash and Dougherty, 1995b).

The aquifer (sand stringer) tapped by the Goddard2 well is interpreted to have a thickness of 30 m based on the thickness of the sand at that elevation in the Goddard1 well 12.2 m away (Figure 6). The fine-grained unit at the base of the 21.3 m screened interval in the Goddard2 well is interpreted to be a thin lens, so the Goddard2 well partially penetrates the aquifer. The producing sand in the Goddard2 well is surrounded by clay, silty clay, and silty sand that, as an aggregate, are not impermeable and will yield water from storage; drillers' logs indicate fine-grained sediments are not lithified or highly compacted. Other sand bodies with geometry similar to that of the aquifer tapped by the Goddard2 well (length > width > thickness) are inter-

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**Fig. 7.** Log-log plot of drawdown vs. time using Theis conceptual model to attempt a match with measurements at the Goddard2 well during the constant-rate pumping test. Pumping rate is 6.5 m$^3$/min$^{-1}$, aquifer thickness is 21.3 m. Theis curve 1 is the solution of Mills (1991) which requires an unrealistically low specific storage value of $4.7 \times 10^{-8}$ m$^{-1}$ for a match. Theis curves 2 and 3 have more realistic specific storage values, but fits to the data still are poor.

**Fig. 8.** Schematic diagram of floodplain environment showing linear sand stringers surrounded by fine-grained vertical accretion deposits. From Walker and Cant, 1979, Figure 8A, reprinted by permission of the Geological Association of Canada.
Fig. 9. Seismic stratigraphic units and faults interpreted from CGISS seismic line (Figure 5). Length reference across the profile is the CDP (Common Depth Point) Range, given in meters. LS is land surface (datum) which is relatively flat along the profile. Line is oriented at a high angle to faults and to the direction of sediment influx to the basin. The tops of seismic stratigraphic units 1, 2, and 3 are highlighted. These units are interpreted to be volcanics, prodelta/deep-water lacustrine, and delta-plain sand, respectively; unit 4 is interpreted to be floodplain/deltaic deposits (Barrash and Dougherty, 1995b).

Interpreted to be distributed as separate units surrounded by finer grained sediments within the floodplain environment of the aquifer system. A normal fault parallel to the long axis of the sand stringer offsets the aquifer between the Goddard2 well and the Millstream and Westmoreland wells (Figure 5).

Simulation of Goddard2 Well Pumping Test

Based on the conceptual model presented above, the aquifer tapped by the Goddard2 well has been modeled as a 30 m thick, 9.2 km long sand body whose width is truncated by a fault on the NE side such that the remaining aquifer width is about 400 m. The aquifer is surrounded by fine-grained material that is 114 m thick above and 91 m thick below the sand-stringer aquifer (Figure 10). The Goddard2 well was placed 4 km from the NW end and 5.2 km from the SE end of the aquifer. Hydraulic parameters have been treated as constant within the two hydrologic units (Figure 11). The aquifer is modeled with isotropic hydraulic conductivity of 0.017 cm s\(^{-1}\), and the aquitard was given a 5:1 horizontal-to-vertical anisotropy ratio (Figure 11). The long axis of the aquifer is aligned parallel to the sediment influx direction (axis of the western Snake River Plain), and also is parallel to the fault (fault B in Figure 5) that is modeled as a vertical no-flow boundary fully cutting the flow domain. The fault is located 152 m NE of the Goddard2 well in the model. Outer boundaries of the model domain are placed at great enough distances from the pumping well that they may be treated as no-flow boundaries.

The model domain is discretized into 30 layers with 87 rows (NE-SW) \(\times\) 113 columns (NW-SE). Thicknesses of different layers vary, with finer discretization toward material property boundaries and toward the bottom of the partially penetrating pumping well. The Goddard2 well partially penetrates the 30 m
For a basalt sand indicates minimal drawdown is expected by the end of the test. Test influence at the Settlers well is evaluated indirectly by noting that drawdown is below measurable levels in the aquitard near the location of this well. Additional sand-stringer aquifers were not included in the model presented here, but this is a direction for future efforts as additional information becomes available on specific units locally, or with stochastic modeling of the distribution of sand-stringers regionally (e.g., Fogg, 1989).

**Summary and Conclusions**

Drawdown in a well can be modeled accurately in MODFLOW with a discretization scheme where the X and Y (column and row) dimensions of the cell containing the well are equal to the effective diameter of the well, where the cells adjacent to the well cell along orthogonal grid-axis directions have very small cell widths, and where cell widths increase progressively outward with an expansion factor, \( \alpha \), of 1.2 to 1.5. The validity of this discretization scheme has been demonstrated for axisymmetric and nonaxisymmetric confined aquifer scenarios. By extension MODFLOW can be used to simulate drawdown accurately at a well in a heterogeneous aquifer system because the limitations on accuracy of drawdown simulations at a well in MODFLOW are related to discretization near the well and are not inherent in the model structure.

A conceptual model for the hydrogeologic setting of the Goddard2 well constant-rate pumping test that is consistent with available data is a partially penetrating well in a sand-stringer aquifer (in a floodplain environment) receiving leakage from surrounding fine-grained sediments and truncated by a fault (no-flow boundary). This conceptual model was used to simulate the Goddard2 pumping test with MODFLOW and the discretization scheme described above. Results are not unique but provide a framework for evaluating elements that are significant in local and regional ground-water flow, and provide a conceptual model in the Boise Valley aquifer system to be tested and iteratively improved with new data and with future aquifer testing opportunities in the area.

![Figure 11](image1.png)

Fig. 11. Section through hydrostratigraphic units and the partially penetrating pumping well showing dimensions, hydraulic parameters, and distribution of model layers.

![Figure 12](image2.png)

Fig. 12. Log-log drawdown vs time plot for constant-rate pumping test at the Goddard2 well showing measured and simulated behavior. Note repeated pumping rate adjustments to counter downward drift of pumping rate.
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