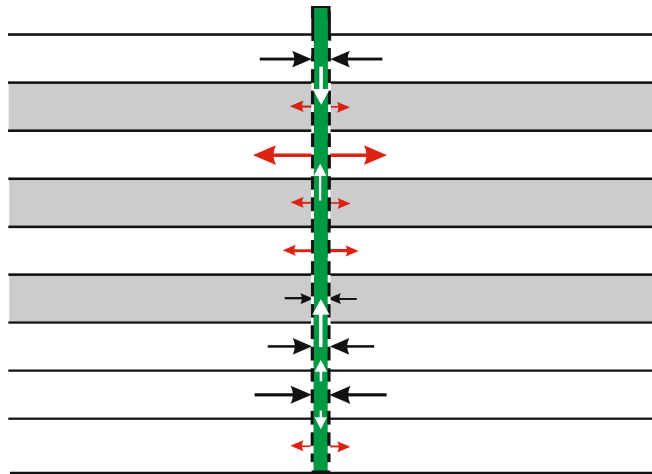


Use of the Multi-Node Well (MNW) Package When Simulating Solute Transport with the MODFLOW Ground-Water Transport Process



Techniques and Methods 6-A15

Cover: Conceptual cross-sectional view of a nonpumping multi-node well showing complex intraborehole flow (see figure 5 and related discussions for more details).



Use of the Multi-Node Well (MNW) Package When Simulating Solute Transport with the MODFLOW Ground-Water Transport Process

By L. F. Konikow and G. Z. Hornberger

Techniques and Methods 6-A15

**U.S. Department of the Interior
U.S. Geological Survey**

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
Area		
square foot (ft ²)	0.09290	square meter (m ²)
Volume		
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Flow rate		
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic foot per day (ft ³ /d)	0.02832	cubic meter per day (m ³ /d)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

PREFACE

This report describes modifications to *MODFLOW-GWT*, a three-dimensional solute-transport model developed by the U.S. Geological Survey (USGS). The modifications improve the capability of *MODFLOW-GWT* to accurately simulate transport in cases that involve fluxes to or from multi-node wells simulated with the MNW package.

The code and documentation for this revised *MODFLOW-GWT* model, including files for the test problem, are available for downloading over the Internet from a USGS software repository. The repository is accessible from a Web site for USGS ground-water models at http://water.usgs.gov/software/ground_water.html. When this code is revised or updated in the future, new versions or releases will be made available for downloading from this site.

Although extensive testing of the modifications of the code indicates that this model will yield reliable calculations for a variety of field problems, the user is cautioned that the accuracy of the model can be affected appreciably for certain combinations of parameter values. Users are encouraged to report any errors in this report or in the code to the contact listed on the appropriate software distribution Web page.

Use of the Multi-Node Well (MNW) Package When Simulating Solute Transport With the MODFLOW Ground-Water Transport Process

By Leonard F. Konikow and George Z. Hornberger

ABSTRACT

This report describes modifications to a U.S. Geological Survey (USGS) three-dimensional solute-transport model (*MODFLOW-GWT*), which is incorporated into the USGS *MODFLOW* ground-water model as the Ground-Water Transport (GWT) Process. The modifications were made to create compatibility between the Multi-Node Well (MNW) Package for *MODFLOW* and the *MODFLOW-GWT* model. This compatibility improves the capability of *MODFLOW-GWT* to represent accurately solute transport in simulations that include multi-node wells because long-screen wells or long open boreholes that extend through multiple model layers can provide fast pathways for solutes to move from one location to another in a ground-water flow system. For nonpumping multi-node wells (used to simulate open boreholes or observation wells, for example), a simple routing and local mixing model was developed to calculate nodal concentrations within the borehole. A depth-averaged concentration is calculated for such nonpumping wells. For pumping multi-node wells (either withdrawal or injection) in which the flow between the well and the ground-water system is in the same direction at all nodes, the average concentration in the well is calculated as a flux-based mean assuming complete and instantaneous mixing in the wellbore of all inflows. For pumping multi-node wells (either withdrawal or injection) in which the flow between the well and the ground-water system is not unidirectional, the concentration distribution within the well is calculated using the same routing and local mixing model used for a nonpumping multi-node well, with the added assumption that the flux pumped in or out of the well is added or removed above the first well node.

INTRODUCTION

The Multi-Node Well (MNW) Package (Halford and Hanson, 2002) allows *MODFLOW-2000* (Harbaugh and others, 2000) to simulate wells that extend beyond a single model node. That is, individual wells are not restricted to a single point in the finite-difference grid, but can now be more realistically associated with a discrete length. This association allows the

simulated well to penetrate more than one model layer or to represent a horizontal well.

The MNW Package allows the user to specify a group of nodes that are associated with a single well. Specified fluxes can be defined for each node, which are then added to obtain a net rate for the well. The net flux can be negative (representing a withdrawal well), positive

(representing an injection well), or zero (representing a nonpumping well or a long-screened observation well). The net flux represents the addition or removal of water from the ground-water system, and corresponds with the flow at the wellhead.

Regardless of the net flux, when a well is linked to multiple nodes of the finite-difference grid, then the flow between the model domain and the well can vary greatly in magnitude (and perhaps in direction) among the various nodes linked to the single well. If head losses inside a well are negligible compared to head losses between the well and the adjacent aquifer, it can then reasonably be assumed that the hydraulic head within the well will equilibrate to a single representative value. Because the heads in the aquifer at various model nodes encompassing a multi-node well will vary depending on local and regional aquifer properties and boundary conditions, a well can have nonuniform borehole flow (or intraborehole flow) that is greater than the net withdrawal or injection specified for the well. This intraborehole flow, in turn, can have a major effect on the water-quality distribution within the aquifer, as noted by Halford and Hanson (2002).

For the case of a nonpumping well, differing aquifer heads at the multiple well nodes will produce intraborehole flow, with

ground water entering the well at one or more nodes and exiting from the well in other nodes (fig. 1). The inflows to the well will equal the outflows because the net flux is zero for a nonpumping well. (Note that in the convention used in figure 1, the subscripts “SNK” and “SRC” are defined and used in relation to the aquifer, so that flow into the well, for example, would correspond with outflow from the aquifer—a fluid sink with respect to the aquifer.) Solute will be transferred by advection through the well from aquifer cells having higher heads to aquifer cells having lower heads at rates proportional to the fluid fluxes. Where water enters the well, it will mix with water in the borehole and the mixture will flow towards well discharge nodes. If water enters at different concentrations at multiple nodes, the concentrations will change from node to node in the borehole at a given time. Solute transfer to the ground-water system at discharging nodes will change concentrations downgradient from a multi-node well.

For multi-node pumping wells, the MNW Package inherently assumes that the pump intake is located above (closer to the land surface) the first node of the multi-node well (R.T. Hanson, U.S. Geological Survey, written commun., 2005). If the withdrawal or injection rate is sufficiently high so that

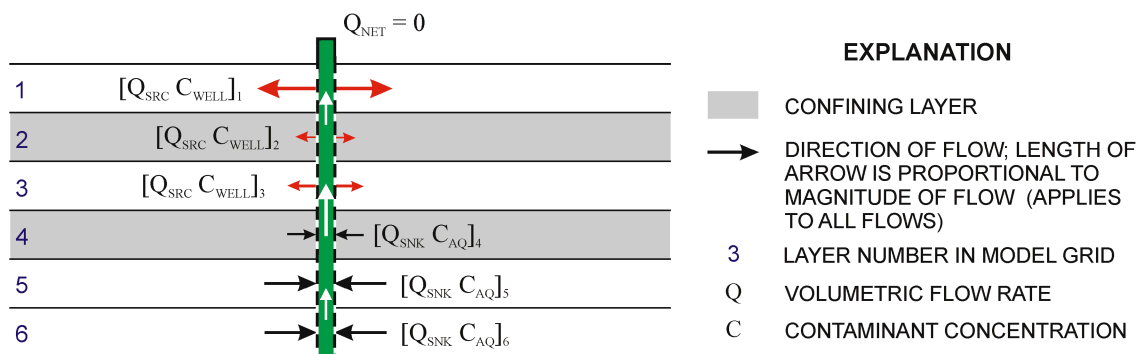


Figure 1. Conceptual cross-sectional view of a nonpumping ($Q_{NET}=0$) vertical well that is connected to multiple layers in the model grid for a case where ground-water head increases with depth and intraborehole flow is consequently upwards.

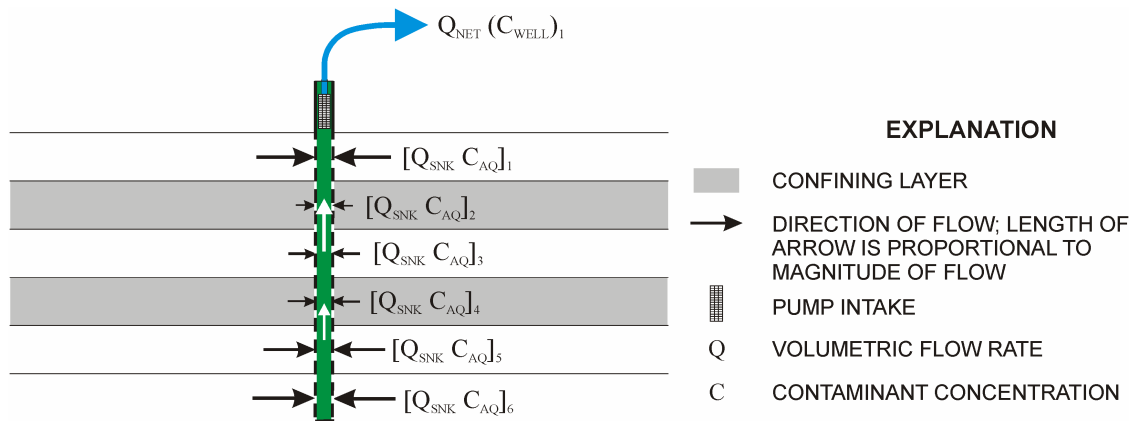


Figure 2. Conceptual cross-sectional view of a multi-node withdrawal well ($Q_{NET} < 0$) in which water enters the well at all well nodes.

the flux between the aquifer and the well is in the same direction at every node of the well (as in figure 2), then intraborehole flow will have no effect on the solute concentration in the wellhead discharge for a withdrawal well or on the solute concentration in the recharge from an injection well. For such a unidirectional borehole-flow case with a multi-node injection well, there should be no concentration change within the borehole and the borehole concentration is always equal to the concentration in the fluid being injected (which must be defined by the user). For such a unidirectional-flow case with a multi-node withdrawal well (fig. 2), any potential concentration difference within the borehole would have no effect on the transport calculations for the ground-water

system or on the concentration distribution in the ground-water system because flow at all nodes is from the aquifer into the well.

It is feasible, however, that if the pumping rate is sufficiently small, that a pumping well can behave similarly to a nonpumping well in that substantial head differences in the ground-water system along the length of the borehole can result in a withdrawal well that has one or more nodes in which water enters the aquifer (fig. 3) or an injection well that has one or more nodes in which water flows into the well from areas of relatively high head in the aquifer (fig. 4). As in the case of a nonpumping well, this nonuniform wellbore flow can also affect the water-quality patterns in the ground-water system.

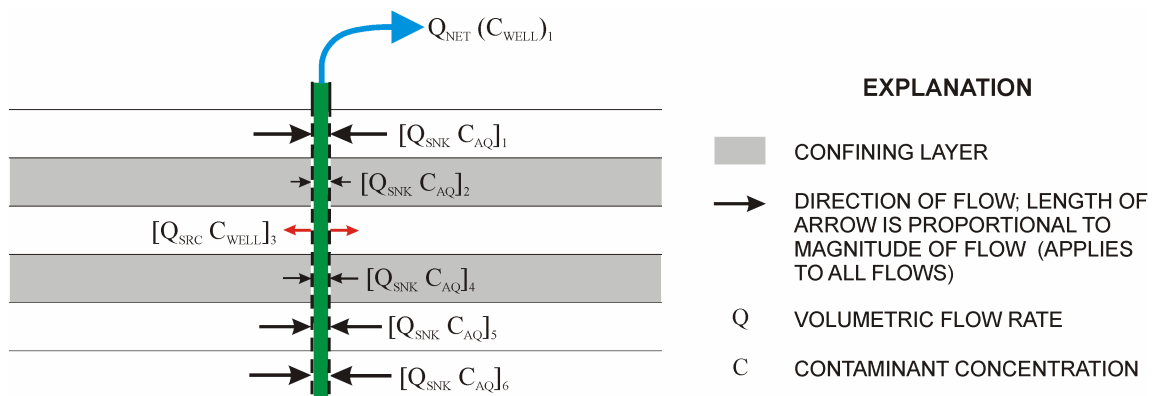


Figure 3. Conceptual cross-sectional view of a multi-node withdrawal well that has complex intraborehole flow.

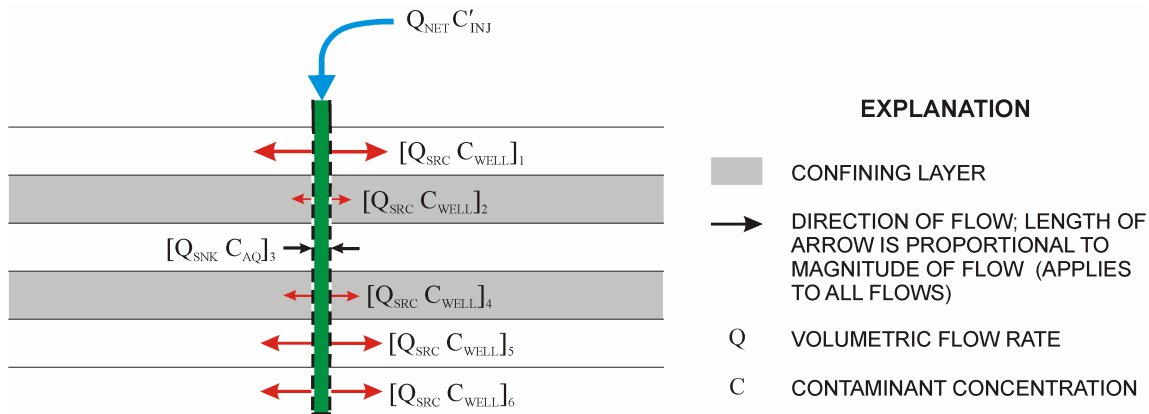


Figure 4. Conceptual cross-sectional view of a multi-node injection well ($Q_{NET}>0$) that has complex intraborehole flow.

The MNW Package of Halford and Hanson (2002) includes a simple approach to estimating water-quality effects with the *MODFLOW* model. This approach requires the user to associate a water-quality (concentration) value with each node. If flow is into a well at that node, it enters at the specified value of concentration (which remains constant over time during a stress period). If inflow occurs from multiple nodes, a flux-based averaging method is used to calculate the concentration in the well. This approach, however, ignores nonuniform initial spatial distributions of solute concentrations in the aquifer and the effects of related transient transport and dispersion processes. Hence, this simple approach has limited applicability.

If a model user is interested in calculating more accurately the effects of a multi-node well on water-quality patterns in a ground-water system or temporal changes in the average concentration in the borehole, then they should simulate solute transport in the aquifer simultaneously with flow simulation. This coupled simulation can be accomplished by activating the Ground-Water Transport Process of *MODFLOW* (the *MODFLOW-GWT* model) (Konikow and others, 1996; Kipp and others, 1998;

Heberton and others, 2000; Konikow and Hornberger, 2003).

The purpose of this report is to document the inclusion of the MNW Package in the *MODFLOW-GWT* model. The report describes how solute concentrations in a multi-node well are calculated. This implementation does not require the creation of an additional input data set for the GWT model, but rather uses input data already required for the MNW Package. This report describes these linkages and the use of the input data for MNW Package as documented by Halford and Hanson (2002). The report also describes a new optional output package (MNWO Package) for concentration values in multi-node wells calculated when the MNW Package is used with *MODFLOW-GWT*.

WELL CONCENTRATIONS AND SOLUTE BUDGETS

High-Rate Pumping Well

If the pumping rate in a multi-node injection well is sufficiently high so that flow leaves the borehole along its entire

open or screened length, then it can be assumed that water within the borehole will become completely mixed at time scales smaller than the length of a typical time increment used to solve the equations of flow and transport in the ground-water system. Because the external fluid is the only source of solute to the borehole, there should be no changes or differences in solute concentration within the borehole and the specified external source concentration (C'_{INJ}) would be the concentration in the fluid recharging the aquifer at all nodes of the well.

If the pumping rate in a withdrawal well is sufficiently high so that flow enters the borehole along its entire open or screened length, and the pump intake is located above the uppermost well node that interacts with the ground-water system (fig. 2), then the solute concentration in the well discharge will be a function of the flux-weighted mean concentration of the inflows at all nodes of the well. This is consistent with an assumption of complete mixing within the borehole, allowing for differences in solute concentration entering the borehole because of variations in solute concentration in the ground-water system from node to node. By assuming (1) complete and instantaneous local mixing in the well, (2) that no reactions affect solute concentration, and (3) that wellbore storage is negligible, the concentration in water discharging from a high-rate multi-node withdrawal well (fig. 2) can be computed using a simple mixing formula that computes a flux-weighted average concentration (similar to eq. 1 of Halford and Hanson, 2002) on the basis of fluid inflows as

$$C_{well}^t = \frac{\sum_{i=1}^n [Q_{snk} C_{aq}^t]_i}{\sum_{i=1}^n [Q_{snk}]_i}, \quad (1)$$

where Q_{snk} is the volumetric flow rate (in units of cubic length over time) at a node (or finite-difference cell) from the aquifer into the well (negative in sign according to *MODFLOW* convention because it represents a withdrawal from the aquifer), C_{aq} is the concentration in the aquifer cell at the start of the time increment, n is the number of nodes in a well, i is an index for the number of individual withdrawal nodes connected to a multi-node well, the subscript snk is a directional indicator of flow relative to the aquifer, and the superscript t represents the present time increment. The concentration in any flow out of the well (C_{well}) during time increment t by withdrawal to the land surface is equal to the mixed concentration in the well during that time increment.

In multi-node wells simulated with the MNW Package, withdrawal from a well can be limited by drawdown constraints specified by the user. For example, in a withdrawal well this would be important if drawdown in the well causes the water level to fall below the level of the pump intake. In such cases, the withdrawal rate specified by the user will be overridden by a reduced value calculated on the basis of the constraints. Thus, the net withdrawal from the well (Q_{net}), defined as $Q_{net} = Q_{src} - |Q_{snk}|$ over all nodes in a multi-node well (where Q_{src} is the volumetric flow rate at a node from the well into the aquifer) may be less than the withdrawal specified by the user in the input data file (which is defined in the MNW input instructions as “the *desired* volumetric pumping [withdrawal] or recharge [injection] rate,” or Q_{des}). Q_{net} is calculated as the sum of all fluxes between aquifer nodes and the multi-node well. Similarly, the user-specified injection rates will be reduced if injection head exceeds a specified limit. The MNW Package partitions Q_{net} among the various nodes

connected to a multi-node pumping well on the basis of relative heads and hydraulic conductances.

Nonpumping Well

Flow will occur within the borehole of a nonpumping multi-node well ($Q_{net} = 0$) if aquifer heads differ between nodes because long well screens are equivalent to a high hydraulic conductivity inclusion. Internal flow in observation wells, abandoned open boreholes, or unpumped horizontal wells could be simulated with this approach (fig. 1). This intraborehole flow can also transport dissolved chemical constituents and affect the solute concentrations in the ground-water system. In a nonpumping borehole with intraborehole flow, it is observed that water-quality differences can be present within the borehole (Church and Granato, 1996, and Paillet and others, 2002). Such water-quality differences may occur in a nonpumping well because the intraborehole flow likely represents a slow laminar flow regime, and, therefore, it cannot be assumed that complete mixing occurs within the fluid volume contained in the borehole (as assumed for a high-rate pumping well). Rather, it may be more reasonable to assume that fluid entering the borehole at one location only mixes with the borehole fluid at that location, and the blended water then slowly displaces the fluid in the direction of the intraborehole flow. For example, in figure 1, the concentration in the well in layer 6 would be equal to the concentration in the aquifer in layer 6. The fluid and solute in the well in layer 6 then flows upwards to layer 5, where it mixes with more ground water entering the well at a possibly different concentration. Similar flow and mixing occurs in layer 4. However, because there is only outflow from the well above layer 4, the concentration in the well in layers 1, 2, and

3 will equal the concentration leaving layer 4 by upward flow. Therefore, for cases of nonpumping multi-node wells, solute concentration in water in the well is allowed to vary from node to node, and the nodal concentrations within a nonpumping multi-node well will be calculated using a simple routing and local mixing model (similar to that used in the Streamflow-Routing (SFR1) Package of Prudic and others, 2004).

Head variations along the length of a borehole can be complex and may be more complicated in a multi-aquifer system, where intraborehole flow can change direction—perhaps multiple times (fig. 5). In this example, the node in layer 8 is considered a “strong source” with respect to the borehole (it is a “sink” for the aquifer) because the direction of intraborehole flow is away from this node towards both the upper and lower adjacent nodes. The concentration at this well node can be set equal to the concentration in the adjacent model layer 8 node because that is the only source of inflow to this node of the multi-node well. The node in layer 3 is considered a “strong sink” for the borehole because the direction of intraborehole flow is into this node from both adjacent nodes. The concentration at this node cannot be calculated until after the concentrations in both adjacent nodes are defined by the routing algorithm.

The routing algorithm is always implemented after the flow equation is solved. Because complex intraborehole flow includes a fluid source term for the ground-water system, the concentration associated with that fluid source must be defined before the solute-transport equation for the ground-water system can be solved for that time increment. Therefore, the routing algorithm is implemented before the transport equation is solved, and it uses aquifer concentrations from the end of the previous time increment (or from the

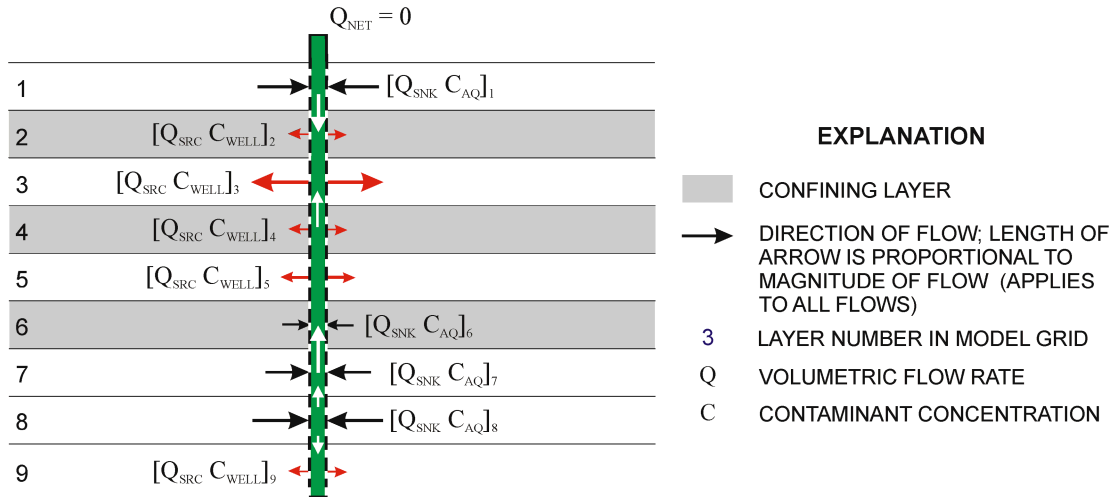


Figure 5. Conceptual cross-sectional view of a nonpumping multi-node well that has complex intraborehole flow.

specified initial concentrations for the first time increment). This solution is analogous to the method used for computation of solute concentration in a lake with the LAK3 Package (see eq. 17, Merritt and Konikow, 2000).

The first step in the routing algorithm is to compute the flow directions within the borehole on the basis of known fluxes between the aquifer and the well at all nodes of the multi-node well. All nodes in a nonpumping multi-node well are scanned and fluxes between nodes are tallied. Next, end nodes (the first and last nodes of the multi-node well) are checked to see if the direction of flow is into the well from the aquifer; if it is, the concentration at the well is set equal to the concentration in the aquifer at that node. Otherwise, if there is flow from the well into the aquifer, the concentration at the well will be set equal to the concentration in the adjacent well node, which by necessity is the only possible source of water to the end node in the well, after that concentration is defined. After the end nodes are checked, the concentration at well nodes representing “strong sources” to the well (sinks to the aquifer) are defined.

From the concentrations initially defined at end nodes and at strong sources, the solute fluxes can be routed to adjacent nodes and the concentration in those adjacent nodes defined on the basis of a simple mixing formula as

$$C_i^t = \frac{Q_{i-1} C_{i-1}^t - [Q_{snk} C_{aq}^{t-1}]_i}{Q_{i-1} - [Q_{snk}]_i}, \quad (2)$$

where C_i is the concentration at well node i (corresponding to layer i in the example vertical well shown in figure 5, but this one-to-one correspondence between layer number and well node number is not a requirement), Q_{i-1} is the intraborehole flow between well node $i-1$ and node i (positive for flow towards higher values of i), $[Q_{snk} C_{aq}]_i$ is the solute mass inflow from node i in the aquifer, and the superscript $t-1$ represents the previous time increment. The bracketed terms on the right side of eq. 2 are subtracted because the sign convention for the flow term is that Q_{snk} is negative for inflow to the well (discharge from the ground-water system). This node-to-node routing process is repeated until no additional nodes can have their

concentrations defined this way. Then nodes that are strong sinks for the wellbore (flow into the node from both directions) are checked, and if not already defined by the routing from strong sources, their nodal concentrations are defined next.

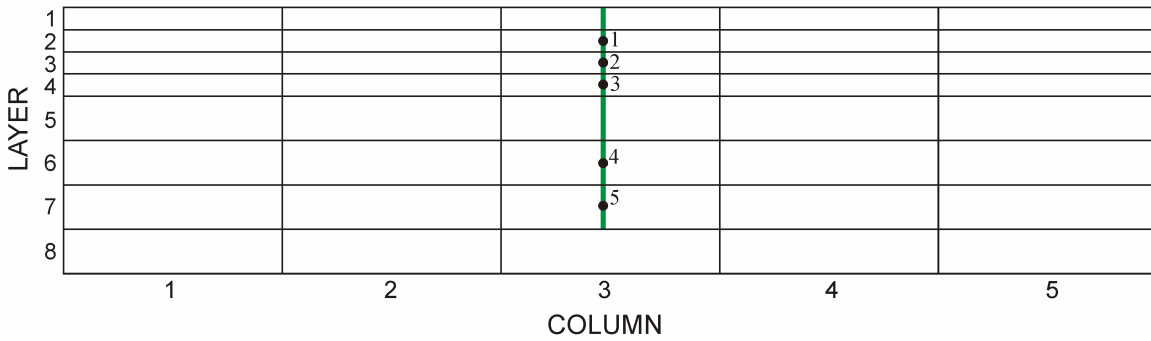
Although not illustrated, it would also be possible that the head in the aquifer adjacent to several nodes of a multi-node well would be exactly identical. For such a condition, we would expect that there would be no intraborehole flow over that segment of the multi-node well. However, at the location of such well nodes, there could still be a lateral flow in that model layer because of a regional hydraulic gradient within the aquifer. For any node of a multi-node well for which there is no flow to or from both adjacent well nodes, it is assumed that there is no intraborehole mixing with fluid in adjacent nodes of the well and that the concentration at such a node in the well is equal to the concentration in the aquifer adjacent to this node. Thus, as a final step in the routing process to calculate the solute concentration distribution in a nonpumping multi-node well, a check is made for nodes in which there is no intraborehole flow entering or leaving that segment of the multi-node well; if such a condition is found, the concentration in the well at that node is then set equal to the concentration in the aquifer at that location.

After the concentration has been defined at all nodes of a multi-node well, the average concentration in the well can be defined. However, because there is not complete mixing in a nonpumping well, the average concentration must be defined on a basis other than flux-weighted mixing. For a nonpumping multi-node well, the average concentration can be defined as a concentration that would be measured in a volume of water collected using a sampling device that continuously obtains and integrates discrete samples at every location

as it is lowered (or raised) through the entire length of the borehole at a constant rate. This would represent a depth-averaged concentration in a vertical well (or length-averaged concentration in a nonvertical well). This average concentration is not used in any calculations, but is reported for information purposes in the output files for the Multi-Node Well Observation Package described below.

The method used to calculate the total length of the well and the length of the segment of the well associated with each node (and each nodal concentration) is illustrated by examples in figures 6 and 7. The method can account for a well that has multiple discrete sections of well screen. The following working assumptions are made:

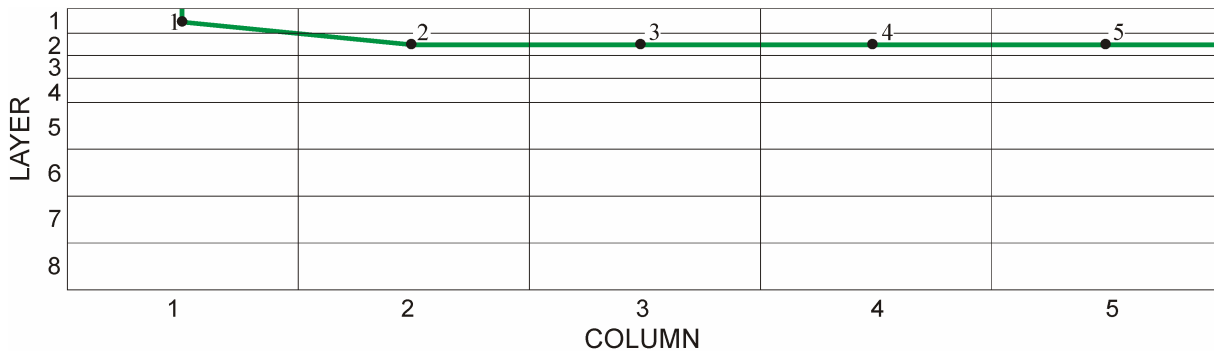
- A well is assumed to fully penetrate each cell in which a well node is located.
- Where a multi-node well is open to the aquifer, the open interval of the well is assumed to pass through the block-centered node in the finite-difference cell.
- The length between two successive nodes is defined as the distance between those two nodes. Half the length of an internodal section is assigned to each node. Thus, if two nodes are not adjacent to each other (such as well nodes 3 and 4 in fig. 6), it is possible that the length of well associated with a node can be longer than the maximum cell dimension. Proper calculation of lengths, therefore, requires that nodes for each multi-node well be listed in sequential order in the input data file.
- For the first node, the length of the water column in the well is assumed to extend from the location of the block-centered node vertically



EXPLANATION

- | MULTI-NODE WELL
- ³ GRID NODE CONNECTED TO MULTI-NODE WELL, AND SEQUENTIAL WELL-NODE NUMBER

Figure 6. Schematic cross-sectional view through a *MODFLOW* grid showing a vertical nonpumping multi-node well open to two discrete intervals in layers 2-4 and 6-7. The borehole is assumed to extend to the top of the model grid to compute total borehole length.



EXPLANATION

- MULTI-NODE WELL
- ³ GRID NODE CONNECTED TO MULTI-NODE WELL, AND SEQUENTIAL WELL-NODE NUMBER

Figure 7. Schematic cross-sectional view through a *MODFLOW* grid showing a mostly horizontal nonpumping multi-node well open to columns 2-5 in layer 2 and column 1 in layer 1. The borehole is assumed to extend vertically from the first node to the top of the model to compute total borehole length.

upward to either the top of the uppermost active grid layer or to the elevation of the head in the first node of the well, whichever is lower (see node 1 in figures 6 and 7). Because of this assumption, it is important that when defining the sequence of nodes in a nonpumping multi-node well, that the user assure that the first

node in the sequence represents the well node located closest to the wellhead. In figure 6, the length of well associated with node 1 would be equal to the sum of the thicknesses of the top two layers.

- The segment length associated with the final end node is assumed to

equal half the internodal length to the previous well node, whether adjacent or not, plus the distance from the end node to the terminating cell wall at the intersection with the extended line of the final internodal segment. This is calculated as the distance from the intersection of this line with one of the cell faces to the node center. For the relatively simple case illustrated in Figure 6, the length of the final (5th) segment would be equal to the thickness of layer 7, and for the example in Figure 7, it would equal the width of column 5.

After all the lengths are calculated, they are used as weights in computing the average concentration in the well, as in the following equation

$$\bar{C} = \frac{\sum_{i=1}^n (L_i C_i)}{\sum_{i=1}^n (L_i)} , \quad (3)$$

where \bar{C} is the length-averaged concentration in the well and L_i is the length of the i^{th} segment of the well.

Low-Rate Pumping Well

If the pumping rate is viewed as transitional between zero and some arbitrarily high rate, the intraborehole flow pattern can then be viewed as representing a continuum between a complex multidirectional intraborehole flow pattern possible with a nonpumping multi-node well (fig. 5) and a simple unidirectional flow pattern for a high-rate pumping well (fig. 2). Increasing the pumping rate causes the flow pattern to shift towards a simple unidirectional mode. However, at sufficiently low pumping rates, the flow pattern may still be as complex as for a nonpumping case. If the withdrawal (or

injection) rate specified for a pumping well is insufficient to induce unidirectional flow between all well nodes and the corresponding aquifer cells, the resulting complex intraborehole flow pattern can generate a nonuniform distribution of solute concentrations in the borehole, similar to that in a nonpumping multi-node well. For example, Izbicki and others (2005) collected depth-dependent water-quality samples in a well under pumping conditions and demonstrated large changes in chloride concentration with depth. Therefore, the assumption of complete mixing in a pumped borehole may not be valid, and water entering the ground-water system from a node in a withdrawal well (such as layer 3 in figure 3), for example, may not have the same solute concentration as water discharging through a pump at the wellhead. Similarly, water entering the ground-water system from one node in a multi-node injection well may not have the same solute concentration as water entering the ground-water system from another node (see figure 4).

The model will automatically detect if a pumping multi-node well has a complex multidirectional flow pattern between the borehole and the ground-water system. If it does, the model will calculate the concentration distribution in the wellbore using the same routing routine described above for nonpumping wells. This will assure that water leaving the well, whether to the ground-water system or to the land surface, will have a concentration consistent with a local (single node) mixing assumption rather than a less rigorous assumption of total instantaneous mixing within the entire borehole. To calculate the solute distribution within the borehole using the routing routine, the additional flux between the well and the land surface (Q_{net}) is assigned to the upper bound of the first well node (consistent with the MNW

Package assumption that a pump is always located above the screened or open interval of the well). In effect, the pump can be considered to represent node “zero” in the string of well nodes.

The concentration everywhere in the borehole of a multi-node injection well will not necessarily equal the concentration of the external source fluid (C'_{INJ}), which is specified by the user, if aquifer water enters an injection well at one or more well nodes even while external water is injected (fig. 4). Because the concentration at any node where water enters the well is known from the solution to the transport equation at the end of the previous time increment, the concentration distribution in a multi-node injection well (and in the outflow from the well, where present) can be computed directly from eq. 2 and the associated routing routine described above. The only addition to the routing routine in the case of a low-rate injection well is to treat the injection from the external source (at a known flow rate and concentration) as derived from an additional node (node zero) above the first well node, which can only enter the first node of the well and is routed down from there with flow and concentration adjusted as appropriate according to eq. 2.

Flowing Well

A flowing artesian well can be simulated with the MNW Package. An artificially high discharge rate, Q_{des} , and a minimum head equal to the wellhead elevation are specified. The desired discharge cannot be maintained and discharge is calculated with a specified-head condition instead (K.J. Halford, U.S. Geological Survey, written commun., 2005). Although there may be no pump in a flowing artesian well, the hydraulic interaction with the ground-water system is

the same as if the well were pumped at the calculated discharge rate. Therefore, solute transport in a flowing artesian well is simulated the same as in a pumping well, and solute routing in the borehole will be applied if the flow between the well and the ground-water system is not in the same direction at all nodes.

Solute Budget Calculations

The solute mass balance computed by *MODFLOW-GWT* includes an itemization of all budget items that represent mass entering or leaving the transport model domain. Solute mass entering or leaving the transport model domain through all multi-node wells is itemized separately. Fluid and solute in the borehole of a multi-node well is considered to be external to the model domain for this calculation. Thus, the solute flux (or loading) into or out of the model domain through multi-node pumping wells is not included directly in the overall solute mass balance computed and printed by *MODFLOW-GWT*. The mass balance for the transport model is instead computed on the basis of summations of individual fluxes at all nodes of all multi-node wells. This mass-balance computation is consistent with the way in which fluid mass balances and budgets are computed in *MODFLOW* for multi-node wells with the MNW Package. The solute flux (both for a time increment and cumulative) into or out of the model domain through multi-node pumping wells is, however, calculated and made available for inspection in optional separate output files that record data for each well (see MNW Package below).

The solute mass removed from the transport domain in a multi-node well is based on the computed nodal values of Q_{snk} times the appropriate aquifer concentration (C_{aq}^*) summed over all nodes as

$$M_{out} = \sum_{i=1}^n [Q_{snk} C_{aq}^*]_i \Delta t, \quad (4)$$

where M_{out} is the solute mass discharged from the aquifer into the well during a transport time increment, n is an index of the number of nodes in the multi-node well, and Δt is the length of the time increment. The time level for the appropriate aquifer concentration in eq. 4 depends on whether the concentration at the sink node of the multi-node well was computed using eq. 1 (for a high-rate pumping well) or eq. 2 (for a nonpumping or low-rate pumping well). In the former case, $[C_{aq}^*]_i = [C_{aq}^t + C_{aq}^{t-1}]_i / 2$, whereas in the latter case $[C_{aq}^*]_i = [C_{aq}^{t-1}]_i$.

The use of an averaged concentration for the former case is the same approach used for a fluid sink, such as a simple single-node well in the WEL Package of *MODFLOW* (see Konikow and others, 1996, p. 25).

The solute mass added to the transport domain from a multi-node well is calculated as a summation over all nodes as

$$M_{in} = \sum_{i=1}^n [Q_{src} C_{well}^t]_i \Delta t, \quad (5)$$

where M_{in} is the solute mass entering the aquifer by flow out of the well during a transport time increment and $[C_{well}]_i$ is the concentration in the well at the i^{th} well node, where fluid is entering the aquifer from the well. The values of Q_{net} , Q_{snk} , and Q_{src} are updated for each time step used in solving the flow equation, and values of C_{well} , C_{aq} , M_{out} , and M_{in} are updated for each time increment used to solve the solute-transport equation (it is possible that more than one time increment would be used to solve the transport equation for each time step used to solve the flow equation). The value of $[C_{well}]_i$ would equal C'_{INJ} for a high-rate injection well and would be computed by

routing for a nonpumping or low-rate pumping well.

Identifying Q_{net} is important for the solute-budget considerations because the sum of all nodal flows into or out of one multi-node well (Q_{snk} or Q_{src}) does not necessarily represent the fluid flux out of or into the ground-water system, respectively. This result occurs because in the low-rate case, some of the flux between the well and the model domain can represent internal flow through the well between different layers or cells of the model rather than flow between the model domain and an external fluid source or sink. Therefore, although the nodal values of Q_{snk} and Q_{src} are used in calculating the solute budgets for multi-node wells within the transport model domain, the solute added or removed from the ground-water system must be calculated on the basis of Q_{net} and the appropriate concentration. For a multi-node withdrawal well the appropriate concentration is C_{well} , and for a multi-node injection well the appropriate concentration is C'_{INJ} (fig. 4), a value specified by the user in the input data set.

The model computes the solute mass removed from the transport domain in a multi-node withdrawal well on the basis of the computed value of Q_{net} as

$$M_{netout} = Q_{net} \Delta t [C_{well}^t]_1, \quad (6)$$

where M_{netout} is the solute mass removed from the ground-water system with the well discharge. Because the pump is always assumed to be located above the first node of the well, the concentration in the well discharge at the wellhead will always be equal to the concentration at the first well node, which will have the same value whether it's computed by routing and local mixing or by assuming complete mixing within the borehole. These calculations are

accumulated over time and written as supplemental information with the solute budget, but are not included directly in the calculation of residuals.

The solute mass added to the transport domain from a multi-node injection well is calculated from Q_{net} as

$$M_{netin} = Q_{net} \Delta t C'_{INJ}, \quad (7)$$

where M_{netin} is the solute mass injected into the aquifer from the well during a time increment. As is done for the net mass discharged from multi-node wells, the values of net mass injected are accumulated over time and written as supplemental information with the solute budget, but are not included directly in the calculation of residuals.

Accurate calculations of solute flux and changes in concentration related to intraborehole flow in multi-node wells require that the fluid fluxes be accurately computed by the MNW Package. The FORTRAN code developed and originally released with the documentation of the MNW Package is written using single-precision variables. This may not yield sufficient numerical precision in some cases. For example, a test case for a nonpumping multi-node well in a regional flow field yielded a sum of inflows equal to 5.4079 m³/s, and a sum of outflows equal to 5.3962 m³/s, an imbalance (and error) of about 0.2 percent. This imbalance in fluid flux would then cause an error in the solute-transport model. Therefore, the MNW code was modified by changing all variables used in calculating the flux into or out of multi-node wells to double-precision variables. After this modification, the same test case was run again, and both sums were then calculated to equal exactly 5.4005 m³/s. Thus, the double-precision version of the MNW Package is incorporated into *MODFLOW* (Version 1.15.01) and into *MODFLOW-GWT*.

INPUT DATA CONSIDERATIONS

The use of the MNW Package for flow does not require the use of a separate GWT Package or the use of an additional input data set for transport. Instead, GWT uses standard MNW Package input data.

Data for each node of a multi-node well are read in a list that associates a number of variables with each of the nodes, including the specified volumetric flow rate (Q_{des}) and a water-quality value ($QWval$) (see Halford and Hanson, 2002, p. 14). If a well is associated with multiple nodes, it is conceptually simplest if the user specifies a flow for only the first of the multiple nodes and zero flow for the other nodes linked with this individual well. This nonzero nodal value is then assumed to apply to the multi-node well as a whole. This input style is strongly recommended for clarity and understanding of model input. However, the MNW Package allows the user to list a nonzero value for Q_{des} for as many nodes of a multi-node well as desired—there are no formal restrictions. In such an instance, the desired volumetric flow rate for the well ($[Q_{des}]_{well}$) is then recomputed as the summation of all the individual values for all nodes associated with the well as

$$[Q_{des}]_{well} = \sum_{i=1}^n [Q_{des}]_i, \quad (9)$$

where $[Q_{des}]_i$ are the specified volumetric flow rates for individual nodes composing a multi-well node. If $[Q_{des}]_{well} < 0.0$, the well is a withdrawal well. If $[Q_{des}]_{well} > 0.0$, the well is an injection well. If $[Q_{des}]_{well} = 0.0$, even though individual nodes might have nonzero values of Q_{des} associated with them, the well is considered to be a non-pumping well.

In the list of nodes defining the multi-node well, nodes may be listed in any

order—it doesn't make any difference with respect to flow calculations. However, as noted above, when calculating solute concentrations in a nonpumping multi-node well, defining the order of nodes is critical, and the data list must be constructed and ordered so that the first node listed represents the node closest to the wellhead (node 1 in figures 5 and 6), the last node listed represents the node furthest from the wellhead (node 5 in figures 5 and 6), and all nodes be listed in sequential order from the top to the bottom of the well (corresponding to the order of first to last well nodes).

The numerical solution of the solute-transport equation requires that whenever and wherever fluid enters the model domain, that a source concentration be specified for that fluid. Therefore, for a multi-node injection well, the user must specify what the solute concentration is in the source fluid. If an injection rate for a well is associated with the first node of a multi-well injection well, which is the proper procedure, then the source concentration should be specified for that node. However, if flows and source concentrations are defined for multiple nodes, and if that multi-node well is defined as an injection well by eq. 9, then the source concentration for the injected fluid (C'_{INJ}) will be assumed to be equal to the value of $QWval$ associated with the first node in a particular multi-node well; all other values of $QWval$ in the list will be ignored in a solute-transport simulation.

The input instructions for the MNW Package require that a value for $QWval$ be specified for every node of a multi-node well, regardless of the value of the volumetric flow rate ($Qdes$). When the GWT Process is active, however, the solution to the solute-transport equation will yield values of concentration to be associated with nodes in which the volumetric flow rate to a well is less than or equal to zero. Thus, all values of $QWval$ for

nodes where $Qdes \leq 0$ are read by the code but ignored in its internal computations. The user must include values for this variable even when it will not be used by the model. Users should specify $QWval = 0.0$ for these nodes.

The *MODFLOW-GWT* model allows the user to solve the transport equation over a subset of the primary grid used to solve the flow equation—this subdomain is called a transport subgrid. For specifying the locations of nodes in a multi-node well, GWT requires that a multi-node well be either entirely outside of the transport subgrid or entirely within the transport subgrid. If the model detects that a multi-node well includes some nodes inside the transport subgrid and some nodes outside the transport subgrid, a warning message will be printed and execution of the code will stop.

MULTI-NODE WELL OBSERVATION PACKAGE (MNWO)

The calculated concentration (and optional additional information) for each multi-node well located within the transport subgrid can be recorded at every time increment. The specific nature of the recorded and written calculated concentration in the well will depend on the flow. For withdrawal wells ($Q_{net} < 0$), the MNWO Package will record the calculated concentration in the well discharge. For injection wells ($Q_{net} > 0$), the MNWO Package will record the flux-weighted average concentration in the borehole; for a high-rate injection well, this would be equal to the user-specified source concentration (C'_{INJ}). For nonpumping wells and low-rate injection wells, the MNWO Package will record the length-weighted average concentration in the borehole. At

each multi-node well designated for observation, the time and concentration in the well after each transport time increment will be written to a separate output file (or files) to facilitate graphical postprocessing of the calculated data. The input file for specifying multi-node wells for observation is read if the file type (Ftype) “MNWO” is included in the *GWT* name file.

Multi-node wells can be designated for recording observed concentrations (and other data) through use of the site identification label (or name). The “MNWsite” parameter is an optional label that can be specified in the input data set for the MNW Package (see Halford and Hanson, 2002, p. 15). The MNWO Package, however, will only work for multi-node wells that have had a unique site label specified in the MNW input data.

Although it is expected that a multi-node well will include more than one node

in the grid, it is possible and allowable for a single-node well to be included in the list of multi-node wells read by the MNW Package. If a single-node injection well is specified for observation in this Package, it will simply record the user-specified source-fluid concentration, which is constant during a stress period. It will not record the concentration in the aquifer; if those are desired, concentrations calculated at specific nodes in the grid can be retrieved using the standard Observation Well (OBS) Package available for the *MODFLOW-GWT* model. Similarly, if a single-node withdrawal well is specified for observation in this package, it will record the values of aquifer concentration at the node corresponding to the location of this well (in this case, an identical record would be obtained using the OBS Package [see Konikow and others, 1996, p. 77]).

FOR EACH SIMULATION, IF *MNWO* PACKAGE USED:

1. Data: MNWOBS

MNWOBS Number of multi-node wells for which concentrations in wells are to be saved.

FOR EACH MULTI-NODE WELL TO BE MONITORED:

2. Data: MNWsite UNIT MNWoflag

MNWsite Name of multi-node well, as identified by using “**SITE:**” option in input data set for MNW Package (see Halford and Hanson, 2002, p. 15).

UNIT Unit number for output file.

MNWoflag A flag to indicate what information for this particular multi-node well is written to its output file. If *MNWoflag* = 0, time and concentration in the well are saved and written to a separate output file. If *MNWoflag* = 1, additional columns of information about mass flux will be printed. If the well was specified as a nonpumping well ($Q_{net} = 0.0$), intraborehole mass flux through this well during each time increment and cumulative intraborehole mass flux through this well will be written in columns 3 and 4. Otherwise, for pumping wells, the mass flux removed from (or injected into) the ground-water system for the time increment (as calculated using eq. 6 or eq. 7, as appropriate) and cumulatively will be written in columns 3 and 4, respectively. Additionally, the mass flux into the well from the ground-water system during the time increment (from eq.

4), the cumulative mass flux into the well, the mass flux out of the well and into the ground-water system during the time increment (from eq. 5), and the cumulative mass flux out of the well will be written in columns 5 through 8. If `MNWOf1ag = 2`, time and concentration in the well and additional data on the calculated concentration at every well node are saved and written to a separate output file (but no data on mass flux is recorded). If `MNWOf1ag = 3`, all data (time, concentration in the well, mass flux information, and concentration at individual nodes) are saved and written to the output file.

Notes:

`MNWsite` is a text string limited to 11 alphanumeric characters. A unique unit number must be specified for each observation well in Record 2 and matched to a DATA file type and file name in the *GWT* name file.

OTHER OUTPUT CONSIDERATIONS

The MNW Package normally prints information about the multi-node wells to the main *MODFLOW* listing file. This information is printed by the program after the solution to the flow equation for a given time step is achieved; in the output file, the information is written prior to (and located above) the calculated budget information for that time step. When GWT is active, however, these output actions are normally taken prior to solving the transport equation for that same time step. Consequently, the standard approach in the MNW Package to write relevant output information would not have access to data on calculated concentrations for that time step. Therefore, for cases in which the MNW Package is used in a transport simulation, the printing of the MNW information has been delayed until after the transport equation has been solved. The only effect this delay has on the main *MODFLOW* output file (or listing file) is to place the MNW information below the flow budget information (instead of above it). Water-quality information included in this output will then include concentration values calculated by the transport model.

Similarly to that described above, water-quality information included in other optional MNW output files will be based on updated concentration values calculated by GWT. The “BYNODE” file will include the concentration value in the well at every node of each multi-node well (as opposed to the concentration in the aquifer at the node). In the case of pumping multi-node wells, where complete mixing is assumed, the concentration will be the same at all nodes in a particular well. In the case of nonpumping multi-node wells, however, the concentration can vary between nodes in a single well. The “QSUM” output file includes summary information about each multi-node well (rather than for each node of a multi-node well). For this file, the output has been modified so that the written water-quality values will represent the average concentration in the well. A flux-weighted average is reported for pumping wells, which is consistent with the complete mixing model. A depth-weighted average concentration is reported for nonpumping wells. The “WEL1” output file has not been modified to recognize concentration values calculated by GWT.

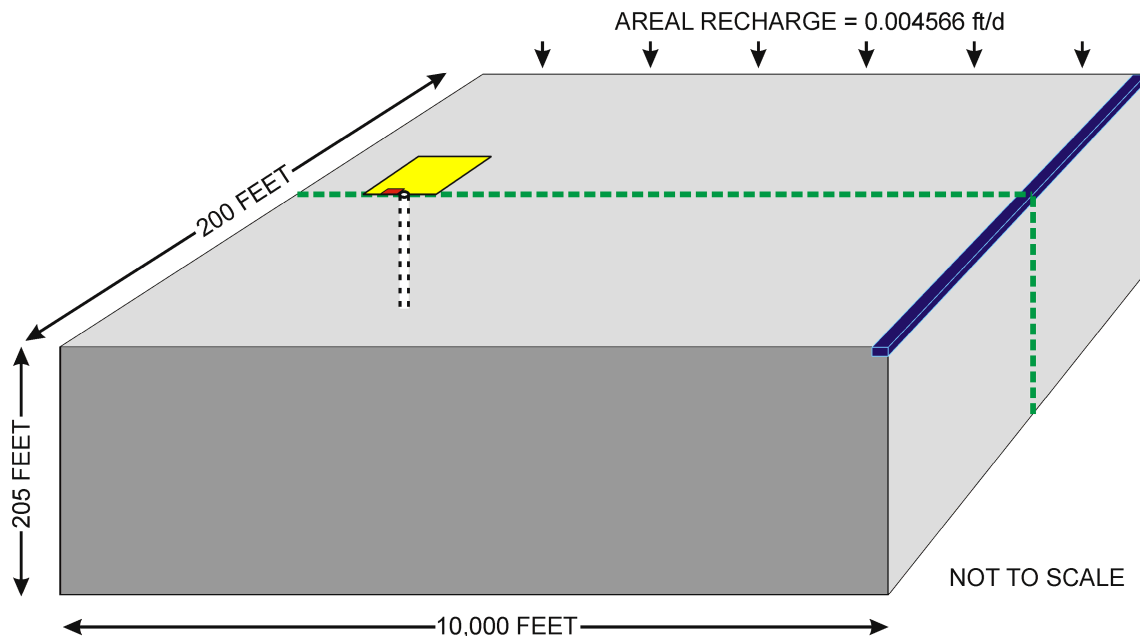
TEST PROBLEM

Problem Description

A test problem was developed to evaluate the model and to demonstrate its value. This problem is a slightly modified version of the one documented by Reilly and others (1989). Their numerical experiments demonstrated that appreciable wellbore flow can occur in observation wells screened through multiple layers, even in homogeneous aquifers having small vertical head differences (less than 0.01 ft between the top and bottom of the screen).

The hypothetical unconfined ground-water system represents regional flow that is predominantly lateral, but includes some vertical components because of diffuse areal

recharge (at a rate of 0.004566 ft/d) and a constant-head boundary condition at the surface of the right side of the regional ground-water system that controls discharge (fig. 8). No-flow boundaries are on all other external boundaries. The system is substantially longer (10,000 ft) than it is thick (205 ft) or wide (200 ft); the width was selected to eliminate any important effect of the position of that lateral no-flow boundary on the solution in the area of the well. A nonpumping borehole with a 60-ft screen is located close to the left side of the system (about 252 ft from that boundary). Other properties of the system and the model are



EXPLANATION






-  AREA OF TRANSPORT SUBGRID
-  INITIAL LOCATION OF CONTAMINANT
-  PLANE OF SYMMETRY
-  MULTI-NODE WELL
-  CONSTANT-HEAD OUTFLOW BOUNDARY

Figure 8. Conceptual diagram showing geometry and boundaries for three-dimensional test problem with a nonpumping multi-node well.

listed in table 1. Reilly and others (1989) simulated the regional system with a two-dimensional cross-sectional model, arguing that the width of the cross section was irrelevant for their analysis, and applied a local (approximately a 100-ft by 100-ft area) three-dimensional flow model in the vicinity of the wellbore. Their local model was discretized vertically into 5-ft layers and used a variably spaced areal grid with a minimum spacing of about 0.33 ft by 0.33 ft around the borehole, and they represented the borehole using a relatively high vertical hydraulic conductivity (as compared to the aquifer), the value of which was based on equivalence of Darcy's law to the equation for laminar pipe flow (Reilly and others, 1989, p. 272).

The approach used here was to simulate the regional flow system with a three-dimensional model for a width sufficient to minimize any effects of that dimension on the flow field close to the

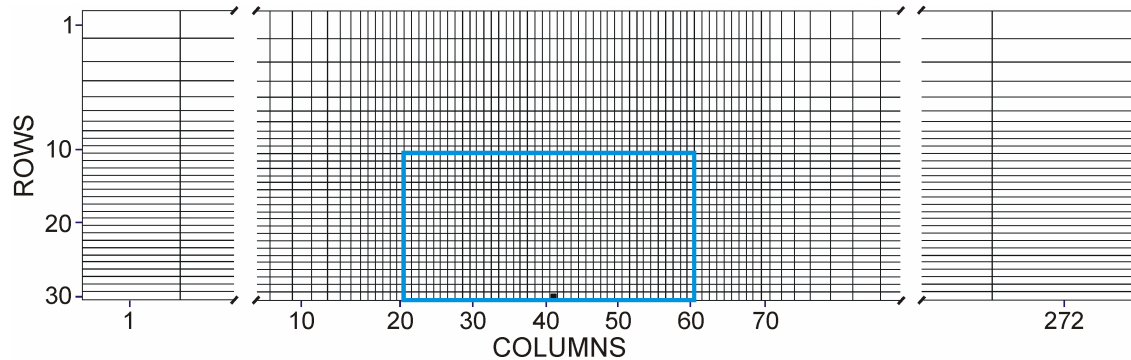
borehole. Because a vertical plane of symmetry is present, and passes through the well, only one-half of the domain outlined by Reilly and others (1989) was simulated here (with model dimensions being 10,000 ft long by 100 ft wide by 205 ft deep). The solute-transport model was applied to a local area around the well using a transport subgrid. Within the transport subgrid, which included 20 rows, 40 columns, and 41 layers of cells, a uniform areal cell spacing of 2.5 ft was used. Outside of the uniformly spaced subgrid, the lateral grid spacing was increased geometrically to a maximum spacing of 50.25 ft in the row (*x*-) direction and 9.55 ft in the column (*y*-) direction (see fig. 9). The vertical discretization (Δz) was 5 ft everywhere in the model domain.

The well was assumed to have a 60-ft well screen and was open to layers 2 through 13 (that is, connected to 12 vertically aligned nodes of the grid) in the bounding row of cells. Reilly and others

Table 1. Selected physical and numerical parameters used in *MODFLOW-GWT* simulation of ground-water flow and transport in a three-dimensional, steady-state flow system containing a multi-node well. [ft/d, feet per day; ft, feet; ft²/d, feet squared per day]

Parameter	Value
Horizontal hydraulic conductivity	250 ft/d
Vertical hydraulic conductivity	50 ft/d
Well radius	0.133 ft
Well "skin"	2.6
Effective porosity	0.20
Longitudinal dispersivity	0.0 ft
Horizontal transverse dispersivity	0.0 ft
Vertical transverse dispersivity	0.0 ft
Diffusion coefficient	0.0 ft ² /d
Recharge rate	0.004566 ft/d
CELDIS (Courant number criteria)	1.0
NPTPND (initial number of particles per node)	8 or more ¹

¹ The value of NPTPND was increased to 275 in a block of cells surrounding the well.



EXPLANATION

- MULTI-NODE OBSERVATION WELL
- BOUNDARY OF TRANSPORT SUBGRID
- ∕ ∕ BREAK IN CONTINUITY OF GRID MAP

Figure 9. Map view of *MODFLOW* finite-difference grid showing location of transport subgrid and nonpumping multi-node well in the test problem.

(1989) reported that their well was represented by a cell having areal dimensions of 0.333 ft by 0.333 ft, which yields a cross-sectional area of 0.111 ft². Because it is assumed that the well lies on the plane of symmetry in the grid, a well radius is assigned in the model that yields an equivalent cross-sectional area to one-half of the cross-sectional area of the well in the simulation of Reilly and others (0.0555 ft²). For a well with a circular casing, this equivalent cross-sectional area would require a well radius of 0.133 ft. It also was assumed that there would be a linear well-loss coefficient represented by a nondimensional skin coefficient (see Halford and Hanson, 2002). The value of the “skin” was adjusted to achieve a vertical profile of flows between the aquifer and the well that closely matched that of Reilly and others (1989, fig. 2).

Reilly and others (1989) were concerned with “two situations that represent extreme possibilities for the misrepresentation of aquifer contamination from well samples.” They did not, however, actually simulate solute transport in their analysis of these two cases. For this report, only their first situation was evaluated, in

which they postulate a contaminant plume in the shallow part of the aquifer intersects the upper part of the well screen in the monitoring wellbore. For this case, an initial mass of contaminant was placed in layer 1, immediately upgradient from the borehole, as an initial condition for the solution of the transport equation in the presence of a multi-node well. The solute was assigned an initial concentration of 100 in the 32 cells of layer 1 located within rows 26 to 30 and columns 33 to 40. The simulation was then run for a stress period length of 1.0 year, assuming steady-state flow prevailed.

Heads were calculated using the PCG2 solver in *MODFLOW-2000*. Concentrations were calculated using the MOCWT method in *MODFLOW-GWT*, which is a variant of the method of characteristics that uses volume-weighted particles to track advection. Selected numerical parameters are also listed in table 1. In applying the MOCWT method, a background particle density of 8 particles per cell was used, but a higher density of particles (up to 275 particles per cell) was used in the vicinity of the well.

Model-Simulation Results

The flow model converged to a steady-state head distribution in 225 iterations with a 0.00 percent discrepancy. The head in the well was calculated to be 4.932 ft and the head distribution in the aquifer near the nonpumping multi-node well indicates that water should flow from the aquifer into the upper part of the borehole and discharge back into the aquifer through the lower part of the well (fig. 10). The MNW Package calculates the flow between the aquifer and each node of the borehole and writes these data to a separate output file (the MNW BYNODE output file). These flows along the length of the borehole are plotted in figure 11, and the

results show an excellent match to those published by Reilly and others (1989, fig. 2). Inflow to the well is greatest near the top of the well screen and outflow is greatest near the bottom of the well screen. The calculated total flow into the borehole was 9.79 ft³/d, which compares closely with 9.63 ft³/d reported by Reilly and others (1989). (Note that to adjust for using symmetry to simulate half the original domain size, the indicated flow rates were calculated by doubling flows calculated with the reduced domain size.)

Although Reilly and others (1989) hypothesized that the intraborehole flow

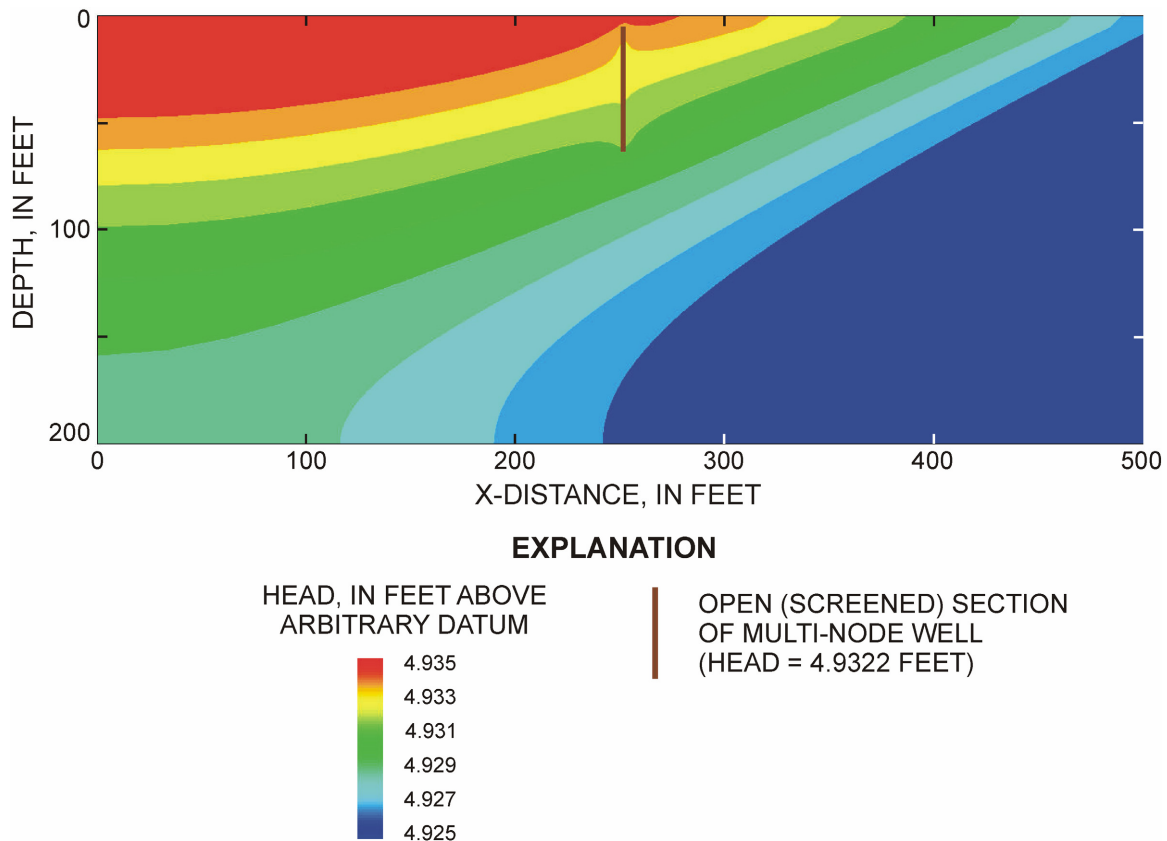


Figure 10. Calculated head distribution in vertical section near well on plane of symmetry (shown in Fig. 8). For clarity, only upgradient 5 percent of domain is shown (flow model domain extends to 10,000 feet in x-direction).

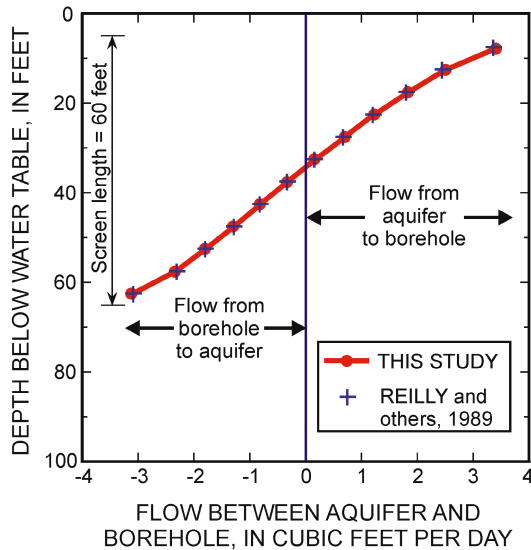


Figure 11. Adjusted flow rates between the aquifer and the borehole with depth calculated with the Multi-Node Well Package in *MODFLOW* for the test problem.

would have a substantial effect on contaminant spreading, they did not provide any quantitative analysis to demonstrate that effect. The revised *MODFLOW-GWT* code documented in this report enables such a quantitative analysis to be performed. The results show that a contaminant plume initially located only in the upper 5 ft of the aquifer rapidly spread to depths of 40 to 60 ft in the aquifer because of downward flow in the borehole open to the deeper parts of the aquifer (fig. 12). The initial slug of contaminant in layer one moves downward over time in response to the local velocity field and is reduced in size and mass in layer 1 because of capture by the well and because there is no source adding new contaminants at the water table. The reduction in contaminant mass in the shallowest part of the aquifer is matched by the increase in mass in the deeper part of the aquifer—to depths where the contaminant would not have been expected if not for the pathway provided by the open borehole. In 1 year, high concentrations (greater than 1.0 percent of the source concentration) had spread

about 21 ft downgradient from the borehole, 12 ft upgradient from the borehole, and 15 ft laterally from the borehole at depths of 55 to 60 ft in the aquifer (figs. 12 and 13). The concentration profiles shown in figures 12B and 12C include some apparent dispersion induced by the smoothing function inherent in the visualization software.

The MNWO Package was used to track the depth-averaged relative concentration in the multi-node well, as well as solute mass flux through the borehole. The changes in concentration with time are shown in figure 14, which was plotted directly from data in the MNWO output file. The oscillations in the breakthrough curve are related to the discrete nature of the particles used to track advective transport in the method of characteristics. In this case, particles with both low and high concentrations converged on the uppermost well nodes from all directions. Because a discrete and limited number of particles were used, the particles with low and high relative concentrations entered well cells at different ratios each time increment, resulting in oscillations over time in the mixed (or averaged) concentrations in the well nodes that represent fluid sinks to the aquifer. The oscillations are greatest when dispersion is zero (as in this example); oscillations can be reduced with higher dispersion and when using a greater density of particles.

In the example described above, the MNWO output file records the depth-averaged concentration in the well because the well was a nonpumping one. For the case of a nonpumping multi-node well, the user may be interested in evaluating the model-calculated variation in concentration in the well. These data are contained in the “BYNODE” MNW output file (“wellbore.byn” in this example problem). These results for this example are shown in

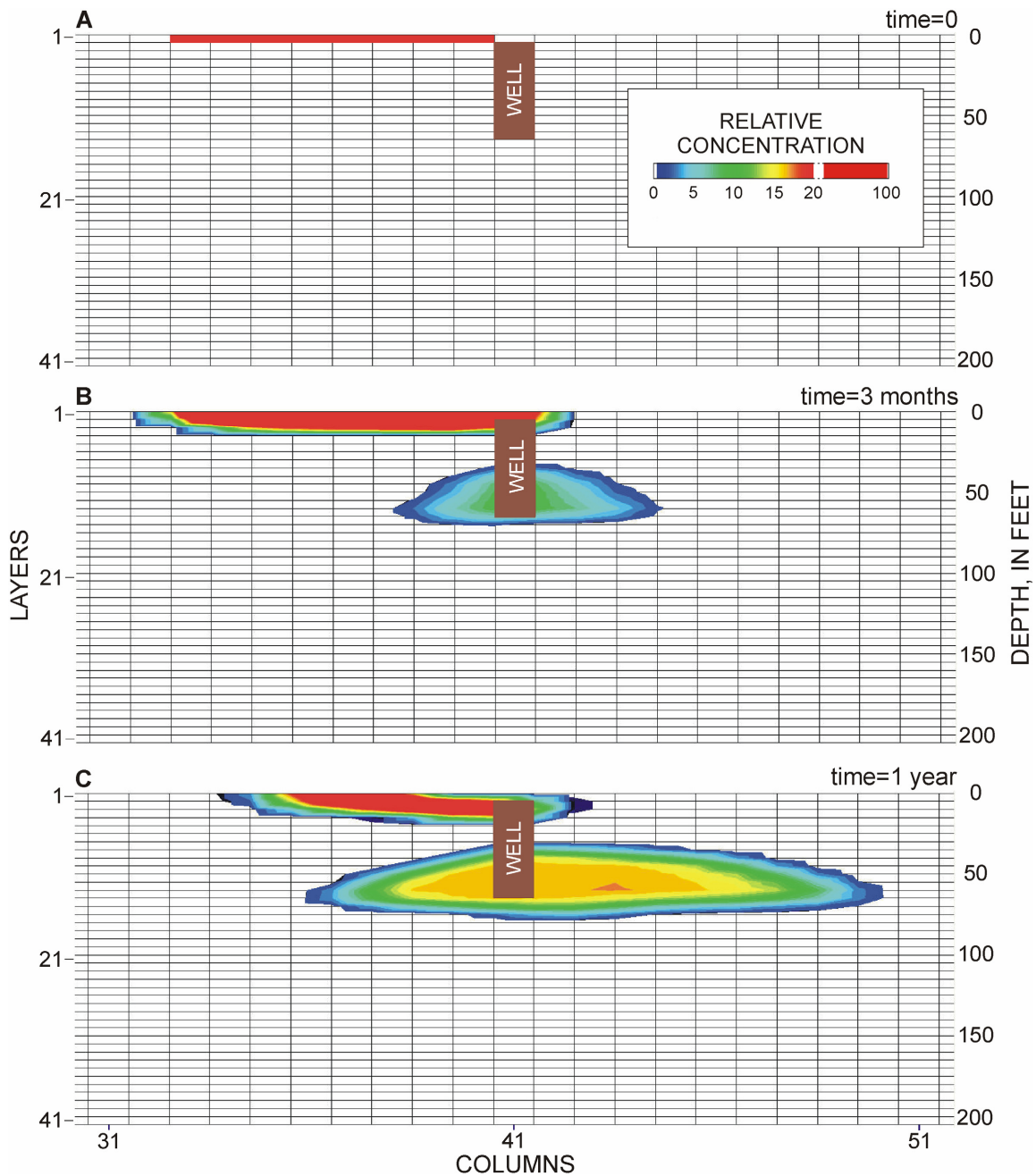


Figure 12. Calculated spreading of contaminant in presence of multi-node well showing relative concentrations in vertical section along row 30 of grid (representing the plane of symmetry): (A) initial conditions ($C_0=100$), (B) plume at 3 months, and (C) plume after 1 year. Note that only part of the grid in the column direction is shown; concentrations less than 1.0 are not shown.

figure 15, and the profile reflects that inflow has the highest relative concentration in the uppermost well node and that the

concentration doesn't change in the deeper part of the borehole where there is outflow from the well to the aquifer.

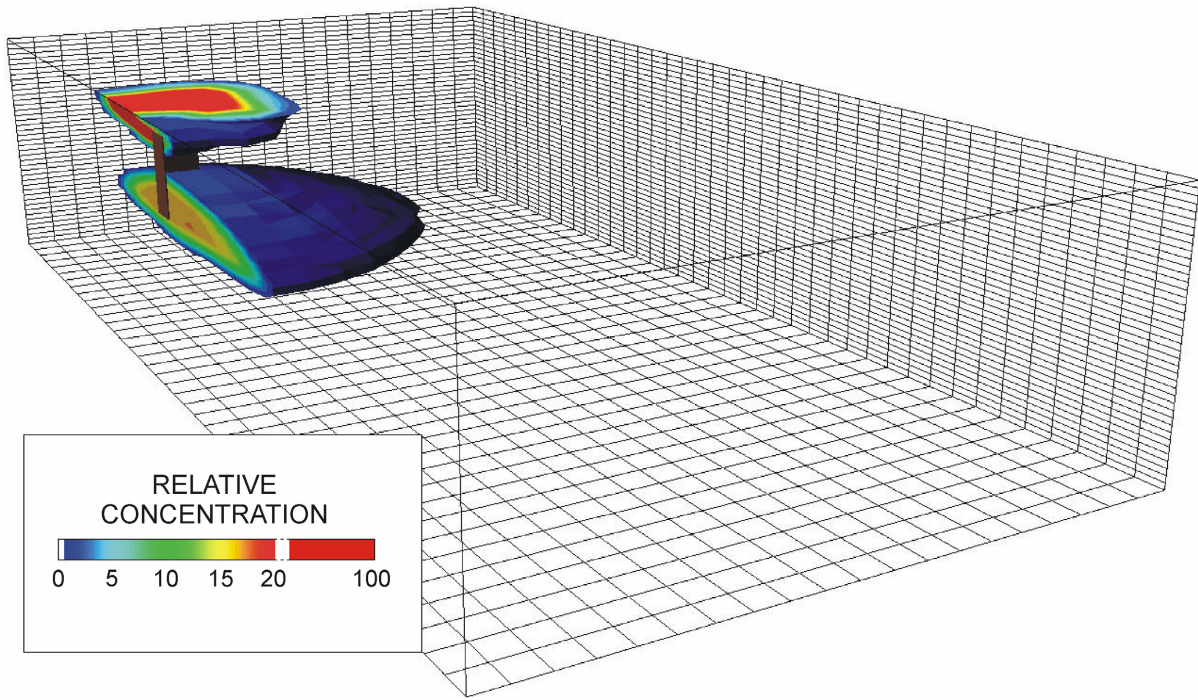


Figure 13. Three-dimensional perspective of model transport domain for the test problem showing simulated contaminant plume emanating from lower part of well after 1 year (concentrations < 1.0 not shown).

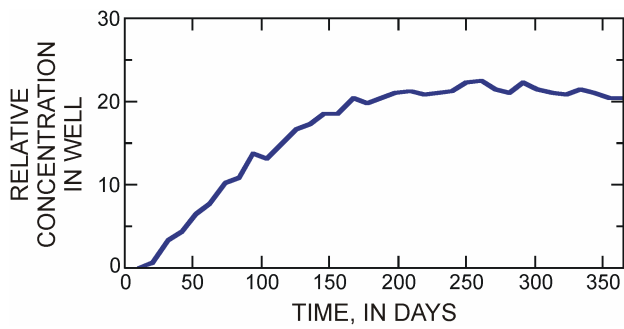


Figure 14. Calculated depth-averaged concentration in nonpumping multi-node well in the test problem.

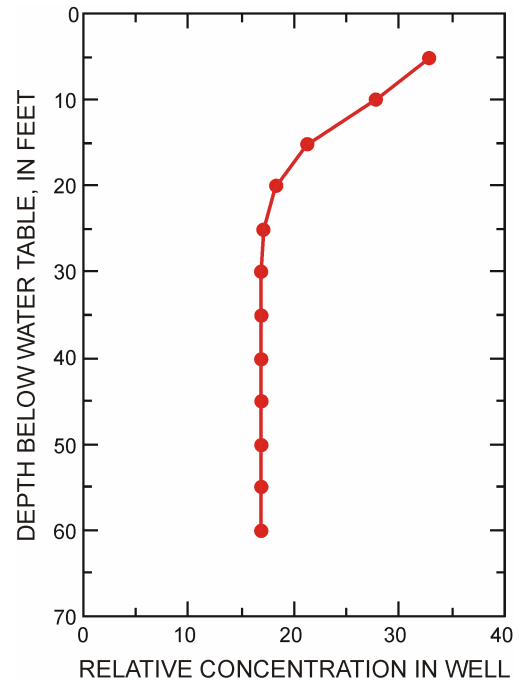


Figure 15. Concentration variations within the borehole of the nonpumping multi-node well in the test problem after 1 year.

SELECTED INPUT DATA AND PRINTED RESULTS FOR TEST SIMULATION

This simulation is designed to demonstrate the capability of the Multi-Node Well (MNW) Package when used in conjunction with the Ground-Water Transport (GWT) Process of *MODFLOW* (*MODFLOW-GWT*). As described above, the test case simulates a regional flow field with a single nonpumping multi-node well. Selected sections of several key input and output data files are shown below—sometimes with annotations; gaps in the listings are indicated by an ellipsis. Not all files are shown. A complete set of these

files is available for distribution at the Web sites described in the Preface. Contents of some files are enclosed in a border and explanations are noted outside of the border; for other files, explanations are sometimes included as comments following a semicolon on the line being explained. Font sizes in the following listings are sometimes reduced so that lines will fit within page margins. Information pertaining specifically to the MNW Package is highlighted in yellow.

Selected Input Files

Following (enclosed in a border) are the contents of the *MODFLOW* name file for the test simulation; explanations are noted outside of border:

File name: wellbore.nam

LIST	14	wellbore.lst	← Output file for MODFLOW-2000
DIS	15	wellbore.dis	← Input file for Discretization Package
BAS6	18	wellbore.bas	← Input file for Basic Package
OC	19	wellbore.oc	← Input file for Output Control option
LPF	20	wellbore.lpf	← Input file for Layer-Property Flow Package
DATA (BINARY)	2	calced.bhd OLD	← Initial head data
RCH	21	wellbore.rch	← Input file for Recharge Package
PCG	22	wellbore.pcg	← Input file for PCG Package
MNW1	23	wellbore.mnw	← Input file for Multi-Node Well (MNW) Package
GWT	24	wellbore.gwt	← Name file for Ground-Water Transport Process
DATA (BINARY)	4	wellbore.bhd REPLACE	← Output file for calculated heads (binary)
DATA (BINARY)	33	wellbore.bud REPLACE	← Output file for cell-by-cell budget data
↑	↑	↑	↑
1	2	3	4

- 1 Ftype (the type of file)
- 2 Unit number
- 3 File name (name chosen to reflect contents of file)
- 4 Option to replace any existing file with this name

Following are the contents of the Multi-Node Well (MNW) Package input file for the test simulation; explanations are noted outside of border (see Halford and Hanson, 2002, for more detailed explanation):

File name: wellbore.mnw

12 -1 0 Reference SP = 1	← 1
SKIN	← 2
FILE:wellbore.byn BYNODE:11	← 3
FILE:wellbore.qsu QSUM:12	← 4
12	← 5
2 30 41 0. 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
3 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
4 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
5 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
6 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
7 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
8 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
9 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
10 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
11 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
12 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6
13 30 41 0. MN 0.00E+000 1.3330000000000E-001 2.60E+000 0.00E+000 0.00E+000 0 SITE:Well11	← 6

- 1 MXMNW, IWL2CB, IWELPT, reference stress period.
- 2 LOSSTYPE.
- 3 Optional output: BYNODE file.
- 4 Optional output: QSUM file.
- 5 ITMP (number of active well nodes for this stress period).
- 6 Well-node information. The first node is linked to the others by inclusion of the MN tag on each subsequent line; this creates a multi-node well. Data columns are: Layer, Row, Column, Qdes, (MN), QWval, Rw, Skin, Hlim, Href, Iqwgrp, SITE.

Following (enclosed in a border) are the contents of the Ground-Water Transport (GWT) Process name file; explanations are noted outside of border:

File name: wellbore.gwt

CLST 25 wellbore.out	← Output file for Ground-Water Transport Process
MOCWT 26 wellbore.moc	← Input file for GWT using volume-weighted MOC transport solver
IPDA 88 wellbore.ipda	← Input file for spatially varying initial particles
BFLX 27 wellbore.bflx	← Input file for boundary flux package
CRCH 28 wellbore.crc	← Input file for concentration of recharge
CNCA 29 wellbore.cna	← Output file for calculated concentrations
VELA 30 wellbore.vla	← Output file for calculated velocities
MNWO 33 wellbore.mno	← Input file for MNW observation well records
DATA 47 wellbore.mn1	← Output file for MNW observation well records

↑ ↑ ↑
1 2 3

- 1 Ftype (the type of file)
- 2 Unit number
- 3 File name (name chosen to reflect contents of file)

Following (enclosed in a border) are the contents of the Multi-Node Well Observation (MNWO) Package input file for the test simulation; explanations are noted as comments at the end of each record:

File name: wellbore.mno

1	;	MNWOBS,	MNW Observation well data
Well1 47 1	;	site, unit number,	MNWoflag

Selected Output Files

Following are the contents of the main *MODFLOW* output file for the test simulation:

File name: wellbore.lst

```
MODFLOW-2000
U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL
VERSION 1.15.01 04/05/2005
```

This model run combines GLOBAL and LIST output into this single file.

```
GLOBAL LISTING FILE: wellbore.lst
UNIT 14
```

```
OPENING wellbore.dis
FILE TYPE:DIS UNIT 15 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL
```

```
OPENING wellbore.bas
FILE TYPE:BAS6 UNIT 18 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL
```

```
OPENING wellbore.oc
FILE TYPE:OC UNIT 19 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL
```

```
OPENING wellbore.lpf
FILE TYPE:LPF UNIT 20 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL
```

```
OPENING calced.bhd
FILE TYPE:DATA(BINARY) UNIT 2 STATUS:OLD
FORMAT:BINARY ACCESS:SEQUENTIAL
```

```
OPENING wellbore.rch
FILE TYPE:RCH UNIT 21 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL
```

OPENING wellbore.pcg
FILE TYPE:PCG UNIT 22 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.mnw
FILE TYPE:MNW1 UNIT 23 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.gwt
FILE TYPE:GWT UNIT 24 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.bhd
FILE TYPE:DATA(BINARY) UNIT 4 STATUS:REPLACE
FORMAT:BINARY ACCESS:SEQUENTIAL

OPENING wellbore.bud
FILE TYPE:DATA(BINARY) UNIT 3 STATUS:REPLACE
FORMAT:BINARY ACCESS:SEQUENTIAL

THE FREE FORMAT OPTION HAS BEEN SELECTED

DISCRETIZATION INPUT DATA READ FROM UNIT 15
Data read from D:\Data Sets\MNW\wellbore\GWT_MNW\wellbore.dis
File generated on 5/25/2005 10:11:10 AM
41 LAYERS 30 ROWS 272 COLUMNS
1 STRESS PERIOD(S) IN SIMULATION
MODEL TIME UNIT IS DAYS
MODEL LENGTH UNIT IS FEET

U.S. GEOLOGICAL SURVEY
Ground-Water Transport Process (GWT)
GWT (Version 2.4 BETA) 12/05/2005

GWT BASIC INPUT READ FROM UNIT 26
GWT OUTPUT ON FILE UNIT 25

THE GROUND-WATER TRANSPORT PROCESS IS ACTIVE

THE OBSERVATION PROCESS IS INACTIVE
THE SENSITIVITY PROCESS IS INACTIVE
THE PARAMETER-ESTIMATION PROCESS IS INACTIVE

MODE: FORWARD

...

MNW1 -- MULTI-NODE WELL PACKAGE, VERSION 1, 8/13/2002.

INPUT READ FROM UNIT 23

MAXIMUM OF 12 WELLS

CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0

The heads at the beginning of SP: 1 will be the default reference elevations.

Flow rates will not be estimated after the9999th iteration

A BYNODE data input file will be written to wellbore.byn on unit 11

A QSUM data input file will be written to wellbore.qsu on unit 12
 334560 ELEMENTS IN X ARRAY ARE USED FOR MNW1

...

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES	L**3	RATES FOR THIS TIME STEP	L**3/T
IN:		IN:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	0.0000	CONSTANT HEAD =	0.0000
RECHARGE =	1642883.8750	RECHARGE =	4501.0518
MNW =	1786.9209	MNW =	4.8957
TOTAL IN =	1644670.7500	TOTAL IN =	4505.9473
OUT:		OUT:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	1642883.7500	CONSTANT HEAD =	4501.0513
RECHARGE =	0.0000	RECHARGE =	0.0000
MNW =	1786.9209	MNW =	4.8957
TOTAL OUT =	1644670.6250	TOTAL OUT =	4505.9468
IN - OUT =	0.1250	IN - OUT =	4.8828E-04
PERCENT DISCREPANCY =	0.00	PERCENT DISCREPANCY =	0.00

TIME SUMMARY AT END OF TIME STEP	1 IN STRESS PERIOD	1
SECONDS	MINUTES	HOURS
TIME STEP LENGTH	3.15360E+07	5.25600E+05
STRESS PERIOD TIME	3.15360E+07	5.25600E+05
TOTAL TIME	3.15360E+07	5.25600E+05

Entry	LAY	ROW	COL	Q	H-Well	H-Cell	DD	QW-Avg	s-LINEAR	s-NonLINEAR
1	2	30	41	-1.71315	4.93222	4.93308	4.93222	32.7160	0.853341E-03	0.00000
2	3	30	41	-1.24043	4.93222	4.93284	4.93222	27.7536	0.617890E-03	0.00000
3	4	30	41	-.906686	4.93222	4.93267	4.93222	21.2355	0.451660E-03	0.00000
4	5	30	41	-.613199	4.93222	4.93253	4.93222	18.3247	0.305481E-03	0.00000
5	6	30	41	-.340668	4.93222	4.93239	4.93222	17.0279	0.169739E-03	0.00000
6	7	30	41	-.815486E-01	4.93222	4.93226	4.93222	16.7443	0.406772E-04	0.00000
7	8	30	41	0.168571	4.93222	4.93214	4.93222	16.7443	-.839019E-04	0.00000
8	9	30	41	0.413198	4.93222	4.93202	4.93222	16.7443	-.205745E-03	0.00000
9	10	30	41	0.656765	4.93222	4.93190	4.93222	16.7443	-.327061E-03	0.00000
10	11	30	41	0.906529	4.93222	4.93177	4.93222	16.7443	-.451463E-03	0.00000
11	12	30	41	1.18058	4.93222	4.93163	4.93222	16.7443	-.587961E-03	0.00000
12	13	30	41	1.57003	4.93222	4.93144	4.93222	16.7443	-.781940E-03	0.00000

Multi-Node Rates & Average QW							
Site Identifier	ENTRY:	Begin	End	Q-Total	H-Well	DD	QW-Avg
Well1		1	12	-.374478E-10	4.93222	4.93222	20.3967

Following are the contents of the main Ground-Water Transport Process output file for the test simulation:

File name: wellbore.out

U.S. GEOLOGICAL SURVEY
Ground-Water Transport Process (GWT)
GWT (Version 2.4 BETA) 12/05/2005

LISTING FILE: wellbore.out UNIT 25

OPENING wellbore.mocIPDA
FILE TYPE:MOCWT UNIT 26 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.ipda
FILE TYPE:IPDA UNIT 88 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.bflx
FILE TYPE:BFLX UNIT 27 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.crc
FILE TYPE:CRCH UNIT 28 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.cna
FILE TYPE:CNCA UNIT 29 STATUS:UNKNOWN
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.vla
FILE TYPE:VELA UNIT 30 STATUS:UNKNOWN
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.mno
FILE TYPE:MNWO UNIT 33 STATUS:OLD
FORMAT:FORMATTED ACCESS:SEQUENTIAL

OPENING wellbore.mn1
FILE TYPE:DATA UNIT 47 STATUS:UNKNOWN
FORMAT:FORMATTED ACCESS:SEQUENTIAL

GWT BASIC INPUT READ FROM UNIT 26

Test simulation for GWT/MNW
Wellbore project

MAPPING OF SOLUTE-TRANSPORT SUBGRID IN FLOW GRID:
FIRST LAYER FOR SOLUTE TRANSPORT = 1 LAST LAYER FOR SOLUTE TRANSPORT = 41
FIRST ROW FOR SOLUTE TRANSPORT = 11 LAST ROW FOR SOLUTE TRANSPORT = 30
FIRST COLUMN FOR SOLUTE TRANSPORT= 21 LAST COLUMN FOR SOLUTE TRANSPORT = 60

UNIFORM DELCOL AND DELROW IN SUBGRID FOR SOLUTE TRANSPORT

NO. OF LAYERS = 41 NO. OF ROWS = 20 NO. OF COLUMNS = 40
 NO SOLUTE DECAY
 NO MOLECULAR DIFFUSION

BOUNDARY FLUX PACKAGE ACTIVATED
 NO ET IN SIMULATION: IEVTTP NOT READ
 IRCHTP= 1
 RECHARGE APPLIED AS BOUNDARY FLUX ON TOP FACE

...

SITE ID FOR 1 MNW WELL DESIGNATED FOR OBSERVATION:

WELL #	SITE ID	UNIT	MNWoflag
1	WELL1	47	1

DATA FOR MNW WELLS DESIGNATED FOR OBSERVATION WILL BE WRITTEN ON UNIT NUMBERS LISTED ABOVE

MNWO OUTPUT:

MNWoflag = 0: TIME, CONCENTRATION AT WELL
 MNWoflag = 1: TIME, CONCENTRATION AT WELL, PLUS EXTENDED MNW MASS FLUX INFO
 MNWoflag = 2: TIME, CONCENTRATION AT WELL, PLUS CONCENTRATIONS AT WELL NODES
 MNWoflag = 3: TIME, CONCENTRATION AT WELL, MASS FLUX INFO, CONC. AT WELL NODES

...

MNW CONCENTRATIONS FOR THIS STRESS PERIOD
 (ONLY FOR MNW NODES WITHIN TRANSPORT SUBGRID)

WELL NO.	LAYER	ROW	COLUMN	VOL/T	EXTERNAL	
					SOURCE CONC	SITEID
1	2	41	30	-1.7131E+00	0.0000E+00	Well1
2	3	41	30	-1.2404E+00		Well1
3	4	41	30	-9.0669E-01		Well1
4	5	41	30	-6.1320E-01		Well1
5	6	41	30	-3.4067E-01		Well1
6	7	41	30	-8.1549E-02		Well1
7	8	41	30	1.6857E-01		Well1
8	9	41	30	4.1320E-01		Well1
9	10	41	30	6.5676E-01		Well1
10	11	41	30	9.0653E-01		Well1
11	12	41	30	1.1806E+00		Well1
12	13	41	30	1.5700E+00		Well1

...

SOLUTE BUDGET AND MASS BALANCE FOR TRANSPORT SUBGRID

VALUES CALCULATED AT END OF:
 STRESS PERIOD 1 OUT OF 1
 FLOW TIME STEP 1 OUT OF 1
 TRANSPORT TIME INCREMENT 35 OUT OF 35

ELAPSED TIME = 3.6500E+02

External MNW mass flux (based on wellhead flow) (L**3)(M/VOL)

Cumulative mass flux into aquifer by MNWs = 0.0000E+00

Cumulative mass flux out of aquifer by MNWs = 0.0000E+00

CHEMICAL MASS IN STORAGE:

INITIAL: MASS DISSOLVED = 3.9739E+04 MASS SORBED = 0.0000E+00
PRESENT: MASS DISSOLVED = 3.9744E+04 MASS SORBED = 0.0000E+00

...

CHANGE IN MASS STORED = 4.6619E+00

CUMULATIVE SOLUTE MASS (L**3)(M/VOL)

IN:

CONSTANT HEAD = 0.0000E+00
SUBGRID BOUNDARY = 0.0000E+00
RECHARGE = 0.0000E+00
MULTI-NODE WELLS = 2.2566E+04

TOTAL IN = 2.2566E+04

OUT:

CONSTANT HEAD = 0.0000E+00
SUBGRID BOUNDARY = 0.0000E+00
RECHARGE = 0.0000E+00
MULTI-NODE WELLS = -2.2566E+04

TOTAL OUT:WEIGHTED PTS= -2.2566E+04

PARTICLE-BASED RESIDUAL = -4.6626E+00

PERCENT DISCREPANCY = 2.0662E-02 RELATIVE TO MASS FLUX OUT, BASED ON PTS.

Following are the contents of the MNWO output file for the test simulation. The concentration data ("WELL-CONC") included in this output file are also plotted in figure 14.

File name: wellbore.mnl

DATA FOR MNW WELL DESIGNATED FOR OBSERVATION

SITE Well11

TIME	WELL-CONC	MASS FLUX IN BOREHOLE		MASS INTO BOREHOLE		MASS OUT OF BOREHOLE	
		PRESENT t	CUM.	PRESENT t	CUM.	PRESENT t	CUM.
1.0429E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.0857E+01	5.9829E-01	2.2592E+01	2.2592E+01	-2.2592E+01	-2.2592E+01	2.2592E+01	2.2592E+01
3.1286E+01	3.3502E+00	1.2651E+02	1.4910E+02	-1.2651E+02	-1.4910E+02	1.2651E+02	1.4910E+02
4.1714E+01	4.3551E+00	1.6445E+02	3.1356E+02	-1.6445E+02	-3.1356E+02	1.6445E+02	3.1356E+02
5.2143E+01	6.5589E+00	2.4767E+02	5.6123E+02	-2.4767E+02	-5.6123E+02	2.4767E+02	5.6123E+02
6.2571E+01	7.7873E+00	2.9406E+02	8.5529E+02	-2.9406E+02	-8.5529E+02	2.9406E+02	8.5529E+02

...

3.1286E+02	2.1011E+01	8.4828E+02	1.8247E+04	-8.4828E+02	-1.8247E+04	8.4828E+02	1.8247E+04
3.2329E+02	2.0844E+01	8.4451E+02	1.9092E+04	-8.4451E+02	-1.9092E+04	8.4451E+02	1.9092E+04
3.3371E+02	2.1459E+01	8.9331E+02	1.9985E+04	-8.9331E+02	-1.9985E+04	8.9331E+02	1.9985E+04
3.4414E+02	2.1013E+01	8.7358E+02	2.0859E+04	-8.7358E+02	-2.0859E+04	8.7358E+02	2.0859E+04
3.5457E+02	2.0525E+01	8.5248E+02	2.1711E+04	-8.5248E+02	-2.1711E+04	8.5248E+02	2.1711E+04
3.6500E+02	2.0397E+01	8.5488E+02	2.2566E+04	-8.5488E+02	-2.2566E+04	8.5488E+02	2.2566E+04

Following are the contents of the BYNODE output file for the test simulation. The concentration data (QW-Avg) included in this output file represent nodal values in the multi-node well and are also plotted in figure 15.

File name: wellbore.byn

SiteID	Entry	NODE	Total_Time	Q	H-Well	H-Cell	QW-Avg
...							
Well1	1	16089	365.00000	-1.7131450	4.9322224	4.9330757	32.716038
Well1	2	24249	365.00000	-1.2404266	4.9322224	4.9328403	27.753590
Well1	3	32409	365.00000	-.90668571	4.9322224	4.9326740	21.235537
Well1	4	40569	365.00000	-.61319940	4.9322224	4.9325278	18.324675
Well1	5	48729	365.00000	-.34066847	4.9322224	4.9323921	17.027941
Well1	6	56889	365.00000	-.81548553E-01	4.9322224	4.9322630	16.744301
Well1	7	65049	365.00000	0.16857103	4.9322224	4.9321385	16.744301
Well1	8	73209	365.00000	0.41319797	4.9322224	4.9320166	16.744301
Well1	9	81369	365.00000	0.65676482	4.9322224	4.9318953	16.744301
Well1	10	89529	365.00000	0.90652868	4.9322224	4.9317709	16.744301
Well1	11	97689	365.00000	1.1805792	4.9322224	4.9316344	16.744301
Well1	12	105849	365.00000	1.5700321	4.9322224	4.9314404	16.744301
EndOfFile	EndOfFile	EndOfFile					

Following are the contents of the QSUM output file for the test simulation showing summary values for the entire multi-node well.

File name: wellbore.qsu

SiteID	Entry	Total_Time	Qin	Qout	Qsum	H-Well	QW-Avg
Well1	00001-00012						
Well1	00001-00012	365.00000	-.37447823E-10	0.0	-.37447823E-10	4.9322224	20.396748
EndOfFile	EndOfFile	EndOfFile					

SUMMARY AND CONCLUSIONS

The Multi-Node Well (MNW) Package allows *MODFLOW* to simulate wells that extend beyond a single model node. Because multi-node wells can allow nonuniform flow to occur within the borehole, solute can be transported directly from one model node to another through the

well. In some cases, this intraborehole transport can facilitate the movement of contaminants through a ground-water system and thereby needs to be recognized when calculating changes in concentration in the system. The *MODFLOW-GWT* solute-transport model was modified to

provide compatibility with the MNW Package. If the flow between a multi-node well and the model domain is in the same direction at all well nodes, the solute concentration in the borehole is assumed to be uniform and consistent with an assumption of complete mixing within the borehole during a given time increment. If the flow between a multi-node well and the model domain is complex and into the well at some nodes while out of the well at other nodes, the solute concentration in the borehole is computed using a routing algorithm that only assumes local mixing at each node in the well during a given time increment.

A test problem was designed to simulate ground-water flow and solute transport in a ground-water system that contains a contaminant plume near its top surface and a borehole extending through multiple model layers (represented as a multi-node well). In the test problem, the flow model converged to a steady-state head distribution with a 0.00 percent discrepancy. Model-simulated flows along the length of the borehole compare closely with previously reported results. *MODFLOW-GWT* was used to analyze solute transport through the borehole and demonstrate that intraborehole flow has a substantial effect on simulated contaminant spreading. Changes in contaminant concentration with time indicate that the presence of the long borehole enabled a secondary contaminant plume to develop at a greater depth in the ground-water system than would have occurred if the well did not exist or had been effectively plugged or sealed. Coincident with the solute transfer to greater depths through the borehole is a reduction in solute mass in the shallowest part of the ground-water system.

This report documents the assumptions, methods, and input data

requirements for using the *MODFLOW-GWT* model to simulate solute transport in a ground-water system containing a multi-node well. This enhancement improves the capability of *MODFLOW-GWT* to accurately simulate transport in cases that involve fluxes to or from multi-node wells. The test problem confirmed the numerical accuracy of the revised model.

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