ground water

Methods Note/

Representing Pump-Capacity Relations in Groundwater Simulation Models

by L.F. Konikow

Abstract

The yield (or discharge) of constant-speed pumps varies with the total dynamic head (or lift) against which the pump is discharging. The variation in yield over the operating range of the pump may be substantial. In groundwater simulations that are used for management evaluations or other purposes, where predictive accuracy depends on the reliability of future discharge estimates, model reliability may be enhanced by including the effects of head-capacity (or pump-capacity) relations on the discharge from the well. A relatively simple algorithm has been incorporated into the widely used MODFLOW groundwater flow model that allows a model user to specify head-capacity curves. The algorithm causes the model to automatically adjust the pumping rate each time step to account for the effect of drawdown in the cell and changing lift, and will shut the pump off if lift exceeds a critical value. The algorithm is available as part of a new multinode well package (MNW2) for MODFLOW.

Introduction

The capacity of a pump installed in a well to deliver water depends on several factors, including the size of the pump and the power of the motor, as well as the lift, or vertical distance over which the water must be raised. Boonstra and Soppe (2007) relate pump efficiency and pump performance to the total dynamic head, which they state "is made up of (1) the water-level depth inside the pumped well . . . ; (2) the above ground lift; and (3) head losses due to friction and turbulence in the discharge pipelines."

There are a number of reasons why well yields and pump performance might decrease over time. Some involve damage or deterioration to the pump or well screens. Others simply are related to changing heads over time. Driscoll (1986, p. 583) gives an example for a deep-well turbine pump where "the total head would be as low as 60 feet (18.3 m) during a season of high water level or minimum withdrawal of water; but during another season, the total head might be 100 feet (30.5 m) because the water level in the aquifer has decreased or interference from adjacent wells has increased. Under these conditions, the rate of pumping would range from nearly 1,340 gpm [gallons per minute] (7,300 m^3/day) down to about 620 gpm (3,380 m^3/day)."

Conceptually, after pumping starts, the water level in the well will decline over time and the lift (and total dynamic head) required to discharge at a fixed point and elevation above the land surface will increase. As the total dynamic head increases, more work is required to lift and discharge a unit volume of water, so the discharge from a standard constant-speed pump will tend to decrease. The methods described in this note are not applicable to a variable-speed pump designed to maintain a constant discharge under conditions of changing lift.

Most pump manufacturers provide performance curves for their products that typically include a head-capacity (or pump-capacity) curve relating the total dynamic head to the discharge rate (Boonstra and Soppe 2007). A hypothetical example set of performance curves having representative shapes is shown in Figure 1A. Near the design capacity or maximum flow rate of the pumps (termed "runout" by Pritchard [2007]), the curves are steeper and there is a relatively small change in discharge

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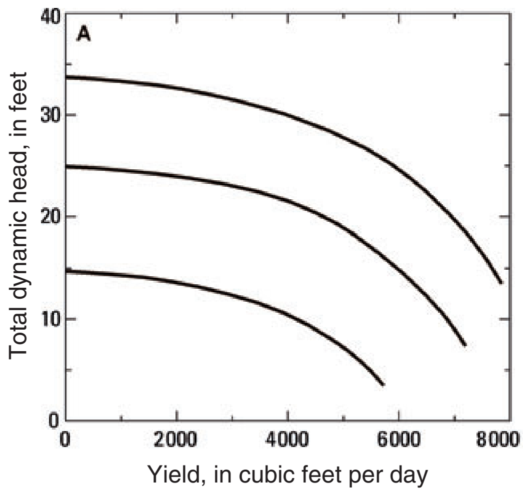

Figure 1. Plots showing (A) hypothetical but representative performance (pump-capacity) curves for three models (and sizes) of vertical turbine pump, with the top curve representing the largest pump and (B) points defined for approximation of top curve using linear interpolation.

for a unit change in total dynamic head. As the lift increases, however, the curves tend to flatten out and there may be a relatively large change in discharge for a unit change in total dynamic head—until a point is reached where the pump can no longer provide water and the discharge goes to zero. This point is called the "shut-off head" (Pritchard 2007; Driscoll 1986, p. 585).

In applying a groundwater flow model, there may be cases where it is deemed valuable to incorporate the relation between pump capacity and lift because as drawdown increases with time, the well yield will be reduced. Where historical data on discharge from wells are based on metering or other estimates of the total volume produced over a given time period, incorporating these relations may provide little or no added value for model calibration because there are no observations of temporal changes in production as a function of drawdown. However, if the groundwater flow model is used to make predictions of future behavior of the flow system, evaluation of management scenarios, or for small-scale studies near a pumping center, the use of these head-capacity curves may add more realism and defensibility to predictions of future conditions.

This article describes the incorporation of head-capacity curves for constant-speed pumps into the MODFLOW groundwater flow simulation model (Harbaugh et al. 2000; Harbaugh 2005). This new feature is part of a new multinode well (MNW2) package (Konikow et al. 2009), but is also applicable to single-node wells.

Numerical Implementation

The new MNW2 package provides the user an option to specify a performance curve (head-capacity curve) for each well. Use of this option will generally lead to a gradual automatic adjustment of the well discharge rate over a large range in water levels (although the rate of adjustment depends on the slope of the performance curve).

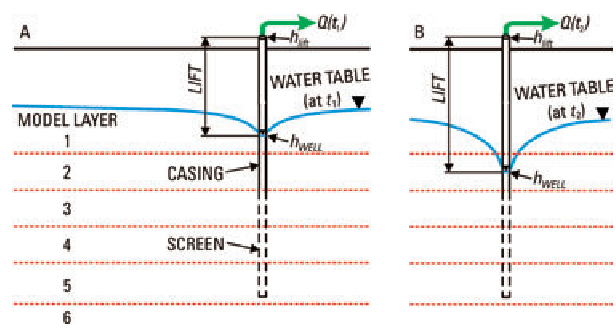

Figure 2. Schematic cross section of an unconfined aquifer showing a multinode well open to parts of three model layers, and the relation of the lift (or total dynamic head) to the reference elevation (h_{lift}) and the water level in the well (h_{WELL}) at two different times. Q at time 1 (A) is greater than Q at time 2 (B) with greater drawdown after a period of pumping.

Pump-capacity adjustments are based on the elevation of the outflow (discharge) location only. Therefore, the user must specify a reference elevation (h_{lift}) corresponding to the elevation of the discharge point (Figure 2). The model will then automatically compute the lift (or total dynamic head) based on the difference between the reference elevation and the most recently calculated water level in the well (h_{WELL}). At a later time, while pumping continues and drawdown increases, the lift increases (Figure 2B). The pump discharge may therefore decrease because more energy is required to lift water a greater distance. If one also wants to account for head loss because of friction and turbulence in the pipes, the reference elevation can be artificially increased proportionately to obtain the desired total effect.

Details about the MNW2 numerical scheme are described by Bennett et al. (1982), Halford and Hanson (2002), Neville and Tonkin (2004), and Konikow et al. (2009). If the pump-capacity option is activated, at the beginning of each iteration cycle MNW2 updates the net discharge from the well on the basis of the most recent value of the water level in the well and the user-defined pump-capacity curve. Consequently, the discharge rate from the well may vary from one time step to the next during a particular stress period. In contrast, the standard well package in MODFLOW imparts a discharge rate that is constant during the entire length of a stress period.

The MNW2 user must enter a table of values representing discrete points on the head-capacity curve for the pump. The two end points of the provided curve should represent values of total dynamic head corresponding with zero discharge and the maximum design discharge, respectively. In addition, a minimum of one additional intermediate point on the curve must be specified. MNW2 applies linear interpolation to estimate the yield for any value of total dynamic head between defined points. The use of four intermediate points leads to a very accurate approximation over the entire range of heads (Figure 1B).

Because the pump-capacity curves may be nonlinear and, where gently sloping, small changes in lift may induce large changes in discharge, the overall numerical solution may become unstable, fail to converge, or oscillate. To minimize such numerical problems, several steps are taken in the code; these steps are described in detail by Konikow et al. (2009). Even with these preprogrammed measures to facilitate convergence, numerical problems may still occur. In such cases, the user may have to change numerical solution tolerances, reduce the time-step size, increase the allowable number of iterations, adjust the pump-capacity relations, or turn off the option to use pump-capacity relations.

The model assumes that for any total dynamic head equal to or less than the minimum head end point (on the right side of the curve in Figure 1B), the discharge will equal the maximum-operating discharge. For any total dynamic head equal to or greater than the maximum head end point (on the left end of the curve), the model assumes that the discharge equals zero. If the discharge is thereby set to zero, and at a later time or subsequent iteration the water level in the well rises sufficiently that the lift does not exceed the maximum total dynamic head, pumping will resume.

Demonstration of Capabilities

Description of Hypothetical Groundwater System (Modified Reilly Problem)

To test and illustrate the use of pump-capacity (head-capacity) curves, a hypothetical groundwater system was developed. The problem is based on one described by Reilly et al. (1989) and slightly modified by Konikow and Hornberger (2006a, 2006b). This same test problem is further modified here to help evaluate the pump-capacity calculations and to illustrate their potential value.

The hypothetical, unconfined groundwater system represents regional flow that is predominantly horizontal but includes some vertical components. The system is substantially longer (10,000 feet) than it is thick (205 feet) or wide (200 feet). A borehole with a 60-feet screen is located close to the no-flow boundary on the upgradient side of the system. The well is assumed to have a skin that is about 1.6 feet thick with a hydraulic conductivity that is 5% of that of the aquifer. Other properties of the system and the model are described in detail by Reilly et al. (1989), Konikow and Hornberger (2006a, 2006b), and Konikow et al. (2009).

Konikow and Hornberger (2006a, 2006b) simulated this three-dimensional hypothetical regional flow system using a variably spaced areal grid (over half the domain space because of the presence of a plane of symmetry). In the local area around the well, a relatively fine and uniform areal cell spacing of 2.5 feet by 2.5 feet was used. The vertical discretization was 5 feet everywhere in the model domain, and the top layer was assumed to be unconfined.

To demonstrate the effects of using pump-capacity curves, the Reilly problem was modified so that the long borehole had a pump with a characteristic performance curve that followed the upper curve in Figure 1A; this curve was discretized using four intermediate points, as shown in Figure 1B. The pumping rate was set at -7800 ft^3/d, which equals the maximum capacity of the pump, so that the drawdown would be large enough to illustrate clearly the effects of using pump-capacity curves to limit discharge.

Test Problem 1: Effect of Using Pump-Capacity Relations

In the first test, a 300-d transient stress period followed the initial steady-state stress period. The 300 d were divided into 20 time steps using a time-step multiplier of 1.2. The reference elevation for calculating lift (h_{lift}) was set equal to 10.0 feet (note that the elevation of the top surface of the grid is 0.0 feet).

The results (solid lines in Figure 3) show that the net discharge remained unchanged at the desired rate until the fourth time step. During the first three time

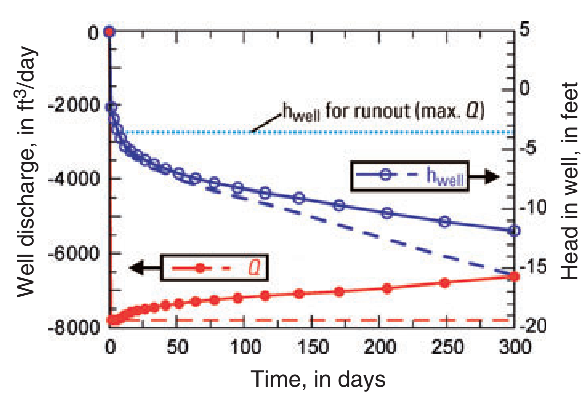

Figure 3. Results for test problem 1 of applying the pump-capacity relations to the modified Reilly problem in which the desired discharge equals -7800 ft^3/d for a 300-d transient stress period (solid lines). For reference, dashed lines show responses without considering pump-capacity relation.

steps, the calculated lift was sufficiently small that the maximum discharge of the pump was allowed. In time step 4, the water level in the well fell below that for runout at −3.65 feet (yielding a lift exceeding 13.65 feet), and the discharge was reduced in accordance with the pump-capacity curve. From the time step 4 on, the net discharge from the well was reduced gradually each time step as the head in the well declined (and the pumping lift increased) continually throughout the simulation. By the end of the simulation, the discharge had been reduced by about 15% (from −7800 ft^3/d to about −6620 ft^3/d).

For comparison, Figure 3 also shows (as dashed lines) the responses of the system if the pump-capacity relation had not been considered (i.e., if well discharge was constant). Without the effects of the pump-capacity relation, the drawdown in the well would have been increased by an additional 3.8 feet (about 23%). If this simulation had been a predictive run for evaluating future pumpage, substantial error could have been introduced if the pump-capacity relations had not been considered.

Test Problem 2: Well Shut-Down and Reactivation

A second test was evaluated to assure that the pump-capacity curves can shut a pump off if the lift increases substantially, as well as allow it to be turned back on if the head in the well subsequently rises sufficiently. In this variation of the previous test, heads were simulated for two 365-d transient stress periods (after an initial steady-state stress period). During the first transient stress period, three single-node pumping wells located near the multinode well were set at discharge rates equal to −4000 ft^3/d each; and during the second transient stress period, these three wells were shut off so that heads would recover. Both transient stress periods were simulated using 15 time steps and a time-step multiplier of 1.2. Everything else was unchanged from the previous test. The results (Figure 4) show that the simulated net discharge from the multinode well was reduced relative to the specified maximum discharge during every time step, until it was reduced to zero during the 12th time step when the head in the well dropped below the value yielding a lift greater than the maximum lift for this pump. During the first time step of the second transient stress period, the heads recovered quickly and sufficiently such that the pump in the multinode well was reactivated. The computed net discharge continued to increase as the water levels rose in response to shutting off the three nearby wells.

These two tests indicate that the pump-capacity relations work as expected on a conceptual basis. Additional tests (not described herein) indicated that under some circumstances, oscillatory behavior and/or nonconvergence occurred, but these problems were eliminated or minimized by adjusting numerical parameters or time-step size. To reiterate, the use of pump-capacity relations is optional in the MNW2 package (Konikow et al. 2009), and the user can deactivate it during any one or all stress periods of a simulation.

Conclusions

For a constant-speed pump, the discharge from a well depends on the total dynamic head (or lift) against which the pump works. As the lift increases, the discharge decreases. If the lift becomes too great, the pump will shut off. Representing these effects in a groundwater flow simulation model can result in more realistic predictions of the future behavior of a groundwater system.

A method to simulate the relation between well yield and lift has been developed and incorporated into the MODFLOW groundwater simulation model as an optional part of a new MNW2 package (Konikow et al. 2009). The results of testing use of the pump-capacity curves in a hypothetical groundwater system (modified Reilly problem) show that the method can realistically reduce the pumping rate as drawdown progresses and lift increases over time. The testing also showed that the pump will shut off when the lift exceeds the maximum capacity of the pump and that the pump will restart at a later time if the water level in the well subsequently rises sufficiently such

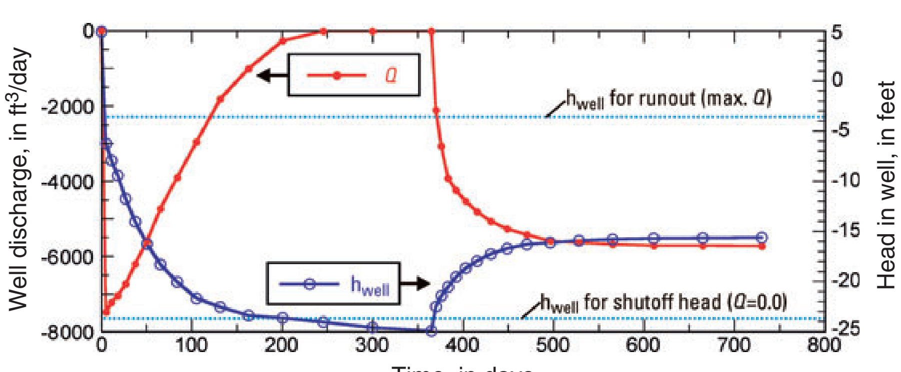

Figure 4. Results for test problem 2 of applying the pump-capacity relations to the modified Reilly problem in which the desired discharge equals −7800 ft^3/d for two 365-d transient stress periods with three nearby wells pumping at −4000 ft^3/d during the first transient stress period. When the head in the well drops below −23.75 feet, the lift is greater than the maximum capacity of the pump, the pump is shut off, and the well discharge becomes zero.

that the new smaller lift again falls within the operating range of the pump.

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References

Bennett, G.D., A.L. Kontis, and S.P. Larson. 1982. Representation of multiaquifer well effects in three-dimensional groundwater flow simulation. *Ground Water* 20, no. 3: 334–341.

Boonstra, H., and R. Soppe. 2007. Well design and construction. In *The Handbook of Groundwater Engineering*, 2nd ed., ed. J.W. Delleur, chap. 11. Boca Raton, Florida: CRC Press.

Driscoll, F.G. 1986. *Groundwater and Wells*, 2nd ed., 1089. St. Paul, Minnesota: Johnson Filtration Systems Inc.

Halford, K.J., and R.T. Hanson. 2002. User guide for the drawdown-limited, multi-node well (MNW) package for the U.S. Geological Survey's modular three-dimensional ground-water flow model, versions MODFLOW-96 and MODFLOW-2000. USGS Open-File Report 02–293. Reston, Virginia: USGS.

Harbaugh, A.W. 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model—The ground-water flow process. USGS Techniques and Methods 6-A16. Reston, Virginia: USGS.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process. USGS Open-File Report 00–92. Reston, Virginia: USGS.

Konikow, L.F., G.Z. Hornberger, K.J. Halford, and R.T. Hanson. 2009. Revised multi-node well (MNW2) package for MODFLOW ground-water flow model. USGS Techniques and Methods 6-A30, Reston, Virginia: USGS.

Konikow, L.F., and G.Z. Hornberger. 2006a. Modeling effects of multinode wells on solute transport. *Ground Water* 44, no. 5: 648–660.

Konikow, L.F., and G.Z. Hornberger. 2006b. Use of the multinode well (MNW) package when simulating solute transport with the MODFLOW ground-water transport process. USGS Techniques and Methods 6-A15. Reston, Virginia: USGS.

Neville, C.J., and M.J. Tonkin. 2004. Modeling multiaquifer wells with MODFLOW. *Ground Water* 42, no. 6: 910–919.

Pritchard, R. 2007. Groundwater pumps. In *Groundwater and Wells*, 3rd ed., ed. R.J. Sterrett, chap. 12, 551–595. New Brighton, Minnesota: Johnson Screens.

Reilly, T.E., O.L. Franke, and G.D. Bennett. 1989. Bias in groundwater samples caused by wellbore flow. *Journal of Hydraulic Engineering* 115, no. 2: 270–276.