Simulation of the Effects of Seasonally Varying Pumping on Intraborehole Flow and the Vulnerability of Public-Supply Wells to Contamination

by Richard M. Yager¹ and Charles E. Heywood²

Abstract

Public-supply wells with long screens in alluvial aquifers can produce waters of differing quality from different depths. Seasonal changes in quality are linked to seasonal changes in pumping rates that influence the distribution of flow into the well screens under pumping conditions and the magnitude and direction of intraborehole flow within the wells under ambient conditions. Groundwater flow and transport simulations with MODFLOW and MT3DMS were developed to quantify the effects of changes in average seasonal pumping rates on intraborehole flow and water quality at two long-screened, public-supply wells, in Albuquerque, New Mexico and Modesto, California, where widespread pumping has altered groundwater flow patterns. Simulation results indicate that both wells produce water requiring additional treatment to maintain potable quality in winter when groundwater withdrawals are reduced because less water is derived from parts of the aquifer that contain water requiring less treatment. Simulation results indicate that the water quality at both wells could be improved by increasing average winter-pumping rates to induce more lateral flow from parts of the aquifer that contain better quality water. Arsenic-bearing water produced by the Albuquerque well could be reduced from 55% to 45% by doubling average winter-pumping rate, while nitrate- and uranium-bearing water produced by the Modesto well could be reduced from 95% to 65% by nearly tripling the average winter-pumping rate. Higher average winter-pumping rates would also reduce the volume of intraborehole flow within both wells and prevent the exchange of poor quality water between shallow and deep parts of both aquifers.

Introduction

Boreholes with long-screen intervals (defined in this paper as more than 20 m in length) can transport significant quantities of water between aquifer system intervals that may be hydraulically separated by confining units under natural conditions. Bexfield et al. (2012) measured as much as 1120 m³/d of upward flow through a public-supply well under ambient conditions in Albuquerque, New Mexico. In a regional simulation of transient groundwater flow, Hanson et al. (2004) concluded that 19% of groundwater flow into deeper portions of the Santa Clara Valley (California) aquifer system occurred by intraborehole flow through more than 600 long-screened wells that were represented as multi-node wells in the groundwater flow model. Several studies have utilized both geochemical sampling methods and several other methods to investigate the effects of intraborehole flow on groundwater quality in deep aquifer system intervals where confining units might otherwise limit the potential for contamination. Zinn and Konikow (2007) simulated groundwater flow and transport through long-screened wells to demonstrate the potential effect of intraborehole flow on the groundwater age distribution within a simple conceptual aquifer system. Johnson et al. (2011) simulated the effect of intraborehole flow within inactive wells on the “zones of transport” to public-supply wells and demonstrated the vulnerability of public-supply wells in confined aquifers to shallow contaminant sources through intraborehole flow. Landon et al. (2010) utilized depth-dependent sampling to document contaminant transport between multiple depths in aquifer systems through long-screened public-supply...
wells near York, Nebraska, and Modesto, California. Ma et al. (2010) demonstrated the complicating effects of intraborehole flow on the numerical simulation of a tracer experiment. Halford et al. (2010) discuss improvements in pumped water quality from public-supply wells in Antelope Valley (California) obtained through grouting of selected intervals to reduce the entry of arsenic-bearing water. Rotzoll (2010, 2012) describes the observed and simulated displacement of salinity profiles within long-screened monitoring wells through intraborehole flow that results from pumping nearby public-supply wells in the Pearl Harbor aquifer (Hawaii).

Companion reports in this issue (Bexfield and Jurgens 2014; Jurgens et al. 2014) discuss seasonal changes observed in the quality and age of water pumped from two public-supply wells and provide evidence linking the seasonal changes to intraborehole flow within the wells. The two public-supply wells are in alluvial aquifer systems of the Middle Rio Grande Basin (Albuquerque, New Mexico) and San Joaquin Valley (Modesto, California). Contaminants from shallow and/or deep sources at each site can be transported via intraborehole flow within long-screened public-supply wells. Both sites contain anthropogenic (nitrate) and natural (arsenic or uranium) contaminants. Although mitigation of the vulnerability of pumped groundwater to anthropogenic contaminants from shallow sources is a common goal at both sites, the natural contaminant source depths at the sites differ (deep vs. shallow), as do the vertical hydraulic gradients under ambient (nonpumping) conditions (upward vs. downward). Both sites are subject to similar seasonal pumping cycles, in which groundwater withdrawals are greater in summer than winter. The reduction or cessation of pumping from long-screened public-supply wells during winter allows contaminant migration through intraborehole flow at both sites.

This article discusses groundwater flow and transport simulations that illustrate the effects of seasonal pumping on intraborehole flow within the public-supply wells and on the water quality of pumped groundwater. Simulation results are analyzed to explain the increase in contaminant concentrations observed during the winter in both public-supply wells and to quantify the relationship between pumping rates and the quality of pumped groundwater. The simulations demonstrate that seasonal changes in average pumping rates can cause seasonal changes in water quality. This study extends previous studies by demonstrating that in cases where water quality is affected by seasonal changes in intraborehole flow, judicious wellfield management practices can be employed to partially control its adverse effects.

**Hydrogeologic Settings**

Both study areas are in large regional alluvial basins. Although extensive confining units may be present in the deeper portions of these basins, they are absent in the shallow portions of the aquifer systems simulated for this study. Because laterally discontinuous lenses of lower permeability sediments impede vertical groundwater flow, the groundwater conditions are considered “semi-confined” at the screen depth intervals of the two public-supply wells in this study.

**Albuquerque**

The city of Albuquerque is located in the Middle Rio Grande Basin of central New Mexico (Figure 1). The climate is semiarid with a mean annual precipitation of 220 mm. The Middle Rio Grande Basin contains alluvial fill as much as 4500 m thick comprised of the unconsolidated to moderately consolidated sediments of the Santa Fe Group that were deposited in fluvial, lacustrine, or piedmont slope environments (Thorn et al. 1993). The basin is bounded primarily by mountains on the north and east and by several smaller uplifts, a fault zone, and an adjacent structural basin on the west. Conditions within the aquifer system are generally unconfined, but are semi-confined at depth. Depths to water in the Albuquerque area range from 1 m to more than 200 m.

Recharge to the Santa Fe Group aquifer system is primarily through seepage from the Rio Grande and associated irrigation canals (Figure 2A), but mountain-front recharge and leakage from water distribution systems in urban areas also recharge the aquifer (Bexfield et al. 2011). Groundwater discharges from the aquifer system through agricultural drains, groundwater withdrawals for public supply and irrigation, and riparian evapotranspiration. Essentially, all drinking water for the Albuquerque metropolitan area was supplied by groundwater withdrawals from the Santa Fe Group aquifer system before 2008. As a result, the large and extensive decline in water levels of more than 100 feet has altered the direction of groundwater flow in the area (formerly toward the Rio Grande) toward pumped wells (Bexfield and Anderholm 2002).

The Albuquerque public-supply well selected for this study (referred to as the Albuquerque well herein) is screened from 107 to 359 m below land surface (mbls). The well is generally pumped periodically at 17,300 m³/d, during operation, but average pumping rates since the...
year 2000, based on total seasonal withdrawals, ranged from 1380 to 5180 m³/d for the winter (November to mid-March) and summer (mid-March through October), respectively. The Albuquerque well produces groundwater with arsenic concentrations ranging from about 7 to 13 µg/L, and arsenic concentrations typically are higher during winter than summer (Bexfield and Jurgens 2014). The age distributions of groundwater produced by the well during the winter and summer were estimated using three environmental tracers. Groundwater chemistry and wellbore flow data indicate that the produced water is a mixture of recent (post-1950) recharge at shallow depths (less than 95 mbls) that contains some volatile organic contaminants (VOCs), 6500 year-old pristine water at intermediate depths (95 to 250 mbls), and very old (more than 20,000 years) water at the bottom of the well screen that contains arsenic at concentrations as much as 35 µg/L (Figure 3; Jurgens et al. 2014). The results of a ternary mixing model indicate that the proportion of very old arsenic-bearing water produced by the well was greater in the winter (74%), when withdrawal rates were lower, than in the summer (39%), when withdrawal rates were higher (Jurgens et al. 2014).

Intraborehole flow was measured with an electromagnetic flow meter in the Albuquerque well during December 2007 under ambient conditions after the well had not been pumped for 47 days (Bexfield et al. 2012). Flow was upward through most of the borehole and was as much as 1120 m³/d at 200 mbls. The borehole primarily gained water from the aquifer below 200 mbls and primarily lost water to the aquifer above 157 mbls (Figure 3). The upward direction of flow through the borehole during ambient conditions is consistent with the measured hydraulic gradient in the vicinity of the well, which is upward when the well is not pumped (Bexfield et al. 2012). Very old arsenic-bearing water flows upward through the borehole and exits the borehole into the aquifer above 200 mbls during periods in the

Figure 2. Conceptual hydrogeologic models of aquifers tapped by public-supply wells near (A) Middle Rio Grande aquifer system near Albuquerque, New Mexico, and (B) San Joaquin Valley aquifer system near Modesto, California.
winter when the well is inactive. Later, when the well is pumped, a portion of the groundwater derived from the upper part of the aquifer contains arsenic-bearing water from the lower part of the aquifer that had previously migrated through the borehole. The borehole flow data indicate that during pumping conditions about 40% of the groundwater produced by the well is derived from the well screen below 200 mbls, while 60% is derived from the well screen above 175 mbls (Figure 3).

**Modesto**

The city of Modesto is located in the San Joaquin Valley, which occupies the southern two-thirds of the Central Valley of California (Figure 1). The Central Valley is a large, asymmetric structural trough filled with marine and continental sediments up to 10,000 m thickness (Page 1986). The San Joaquin Valley is a depression more than 400 km long and 30 to 90 km wide and is bounded on the west and east by the Coastal Ranges and the Sierra Nevada, respectively. The Modesto area is situated on a belt of coalescing fluvial fans of low relief that lie between the dissected uplands to the east and the nearly flat surface of the valley floor. The underlying sediments are a heterogeneous mixture of unconsolidated and interlayered lenses of gravel, sand, silt, and clay (Burow et al. 2004). The aquifer is unconfined in the shallow part of the system, becoming semi-confined with depth. Depth to water varies from more than 20 m near the Valley margins in the east to less than 3 m near the center of the basin (Jurgens et al. 2008; Burow et al. 2008).

The Modesto area has a semiarid climate and receives an average of 315 mm of precipitation per year. Irrigation in the agricultural area just outside of Modesto has increased groundwater recharge rates to more than 600 mm/year in some locations (Burow et al. 2008). Recharge to the aquifer is primarily from agricultural irrigation and seepage from streams and rivers entering the valley near the mountains (Figure 2B). Pumping is the primary form of groundwater discharge. Groundwater not captured by pumping wells discharges primarily to the San Joaquin River, which drains the northern part of the San Joaquin Valley to San Francisco Bay (Burow et al. 2008). Although groundwater levels have not declined dramatically in the Modesto area, irrigation pumping and recharge from return flows have increased the rate of groundwater flow through the aquifer compared with predevelopment conditions and created persistent downward hydraulic gradients (Burow et al. 2004).

Public-supply wells in the vicinity of Modesto generally range in depth from about 18 m to over 120 m and commonly have screened intervals exceeding 20 m in length. The Modesto public-supply well selected for this study (referred to as the Modesto well herein) is screened from 31 to 113 mbls (Figure 4) and is generally pumped at 8640 m$^{3}$/d, when operated, yielding average rates, based on total seasonal withdrawals that range

![Figure 3. Well completion for Albuquerque public-supply well. Also shown are groundwater model layers above bottom of well and arsenic concentrations measured in groundwater sampled from nearby monitoring well; measured and simulated borehole flow data for ambient and pumped conditions in December 2007; and profile showing simulated percent of water withdrawn by depth interval during winter 2002 to 2003 and summer 2003.](image-url)
Groundwater Flow Models

Albuquerque

Groundwater flow in a 24-km² area surrounding the Albuquerque well was simulated with a local scale model that was numerically coupled to a modified version of the regional groundwater flow model of the Middle Rio Grande Basin (Heywood 2013). Both the local and regional models were developed using MODFLOW and utilized transient simulations that represented the period 1900 through 2008. Conditions prior to 1900 were represented by a single steady-state stress period. Fifteen 5-year stress periods represented 1900 through 1974 and fifteen 1-year stress periods represented 1975 through 1989. The period from 1990 through 2008 was divided into annual cycles that each contained a 230-day summer stress period (beginning in March) followed by a 135-day winter stress period to represent increased pumping in the summer and decreased pumping during the winter. The winter of 2007 to 2008 was further divided into shorter stress periods (not included in the original model of Heywood, 2013) represent a month-long shutdown of the Albuquerque well, followed by a 1-day stress period of pumping to represent intraborehole flow during borehole flow logging in December 2007. Average seasonal withdrawal rates were based on the reported daily pumpage, and a withdrawal rate of 3630 m³/d was specified for the 1-day stress period in December 2007, which was the measured rate during borehole flow logging.

With respect to the regional model, the local model domain is spatially discretized with a 5:1 horizontal refinement ratio, resulting in a 40 by 60 grid of square cells, each 100 m on a side. The nine layers in the regional model are refined vertically into 45 local model layers. The combined thickness of the top two model layers ranges from 25 to 134 m to accommodate the variable thickness of the unsaturated zone. The underlying 96-m thick section of the aquifer at intermediate depths (including the upper quarter of the Albuquerque well screen) was discretized with 32 relatively thin 3-m layers (Figure 3) to represent heterogeneity in hydraulic conductivity. The deeper layer thicknesses ranged from 24.5 to 61 m, with the exception of the bottom three layers that retained the same thicknesses (305 to 1983 m) as the bottom layers of the regional model.

The spatial distribution of hydraulic conductivity within the 96-m intermediate depth section in the local model domain was generated with Transition Probability Geostatistical Software (TPROGS; Carle et al. 1998). Values of low, intermediate, and high hydraulic conductivity statistically generated with TPROGS were conditioned on the distribution of fine, moderate, and coarse-grained materials (0.09, 0.8, and 34 m/d, respectively) determined from geophysical and lithologic logs at 15 boreholes within the model domain (Heywood 2013). The distribution of hydraulic conductivity in model layers above and below the 96-m section (8 to 60 and 0.02 to 9 m/d, respectively) was similar to that in the regional model, but the values were adjusted during calibration to measured water levels and CFC, tritium, and C-14 concentrations measured in monitoring wells within the local model area.

The local model was run independently from the regional model using time-varying specified heads for the lateral boundaries that were previously computed by a coupled regional-local model simulation using the local grid refinement method of MODFLOW-LGR2 (Mehl and Hill 2013). The top model layer contains specified flow boundaries that represent recharge from sewer and water distribution pipelines, infiltration from an unlined storm water diversion canal, and infiltration beneath ponds and irrigated fields. Groundwater withdrawals from 33 wells within the local model domain were simulated with the Multi-Node Well Package (MNW2) of MODFLOW.
Figure 4. Well completion data and borehole flow data for Modesto public-supply well (modified from Jurgens et al. 2008). Also shown are groundwater model layers and nitrate, uranium, and specific conductance concentrations measured in groundwater sampled from nearby monitoring well; measured and simulated borehole flow data for pumped conditions in August 2004; and profile showing simulated percent of water withdrawn by depth interval during winter and summer using reported pumping rates. Negative percent indicates outflow of water from well.

(Konikow et al. 2009). The transient flow fields computed by the local model were used to simulate the transport of five environmental tracers (carbon-14, tritium, and three chlorofluorocarbon species: CFC-11, CFC-12, and CFC-113) with the solute transport code MT3DMS (Zheng and Wang 1999).

Parameters that represented recharge, hydraulic conductivity and effective porosity in the local model were estimated using PEST (Doherty 2004) to fit simulated water levels to 117 water level measurements and simulated concentrations of the five environmental tracers to 126 concentration measurements (Heywood 2013). The calibrated model reproduces measured water levels with a standard error of 2.1 m (10% of the 20-m measurement range) and also reproduces the measured distribution of intraborehole flow in the Albuquerque well under pumped conditions in December 2007 (Figure 3).

The proportions of recent (post-1950) and very old (arsenic-bearing) groundwater pumped by the Albuquerque well were estimated in separate 108-year transport simulations of these two components of groundwater. The remaining proportion of water pumped by the Albuquerque well corresponds to water with an intermediate age between the recent and very old fractions that was not represented explicitly in the transport simulations. The initial concentration of recent water solute was specified as zero throughout the model domain. Recharge that entered the model domain after 1950 was assigned a concentration of 100% recent water. Initial concentrations of zero and 100% were specified for the very old groundwater fraction above and below 250 mbls, respectively.

Modesto

Groundwater flow in a 29-km² area surrounding the Modesto well was simulated with a modified transient version of the steady-state flow model of Burow et al. (2008), to represent seasonal changes in pumping. The local scale model had a uniform grid of 200 rows with 34-m spacing and 100 columns with 72-m spacing and 200 layers with a uniform thickness of 0.6 m (Burow et al. 2008). The thin model layers correspond to the thickness of individual hydrofacies units, whose spatial distribution is constrained by borehole lithologic data. The spatial variation of hydraulic conductivity within the flow model was based on one realization of the spatial distribution of hydrofacies selected from a set of many realizations (Burow et al. 2008) that was constructed with a three-dimensional hydrofacies model using the program TPROGS (Carle et al. 1998).

Lateral boundaries of the local model were specified using head and flux values from the regional groundwater flow model of the northeastern San Joaquin Valley (Phillips et al. 2007) that encompassed the Modesto area. Recharge in the local model was derived from agricultural and urban water budget subareas from the regional model and includes agricultural return flow and
leakage from water distribution lines (Burow et al. 2008). In the steady-state local model (Burow et al. 2008), groundwater withdrawals were distributed among 22 production wells, seven of which were represented with the Multi-Node Well (MNW) package of MODFLOW (H alford and Hanson 2002). In the revised transient local model, the Modesto well was represented with the revised Multi-Node Well Package (MNW2) of MODFLOW (Konikow et al. 2009), and the remaining 21 wells were represented with the MODFLOW Well Package (Harbaugh 2005). Flows to and from these 21 wells for each model layer were specified using the flows previously computed by the MNW package for the steady-state simulation. Average seasonal withdrawal rates were based on the reported daily pumping.

Burow et al. (2008) calibrated the original steady-state version of the local model using a combination of parameter estimation with MODFLOW (Hill et al. 2000) followed by a systematic manual calibration to estimate hydraulic conductivities of the four hydrofacies: gravel, sand, muddy sand, and mud. The calibrated model reproduces measured water levels in 18 monitoring wells screened at multiple depths with a standard error of 0.2 m (11% of the 6.5-m measurement range). Simulated tracer concentrations match measured sulfur hexafluoride (SF6) and 3H concentrations in the Modesto well reasonably well (0.4 vs. 0.7 pptv and 5.8 vs. 4.6 TU) (Burow et al. 2008).

The overall pattern of simulated intraborehole flow within the Modesto well matches the observed intraborehole flow in August 2004 reasonably well (Figure 4) but is offset upward by less than 10 m and over predicts the percentage of water pumped from the upper part of the well screen. The specified withdrawal rate (6650 m3/d) in the simulations is about 24% less than the average rate during measurement. Little inflow was measured above 40 mbls, probably as a result of mineral encrustation that was observed above this depth in the well screen (Burow et al. 2008). Flow to the borehole above 40 mbls could be diverted through the gravel pack and enter the well screen beneath this zone of encrustation, accounting for measured flow rates greater than those simulated. Measured flow near the bottom of the well screen was also not reproduced, possibly because the statistical characterization of hydraulic conductivity does not accurately represent coarse materials at this depth.

The proportion of recent water (recharge) that is assumed to be the source of nitrate and uranium pumped by the Modesto well (Jurgens et al. 2008) was estimated in a separate 25-year transient simulation that tracked the transport of a recent water solute using MT3DMS until the concentration distribution reached a quasi-equilibrium condition. The initial recent water solute concentration was specified as zero throughout the model domain and entered the transport simulation as recharge with a concentration of 100%. The 25 annual periods were divided into winter and summer stress periods (November through April and May through October, respectively) of nearly equal length. Recharge and groundwater withdrawals were specified for each season by apportioning 10% of the estimated annual flows in the year 2000 to the winter and 90% to the summer (City of Modesto, Public Works Department, written communication, 2006). The steady-state distribution of head was specified as the initial head distribution for the transient simulation.

Results and Discussion

Albuquerque

The simulated percentages of recent (post-1950) and old arsenic-bearing waters pumped by the Albuquerque well from 1975 through 2008 are illustrated in Figure 5. The percentage of intermediate-age water in the aquifer accounts for the remainder of the water pumped from the well and is not shown. The increasing percentage of recent water pumped by the well from 1975 through 1986 corresponds to a period of increased groundwater withdrawals in the Albuquerque area (Figure 5A). Simulated pumping rates were higher in the summer than in the winter after 1990, resulting in a larger simulated percentage of recent water pumped in the summer (5% to 10%) than in the winter (2% to 8%). The average seasonal pumping rates differed by a factor of four after 2000, causing marked declines in the simulated percentage of recent water pumped in the winter, and a correlated increase in the percentage of arsenic-bearing water pumped (Figure 5B). The simulated increase in the percentage of arsenic-bearing water is more than three times the decrease in the percentage of recent water because a longer portion of the well is screened through the deeper part of the aquifer that contains arsenic-bearing water and more water is produced through this interval. The simulated seasonal difference in recent water pumped after 2000 (approximately 5%) agrees with the results of ternary mixing models of environmental tracer concentrations for this site (11% recent water pumped in the summer compared to 6% pumped in the winter; Jurgens et al. 2014). The simulated percent of arsenic-bearing water pumped in the summer (35%) is also consistent with the results of the ternary mixing model (39%).

Simulations for three different rates of winter pumping indicated that the percentage of arsenic-bearing water pumped by the Albuquerque well during winters was strongly influenced by the average pumping rate (Figure 6). Summer pumping rates were based on total summer withdrawals from 2000 through 2008, while the 1380-m3/d winter rate simulation is based on average withdrawals during winters from 2000 through 2008. The percentage of arsenic-bearing water in the well decreases as the average winter-pumping rate increases and ranges from 90% with no winter pumping to about 40% with a rate of 2160 m3/d, which is about 50% greater than the historical rate. The spike in the percentage of arsenic-bearing water in December 2007 followed the well shutdown, which was represented in the groundwater flow simulations.
The simulated percentage of arsenic-bearing water produced by the well is larger in the winter than in the summer because a higher proportion of water is produced from the deeper part of the well screen in the winter (Figure 3). About 50% of the flow into the well is derived from depths greater than 250 mbls in the winter, while only 30% of the flow is derived from these depths in the summer. Simulated hydraulic gradients toward the well are much steeper during the summer than the winter because of greater withdrawals from surrounding wells. Under the steeper summer gradient, more water produced by the Albuquerque well is derived from coarse layers that intersect the upper part of the well screen (in particular from 164 to 173 mbls, Figure 3) where arsenic concentrations are lower.

These results indicate that the percentage of arsenic-bearing water in the well decreases as the average winter pumping rate increases, thereby producing more water from shallow depths in the aquifer. The percentage of arsenic-bearing water produced by the well during the winter can be reduced from 55% to 45% by increasing the current average winter-pumping rate from 1380 to 2160 L/s, which would only reduce the arsenic concentration of pumped water by 1 to 2 μg/L (Figure 7). The asymptotic shape of the relationship between the percentage of arsenic-bearing water and the average winter-pumping rate indicates that little additional benefit could be gained by any further increase in the pumping rate.

Periods of inactivity also increase the percentage of arsenic-bearing water in the Albuquerque well. Under simulated ambient (nonpumping) conditions, arsenic-bearing water enters the well through the bottom 160 m of the well screen, flows upward through the wellbore under the prevailing hydraulic gradient, and exits the well through the upper part of the well screen (primarily 164 to 173 mbls). Although increased pumping in the summer could be large enough to remove the arsenic-bearing water from shallower depths in the aquifer, cessation of winter pumping over many years could result in increased arsenic concentrations at these depths in the aquifer. A separate simulation predicted the hypothetical change in the percentage of arsenic-bearing water in pumped water that would have resulted from the cessation of winter pumping from 2000 through 2008. An increase in the percentage of arsenic-bearing water (1% to 6%) was predicted up to 800 m northeast of the Albuquerque well at depths from 160 to 175 mbls 8 years after the cessation of winter pumping (Figure 8). The simulation likely under predicts the potential extent of migration of arsenic-bearing water, however, because the simulated rate of upward flow through the wellbore under ambient conditions is only one-fifth of the measured rate (1120 m³/d) during the 2007 shutdown. The under prediction of the measured upward flow suggests that the magnitude of the actual hydraulic gradient is larger than simulated, possibly because the...
Figure 8. Simulated migration of arsenic-bearing water from a public-supply well in Albuquerque, New Mexico, in winter 2008 after the hypothetical cessation of winter pumping beginning in winter 2000.

actual groundwater withdrawals during the 2007 shutdown were less than those represented in the flow and transport simulations.

Modesto

The simulated percentage of recently recharged nitrate- and uranium-bearing water pumped by the Modesto well during 25 years of pumping is illustrated in Figure 9. The remaining fraction of water pumped by the well is derived from lateral boundaries or recharge prior to the start of the simulation. The percentage of nitrate- and uranium-bearing water pumped by the well displays a steady seasonal pattern over 25 years with higher percentages in the winter (when average pumping rates are lower) than in the summer. By the end of the simulation period, the proportion of nitrate- and uranium-bearing water ranges seasonally from about 95% to 65% for average rates of pumping (780 and 6650 m³/d in winter and summer, respectively). The simulations indicate that the percentage of nitrate- and uranium-bearing water pumped in winter for the historical rate (780 m³/d) is slightly different from the composition of water in the well that would result with no winter pumping.

The simulated percentage of nitrate- and uranium-bearing water produced by the Modesto well is larger in the winter than in the summer because less water is produced from the deeper part of the screened interval during the winter (Figure 4). During summer, about 1990 m³/d (30% of the well yield) is derived from the upper 45 m of the aquifer that contains nitrate- and uranium-bearing water. During the winter, about 400 m³/d (46% of the well yield) is derived from this upper zone and no water enters the well from the transmissive zones below 80 m. Instead, the simulation indicates that about 95 m³/d flows downward through the wellbore and exits the well at depths below 90 m (Figures 4 and 10). The vertical flow through the wellbore in winter is driven by the downward hydraulic gradient that is pervasive.
throughout the model domain. A downward hydraulic gradient also occurs in summer, but the increased pumping throughout the model domain induces horizontal flow from the deeper part of the aquifer, including down gradient areas to the southwest.

The simulation results indicate that the percentage of nitrate- and uranium-bearing water in the well can be lowered by increasing the average winter-pumping rate, thereby producing more water from deeper depths in the aquifer. Model results using three different winter pumping rates indicate that the percentage of nitrate- and uranium-bearing water produced by the well can be reduced from 95% to 70% by substantially increasing the average winter-pumping rate, thereby producing more water from deeper depths in the aquifer. The hypothetical reduction in the percentage of nitrate- and uranium-bearing water and the average winter-pumping rate indicates that little additional benefit could be gained by any further increase in the pumping rate.

Periods of inactivity or low pumping can increase the percentage of nitrate- and uranium-bearing water pumped from the Modesto well. Under simulated ambient conditions, nitrate- and uranium-bearing water enters the well through the upper 65 m of the well screen, flows downward through the wellbore under the prevailing hydraulic gradient at a rate of 430 m$^3$/d, and exits the well at depths below 80 m. However, increased winter pumping could lower nitrate and uranium concentrations in the aquifer. The hypothetical reduction in the percentage of nitrate- and uranium-bearing water in pumped water after 8 years of increased winter pumping was computed by a 25-year simulation that specified 17 years of pumping at historical rates followed by 8 years in which the winter pumping rate was increased from 780 to 2250 m$^3$/d. The simulated increase in winter pumping affected a 2-km$^2$ area southwest (down gradient) of the Modesto well where the fraction of nitrate- and uranium-bearing water was reduced by 5% to 20% (Figure 12A). Most of the reduction within the aquifer occurred at 40 to 80 mbls (Figure 12B).

### Seasonal Pumping and Intraborehole Flow

The simulations of seasonal pumping for both the Albuquerque and Modesto public-supply wells represent constant pumping at average rates that are based on total reported withdrawals for the winter and summer periods. Both simulations indicate that lower average pumping rates during the winter alter the vertical distribution of flow through the well screens and cause degradation in the quality of pumped water. Both simulations also depict intraborehole flow that allows poor quality water to migrate through the wells during periods when they are inactive or pumped at low rates. This poor quality water exits the boreholes and contaminates depth intervals that previously contained good-quality water.

The actual pumping schedule at both wells is not constant, however. For example, in 2008, the Albuquerque well was only pumped about 2.3 h/d during winter and 11.7 h/d during summer. Intraborehole flow could occur during both periods when the well is not pumped for part of a day, but the seasonal periods of the transient simulation are too long to resolve this process. The transfer and storage of poor quality water through intraborehole flow could have a significant effect on the quality of pumped water. The quantity of ambient intraborehole flow through the Albuquerque well during the winter 2008 (estimated using the measured rate of 1120 m$^3$/d) was about 120,000 m$^3$ or 60% of the total volume of water pumped during the winter. Based on the measured flow logs under ambient and pumping conditions (Figure 3) and the simulated flow profile under pumping conditions (Figure 8), the intraborehole flow exited the well at 164 to 173 mbls and a portion of this water was subsequently withdrawn from this interval by pumping. Additional transient simulations based on daily stress periods are required to determine the relative contributions of seasonal pumping and intraborehole flow to the water quality produced by both the Albuquerque and Modesto public-supply wells.

### Management Implications

Increased pumping rates from long-screened public-supply wells during winter to reduce intraborehole flow and improve the quality of the pumped water would require decreased pumping rates during summer, if the total annual water demand was to remain constant. The pumped water in excess of the demand in winter would need to be stored for later use in summer. Simulation results indicate that there is an asymptotic relationship between the quality of water pumped from such wells and the rate of winter pumping, so improvements in water quality could be marginal. Water suppliers have
adopted other methods for improving the quality of water pumped from wells affected by intraborehole flow. Water pumped in winter from the Modesto well is blended with better quality water from surface supplies to reduce the concentrations of uranium before the water enters the distribution system (Ashton 2006). In Antelope Valley, California, the lower half of a public-supply well was grouted to reduce arsenic concentrations of pumped water, with no substantial reduction in well yield (Haldorf et al. 2010). This strategy would be difficult to implement, however, in the Modesto well where the poor quality water enters the well through the upper part of the screen and could significantly reduce the yield from other wells in different hydrogeologic settings. The potential costs of increased pumping and storage during winter would need to be compared with improvements in pumped water quality and the costs of alternative methods of mitigating the effects of intraborehole flow, in order to determine the most prudent course of action.

Conclusions

Water quality issues associated with seasonal pumping and intraborehole flow through both the Albuquerque and Modesto public-supply wells are similar. Both wells are pumped at similar average seasonal rates, with higher pumping rates in the summer and lower rates in the winter and are surrounded by other wells that are also pumped at different seasonal rates. As a result of this situation, both public-supply wells produce water requiring additional treatment to maintain potable quality in the winter when pumping rates are lower. Important differences also exist between conditions at each well, however. The source of poor quality water in the Albuquerque well is more than 20,000-year old, arsenic-bearing water from depths greater than 250 m, whereas in the Modesto well the poor quality source is recent (less than 50 years old) nitrate- and uranium-bearing water from depths less than 45 m. The vertical hydraulic gradient during ambient conditions in the winter is upward at the Albuquerque well and downward at the Modesto well.

Both the Albuquerque and Modesto public-supply wells produce poorer quality water in winter because at lower average pumping rates, less water is derived from the parts of the aquifer that contain better quality water. In contrast, the combined pumping during the summer from many surrounding wells cause larger hydraulic gradients in the vicinity of both wells that induce more lateral flow to the wells from parts of the aquifer that contain better quality water. Water quality in both wells could be improved by increasing the average winter-pumping rates. For example, the percentage of arsenic-bearing water produced by the Albuquerque well during the winter can be reduced from 55% to 45% by doubling the average winter-pumping rate. Similarly, the percentage of nitrate- and uranium-bearing water produced by the Modes to well during the winter could be reduced from 95% to 70% by nearly tripling the average winter-pumping rate.

Poor quality water enters both wells during ambient or low pumping conditions during the winter and then flows through the wellbore before exiting the well into parts of the aquifer that contain better quality water. This intraborehole flow is temporarily stored in the aquifer and then withdrawn by subsequent pumping. The relative contribution of this process to the degradation of pumped water could not be determined with the seasonal stress periods of the simulations described in this study. Transient simulations with daily temporal resolution are required for both models to better quantify the effect of intraborehole flow on pumped water quality.
Groundwater quality in the shallower parts of the aquifer near the Albuquerque public-supply well could deteriorate if winter pumping ceased and allowed upward intraborehole flow of arsenic-bearing water from the deeper parts of the aquifer. Simulation results predict an increase in the percentage of arsenic-bearing water (1% to 6%) in the shallow part of the aquifer as much as 800 m northeast of the well 8 years after the cessation of winter pumping. Conversely, groundwater quality in the deeper parts of the aquifer near the Modesto public-supply well would improve if winter pumping rates were increased to prevent downward intraborehole flow of nitrate- and uranium-bearing water from the shallower parts of the aquifer. Simulation results predict a decrease in the percentage of nitrate- and uranium-bearing water (5% to 20%) in the deep part of the aquifer in a 2-km² area southwest (down gradient) of the Modesto well.

Acknowledgment

Information required to construct and calibrate the groundwater flow models described in this paper was acquired with the assistance of members of the national Transport of Anthropogenic and Natural Contaminants (TANC) team that was part of the U.S. Geological Survey’s National Water Quality Assessment (NAWQA) Cycle 2 study.

References

Ashton, A. 2006. Shuttered wells to service city again; Filters, diluting tanks to treat tainted water. Modesto Bee, September 19, 2006.

Bexfield, L.M., and B.C. Jurgens. 2014. Effects of seasonal well operation on hydrologic conditions and public-supply-well vulnerability to contamination. Ground Water. In press.

Bexfield, L.M., B.C. Jurgens, D.M. Crilley, and S.C. Christenson. 2012. Hydrogeology, water chemistry, and transport processes in the zone of contribution of a public-supply well in Albuquerque, New Mexico. USGS Scientific Investigations Report 2011-5182. Reston, Virginia: USGS.

Bexfield, L.M., C.E. Heywood, L.J. Kaufman, G.W. Rattray, and E.T. Vogler. 2011. Hydrogeologic setting and groundwater flow simulation of the Middle Rio Grande Basin regional study area, New Mexico (section 2). In Hydrologic Settings and Groundwater-Flow Simulations for Regional Investigations of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Investigations Begun in 2004, ed. S.M. Eberts. USGS Professional Paper 1737-B. Reston, Virginia: USGS.

Bexfield, L.M., and S.K. Anderholm. 2002. Estimated water-level declines in the Santa Fe Group aquifer system in the
Abel Groundwater Science and Engineering, 152: 526–537.

Halford, K.J., C.L. Stamos, T. Nishikawa, and P. Martin. 2010. Arsenic management through well modification and simulation. Ground Water 48: 526–537.

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 finite-difference ground-water flow model, version MODFLOW-96 and MODFLOW-2000. USGS Open-File Report 02-293. Reston, Virginia: USGS.

Hanson, R.T., L. Zhen, and C.C. Faunt. 2004. Documentation of the Santa Clara Valley regional ground-water/surface-water flow model, Santa Clara County, California. USGS Scientific Investigations Report 2004-5231. 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.

Heywood, C.E. 2013. Simulations of groundwater flow, transport, and age in Albuquerque, New Mexico, for a study of transport of anthropogenic and natural contaminants (TANC) to public-supply wells. USGS Scientific Investigations Report 2012-5242, 5 p. Reston, Virginia: USGS.

Hill, M.C., E.R. Banta, A.W. Harbaugh, and E.R. Anderman. 2000. MODFLOW-2000, the US Geological Survey Modular Ground-Water Model—User guide to the observation, sensitivity, and parameter-estimation processes and three-post-processing programs. U.S. Geological Survey Open-File Report 00-184, 209 p. Reston, Virginia: USGS.

Izbicki, J.A., A.H. Christensen, and R.T. Hanson. 1999. U.S. Geological Survey combined well-bore flow and depth-dependent water sampler. U.S. Geological Survey Fact Sheet 196-99, 2 p. Reston, Virginia: USGS.

Johnson, R.L., B.R. Clark, M.K. Landon, L.J. Kauffman, and S.M. Eberts. 2011. Modeling the potential impact of seasonal and inactive multi-aquifer wells on contaminant movement to public water supply wells. Journal of the American Water Resources Association 47, no. 3: 588–596.

Jurgens, B.C., M.S. Fram, K. Belitz, K.R. Burow, and M.K. Landon. 2010. Effects of groundwater development on uranium: Central Valley, California, USA. Ground Water 48: 913–928.

Jurgens B.C., K.R. Burow, B.A. Daligish, and J.L. Shelton. 2008. Hydrogeologic, water chemistry, and factors affecting the transport of contaminants in the zone of contribution of a public-supply well in Modesto, eastern San Joaquin Valley, California. USGS Scientific Investigations Report 2008–5156. 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.

Landon, M.K., B.C. Jurgens, B.G. Katz, S.M. Eberts, K.R. Burow, and C.A. Crandall. 2010. Depth-dependent sampling to identify short-circuit pathways to public-supply wells in multiple aquifer settings in the United States. Hydrogeology Journal 18: 577–593.

Ma, R., C. Zheng, M. Tonkin, and J.M. Zachara. 2010. Importance of considering intraborehole flow in solute transport modeling under highly dynamic flow conditions. Journal of Contaminant Hydrology 123: 11–19.

Mehl, S.W., and M.C. Hill. 2013. MODFLOW–LGR—Documentation of Ghost Node Local Grid Refinement (LGR2) for Multiple Areas and the Boundary Head and Flow (BFH2) Package. USGS Techniques and Methods 6-A44. Reston, Virginia: USGS.

Page, R.W. 1986. Geology of the fresh ground-water basin of the Central Valley, California with texture maps and sections. USGS Professional Paper 1401-C. Reston, Virginia: USGS.

Phillips, S.P., K.R. Burow, D.L. Rewis, J.L. Shelton, and B.J. Jurgens. 2007. Hydrogeologic settings and ground-water flow simulations of the San Joaquin Valley regional study area, California (section 4). In Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001, ed. S.S. Paschke. USGS Professional Paper 1737-A. Reston, Virginia: USGS.

Rotzoll, K. 2012. Numerical simulation of flow in deep open boreholes in a coastal freshwater lens, Pearl Harbor Aquifer, O’ahu, Hawai‘i. USGS Scientific Investigations Report: 2012-5009. Reston, Virginia: USGS.

Rotzoll, K. 2010. Effects of groundwater withdrawal on borehole flow and salinity measured in deep monitor wells in Hawaii—Implications for groundwater measurement. USGS Scientific Investigations Report: 2010-5058. Reston, Virginia: USGS.

Thorn, C.R., D.P. McAda, and J.M. Kernodle. 1993. Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, central New Mexico. USGS Water-Resources Investigations Report 93-4149. Reston, Virginia: USGS.

Zheng, C., and P.P Wang. 1999. MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems: Documentation and user’s guide; prepared for U.S. Army Corps of Engineers; monitored by U.S. Army Engineer Research and Development Center.

Zinn, B.A., and L.F. Konikow. 2007. Effects of intraborehole flow on groundwater age distribution. Hydrogeology Journal 15: 633–643.