Prepared in cooperation with the City of Sierra Vista

Evaluation of Simulations to Understand Effects of Groundwater Development and Artificial Recharge on Surface Water and Riparian Vegetation, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona

Open-File Report 2012–1206

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

FRONT COVER
Virga at sunset over the Upper San Pedro Basin, Arizona.

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KEN SALAZAR, Secretary

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2] ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Datums

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Vertical Datum of 1988 (NAVD 88).”

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Datum of 1983 (NAD 83).”

Altitude, as used in this report, refers to distance above the vertical datum.

Evaluation of Simulations to Understand Effects of Groundwater Development and Artificial Recharge on the Surface Water and Riparian Vegetation, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona

By Stanley A. Leake and Bruce Gungle

Abstract

In 2007, the U.S. Geological Survey documented a five-layer groundwater flow model of the Sierra Vista and Sonoran subwatersheds of the Upper San Pedro Basin. The model has been applied by a private consultant to evaluate the effects of projected groundwater pumping through 2105 and effects of artificial recharge at three near-stream sites for 2012–2111. The main concern regarding simulations of long-term groundwater pumping is the effect of artificial model boundaries on modeled response, particularly for pumping near Cananea, Sonora, Mexico, which is adjacent to an artificial no-flow boundary. Concerns regarding the simulations of the effects of artificial recharge near streams include the resolution of the model and the representation of the model properties at the site scale; a possible limited ability of the model to correctly apportion recharge response between increased streamflow and increased evapotranspiration; a limited ability of the model to simulate detailed geometries of artificial recharge areas and evapotranspiration areas; and stream locations with the 820-foot grid spacing of the basin-scale model. In spite of these concerns, use of the U.S. Geological Survey five-layer groundwater flow model by the consultant are reasonable and valid.

Introduction

Pool and Dickinson (2007) published the first five-layer groundwater model of the Sierra Vista and Sonoran subwatersheds of the Upper San Pedro Basin (figs. 1 and 2). Models predating Goode and Maddock (2000) had used a maximum of three layers that did not extend to the headwaters of the San Pedro River near Cananea, Sonora, Mexico (Freethey, 1982; Vionnet and Maddock, 1992; Corell and others, 1996). Goode and Maddock (2000) modeled the entire length of the Upper San Pedro Basin using a four-layer scheme with a model domain that only included the central alluvial portion of the watershed. In contrast, Pool and Dickinson (2007) simulated flow in the alluvial sediments as well as in consolidated rocks underlying alluvium, and in adjacent mountains within the entire Sonoran and Sierra Vista subwatersheds.

Since the release of the groundwater model by Pool and Dickinson (2007) it has been used for specific, limited tasks, including an assessment of the effects of recharge from the City of Sierra Vista treated effluent recharge facility (Brown and Caldwell, 2009) and a study funded by Fort Huachuca (Laurel Lacher, Lacher Hydrologic Consulting, oral commun., 2011). The topic of this review is a subsequent application by Lacher (2011) that updated the model and ran simulations through 2105 with and without population-driven increases in pumping, and a further application by Lacher (2012) that considers the effects of artificial recharge through 2011 at three potential near-stream sites. These applications are the broadest use of the model to date, both spatially and temporally. It is thus worthwhile to evaluate how the USGS model was used, evaluate its apparent strengths and weaknesses, and offer suggestions and strategies for maximizing the strengths and minimizing the weaknesses of this tool in future modeling work.

Purpose and Scope

This report evaluates the use of the USGS groundwater flow model of Pool and Dickinson (2007) by Laurel Lacher of Lacher Hydrological Consulting (Lacher, 2011; 2012). In addition to evaluating Lacher's work, this report provides a general information on effects of groundwater pumping and artificial recharge on connected surface water and evapotranspiration.

Following a brief description of the study area, we discuss concepts related to capture of surface water due to pumping. This is followed by a discussion of the effects of artificial recharge on surface water and evapotranspiration. Next, we present an evaluation of the possible effects of boundary conditions on model projections by Lacher (2011), and evaluate considerations for using the model for the recharge scenarios in Lacher (2012). Finally, we evaluate Lacher's (2012) application of the model more generally and discuss the validity of her conclusions.

Description of Study Area

The portion of the Upper San Pedro Basin described in the USGS model of Pool and Dickinson (2007) extends from the headwaters of the San Pedro River near Cananea, Sonora, Mexico, located about 60 mi south of the international border with Mexico, to the northern boundary of the Sierra Vista subwatershed, about a 1 mi north of the ghost town of Fairbank, Arizona (fig. 1). The total area modeled is about 1,750 mi^2. The Sierra Mariquita, Sierra Los Ajos, and Sierra San Jose are on the margins of the subwatershed in Sonora. The Huachuca Mountains, Mule Mountains, and Tombstone Hills are the primary ranges on the boundaries of the Sierra Vista subwatershed in Arizona. The San Pedro River runs south to north in an entrenched channel through the center of a fault-block basin. The highest range is the Huachuca Mountains (9,466 ft), on the western edge of the Sierra Vista subwatershed just north of the international border. The largest urban area within the modeled domain, the City of Sierra Vista, is between the Huachuca Mountains and the San Pedro River. The population of Sierra Vista in 2011 (including the U.S. Army population at Fort Huachuca) was about 45,000.

The Sierra Vista subwatershed includes an alluvium-filled fault-block basin. The basin is roughly bi-sected by the San Pedro River. Alluvial deposits that fill the basin to a depth of as much as 800 ft—Upper and Lower Basin Fill—are the major water-bearing units in the subwatershed. The semi-consolidated Pantano Formation underlies the basin fill and in places may be an important water-bearing unit that is well connected to the overlying aquifer (Pool and Coes, 1999). Adjacent to, and underlying, the river is a stringer of Pre- and Post-entrenchment alluvium that is about 30 ft thick. The stringer of alluvium is the most permeable part of the hydrogeologic system that drains groundwater from the basin fill, but also is a receptacle that temporarily accepts flood infiltration that discharges back to the river between periodic floodflows.

Timing of precipitation in the region is bimodal. About one-half falls during the North American monsoon, July through mid-September (Adams and Comrie, 1997), and another one-third comes during the winter months. Average annual precipitation across the basin floor is about 16 in. (U.S. Department of the Interior, 2012), although a greater amount falls in the mountains around the basin edge. The low elevation basin vegetation is predominantly grassland and desert scrub with encroaching mesquite. This vegetation grades into oak woodlands in the mountain foothills. Conifers and some aspen occur at the highest elevations.

Numerous studies have described the geology, biology, climate, historical, cultural, and socioeconomic setting of the region. Kennedy and Gungle (2010) provide a comprehensive list of such references and the reader is directed there for more detailed information. Previous groundwater models include those of Freethey (1982), Vionnet and Maddock (1992), Corell and others (1996), and Goode and Maddock (2000). Other evaluations of the hydrologic resources of the region and the current state of the groundwater and surface-water systems include Bryan and others (1934), Brown and others (1966), S.G. Brown and B.N. Aldridge (unpub. data, 1973), Arizona Department of Water Resources (1990), Pool and Coes (1999), Goodrich and others (2000), U.S. Department of the Interior (2005, 2006, 2007, 2008, 2010, 2012), Coes and Pool (2005), Arizona Department of Water Resources (2005a, 2005b), Gungle (2006), Thomas and Pool (2006), Leenhouts and others (2006), Pool and Dickinson (2007), Leake and others (2008), Scott and other (2008), and Kennedy and Gungle (2010).

Concepts Related to Depletion and Accretion of Surface Water from Groundwater Pumping and Artificial Recharge

An understanding of basic concepts of the effects of groundwater withdrawals and artificial recharge on the regional aquifer and connected surface water is important for management of water resources. The following discussion presents basic concepts of system response to pumping and artificial recharge in terms of changes in streamflow and evapotranspiration.

General Concepts of Streamflow and Evapotranspiration Response to Groundwater Pumping

Induced change in rates of inflow to and outflow from an aquifer caused by groundwater withdrawals is referred to as "capture." Concepts of capture were articulated by Theis (1940), who observed that all water withdrawn by a well is balanced by a loss of water from somewhere. Immediately after a well begins withdrawing water, all loss comes from storage around the well. As time progresses, the cone of depression around a well can expand to areas of recharge and discharge, possibly resulting in increases in inflow to an aquifer, decreases in outflow from an aquifer, or a combination of both. Major mechanisms that are responsible for increases in natural recharge and decreases in discharge to surface-water features, resulting from an expanding cone of depression, are summarized as follows:

Increases in natural recharge

- Increased groundwater gradients away from surface-water features (such as losing streams)
- Movement of groundwater divides into an adjacent basin
- Lowering of the water table below the land surface to allow infiltration of previously rejected recharge from runoff

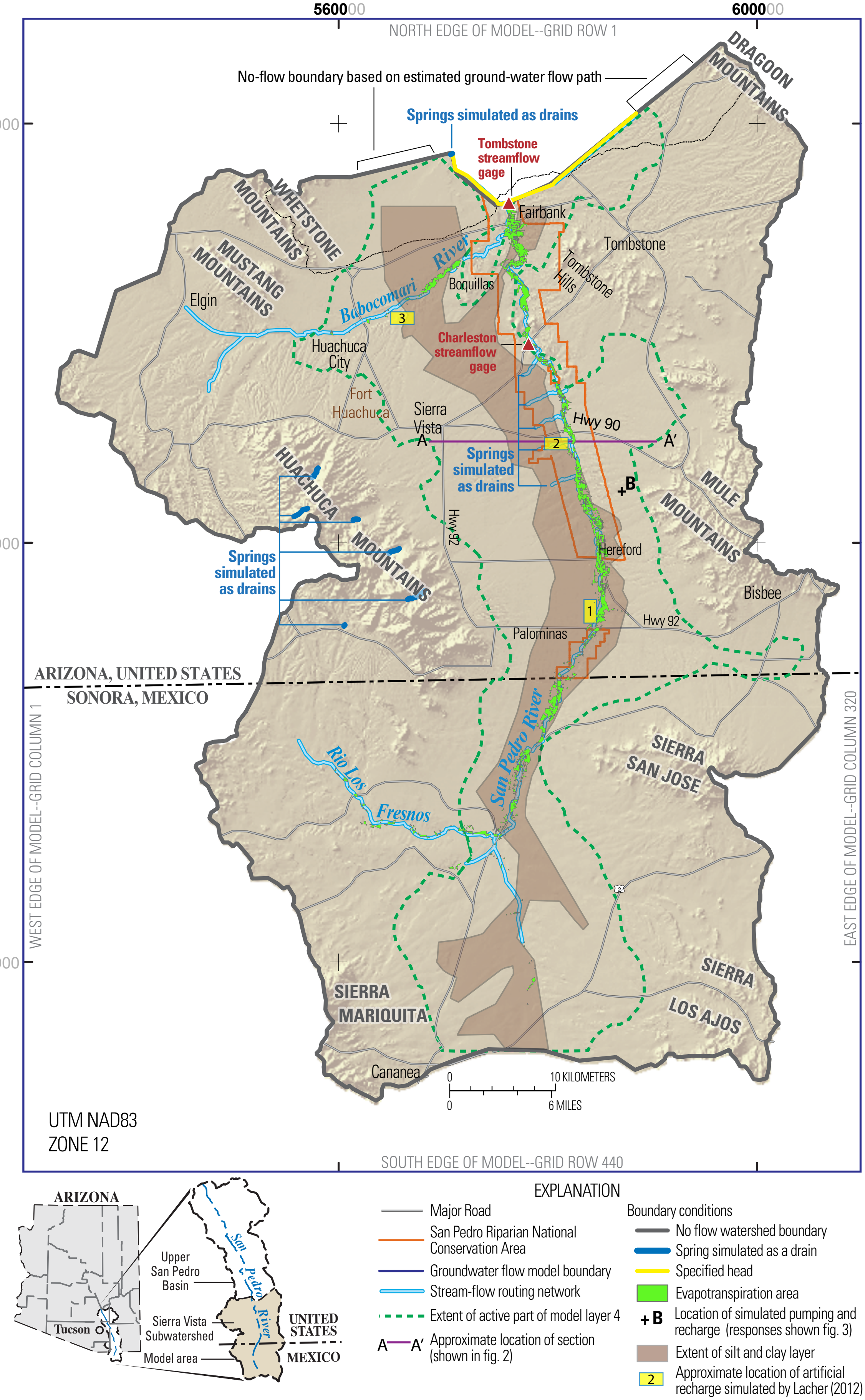

Figure 1. Map showing the lateral extent and boundary conditions of the upper San Pedro Basin groundwater flow model, Arizona, USA, and Sonora, Mexico. Modified from Pool and Dickinson (2007).

Decreases in discharge

- Decreased groundwater gradients towards surface-water features (such as gaining streams)
- Lowering of the water table in areas where groundwater can evaporate or be transpired by phreatophytes

For more in-depth discussions of the effects of groundwater pumping on connected surface water and evapotranspiration, see Barlow and Leake (in press) and Leake (2011). For discussions of potential capture in the Sierra Vista subwatershed, see Leake and others (2008).

Capture can be computed by analytical solutions for simple systems (Glover and Balmer, 1954), but in flow systems with complex aquifer and surface-water geometry and aquifer heterogeneity, groundwater-flow models are likely to produce more realistic simulations of capture. Leake and others (2008) used the groundwater-flow model by Pool and Dickinson (2007, fig. 1) to study capture for hypothetical pumping locations in the lower basin fill of the Upper San Pedro Basin aquifer. The results were "capture maps" that show, for any hypothetical well location in the lower basin-fill aquifer, the fraction of the pumping rate from reduced surface-water flow and evapotranspiration at specific pumping times. Such characterization of capture as a fraction of the well pumping rate is valid if the aquifer system responds linearly to pumping stress (Leake and others, 2008, 2010; Leake, 2011).

Example curves from an actual model run (fig. 3*A*) indicate how a model-computed decrease in aquifer storage, decrease in evapotranspiration and streamflow, and total depletion vary through time for the hypothetical pumping from the lower basin-fill aquifer at the location shown in figure 1 (+B). This set of curves illustrates the observation by Theis (1940) that the initial effect of a well is to take water from storage, as indicated by the rate of storage decrease being equal to 100 percent of the pumping rate at the start of pumping. In this example with a pumping well, "decrease in aquifer storage" represents a release of water from storage in the

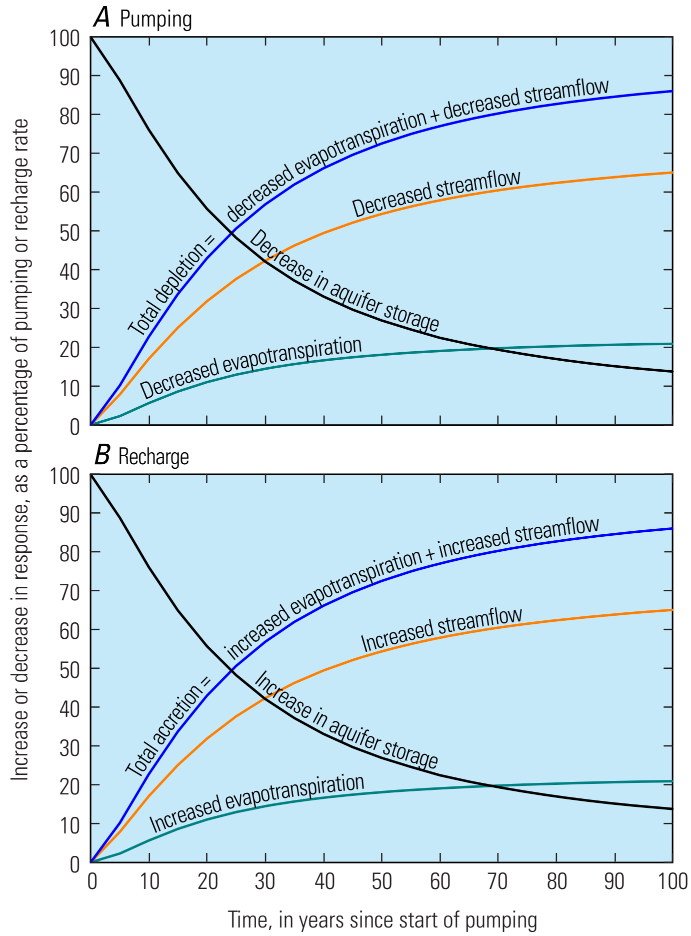

Figure 3. Graph showing model-computed system response to groundwater pumping (*A*) at a constant rate for location designated as "+B" on figure 1, upper San Pedro Basin, Arizona, USA, and Sonora, Mexico. Assuming that the system responds linearly to stresses, responses to artificial recharge (*B*) would be of the same magnitude as for pumping, but opposite in direction. Curves represent responses for pumping and artificial recharge in model layer 4, the lower basin fill aquifer.

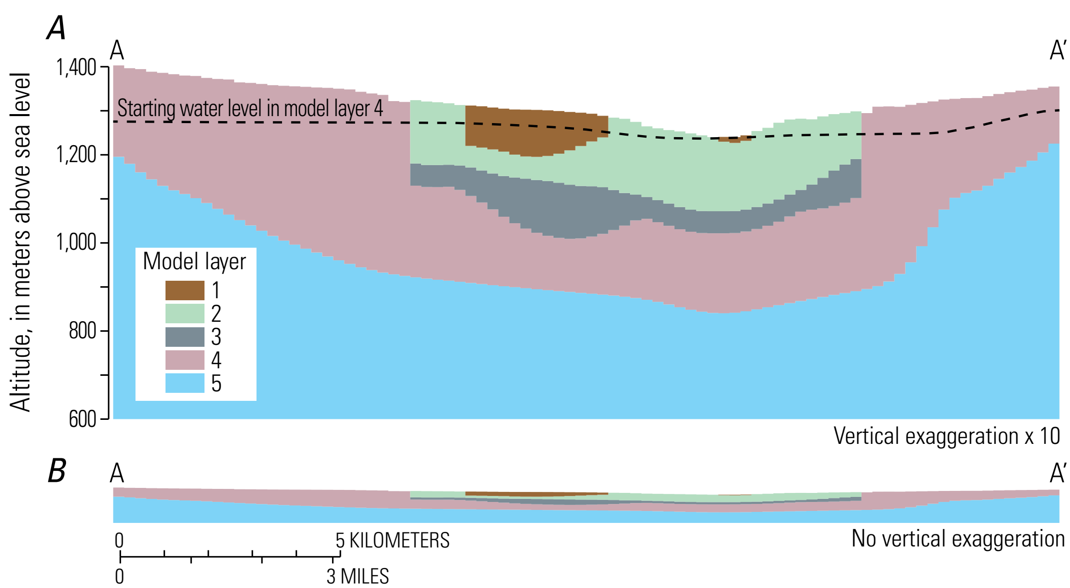

Figure 2. Representations of the geometry of model layers 1–4 and the upper part of layer 5 along section A–A′, shown with (*A*), and without (*B*) vertical exaggeration. Refer to figure 1 for location of section A–A′.

aquifer, including the largest effect of draining of pore spaces at the water table. Additional minor contributions may come from compression of the aquifer skeleton and expansion of water. With time, increased percentages of the pumping rate come from decreased evapotranspiration and streamflow depletion that is, capture). If the model been run to a new steady-state condition (with the added pumping), the rate of decrease in aquifer storage would have reached zero and all of the pumping rate would be accounted for by capture. In this particular case, the largest fraction of the pumping rate is streamflow depletion and the remainder is decreased evapotranspiration.

General Concepts of Streamflow and Evapotranspiration Response to Artificial Recharge

Artificial recharge at a constant rate has the opposite effects of pumping at a constant rate, including an initial effect of all water going into storage at the onset of artificial recharge. As a groundwater mound created by the artificial recharge expands to areas of connected surface water and evapotranspiration by plants, the effect of the recharge is to decrease natural recharge to the aquifer and increase discharge from the aquifer. Major mechanisms that are responsible for decreases in natural recharge and increases in discharge to surface-water features, resulting from an expanding mound of recharged water, are summarized as follows:

Decreases in natural recharge

- Decreased groundwater gradients away from surface-water features (such as losing streams)
- Movement of groundwater divides into the basin with artificial recharge
- Raising the water table to the land surface and preventing infiltration that would have previously recharged the aquifer

Increases in discharge

- Increased groundwater gradients towards surface-water features (such as gaining streams)
- Raising of the water table in areas where groundwater can evaporate or be transpired by phreatophytes; however, raising groundwater levels in some plant root systems can cause anoxic conditions that reduce transpiration.

If a system responds linearly to stresses, such as pumping and artificial recharge, the response to artificial recharge at a given rate will be the quantitative opposite of the response to pumping at the same rate. For example, curves shown in figure 3*B* for hypothetical recharge at the location shown on figure 1 (+ B) are identical to the curves in figure 3*A*, but the labeling reflects increase in aquifer storage, evapotranspiration, and streamflow accretion resulting from the recharge. Note, however, that as the reverse of curves in figure 3*A*, curves in figure 3*B* would represent response to artificial recharge to the lower basin fill aquifer. Artificial recharge to the aquifer in the upper San Pedro Basin is most likely to occur from gravity drainage of water from the land surface to the water table, which is above than the basin-fill aquifer in some locations, particularly near the San Pedro River. For that reason, Leake and others (2008) ran simulations to determine the response of the flow system to recharge to the uppermost active layer in the model by Pool and Dickinson (2007).

When considering use of artificial recharge to mitigate effects of groundwater pumping in the upper San Pedro Basin, it is important to understand that artificial recharge does not “armor” the river from the effects of groundwater pumping. In fact, a possible effect of artificial recharge between pumping centers and the river is to speed up the progression of capture from groundwater pumping. Although speeding the progression of capture is not likely to be significant, the effect could occur if the recharge causes rises in water levels that significantly increase the transmissivity of the aquifer. Instead of armoring, artificial recharge should be thought of as an offsetting effect of groundwater pumping on the river. An implication of this behavior is that effects of pumping and artificial recharge can be computed separately by a model and added together to get a combined effect. In fact, either response can be computed without specific knowledge of natural recharge and groundwater flow directions, as long as the aquifer transmissivity and storage coefficient is known, and pumping or recharge does not change the aquifer properties, or configurations, of connected surface water or areas of evapotranspiration (Leake, 2011). Consideration of movement of solutes from artificially recharged water, however, requires combined simulations of the natural flow system with pumping and artificial recharge rates represented.

Use of the U.S. Geological Survey Upper San Pedro Basin Groundwater Flow Model for Computing Long-Term Effects of Groundwater Pumping and Artificial Recharge

The groundwater-flow model (Pool and Dickinson, 2007) simulated transient groundwater conditions from December 1902 to February 2003, using two seasonal stress periods per year. Lacher (2011) made some minor corrections to historical recharge and pumping rates and used the model to make projections of future groundwater conditions through 2105. Lacher (2012) then used the model to study the effects of artificial recharge at three near-stream sites for 2012–2111. Although the model was designed to simulate effects of various pumping and recharge scenarios, any such application should include evaluations of possible effects of model limitations on the scenario being simulated. The following sections discuss some general considerations for use of the model by Pool and Dickinson (2007) as well as some specific thoughts on applications by Lacher (2011, 2012).

Structure of Model Layers

Lacher (2011, 2012) describes the model by Pool and Dickinson (2007) as having a "stacked bowl" configuration of model layers. When a cross section of the model is viewed with vertical exaggeration (fig. 2*A*), the layers appear as stacked bowls, with model layer 4 recessed into layer 5, layers 2 and 3 recessed into layer 4, and layer 1 recessed into layer 2. With no vertical exaggeration (fig. 2*B*), however, the true relatively flat nature of the layers can be seen.

The layering scheme of the model by Pool and Dickinson (2007) uses two common approaches to represent hydrologic units in model layers (fig. 4). In the approach taken by Pool and Dickinson (2007), the edges of the layers are truncated as shown in figures 2 and 4*B*, and there is no horizontal flow through the vertical edges (sides) of an upper layer from a lower layer. In an actual system, however, a vertical edge of a hydrogeologic unit is uncommon. Instead, units pinch out (thin to nonexistence) at the edges, grade into an adjacent unit, or are interbedded with material in an adjacent hydrogeologic unit (fig. 4*A*). Detailed representation of edges of hydrogeologic units in a basin-scale groundwater model is problematic because sufficient borehole and other subsurface data are not available to accurately define the complex geometry of the edges of a unit.

Units often are truncated in groundwater models rather than represented as tapering to zero thickness. Maintaining a certain amount of saturated thickness in all model cells allows for a robust solution of groundwater flow equations without using the drying and rewetting capability of the model for the thin model cells. The rewetting of cells introduces numerical instabilities of the model and is extremely problematic for obtaining robust solutions in groundwater flow models. Additionally, adjacent model cells with hydraulic conductivity differences on the order of several or more orders of magnitude can result from the approach shown in figure 4*C*. Such representations can cause numerical instability in solving for head and flow in a groundwater-flow model. Instability is minimized with the approach shown in figure 4*B*. Finally, although the approach shown in figure 4*B* ignores lateral groundwater flow into the edges of a flat-lying unit, that flow is likely to be insignificant in comparison to the amount of flow through the tops and bottoms of units. As shown in figure 2*B*, horizontal widths of bottoms and tops of all hydrologic units are large in comparison to the vertical dimensions of truncated edges. Areas of bottoms and tops of units, therefore, are much larger than areas of edges, and flow from one unit to another is not restricted because of this approach. For an example of a groundwater model that uses the approach shown in figure 4*C*, see Faunt and others (2004).

Effects of Artificial Boundary Conditions

If possible, boundaries in a groundwater model should represent physical boundaries of the aquifer system. A no-flow boundary is typically represented in a model where the permeable aquifer material terminates adjacent to laterally or vertically impermeable material. Other types of physical

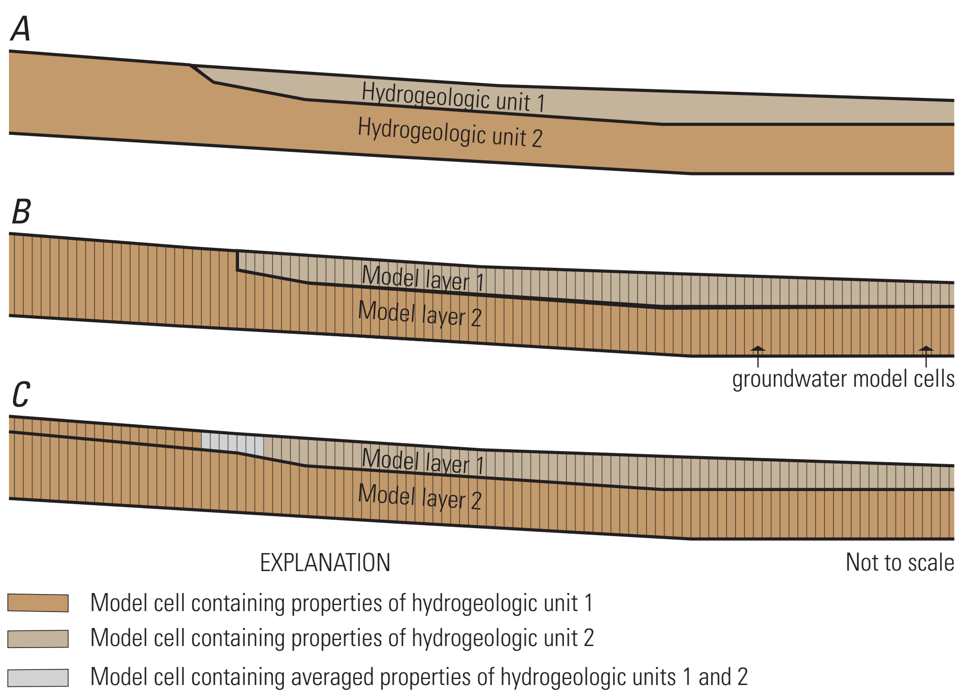

Figure 4. Generalized section showing two hydrogeologic units (*A*) and two approaches that can be used to represent those units in model layers. In the approach taken by Pool and Dickinson (2007), less-extensive shallower layers are inset into more extensive deeper layers (*B*). In an alternate approach, all model layers are laterally extensive and may contain more than one hydrogeologic unit (*C*).

boundaries are coincident with surface-water features or locations where water flows into or out of an aquifer at a known rate. Reilly and Harbaugh (p. 14,2004) state:

> "When physical hydrologic features that can be used as boundary conditions are far from the area of interest, artificial boundaries are sometimes used. The use of an artificial boundary should be evaluated carefully to determine whether its use would cause unacceptable errors in the model. For example, a no-flow boundary might be specified along an approximated flow line at the edge of a modeled area even though the aquifer extends beyond the modeled area. The rationale might be that the artificial boundary is positioned far enough from the area of interest that whatever is simulated in the area of interest would not cause significant flow across that area of the system."

Artificial boundaries in the Upper San Pedro Basin model occur as no-flow boundaries around much of the model perimeter and as specified-head boundaries along two segments of the northern boundary. Pool and Dickinson (p. 42, 2007) were aware of potential problems with the no-flow boundary along the perimeter of the model for some model uses. They stated:

> "All boundaries in this model, except some flow boundaries along the northern extent, were assumed to be no-flow. There were several simulated areas where ground water could flow to adjacent ground-water flow systems; therefore, significant changes would render the no-flow assumption invalid. These conditions may occur where saturated permeable rocks, such as limestone or alluvial deposits, are continuous across the model boundary as in several areas, including the Mule Mountains, the Huachuca Mountains, and areas near Elgin and along the northern and southern model boundaries. These boundaries could be modified by simulating a larger extent, or by simulating the boundary as a general head boundary. Observed changes near boundaries are likely significant in the current simulations only where withdrawals for mine use have occurred near the Copper Queen and Cananea mines. Withdrawals near the Copper Queen mine were not simulated because of a lack of understanding of the ground-water flow system in the area. These withdrawals could only be simulated by using a greater extent in the area. Withdrawals near the Cananea mine were simulated, but induced inflow from the adjacent basin was assumed to be minimal because withdrawals also occur south of the boundary. Errors in the simulation of the regional ground-water flow system that were caused by inaccurate boundaries near both mines likely are small because of the great distance from the nearest areas of natural discharge along streams."

Any potential problems with artificial boundaries noted by Pool and Dickinson (2007) for their simulations are likely to be worse in long-term projections carried out by Lacher (2011) than in original simulations ending in 2003. Potential problems with simulating long-term effects of pumping in the Cananea area results from treating an assumed groundwater divide as a no-flow boundary. If the pumping on either side of the divide is balanced, as Pool and Dickinson (2007) suggest, representation of the divide as a no-flow boundary is reasonable. If more pumping occurs on one side of the divide than on the other, however, accurate simulation of pumping effects would require an extended model domain that allowed movement of the groundwater divide. With regard to computing capture from pumping near Cananea, Leake and others (p. 8, 2008) stated:

> The effects of a well withdrawing water near a ground-water divide would be to move the divide away from the well. Treating the divide as a no-flow boundary tends to overestimate capture in the modeled area, especially for withdrawal locations near the no-flow boundary. For the San Pedro model, most of the area mapped for capture or riparian-system response is not close to ground-water divides that are simulated as no-flow boundaries. An exception is along the southern end of the model near Cananea, Mexico. The simulated capture presented in the next section is close to this suspected ground-water divide; however, capture and riparian-system response in this area are in the lowest range of fractional values shown. A more rigorous treatment of the ground-water divide, therefore, would not change the appearance of the map.

Results of long-term projections from pumping near Cananea should be viewed as uncertain. In addition to concerns expressed by Pool and Dickinson (2007) regarding no-flow boundaries, the constant-head boundaries on the northern side of the model could adversely affect predictions of the effects of pumping in that part of the subbasin. Future predictive applications of the model by Pool and Dickinson (2007) should include evaluations of possible effects of all artificial boundaries in the model.

Effects of Model Detail on Near-Stream Recharge Simulations

Recharge simulations by Lacher (2012) were carried out for the three near-stream sites (fig. 1). The horizontal grid spacing of the model is about 820 ft (250 m) and areas of applied artificial recharge are within a few cells of the San Pedro and Babocomari Rivers. Considerations in using a basin-scale groundwater model to study effects of recharge from the surface to the water table are as follows:

1. The model does not simulate properties of the unsaturated zone, which may include sediments that impede the movement of water from the land surface to the water table. An assumption in using the model is that the specified amount of recharge reaches the water table.

2. With regard to using the basin-scale model, Leake and others (2008) stated, “Site-specific withdrawal or recharge projects may require studies using local hydrologic conditions in the area of interest.” The model represents properties, such as hydraulic conductivity, that are considered to be representative over areas much larger than areas around recharge sites and areas between recharge sites and the nearby streams. Sufficient borehole and geophysical data do not exist to identify small hydrogeologic units and estimate hydraulic properties of such units. Local variations in properties could affect the rates of movement of water from the recharge sites to the nearby streams.

3. The Evapotranspiration Package used in the model is a simplified representation of the functional relation between depth to groundwater and evapotranspiration rate. Pool and Dickinson (2007) attempted to represent an overall estimate of annual evapotranspiration in the modeled area. As shown in figure 3B, the model can compute both responses to artificial recharge: increased evapotranspiration and increased streamflow. The sum model-computed changes in these two components likely are more certain than the relative computed change of each component.

4. The 820-ft grid spacing results in approximations of locations of the streams, evapotranspiration areas, and artificial recharge areas. Approximations of the geometry of features and distances between recharge areas, streams, and evapotranspiration areas may have a minor affect on the timing of system response to recharge.

In spite of these considerations regarding local conditions, use of the model by Lacher (2012) is a reasonable first step in studying how the riparian systems might respond to near-stream recharge at different sites. The recharge study makes assumptions regarding the rates at which water could be applied to the water table in areas of interest. In addition, the model generally can indicate responses in streamflow and evapotranspiration rates using the hydraulic properties, grid resolution, and representation of features that were considered appropriate by Pool and Dickinson (2007) for the basin-scale model. Beyond the analyses of effects of recharge by Lacher (2012), additional data collection and model analyses could be carried out prior to implementing actual recharge projects.

Overall Assessment of Model Applications for Projections of Groundwater Development and Artificial Recharge

Lacher (2011) made some necessary corrections to the model by Pool and Dickinson (2007), updated the model with actual pumping for 2003–10, and extended the model to run through 2105 using projected groundwater pumping. This analysis included groundwater storage change, drawdown, and decreases in evapotranspiration and streamflow. In spite of potential problems from the artificial no-flow boundary near Cananea, the application by Lacher (2011) is a reasonable use of the basin-scale model by Pool and Dickinson (2007). Lacher (2011) lists potential future work using the model. Future applications of the model for long-term projections should include evaluations of the effects of any represented artificial boundaries on computed results, as recommended by Reilly and Harbaugh (2004).

Lacher (2012) used the model to evaluate effects of artificial recharge at the three sites (fig. 1). In spite of the site-specific aspects of the model tasks and uncertainty in partitioning of response between increased evapotranspiration and recharge, application of the groundwater model of the Upper San Pedro Basin for projections of effects of artificial recharge is a reasonable first step in evaluating possible system response. If artificial recharge projects are to be carried out, additional data should be collected for sites of interest. Data collected, including water levels, depths to the water table, hydraulic conductivity, thicknesses of hydrogeologic units, and specific yield, should be compared to values represented in the model. Detailed site-specific models of potential sites will help in understanding possible long-term effects of the recharge. Currently, approaches for such model analyses use finer-grid local scale models that are coupled to the basin-scale model. Possible techniques are local grid refinement (Mehl and Hill, 2005) or an unstructured-grid version of MODFLOW, now being developed (Chris Langevin, U.S. Geological Survey, oral commun., April 3, 2012). Either approach would allow detailed representation of recharge sites and nearby streams and evapotranspiration areas, with the ability of effects of recharge to propagate to coarse-grid areas of the basin-scale model without effects of any artificial model boundaries.

Summary

The U.S. Geological Survey five-layer groundwater flow model of the Sierra Vista and Sonoran subwatersheds of the Upper San Pedro Basin has been used to estimate the effects of projected groundwater pumping through 2105, and to evaluate the relative impacts of artificial recharge on streamflow at two sites near the San Pedro River and at one site near the principal San Pedro River tributary, the Babocomari River. Before a thorough evaluation of these uses can be made, it is important to consider the underlying concepts.

First, artificial recharge that occurs between a pumping center and a river may offset the effects of pumping but will not “armor” the river from the effects of capture. In fact, it is possible for a slightly more rapid progression of capture to occur from increases in recharge due to increased saturated thickness and transmissivity. Second, whereas the groundwater flow model is described as having a "stacked bowls" configuration of model layers, when vertical exaggeration is removed, it is apparent the model layers in the alluvial portion of the watershed are relatively flat-lying. As a result, flow between layers is not restricted because of the lack of horizontal flow through the relatively small, vertically truncated contacts; the areas of the bottoms and tops of layers, where vertical flow between layers occurs, is more than adequate to ensure robust numerical solutions.

The main concern regarding simulations of long-term groundwater pumping is not only the effect of artificial model boundaries on modeled response, particularly for the pumping near Cananea, Sonora, Mexico, but also for artificial boundaries on the northern side of the model. The model includes a no-flow boundary near Cananea under the assumption that pumping was occurring south of the physical boundary that would offset pumping on the northern side, inside the San Pedro Basin. If pumping on one side of the divide is greater than on the other side, simulation of pumping effects would require an extended model domain that allowed movement of the groundwater divide.

Concerns regarding simulations of effects of artificial recharge near streams with the U.S. Geological Survey groundwater flow model include representativeness of the model properties at the site scale; a possible limited ability of the model to correctly apportion recharge response between increased streamflow and increased evapotranspiration; and limited ability of the model to simulate detailed geometry of recharge and evapotranspiration areas and stream locations with the grid dimensions of the basin-scale model. In particular, considerations include:

- the assumption that in the model all specified recharge reaches the water table
- the representativeness of properties, such as hydraulic conductivity between recharge sites and the adjacent surface water
- the ability of the model to represent the relative changes in evapotranspiration and streamflow
- the effects of grid size on representing locations of the streams, areas of evapotranspiration, and artificial recharge areas

In spite of these observations and concerns, uses of the model reviewed in this report appear to be reasonable and valid. However, should additional modeling be done using the U.S. Geological Survey groundwater flow model, the noted concerns should be taken into account and addressed as appropriate to the work, during the modeling exercise as well as in the documentation and reporting that follows.

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