J. ENVIRONMENTAL SYSTEMS, Vol. 27(1) 55-70, 1999

EVALUATION OF STREAMFLOW DEPLETION FOR VERTICAL ANISOTROPIC AQUIFERS*

XUNHONG CHEN

YANFENG YIN

University of Nebraska–Lincoln

ABSTRACT

This article analyzes the effects of aquifer hydraulic conductivity on streamflow depletion due to the use of groundwater for irrigation. The USGS MODFLOW model was used for calculation of streamflow depletion. Simulation results indicate that aquifer horizontal (K_r) and vertical (K_Z) hydraulic conductivity values, as well as the ratio of K_r/K_Z, are critical parameters in the calculation of streamflow depletion. The hydraulic conductivity of streambeds is another important parameter to be taken into account. The process of stream leakage after cessation of pumping (residual leakage) is also dependent on the anisotropy of aquifer hydraulic conductivity. Results show that an analytical solution will significantly overestimate the streamflow depletion for a strongly anisotropic aquifer. This article also discusses the procedures for collecting high-quality data for calculation of the vertical hydraulic conductivity in aquifers.

INTRODUCTION

Groundwater withdrawals for irrigation have changed local groundwater and streamflow dynamics in several states of the Midwest (for example, Nebraska, Kansas, and Colorado). As a result, a number of studies have been conducted to evaluate the aquifer-stream relationship [1-3], and such studies have

*The research was partially supported by Conservation and Survey Division, University of Nebraska-Lincoln and the USGS grant 1434-HQ-96-GR-02683.

been of considerable interest to researchers and policy-makers. Computer-based mathematical models are important tools for the evaluation of stream-aquifer interactions.

An example of a simple mathematical model includes the well-known stream-aquifer analytical solution developed by Glover and Balmer [4]. This solution was derived for simple hydrogeological conditions. Before the 1970s, this analytical solution was often used in the analysis of streamflow depletion due to groundwater pumping [1, 2, 5]. Since then, numerical models have become common in the field of hydrogeology. Numerical models analyze the flow between stream and aquifer under more realistic and complex conditions. Particularly after the development of the three-dimensional groundwater flow model MODFLOW [6], anisotropic and layered aquifer systems can be closely modeled. Application examples include Sophocleous et al. [3] for transient conditions and Conrad and Beljin [7] for steady-state conditions.

For a partially penetrating stream, one of the most important hydrogeological processes near the stream-aquifer interface is the vertical component of water flow. Thus, the vertical hydraulic conductivity of the aquifer and the streambed can play a unique role in stream leakage. Aquifers in stream valleys are often alluvial deposits that exhibit anisotropy in vertical and horizontal hydraulic conductivity. Such hydraulically anisotropic characteristics can result from the processes of sedimentation. The aquifer anisotropy can be measured through pumping test analysis. The horizontal hydraulic conductivity (K_r) can be one to two orders of magnitude larger than the vertical one (K_z). For example, field tests for unconfined alluvial aquifers along the Platte River and the Republican River valleys demonstrated that the ratio of horizontal to vertical hydraulic conductivity in alluvial aquifers can vary from 15 to 70 [8-10]. Examples of aquifer anisotropic characterization for other areas include pumping tests at Vekol Valley, Arizona where the ratio of K_r to K_z ranges from 9 to 63 [11]. The estimated K_r/K_z ratio for an aquifer system on the Susquehanna River, New York, varies from 125 to 250 [12]. Although MODFLOW can be used to model anisotropic aquifer systems, the role of the vertical hydraulic conductivity in the stream-aquifer interactions has not been fully analyzed.

In this study, we will focus on the analysis of the roles of vertically anisotropic hydraulic conductivity in the computation of streamflow depletion caused by uses of groundwater during irrigation seasons. MODFLOW will be used to compute streamflow depletion due to groundwater extraction. First, the numerical model results will be checked with an analytical solution for verification. MODFLOW is then used to calculate the streamflow depletion for various anisotropic aquifers. Furthermore, the residual effects on streamflow after the pumping ceased will also be analyzed to fully understand the stream-aquifer interactions. We will also discuss the procedures for measurement of the vertical hydraulic conductivity.

METHODS

In this study, three-dimensional stream-aquifer models were designed using the USGS groundwater flow model package MODFLOW [6]. We used Visual MODFLOW Version 2.61 [13] for our numerical analyses of stream-aquifer interactions. The groundwater flow model in this package is the updated version of the USGS MODFLOW [14].

The river package in MODFLOW is used to simulate the flow between stream and aquifers. Depending on the relative elevation of the water table in the stream and the aquifer, MODFLOW can simulate a gaining or a losing stream. MODFLOW also calculates a water budget, which includes volumetric flow rates. Each flow component package in MODFLOW calculates its own contribution to the budget. For this study, a water-budget zone is designated around the stream. The model calculates flow rate for each time step of a simulation. The groundwater pumping rate is set as constant during the period of a simulation. The ratio of the stream infiltration rate to the pumping rate indicates the level of stream leakage resulting from a groundwater extraction. A curve of the leakage vs. time is plotted to examine the connectivity between the stream and the aquifers during the period of pumping.

Model Design

The dimension of the model domain is 12,195 by 12,195 m. The thickness of the aquifer is 30.5 m. To minimize the effect of the domain boundary on numerical results, the domain was considered sufficiently large. In plan view, the model area was divided into seventy columns and sixty rows. The number of layers varies from five to twelve, depending on the complexity of the modeled hydrogeological systems. The dimension of the grid size ranges from 6.1 by 6.1 m to 305 by 305 m. The finer grid was used near the areas of specific interest such as streams and pumping wells. The coarse grid was used in the areas farther from stream and pumping well. The grid size increases gradually from the fine-grid area to the coarse-grid area.

In this study, the aquifer is unconfined and the initial water table is the same for all grid cells. The initial water-table elevation in the stream is equal to that in the aquifer. Therefore, there is no water exchange between the stream and the aquifer before pumping begins. This hydraulic equilibrium system, however, ceases after groundwater pumping begins. As soon as the water table declines in the aquifer adjacent to the stream, a hydraulic gradient is generated between stream and aquifer and the stream begins to leak water to the aquifer. The water table in the stream can be modeled either as a constant head or a declining water surface during groundwater pumpage.

Verification

To test the validity of the numerical model and to ensure that the correct procedures have been used in the analysis of the streamflow depletion using the Visual MODFLOW, we compared the results from an analytical streamflow depletion solution [4] with the results from the numerical model. The analytical solution is expressed as follows:

$$\frac{q}{Q} = 1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{r}{\sqrt{4\alpha t}}} e^{-u^2}\, du \tag{1}$$

where q is the rate of stream leakage; Q is the pumping rate at a well; r is the distance between stream and pumping well; t is the pumping time; and α is equal to $K_r b/S_y$, where, K_r, b, S_y are the horizontal hydraulic conductivity, the initial saturated thickness, and the specific yield of the aquifer, respectively. The ratio of q to Q in equation (1) indicates the level of stream leakage. Equation (1) was developed for a simplistic stream-aquifer system condition. For example, it was assumed that the aquifer is isotropic, homogeneous, and semi-infinite in areal extent; and the stream fully penetrates the aquifer. Other assumptions include that there is no recharge to the aquifer; the initial water table is horizontal; and the well is fully penetrating and discharges at a constant rate. This solution has a limited application because actual stream-aquifer systems are much more complex. However, we found that it is very useful for the verification of numerical modeling results.

In the verification, the stream-aquifer systems are simplified for the numerical modeling so that the system conditions meet the assumptions of the analytical solution. Five simulations were conducted. For each simulation, the system condition and the aquifer hydraulic properties are the same except that the distance between the stream and the well differs. The length of the simulation time is 180 days, which includes a 120-day continuous pumping followed by a sixty-day non-pumping period. The aquifer hydraulic parameters used for the analytical solution include K_r = 82.3 m/d, S_y = 0.1, b = 30.5 m, and Q = 5,667 m^3/d. Additional parameters for the numerical model are vertical hydraulic conductivity (K_z = 82.3 m/d) and storage coefficient ($S = 10^{-6}$).

Figure 1 shows the time-q/Q curves for the five simulations where the distance between the stream and well varies from 76.2 to 1,524 m. Apparently, the results from the analytical solution and the numerical model are very close for each simulation. Sophocleous et al. indicated that a small difference (several percentages) existed between the analytical and numerical solutions under a simple system condition [3]. Our results suggest that the differences from both solutions are nominal as long as the grid size is properly designed near the stream and the well. Our numerical experiments indicated that an error of up to 8 percent

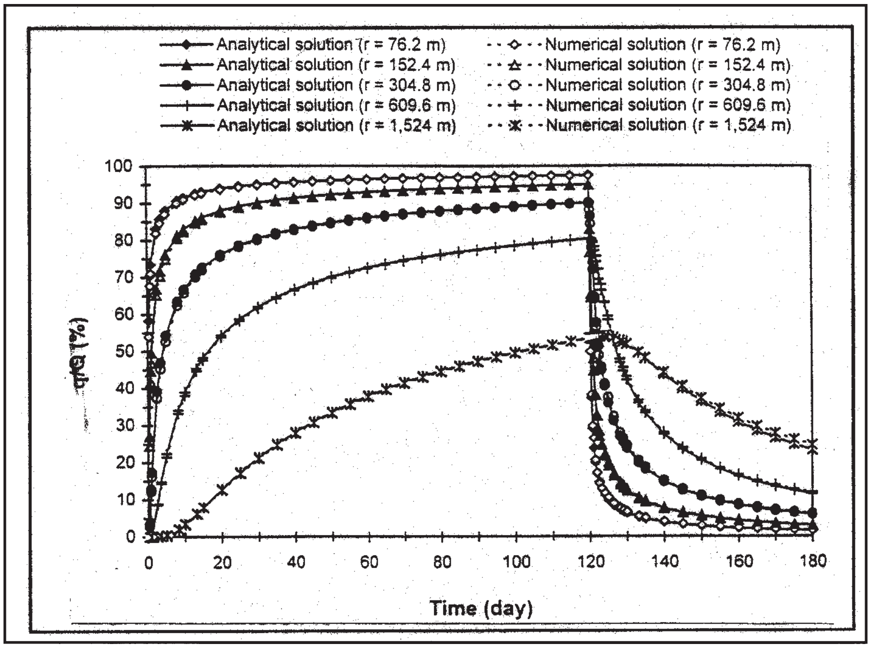

Figure 1. Calculated stream leakage from analytical and numerical solutions for verification of the numerical procedures used in this study. Stream leakage was calculated during and after pumping for five distances (r) between stream and a pumping well.

might be produced when the grid size is poorly designed, even though the system is simple.

SIMULATION RESULTS

The verification indicates that the numerical model is able to analyze the streamflow depletion due to groundwater pumping. The following section will analyze the roles of aquifer anisotropy in stream leakage for stream-aquifer systems where the analytical solution [4] is not applicable.

Vertically Anisotropic Aquifers

We first analyzed the stream-aquifer systems where a low-permeability streambed is absent. When the stream fully penetrates the aquifer, the horizontal flow component from the stream to the aquifer is dominant and the vertical flow component is nominal. Under this circumstance, the impact of the vertical anisotropy of the aquifer hydraulic conductivity is expected to be negligible.

When a stream partially penetrates the aquifer, which is common in nature, the vertical flow near the stream will be more important. We analyzed the stream-aquifer interactions for three types of aquifer systems: $K_z = K_r = 82.3$ m/d, $K_z = 0.1K_r = 8.23$ m/d, and $K_z = 0.01K_r = 0.82$ m/d. The stream penetrates 10 percent of the aquifer of 30.5 m thick. The S and S_y values are 10^{-6} and 0.1, respectively. The width of the stream is 7.62 m. The pumping well is located 152.4 m (500 feet) from the stream and was pumped at a constant rate of 5,667 m^3/d. After pumping stops, the model continues to run for another 120 days to calculate the residual leakage. Table 1 summarizes the parameter values of the stream, aquifer, and pumping well for the simulations.

Streamflow leakage was calculated based on the water budget data output by MODFLOW runs. Figure 2a shows the streamflow-depletion curves for the three aquifers. The results show that the ratio K_r to K_z can significantly affect the flow from stream to aquifer during pumping. When K_r is constant, a larger K_z results in a greater leakage from partially penetrating stream to aquifer during pumping. The results of the residual leakage after pumping stops suggest that it takes longer to reach a new equilibrium between the stream and aquifer where the ratio of K_r/K_z is larger.

The results of the analytical solution [4] are plotted in Figure 2a for references. It is noted that if the stream partially penetrates an aquifer, application of the analytical solution will significantly overestimate the streamflow depletion during pumping. The degree of overestimation depends on the ratio of K_z/K_r. The smaller the ratio of K_z/K_r, the bigger the overestimation. For an aquifer where the $K_r/K_z = 100$, the analytical solution can overestimate the streamflow depletion as four to five times greater than the actual rate. On the other hand, the analytical solution underestimates the residual leakage.

Additional analyses were conducted for three aquifers of a smaller K_r value (41.15 m/d) and three different K_z values (K_z = 41.15, 4.11, and 0.41 m/d, respectively). Other parameters for the stream and aquifer are the same as those used in

Table 1. Parameter Values of the Stream, Aquifer, and Pumping Well Used for the Simulations of Stream-Aquifer Interactions Due to Pumping

Aquifer	Stream	Pumping Well
K_r = 82.3 m/d	Width = 7.62 m	Pumping rate = 5,667 m^3/d
K_r/K_z varies from 1 to 100	Depth = 3.05 m	r = 152.4 m
$S = 10^{-6}$	Streambed Thickness = 0.76 m	Well screen length = 25.92 m
S_y = 0.1		
Aquifer thickness D = 30.5 m	K_s = 0.30 m/d	Pumping duration = 120 days

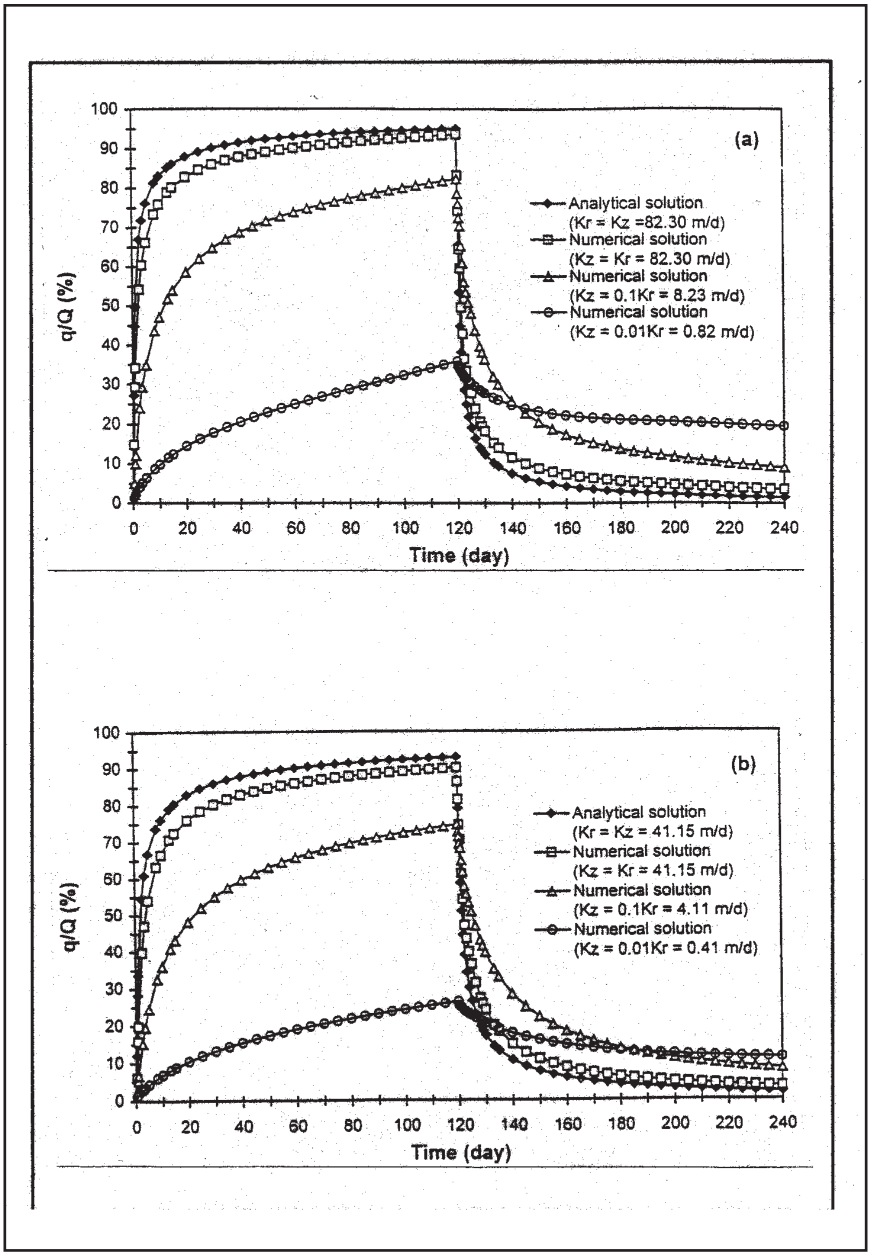

Figure 2. Stream leakage to aquifer of different K_r and K_r/K_z values. Both K_r and K_r/K_z affect the process of streamflow depletion due to pumping. K_r = 82.3 m/d (a) and K_r = 41.5 m/d (b).

the previous examples. Simulation results are presented in Figure 2b. Compared to the results presented in Figure 2a (for K_r = 82.3 m/d), one will find that smaller K_r and K_z values generally produce a smaller leakage during pumping.

The above results suggest that careful characterization of aquifer hydraulic conductivity for both horizontal and vertical directions is a necessary step for study of stream-aquifer interactions. They also suggest that the analytical solution does not provide accurate results for an anisotropic where the stream partially penetrates the aquifer.

Stream Characteristics

Under some circumstances, a streambed may consist of fine-grained sediments (clay and silt) to form a low-permeability streambed. Thus, the hydraulic connection between stream and aquifer will be weaker. Simulations were conducted to analyze the effects of aquifer anisotropy in the occurrence of a streambed. The thickness of the streambed is 0.76 m (2.5 feet), its width is 7.62 m, and K_s (the vertical hydraulic conductivity of streambed) is 0.3 m/d. The stream penetrates 10 percent of the aquifer of 30.5 m thick. See Table 1 for other parameter values. Simulations were conducted for three aquifer systems. Figure 3a shows the stream leakage curves during and after pumping. This figure indicates that the effect of the anisotropy of aquifer hydraulic conductivity on stream leakage is very important when a streambed exists although the stream leakage is much smaller (compared to Figure 2a). For a further evaluation, simulations were conducted using K_s = 0.03 m/d. Again, three types of aquifers were considered. Results of the simulations are shown in Figure 3b. Comparing Figure 3a to Figure 3b suggests that stream leakage during pumping can be very small when the vertical hydraulic conductivity of the streambed is reduced. For this particular case, the effect of a strong anisotropy of the aquifer hydraulic conductivity (for example, K_r/K_z = 100) is still important. The residual leakage shown by Figures 3a and 3b suggests that the stream and aquifer have not reached equilibrium after the 120-day recovery and the stream continues to recharge the aquifer.

During an irrigation season, the water level in the stream may drop. With MODFLOW, a varied stream stage can be dealt with in the analysis of stream leakage. Our simulations accounted for a drop of 0.6 m of stream stage from the beginning to end of the 120-day pumping. The decrease in stream stage was assumed to be linear. Figure 4 shows the simulation results for three types of anisotropic aquifers. As shown by this figure, during the early-pumping period (the first 10 days), the rate of stream leakage increases rapidly. After that, it either approaches an approximately constant condition (for K_r/K_z = 100) or peaks and then decreases with time. The overall leakage is smaller compared to a constant stream stage (Figure 2a). Evidently, the streamflow depletion curves shown by Figure 4 are no longer a continuously increasing process but a complicated process with pumping time. Therefore, whether the stream water surface is constant

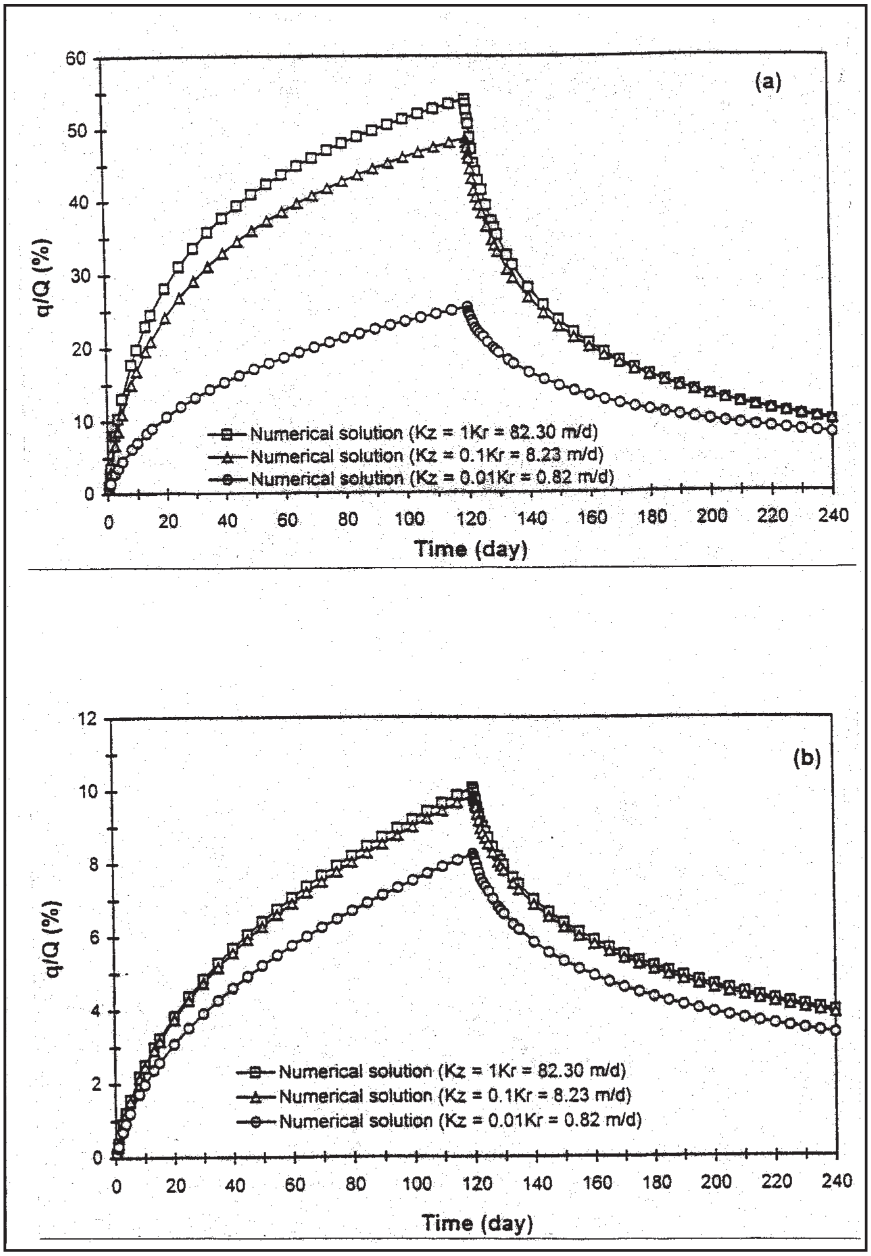

Figure 3. Effect of a low-permeability streambed on streamflow depletion. The vertical hydraulic conductivity of the streambed is 0.3 m/d (a) and 0.03 m/d (b)

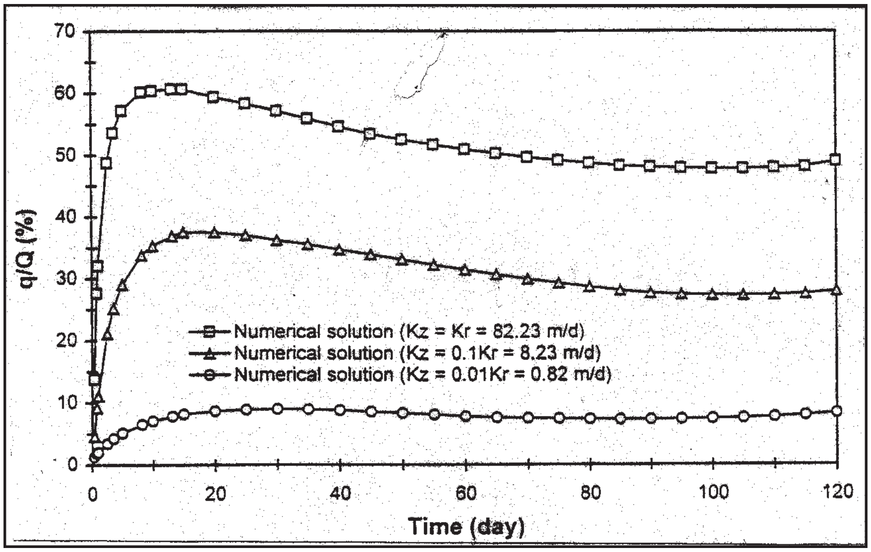

Figure 4. Effect of varied stream stage on stream leakage. Decline of stream stage during pumping reduces stream leakage.

during pumping is a critical factor in the calculation of streamflow depletion. Figure 4 also illustrates the significant effects of the vertical anisotropy of aquifer hydraulic conductivity on stream leakage.

Hydrostratigraphic Features

In some areas, the alluvial-valley aquifer-stream systems are bounded by geology units that are relatively impermeable. For example, an alluvial aquifer in the Republican River valley near Bloomington, Nebraska [15], is contacted by Cretaceous shale on one side of the river valley.

When such an impermeable boundary occurs near a stream, pumping groundwater will produce a larger drawdown in the aquifer, because there will be no significant amount of water moving into the aquifer through that boundary. Again, we conducted simulations for analyses of the role of the anisotropic aquifers in the existence of a lateral geologic boundary. We assume an impermeable boundary was located 152.4 m on the other side of a partially penetrating stream. We considered two cases: 1) absence of a low-permeability streambed and 2) presence of a low-permeability streambed. Figure 5a shows the results of the simulation for three types of aquifer not accounting for a low-permeability streambed. Comparison with the results in Figure 2a indicates that the stream leakage increases only slightly for $K_r = K_z = 82.3$ m/d because of the existence of

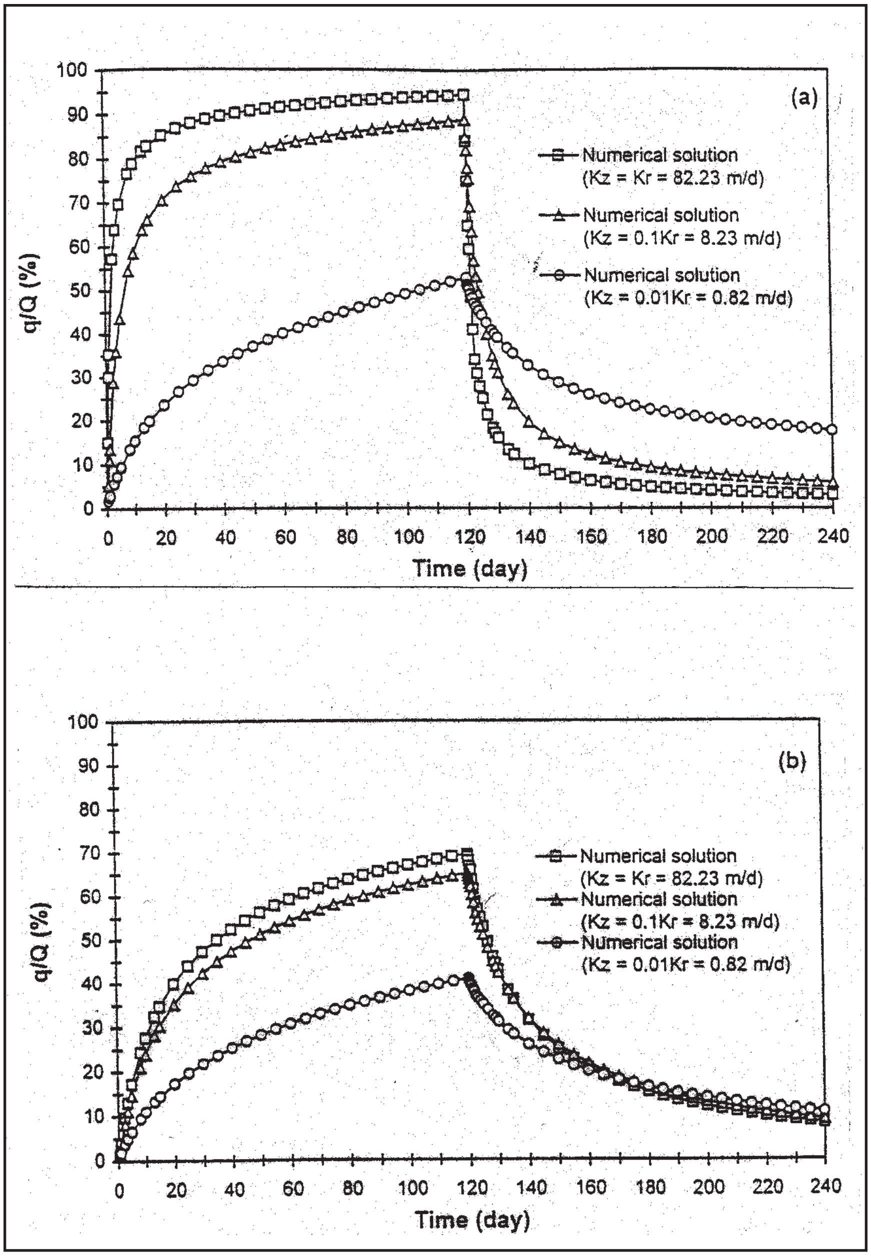

Figure 5. Effect of an impermeable boundary near a stream on stream leakage where a low-permeability streambed is absent (a) and a low-permeability streambed is present (b).

the impermeable boundary. Perhaps this is because a large K_z value enhances the connectivity between the stream and aquifer and thus minimizes the influence of the impermeable barrier. For the other two types of aquifer anisotropy, there is an important increase in stream leakage resulting from the impermeable barrier. For the second case, the K_s value for the streambed is 0.3 m/d. Simulation results are presented in Figure 5b. Compared to the results plotted in Figure 3a, they indicate a significant increase in stream leakage for all three types of aquifers. It is indicated by Figures 5a and 5b that the anisotropic hydraulic conductivity of the aquifer is very important.

DISCUSSIONS

The above simulation results did not account for the infiltration. Precipitation in irrigation areas directly recharge the unconfined aquifers where groundwater is pumped out. Consideration of infiltration will certainly reduce the induced recharge from a stream. This, however, will not hinder our demonstration of the importance of aquifer anisotropy.

The duration of the irrigation season varies from one location to another. It may be much shorter than the duration used for the simulations in this article. Also, groundwater pumping may not be continuous for the entire season. More realistic scenarios are cyclic irrigation schemes—each period of several days of pumping followed by a non-pumping period. The stream leakage for some of the conceptual stream-aquifer systems presented in this article is often very large because of the 120-day continuous pumping. The study of Chen and Yin has demonstrated that the stream leakage is significantly lower when the pumping of groundwater is cyclic [15].

Our simulation results demonstrated that the hydraulic conductivities of aquifer and streambed are critical parameters in the analyses of stream leakage. Aquifer hydraulic conductivity can be measured by grain-size analysis, slug tests, capacity tests, and pumping tests. Pumping tests are classic methods for measurement of vertical aquifer hydraulic conductivity. For a confined aquifer, the Hantush solution [16] or the later version [17] can be used to analyze the test data. For an unconfined aquifer, the Neuman solution [18] can calculate the K_z values from test data. Some tests were not analyzed for the vertical hydraulic conductivity, while others reported the K_z values [9, 11, 19].

Obtaining reliable vertical hydraulic conductivity is still a challenging task to researchers. First, a pumping test needs to be carefully designed, and the pumping duration must be sufficiently long. To generate a vertical flow, a pumping well must be partially screened in an aquifer. During pumping tests, vertical flows are generated only near the well and decrease with radial distance. The vertical flow disappears when the radial distance is greater than $r = 1.5b\sqrt{K_r / K_z}$ for a confined aquifer and $r = b\sqrt{K_r / K_z}$ for an unconfined aquifer, where b is the initial thickness of the saturated aquifer. Therefore, observation wells for measurement of drawdown should be close to the pumping well. Figure 6 shows the sensitivity coefficient ($\partial s/\partial K_z$) of drawdown (s) to K_z at various observation locations from the pumping well (r). Larger magnitude of the sensitivity coefficients provides more reliable information about the aquifer parameter. As shown by Figure 6, the sensitivity magnitude decreases with r both in confined and unconfined aquifers. It decreases very rapidly for r > 10 to 20 m.

The test duration is another factor to consider. The sensitivity coefficients varies also with time. Figure 7 shows the sensitivity of drawdown to K_z with time in both confined and unconfined aquifers. As shown in this figure, the maximum magnitude of the sensitivity occurs in the late time of pumping in a confined aquifer but in the intermediate pumping time in an unconfined aquifer. Apparently, drawdown data from some appropriate intervals give more reliable information for calculation of K_z values. Figures 6 and 7 indicate that sensitivity analysis will help the design of test systems that provide high-quality data.

To calculate the K_z value from pumping test data, graphical approaches [19, 20] or inverse computational methods [8, 9] can be used. When an inverse computational method is used, the reliability of the calculated K_z values can be estimated using statistical procedures [9].

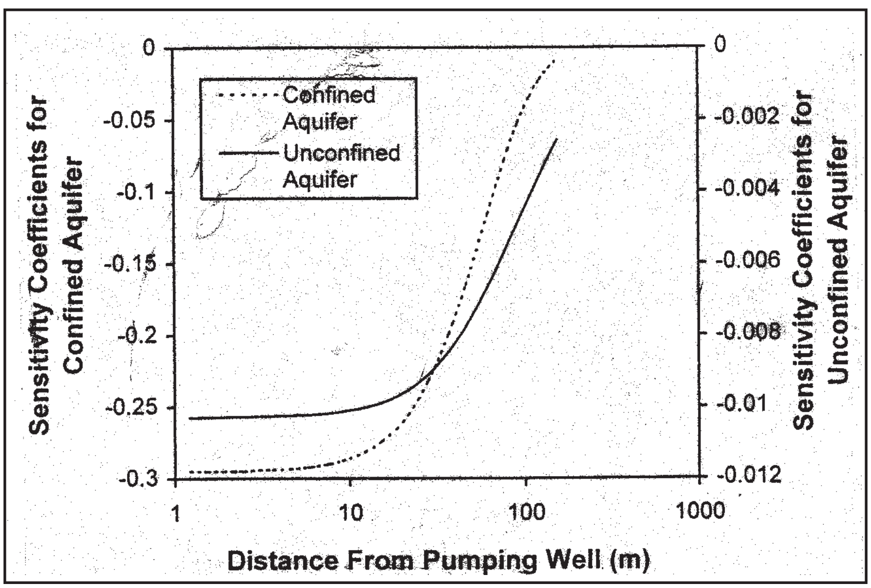

Figure 6. Drawdown sensitivity to vertical hydraulic conductivity K_z decreases with radial distance from a pumping well.

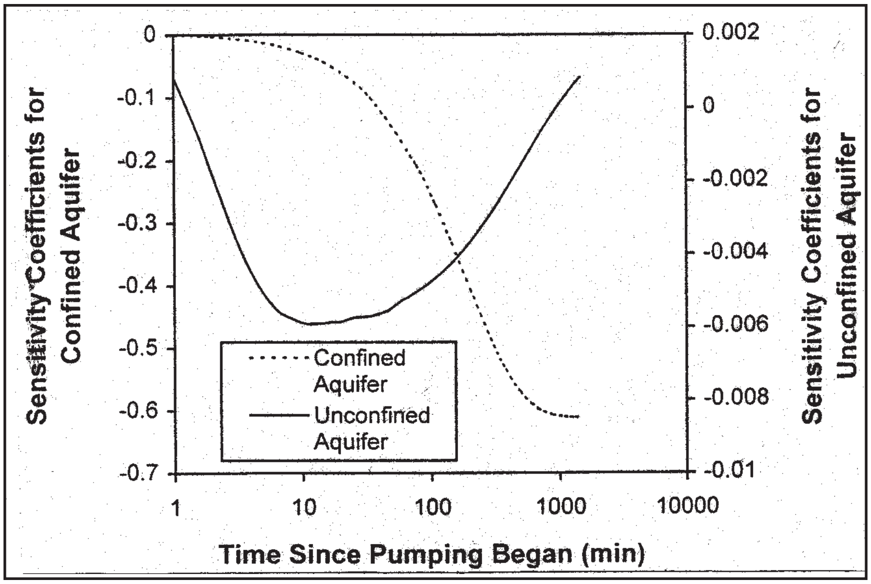

Figure 7. Drawdown sensitivity to vertical hydraulic conductivity K_z varies with pumping time. It behaves differently in confined and unconfined aquifers.

CONCLUSIONS

The vertical anisotropy of aquifer hydraulic conductivity is a very important parameter affecting the stream leakage for stream-aquifer systems where the stream partially penetrates the aquifer. That is because the vertical flow between the stream and aquifer is a dominant mechanism.

The vertical hydraulic conductivity of low-permeability streambed affects stream leakage. A smaller K_s gives a low stream leakage. When a low-permeability streambed occurs, stream stage drops during an irrigation season, or there is an impermeable boundary, aquifer anisotropy still plays an important role.

The analytical solution overestimates the streamflow depletion. The error is even larger for a stronger anisotropic aquifer. While numerical models are available for such a study, measurement of reliable aquifer anisotropy is a necessary first step in the analysis of stream-aquifer systems.

Residual leakage after cessation of pumping must also be carefully analyzed. The results have shown that the stream continues to recharge the aquifer after pumping stops if there is no other source to provide the aquifer with water for recharge.

ACKNOWLEDGMENTS

David Gosselin and Scott Summerside provided technical review. Charlie Flowerday edited the manuscript.

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Direct reprint requests to:

Xunhong Chen
Conservation and Survey Division
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln
Nebraska Hall
Room 113
Lincoln, NE 68588-0517
e-mail: x-chen@unlinfo.unl.edu