Journal of Hydrology, 152 (1993) 31–56

0022-1694/93/$06.00

[2]

Calibrated models as management tools for stream–aquifer systems: the case of central Kansas, USA

Marios Sophocleous*, Samuel P. Perkins

Kansas Geological Survey, The University of Kansas, Lawrence, KS 66047, USA

(Received 27 November 1992; revision accepted 13 April 1993)

Abstract

We address the problem of declining streamflows in interconnected stream–aquifer systems and explore possible management options to address the problem for two areas of central Kansas: the Arkansas River valley from Kinsley to Great Bend and the lower Rattlesnake Creek–Quivira National Wildlife Refuge area. The approach we followed implements, calibrates, and partially validates for the study areas a stream–aquifer numerical model combined with a parameter estimation package and sensitivity analysis. Hydrologic budgets for both predevelopment and developed conditions indicate significant differences in the hydrologic components of the study areas resulting from development. The predevelopment water budgets give an estimate of natural ground-water recharge, whereas the budgets for developed conditions give an estimate of induced recharge, indicating that major ground-water development changes the recharge–discharge regime of the model areas with time. Such stream–aquifer models serve to link proposed actions to hydrologic effects, as is clearly demonstrated by the effects of various management alternatives on the streamflows of the Arkansas River and Rattlesnake Creek. Thus we show that a possible means of restoring specified streamflows in the area is to implement protective stream corridors with restricted ground-water extraction.

Statement of the problem

Many regions of western and central Kansas have experienced significant ground-water and streamflow declines, especially during the last two decades (Sophocleous, 1981; Sophocleous and McAllister, 1987, 1990). Our region of interest (Fig. 1), which is located within the boundaries of the Big Bend Groundwater Management District No. 5 (GMD5), shows streamflow and ground-water declines with time (Figs. 2(a) and 2(c)), whereas precipitation patterns and amounts show no corresponding changes (Fig. 2(a)), implying no

---

* Corresponding author.

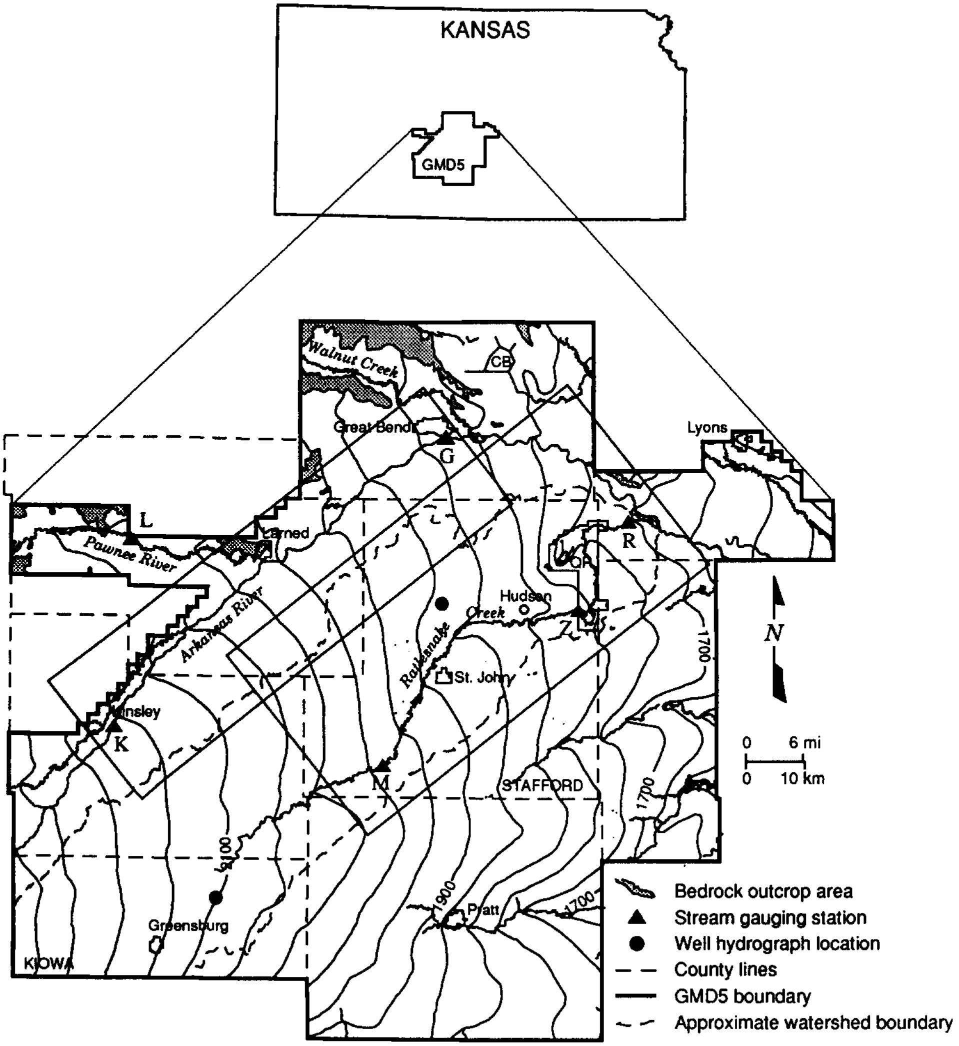


Fig. 1. Study area. Diagonal boxes encompass the two model areas of this study. Upper case letters denote stream-gaging stations (M, Macksville; Z, Zenith; R, Raymond; K, Kinsley; G, Great Bend; L, Larned). Contours represent the predevelopment (1940s and 1950s) water table elevation in feet above mean sea-level (to convert to meters, multiply by 0.3048). CB and QR denote the Cheyenne Bottoms wetland and the Quivira National Wildlife Refuge, respectively.

climate-change effect; however, ground-water rights in the GMD5 show a dramatic increase over the same time period (Fig. 2(b)). The declining trend for the Arkansas River is similarly exhibited by Rattlesnake Creek (Sophocleous, 1992a), a predominantly ground-water-fed stream, also of interest in this study. Concerned with such declining streamflows, the Kansas legislature passed the Minimum Instream Flow Law in 1983, which requires that minimum desirable streamflows be maintained in various streams in Kansas, including the Arkansas River and Rattlesnake Creek.

The lower Rattlesnake Creek watershed (Fig. 1) emcompasses the Quivira National Wildlife Refuge, which is a major stopover point for migratory birds in the Central North American Flyway. The Quivira refuge, established in 1955, obtained a permit to divert up to $27.14 \times 10^6 \mathrm{m}^3$ of water per year (22 000 acre-ft year^{-1}) from Rattlesnake Creek for its operation. However, the average annual streamflow in Rattlesnake Creek at its entrance to the refuge (Zenith gaging station, Z in Fig. 1) during 1981–1990 was $24.21 \times 10^6 \mathrm{m}^3 \mathrm{year}^{-1}$ (19 625 acre-ft year^{-1}), which is less than the permitted water right for the Quivira refuge.

Concerns about declining streamflows of both Rattlesnake Creek and the Arkansas River between Kinsley and Great Bend (Fig. 1), and the desire to explore possible management options to remedy this situation led to this study. Thus two separate areas in the GMD5 were funded for study, one encompassing an area of approximately 1450 km^2 (560 miles^2) on the lower Rattlesnake Creek watershed (lower boxed area in Fig. 1) and one encompassing approximately 1220 km^2 (470 miles^2) of the Arkansas River valley from Kinsley to Great Bend. Both areas are relatively flat, are covered with a veneer of loess and dune sand, and compose a major portion of the Great Bend Prairie of Kansas, with underlying Pleistocene alluvium forming the major aquifer of the region (Latta, 1950; Fader asnd Stullken, 1978; Sophocleous et al., 1988).

Objectives

In this paper we emphasize the potential use of model results to manage stream–aquifer systems. We briefly focus on the impact of irrigation development on the water budget of the region and on management alternatives aimed at restoring streamflows in the streams of interest in this study, with emphasis on the hydrologic effectiveness of protective corridors around the Arkansas River and Rattlesnake Creek. The interested reader is referred to Sophocleous (1992a,b), Sophocleous et al. (1992), and Sophocleous and Perkins (1993) for more details. Because such management-oriented studies may affect people's livelihood, they are controversial. Therefore we believe that it is important to combine parameter estimation (inverse modeling) procedures and predictive modeling to obtain consistent, objective, and repeatable results against which to judge possible conflicting claims. Hence we place some emphasis on model calibration procedures and sensitivity analysis to demonstrate the validity of the modeling results presented here.

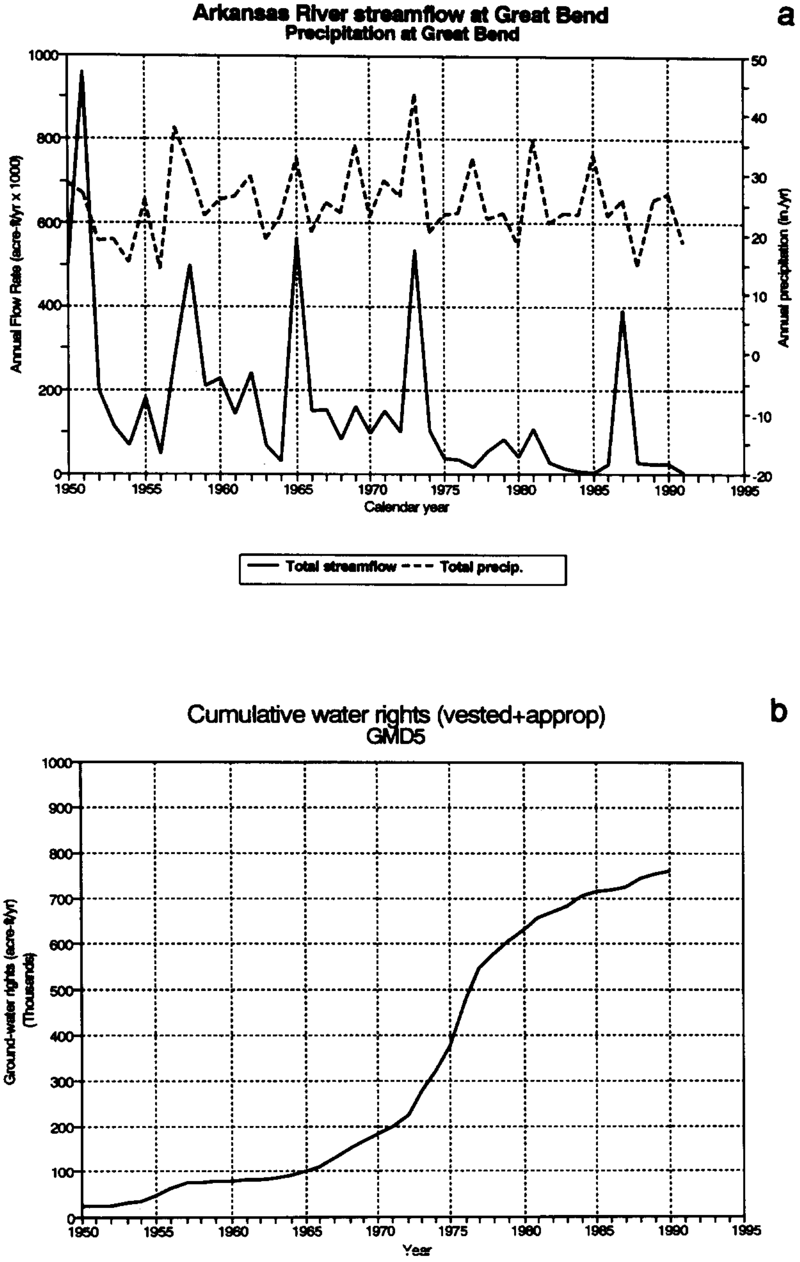


Fig. 2. (a) Annual precipitation and Arkansas River streamflows at Grent Bend. (b) Appropriated cumulative ground-water rights in the GMD5. (c) Two long-term observation well hydrographs in the area (see Fig. 1 for well locations). (To convert acre-ft year^{-1} to m^{3} year^{-1} multiply by 1233.48; to convert in year^{-1} to mm year^{-1} multiply by 25.4.)

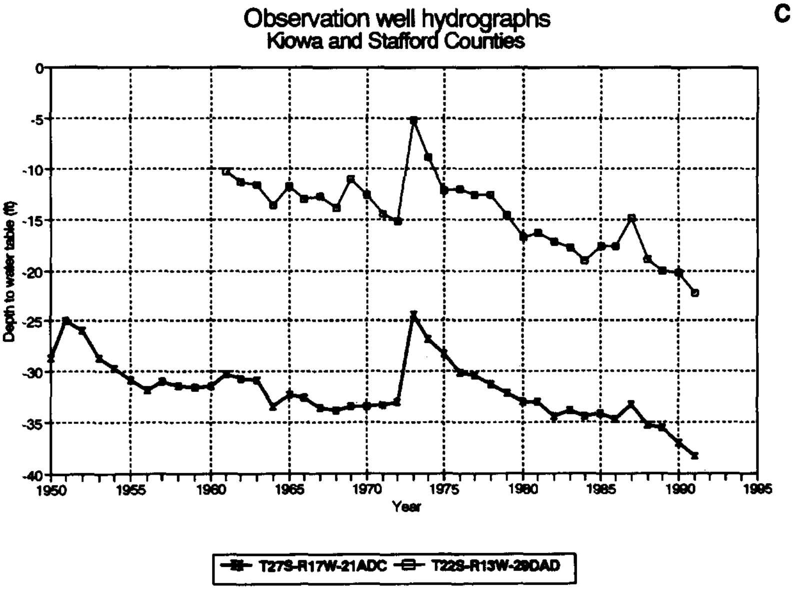
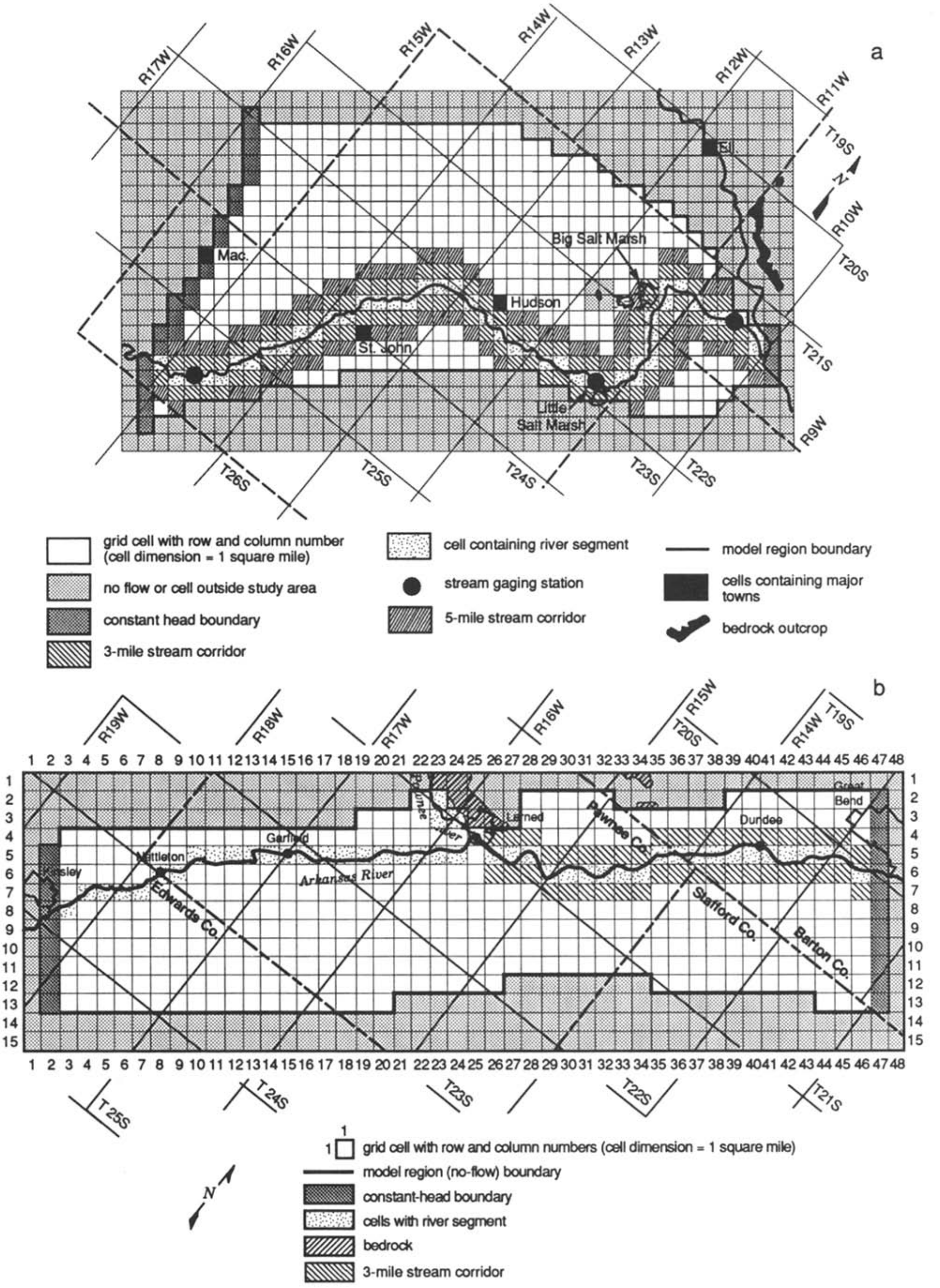


Fig. 2. Continued.

Numerical modeling method

The major thrust of this study is to implement and analyze an appropriate stream–aquifer numerical model for the study areas so that future streamflows and ground-water levels under a variety of conditions can be predicted. The simulation model chosen to evaluate the Arkansas River and lower Rattlesnake Creek stream–aquifer systems is a modified two-dimensional version of the popular US Geological Survey modular finite-difference ground-water model (MODFLOW) of McDonald and Harbaugh (1988) with streamflow routing capabilities as documented by Prudic (1989). A parameter estimation model for MODFLOW (MODINV; Doherty, 1990) was also implemented to optimize model parameters during model calibration. MODINV uses the MODFLOW program as its forward processor to obtain an optimum set of parameter values and measures of their reliability, given the observed data on ground-water levels used in the calibration. In addition, the model provides measures of the overall goodness of fit of the model and a means for examining the validity of various model assumptions. Model simulated and observed heads are matched according to the weighted least-squares criterion, and optimization is achieved using the Gauss–Newton–Marquardt method (Draper and Smith, 1981).


a
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
T19S
T20S
T21S
T22S
T23S
T24S
T25S
T26S
N
Ell.
Big Salt Marsh
Mac.
Hudson
St. John
Little Salt Marsh
grid cell with row and column number (cell dimension = 1 square mile)
no flow or cell outside study area
constant head boundary
3-mile stream corridor
cell containing river segment
stream gaging station
5-mile stream corridor
model region boundary
cells containing major towns
bedrock outcrop
b
R19W
R18W
R17W
R16W
R15W
T20S
R14W
T19S
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Kinsley
Nettleton
Garfield
Pawnee River
Larned
Dundee
Great Bend
Arkansas River
Edwards Co.
Pawnee Co.
Stafford Co.
Barton Co.
T 25S
T 24S
T23S
T22S
T21S
N
grid cell with row and column numbers (cell dimension = 1 square mile)
model region (no-flow) boundary
constant-head boundary
cells with river segment
bedrock
3-mile stream corridor

Model implementation and calibration

Model implementation requires that the study area be divided into grid cells; in this case, cells of 2.6 km^2 (1 $mile^2$) are employed, as shown in Fig. 3. Model implementation also requires that the period of simulation, spanning more than 35 years from predevelopment (ca. 1955) to present-day conditions (1990), be divided into a series of stress periods, represented by the increasing number of ground-water pumping wells in the model area and by the varying incoming streamflows into the model areas (from Kinsley and Larned for the Arkansas River model area; from Macksville for the Rattlesnake Creek model area (Fig. 1)). An annual time step was used in all simulations.

Boundary conditions and hydrogeologic properties

The Rattlesnake Creek model area is bounded by two streamline boundaries roughly coincident with the lower Rattlesnake Creek watershed boundaries (which are not physically differentiable from the rest of the Great Bend Prairie) and two constant-head boundaries, one at the confluence of Rattlesnake Creek with the Arkansas River and one far upstream from the main area of interest, the Quivira refuge (Fig. 1). The Arkansas River model area is bounded by a no-flow (aquifer limit) boundary approximately coinciding with the GMD5 boundary in that area (Fig. 1), a streamline boundary separating it from the Rattlesnake Creek watershed, and two constant-head boundaries near Kinsley and Great Bend, respectively.

The variability of hydrogeologic properties in the model areas is approximated by subdividing the region into a small number (one to four) of constant-parameter, hydrogeologically determined zones. Table 1 summarizes the model-optimized mean hydrogeologic properties of the aquifer in the two model regions.

Calibration

The models for both study areas were calibrated for steady-state and transient-state conditions. For this study we adhered to the principle of parsimony, according to which in a choice among competing hypotheses, other things being equal, the simplest hypothesis (i.e. the one with the smallest possible number of parameters for adequate representation) is preferable.

Fig. 3. (Opposite) Finite-difference grids for the (a) Rattlesnake Creek and (b) Arkansas River model areas. Suggested stream corridors with pumping moratoria are also shown (refer to Management applications' text section for explanations). Streamflow direction in these two grids is from left to right. (To convert miles to kilometers, multiply by 1.609.)

Table 1
Model-optimized average aquifer hydrogeologic parameters

Parameter	Arkansas River model area[a]	Lower Rattlesnake Creek[a]
Hydraulic conductivity (m day^{-1})	50.2 ± 2.7	13.3 ± 6.5
Storativity (dimensionless)	0.23 ± 0.04	0.18 ± 0.00
Recharge (mm year^{-1})	45.7 ± 3.1	48.3 ± 14.7
1990 saturated thickness (m)	27.6 ± 1.3	39.0 ± 1.1

[a] Table numbers represent the mean value ±2 SE.

The results of the steady-state (predevelopment, ca. 1955) analysis for both study areas indicate a satisfactory match between observed and model-simulated water table contours. The standard error of the hydraulic head values is 0.94 m (3.1 ft) for the Rattlesnake Creek model area and 0.88 m (2.9 ft) for the Arkansas River model area. Both standard errors are relatively small compared with the model response, as indicated by the maximum head loss of approximately 102 m (335 ft) in both model areas, denoting an overall good fit of the model. Analysis of residuals confirms the correctness of the numerical models for the two study areas (Sophocleous et al., 1992; Sophocleous and Perkins, 1993).

Starting with the optimized parameter estimates from the steady-state calibration and using a series of stress periods representing the increasing number of ground-water pumping wells with time and the varying incoming streamflows in the model areas, we ran the MODINV parameter estimation program to optimize storativity, recharge, and evapotranspiration (invoked only for the lower Rattlesnake Creek watershed mainly because of the Quivira marsh), keeping the already optimized (from the steady-state calibration) hydraulic conductivity values constant. The covariance matrix and the corresponding correlation coefficient matrix, which indicates correlations between model parameters, were instrumental in discriminating parameter estimates with small standard errors and in deciding between sequential vs. simultaneous parameter optimization. Parameters cannot be uniquely estimated when high correlations are present. In the transient-state runs the ground-water pumpage was held at 70–80% of the appropriated amounts based on water-use reports (Sophocleous et al., 1992).

For the Rattlesnake Creek model area the most detailed water-level survey available was the one we conducted in January 1991, and for the Arkansas River model area it was the December 1985 survey. Therefore for the Rattlesnake Creek model area we ran a predevelopment (1955) to end of 1990 transient-state calibration, and for the Arkansas River model area we ran a predevelopment (1955) to 1985 transient-state calibration. The observed and model-predicted water table contours agree satisfactorily in both cases. The standard error of the hydraulic head values is 0.98 m (3.2 ft) for the Rattlesnake Creek model area and 1.2 m (4.1 ft) for the Arkansas River model area. The models were also successful in predicting real events that were different from those used in the calibration period or that reflected some change in the system, for example, different pumping stresses (Sophocleous, 1992b; Sophocleous et al., 1992; Sophocleous and Perkins, 1993).

Simulation results and model analysis

Volumetric water budgets

The volumetric water budgets for the model areas under both predevelopment and present-day conditions are shown in Fig. 4. The convention followed in MODFLOW is that flow into or out of aquifer storage is considered part of the overall budget inasmuch as accumulation in aquifer storage effectively removes water from the flow system and storage release effectively adds water to the flow, even though neither process in itself involves the transfer of water into or out of the ground-water regime. It is evident from Fig. 4 that the bulk predevelopment input to the stream–aquifer system is ground-water recharge, and that the largest outflows from the system are evapotranspiration losses from the Quivira refuge and the region surrounding it and ground-water (baseflow) contributions to streamflows. In the case of the Arkansas River model, the largest outflows are baseflow contributions and underflow out of the area. It should be noted that irrigation pumpage is a minor element of total system outflow for the predevelopment period.

The overall volumetric water budgets for the model areas during the last stress period (1988–1990) of the transient-state simulation for the Rattlesnake Creek model area and the 1985–1990 run for the Arkansas River model area are also presented in Fig. 4. In contrast to the case for the 1950s and the early 1960s, the present-day dominant outflow component from the aquifer is ground-water pumpage for irrigation, which is a new discharge superimposed on the predevelopment (steady-state) system. This irrigation pumpage must be balanced by one or more of the following: (1) an increase in the aquifer recharge by increased induced leakage from streams and other surface water bodies, drainage of the dewatered aquifer sediments, increased induced leakage from saturated or near-saturated zones above the water table, irrigation return flows, increase in recharge from precipitation resulting from conversion of natural grassland to croplands, decreases in runoff to streams as a result of cultivation, capture of previously ‘rejected’ recharge as surface runoff in

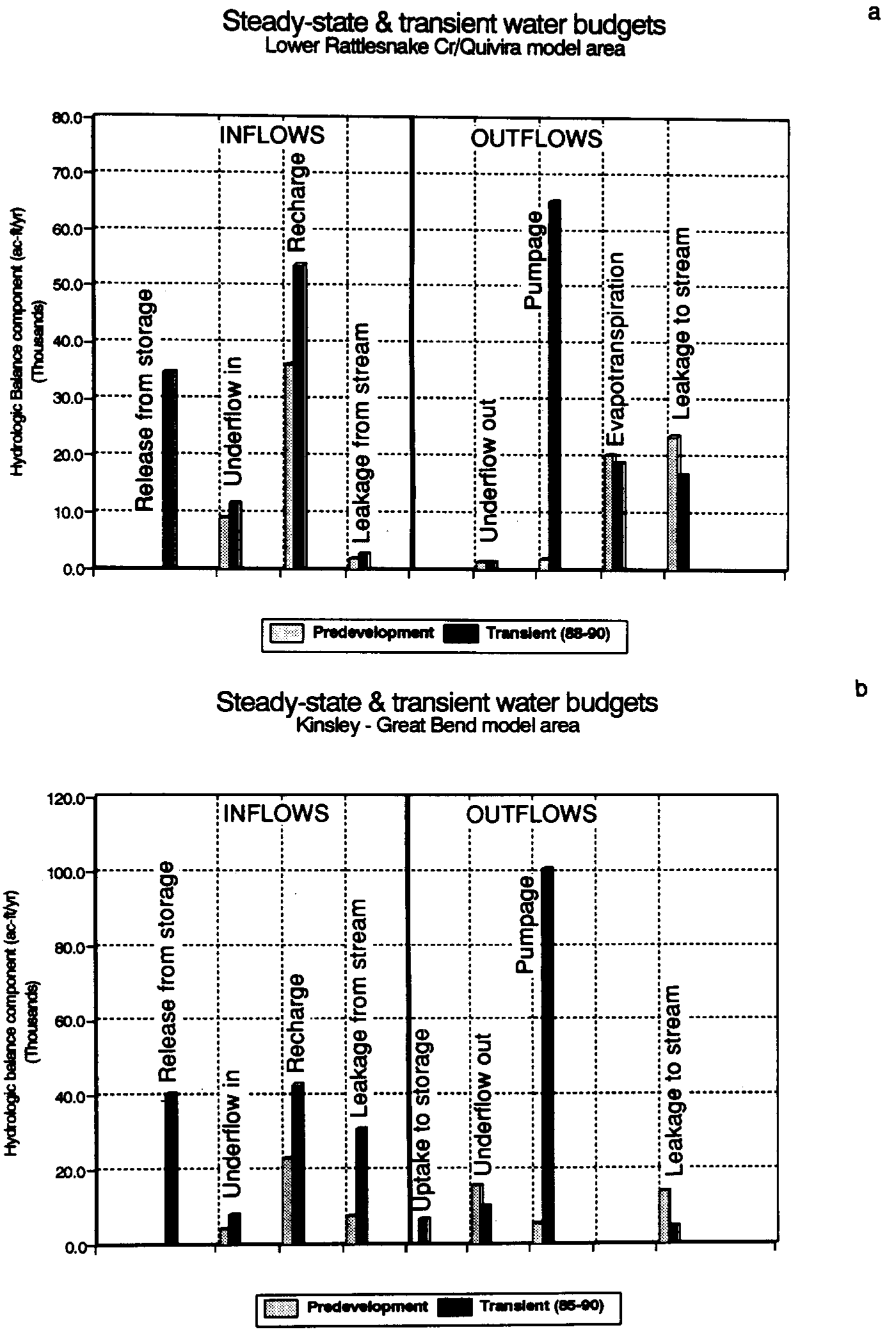


Fig. 4. Predevelopment and present-day water budgets for (a) the Rattlesnake Creek model area and (b) the Arkansas River model area. (To convert acre-ft year^{-1} to m^3 year^{-1} multiply by 1233.48.)

shallow water table areas, increased hydraulic gradients between recharge areas and areas with significant irrigation well development, and increased recharge from below, that is, from saltwater intrusion from the Permian formations; (2) a decrease in the old natural discharge by decreased baseflow contributions to streams resulting from ground-water withdrawals, decreased outflows to seeps and springs, decreased ground-water evapotranspiration, and decreased downward leakage to underlying aquifers; (3) loss of water storage in the aquifer, as manifested by long-term declines in ground-water level. Indeed, a combination of all three types of change is indicated in the water budget of the model areas (Fig. 4), which shows an increase in recharge, a loss of water in storage, and a decrease in baseflow contributions to streamflows and decreased ground-water evapotranspiration losses compared with the predevelopment water budget.

Such computer simulations provide insight into the changes in recharge and discharge resulting from development. The predevelopment budgets give us an estimate of natural recharge, that is, water moving through the ground-water system under the boundary conditions imposed by natural topography, geology, and climate, whereas the budgets for developed conditions give us an estimate of induced recharge, that is, water added to the natural ground-water system in response to artificial boundary conditions imposed at irrigation well fields, farm ponds, drains, etc. Although natural recharge balances natural discharge as baseflow to streams and outflow to springs and wetlands, induced recharge (including irrigation return flow) and ground-water storage (Fig. 4) are the two sources of water to balance artificial ground-water withdrawals. A decrease in baseflow contributions to streamflows and decreased ground-water evapotranspiration losses are also a consequence of artificial ground-water withdrawals. Irrigation development along the lower reaches of Rattlesnake Creek near the Quivira National Wildlife Refuge was minimal because of water salinity problems; this resulted in relatively small decreases in baseflow contributions to streamflow and in ground-water evapotranspiration losses (Fig. 4).

Sensitivity analysis

We also analyzed the model to determine its sensitivity to variations in the values of selected parameters on both the aquifer and the stream. The input and aquifer parameters considered were pumpage, recharge, hydraulic conductivity, and storativity. The stream parameters considered were conductance of the streambed, Manning's roughness coefficient, stream slope, and stream width. Sensitivity to each parameter was determined in two ways: (1) by running the model in a predictive mode from 1990 to 2010 with the

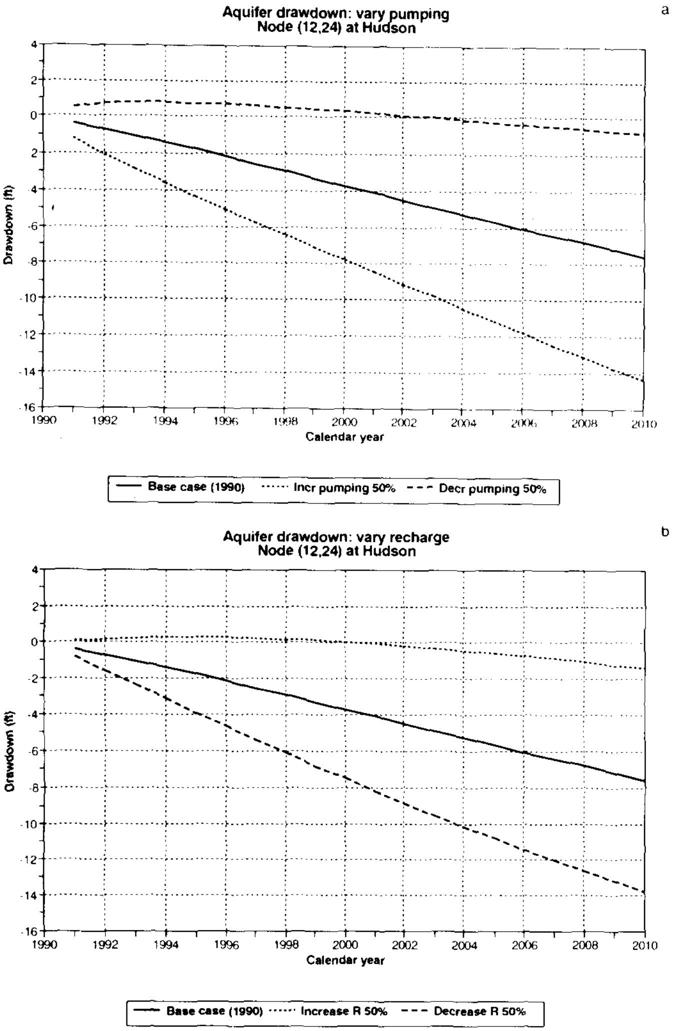


Fig. 5. Rattlesnake Creek model area sensitivity plots of water table drawdown with changing (a) ground-water pumpage and (b) recharge at a grid cell near Hudson; sensitivity plots of streamflow with changing (c) ground-water pumpage and (d) streambed conductance at a grid cell by the Zenith stream-gaging station. (To convert feet to meters, multiply by 0.3048; to convert $ft^3 s^{-1}$ to $m^3 s^{-1}$ multiply by 28.3×10^{-3}.)

optimized parameters for 1990 and by uniformly varying (increasing and decreasing) each parameter by 50%; corresponding changes in ground-water levels or drawdown and instreamflow were observed, tabulated, and graphed at selected nodes within the model area to obtain an initial screening of parameter sensitivity; and (2) by plotting the model-calculated sensitivities (Jacobian matrix) after normalizing them to the corresponding optimized parameters, as was done by Sophocleous (1984).

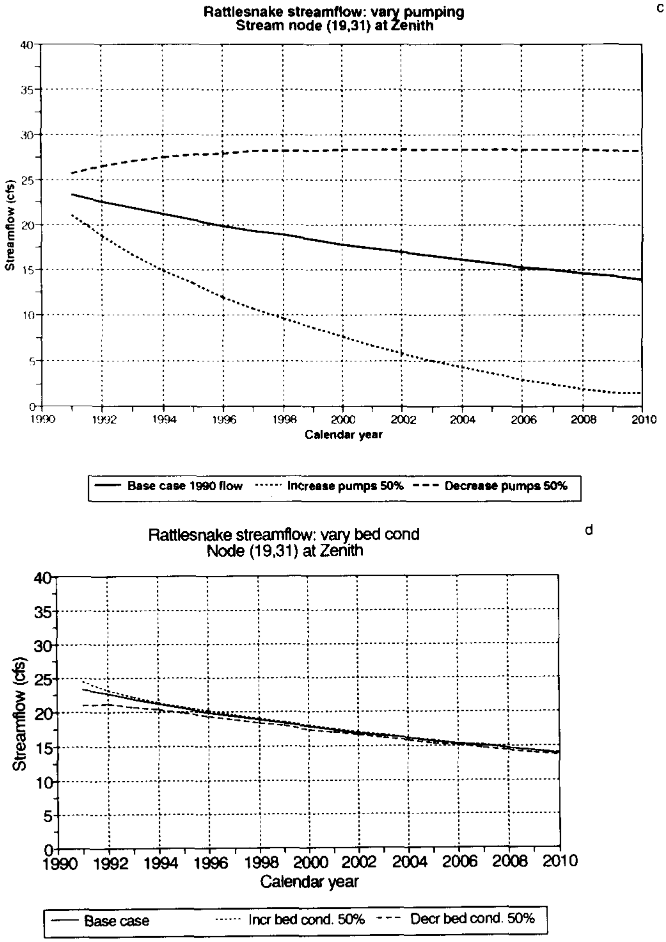


Fig. 5. Continued.

Sensitivity analysis of ground-water levels to changing aquifer and input parameters indicates that ground-water pumpage (Fig. 5(a)) has the greatest effect on aquifer water levels. The water levels are also highly sensitive to the amount of ground-water recharge (Fig. 5(b)), followed by aquifer storativity, aquifer hydraulic conductivity, and ground-water evapotranspiration, in decreasing order of sensitivity. However, different parts of the aquifer respond differently in absolute amount to changing parameters, with the relative significance of some parameters altered in some instances (Sophocleous et al., 1992).

Sensitivity analysis of streamflows to changing aquifer, input, and stream parameters indicates that, like ground-water levels, streamflows respond

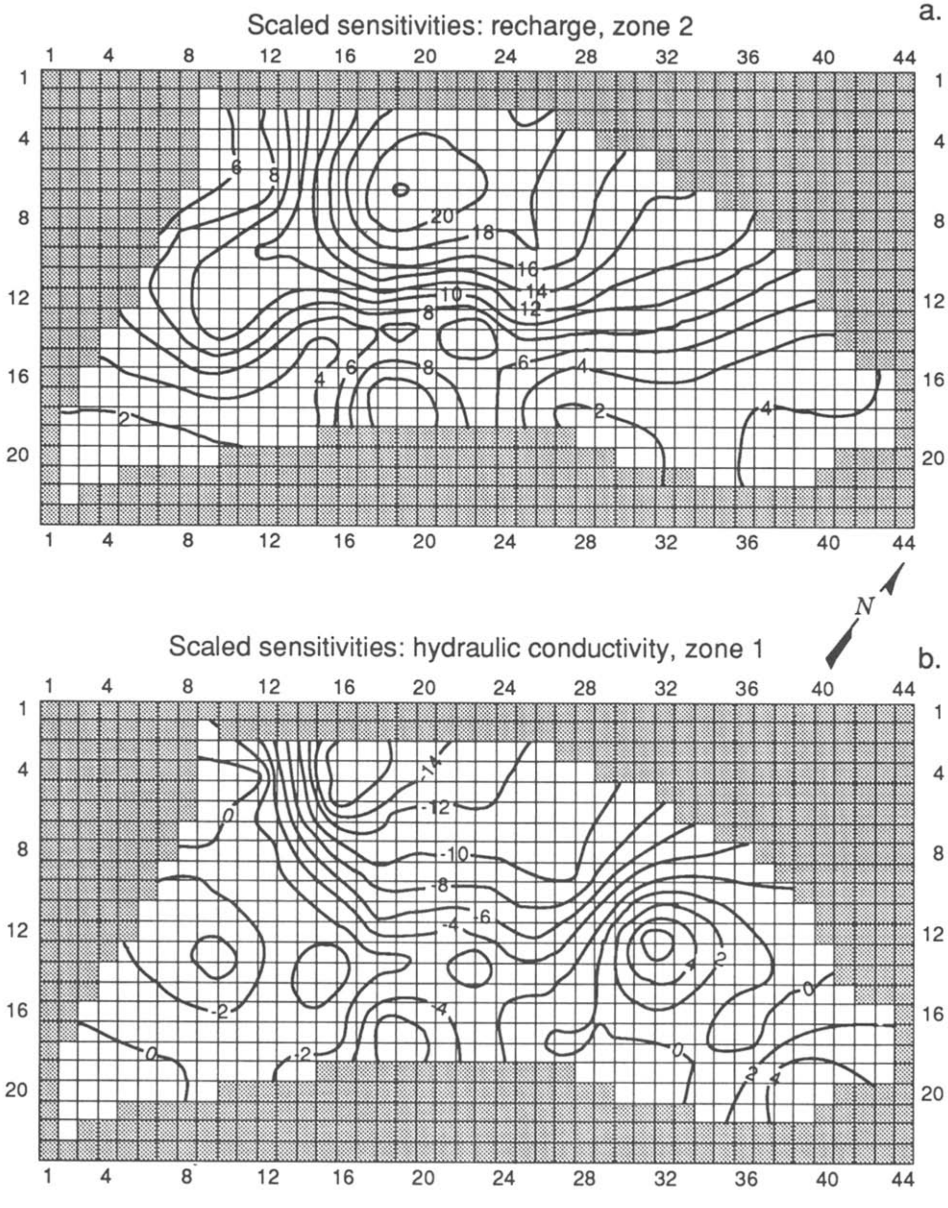


Fig. 6. Scaled sensitivity contours of (a) ground-water recharge and (b) hydraulic conductivity components of the sensitivity (Jacobian) matrix as determined by the inverse model procedure.

differently to various parameters. The aquifer and aquifer input-related parameters in this case have a much more pronounced effect on streamflows than do stream-related parameters. For example, ground-water pumpage (Fig. 5(c)) and recharge are more sensitive parameters than aquifer storativity, hydraulic conductivity, and aquifer evapotranspiration, but all these aquifer variables are much more sensitive parameters than streambed conductance (Fig. 5(d)), Manning's roughness coefficient, stream slope, and stream width. Plots of responses to all stream–aquifer parameters have been given by Sophocleous et al. (1992) and Sophocleous and Perkins (1993).

The spatial variation of the model normalized sensitivities is illustrated in Fig. 6 for the case of (a) recharge, and (b) hydraulic conductivity, for the intermediate-value zones which comprise the largest areal extent in the Rattlesnake model region. Figure 6 shows that there is considerable variation in sensitivity, indicating that additional data points in high-sensitivity areas would improve model results. It also demonstrates that ground-water recharge is more sensitive than hydraulic conductivity, and that the area of greatest model sensitivity to the displayed parameters is the north-west model region in north-west Stafford County. Such sensitivity analyses can be used to evaluate monitoring programs, and ranges of parameter uncertainties. Model calibration cannot be used to estimate parameters to which the model is insensitive.

Management applications

The predictive capabilities of the calibrated models permit hypothetical conditions to be explored by simply changing the data input to emulate the desired situations. Two general sets of scenarios have been tested: (1) effects of climatic fluctuations and changing incoming streamflows in the model areas (climatic fluctuations set); (2) effects of changing pumping patterns, establishing protective stream corridors, and achieving specified desired streamflows (stream corridor set). Selected relevant results primarily from the stream corridor set for both the Arkansas River and the Rattlesnake Creek model areas are outlined in Table 2 and are discussed briefly in what follows.

Kinsley to Great Bend model area

In Fig. 7(a) we show predicted streamflows, not taking into account surface runoff within the model boundaries (this was generally small, of the order of 13 mm year^{-1} (0.5 in year^{-1}) (Sophocleous and McAllister, 1990) and assuming that present conditions of ground-water pumpage, recharge, and the average of the last reported three water years (1988–1990) of incoming streamflows at the Kinsley (0.59 m^3 s^{-1} (20.66 ft^3 s^{-1})) and Larned (0.50 m^3 s^{-1} (17.63 ft^3 s^{-1})) gages persist throughout the 1991–2010 period (base-case scenario). The stream reach from Larned to Great Bend (Fig. 3(b)) is the most vulnerable in the sense that the steepest declines in

Table 2
Management alternatives considered here

(A) *Arkansas River model area*	Results in Figure
(I) Kinsley to Great Bend model area	
(1) Base case: 1990 'conditions' maintained (pumpage 80% of appropriations)	7(a)
(2) 50% pumpage reduction throughout model area	7(b)
(3) 5 km stream corridor with pumping moratorium	7(c)
(4) Incoming streamflows at Kinsley restored to 1970s levels	Not shown
(II) Larned to Great Bend critical model subregion	
(5) 5 km stream corridor with pumping moratorium	8(a)
(6) 50% and higher pumpage reductions throughout critical model region	8(b)
(B) *Lower Rattlesnake Creek model area*	
(1) Base case: 1990 conditions maintained (pumpage 70% of appropriations)	9(a)
(2) Complete pumpage moratorium: maximum streamflow gain	9(a)
(3) 5–8 km stream corridors with pumping moratoria	9(a)
(4) Time-varying stream corridors during a 20 year planning horizon	
(a) 5 km (first decade) followed by 6 km (next decade)	9(b)/1[a]
(b) 5 km (first decade) followed by 8 km (next decade)	9(b)/3
(5) 0.85 $m^3 s^{-1}$ (30 $ft^3 s^{-1}$) streamflow target met within 3 years by employing a 5 km stream corridor with pumping moratorium plus 28.6% pumpage reduction throughout model area	9(b)/4
(6) 50% pumpage reduction throughout model area	9(b)/2

[a] Numbers following a slash indicate numbered curve in figure.

streamflow occur there. The Arkansas River reach from Dundee to Great Bend is particularly vulnerable. Streamflows at Great Bend are predicted to decrease by 100%, whereas at Garfield they are predicted to decrease by 25% by the year 2010 (Fig. 6(a)). Stream reaches 35–46 (each reach corresponds to a 1.6 km (1 mile) grid cell) will be dry by 2010 (Figs. 3(b) and 7(a)). We use Fig. 7(a) as a base case to compare against several possible management scenarios for restoring streamflows to those dry reaches.

A 50% simulated reduction in present-day ground-water pumpage (assuming 80% of appropriate amounts) over the Kinsley to Great Bend study area would restore flows at Great Bend to the level of present-day incoming streamflows at Kinsley over the next 20 years to 2010 (Fig. 7(b)). Streamflows of the Arkansas River segment from Kinsley to Larned would be effectively stabilized.

Imposing a ground-water pumping moratorium for the next 20 years along a 5 km (3 mile) corridor around the Arkansas River (Fig. 7(c)) would definitely improve the streamflow regime not only at Great Bend but also along the

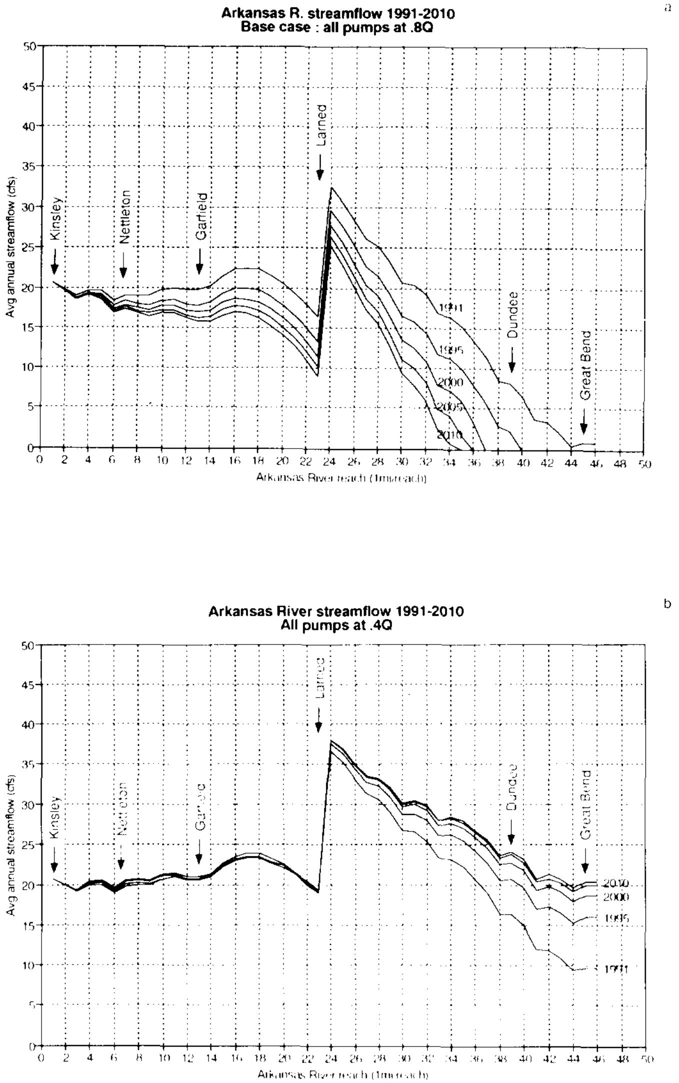


Fig. 7. Model-predicted streamflows for the next 20 years, assuming (a) 1988–1990 water-year average incoming streamflows at Kinsley and Larned (base case), (b) a 50% reduction in 1990 ground-water pumpage, and (c) no ground-water pumpage along a 5 km (3 mile) corridor around the Arkansas River. (To convert $ft^3 s^{-1}$ to $m^3 s^{-1}$ multiply by 28.3×10^{-3}.)

entire Arkansas River segment from Larned to Great Bend (a portion of this corridor along this critical segment of the Arkansas River is shown in Fig. 3(b)), with streamflows above $0.28 m s^{-1}$ ($10 ft^3 s^{-1}$) by 2010 throughout that segment. The established minimum desirable streamflows (MDS) for the

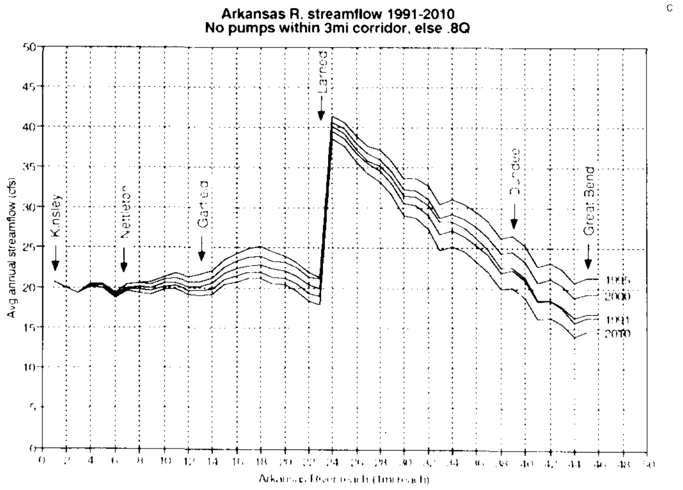


Fig. 7. Continued.

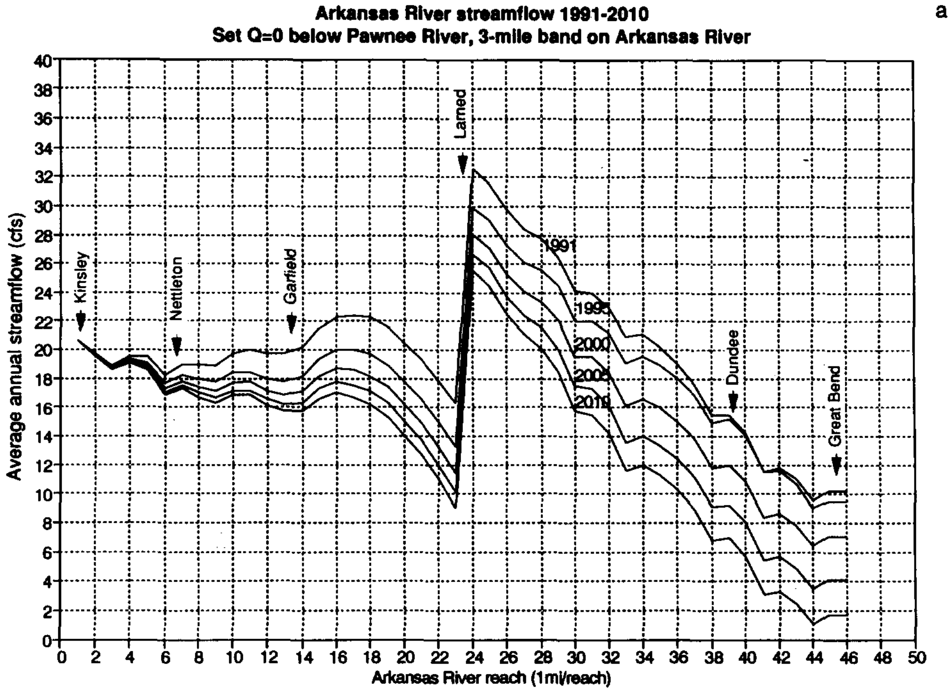
Arkansas River at Great Bend range from 0.06 to 0.28 $m^3 s^{-1}$ (2–10 $ft^3 s^{-1}$) depending on the month of the year.

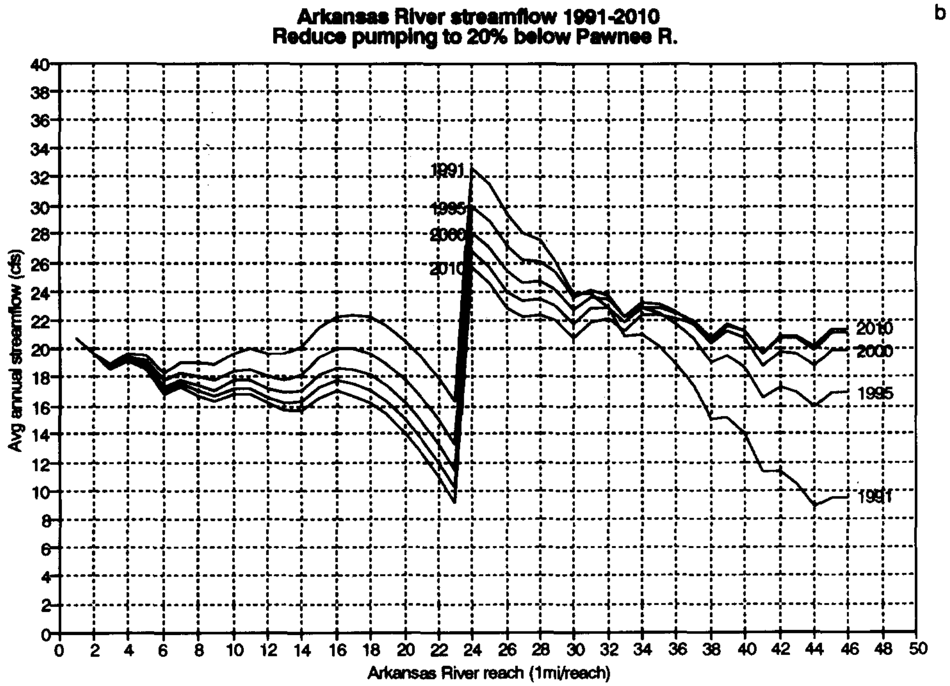
If the incoming streamflows at Kinsley were restored to the average annual streamflows of the 1970s (approximately 2.35 $m^3 s^{-1}$ (83 $ft^3 s^{-1}$)) for the next 20 years, then no present-day pumpage restrictions would be required to maintain adequate streamflows in the Arkansas River (Sophocleous et al., 1992). Streamflows at Great Bend would range from 0.85 to 1.19 $m^3 s^{-1}$ (30–42 $ft^3 s^{-1}$) (compared with almost zero otherwise) over the next 20 years, assuming that present-day pumpage remains unchanged during that period. (This may be the expectation of Kansas in the well-known Kansas–Colorado dispute over the incoming Arkansas River streamflows from Colorado, still being litigated.)

For the next series of simulations of management alternatives for the Kinsley to Great Bend model area, we evaluate what could be done to restore streamflows in the critical Larned to Great Bend reach of the Arkansas River. Reference should be made to Fig. 7(a) for the base case. Figure 8(a) depicts the Arkansas River streamflow profiles for the next 20 years if a 5 km (3 mile) ground-water pumpage moratorium corridor were established around the

---

Fig. 8. (Opposite) Model-predicted streamflows for the next 20 years, assuming 1988–1990 water-year average incoming streamflows at Kinsley and Larned and (a) complete pumpage moratorium along a 5 km (3 mile) corridor around the Arkansas River from Larned to Great Bend or (b) 80% reduction in 1990 ground-water pumpage in the entire model area below the confluence with the Pawnee River. (To convert $ft^3 s^{-1}$ to $m^3 s^{-1}$ multiply by 28.3×10^{-3}.)


a
Arkansas River streamflow 1991-2010
Set Q=0 below Pawnee River, 3-mile band on Arkansas River
Average annual streamflow (cfs)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Arkansas River reach (1mi/reach)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
Kinsley
Nettleton
Garfield
Larned
Dundee
Great Bend
1991
1995
2000
2005
2010


b
Arkansas River streamflow 1991-2010
Reduce pumping to 20% below Pawnee R.
Avg annual streamflow (cfs)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Arkansas River reach (1mi/reach)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
1991
1995
2000
2010
2010
2000
1995
1991

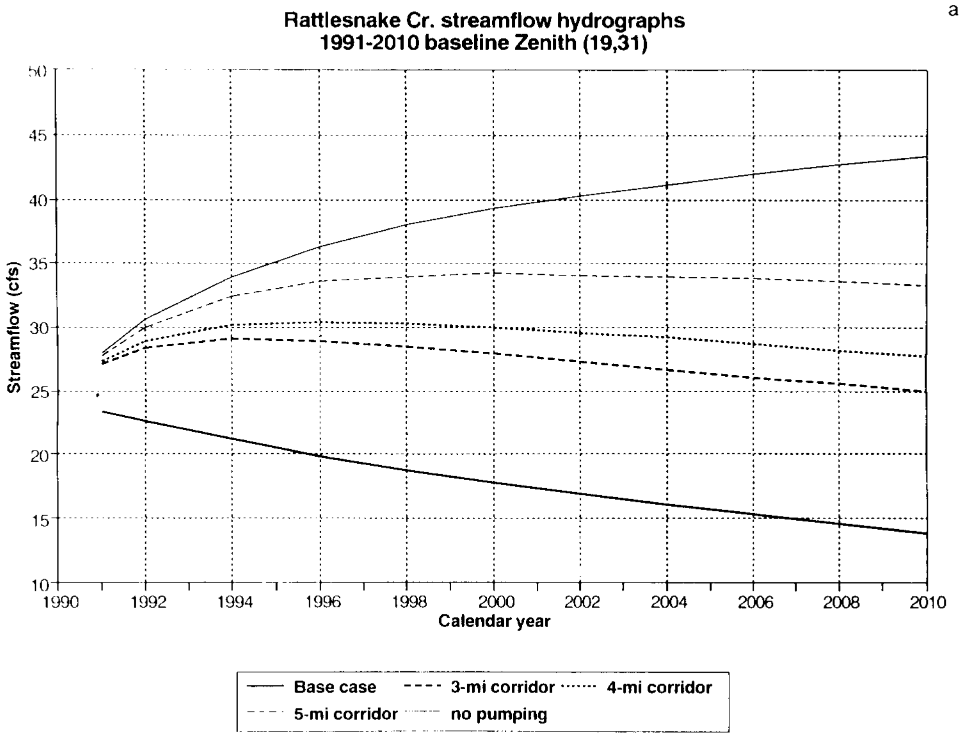


Fig. 9. Predicted effect of various management scenarios on Rattlesnake Creek streamflows at the Zenith gaging station. (Refer to text for explanation of curves. To convert $ft^3 s^{-1}$ to $m^3 s^{-1}$ multiply by 28.3×10^{-3}.)

river from Larned to Great Bend only. This corridor is shown in Fig. 3(b). This management alternative would result in no dry-stream cells in the critical Larned to Great Bend stream reach. However, streamflows at Great Bend will often fall below MDS after the year 2000. Figure 8(b) shows a similar situation to that depicted in Fig. 8(a) except that, instead of employing a corridor around the stream, the entire model area below the confluence with the Pawnee River is subjected to 80% ground-water pumpage reductions. Other percentage reductions (50% and 100%) have been presented by Sophocleous et al. (1992). All these cases would result in no dry-stream cells in the critical Larned to Great Bend segment of the Arkansas River. A 50% reduction would result in a minimum streamflow of approximately $0.17 \, m^3 s^{-1}$ ($6 \, ft^3 s^{-1}$) just west of Great Bend in the 20 year projection period, whereas 80% and complete (100%) pumping reductions would completely stabilize or reverse the declining streamflow trend in that critical stretch of the Arkansas River.

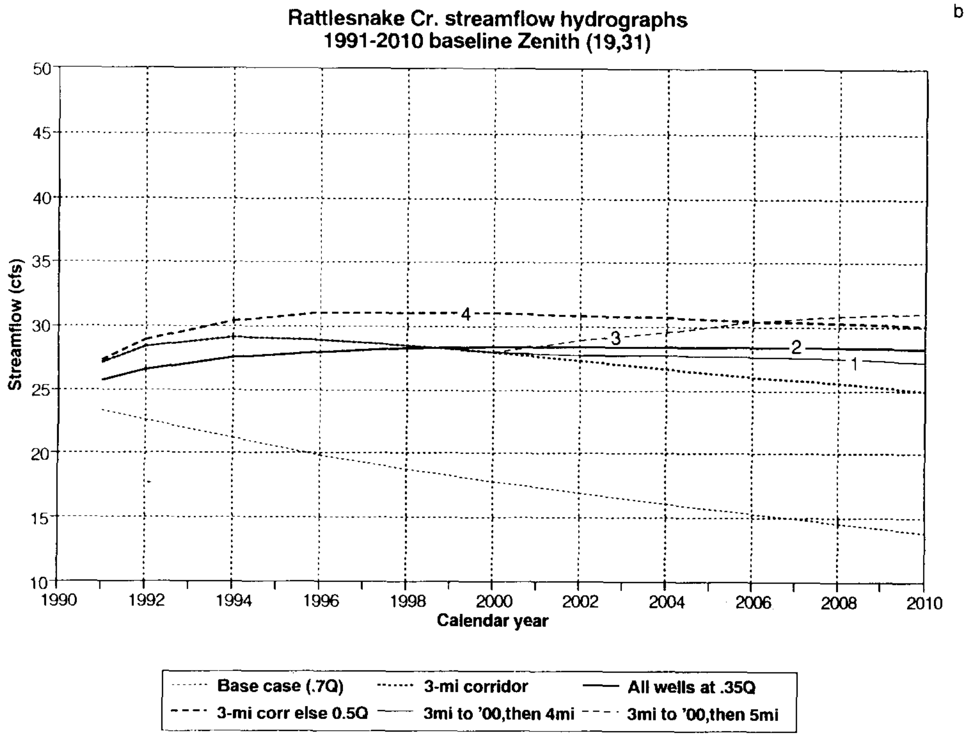


Fig. 9. Continued.

Rattlesnake Creek–Quivira model area

The Rattlesnake Creek streamflows entering the Quivira marsh under various management scenarios are displayed in Fig. 9. The lower curve of Fig. 9 represents the base-case scenario, that is, the predicted Rattlesnake Creek streamflows at the Zenith gaging station for the next 20 years to 2010, assuming that present-day conditions of pumpage, recharge, groundwater evapotranspiration, and incoming streamflows at the Macksville gaging station persist throughout the 1991–2010 period. Future streamflows near the entrance to the Quivira refuge will be declining by approximately 40% by the year 2010, according to the model. The upper curve in Fig. 8 represents the maximum expected Rattlesnake Creek streamflows at the Zenith gaging station if all irrigation wells in the model area are completely shut down for the entire 1991–2010 period and recharge, evapotranspiration, and incoming streamflows at the Macksville gaging station are frozen at present-day levels. The rest of the curves represent predicted streamflows at the Zenith gaging station for various pumpage-moratorium corridors around

Table 3. Management scenarios for enhancing streamflows in the Rattlesnake Creek

	Present-day conditions (base case)	5 km (3 mile) corridor[a]	6 km (4 mile) corridor[a]	8 km (5 mile) corridor[a]	Complete pumpage shutdown[a]
Ground-water pumpage					
10^6 m^3 year^{-1} [b]	85.92	73.87 (−14.0%)	69.73 (−18.8%)	62.56 (−27.2%)	
acre ft year^{-1} [b]	69 655	59 889	56 531	50 719	0
Stream leakage gains					
10^6 m^3 year^{-1}	13.20	20.29 (+53.7%)	23.31 (+76.6%)	27.65 (+109.5%)	37.53 (+184.3%)
acre-ft year^{-1}	10 702	16 447	18 898	22 418	30 424

[a] Parentheses indicate per cent change in ground-water pumpage or stream gains relative to the base case.

[b] Seventy per cent of appropriations.

Rattlesnake Creek (Fig. 3(a)). For a 20 year planning horizon, only stream corridors greater than 6 km (4 miles) with complete pumping shutdown would be effective in stabilizing or increasing streamflows at the entrance to the Quivira marsh (Fig. 9(a)), provided that present-day (1988–1990) climatic conditions remain constant over the next 20 years. Table 3 depicts the relative decreases in pumpage and corresponding gains in streamflows for the various scenarios in the Rattlesnake Creek model area.

Figure 9(b) displays additional temporally varying management options. For example, a 5 km (3 mile) corridor around Rattlesnake Creek with a complete irrigation-well pumping moratorium up to the year 2000 (Fig. 3(a)), followed by a 6 km (4 mile) corridor thereafter until the year 2010 would approximately maintain present-day streamflows (Fig. 9(b), curve 1); however, if an 8 km (5 mile) corridor of irrigation moratorium followed after the year 2000 (Fig. 3(a)), Rattlesnake Creek streamflow at the entrance to the Quivira National Wildlife Refuge (Zenith gaging station) would have increased by almost $0.11\,m^3\,s^{-1}$ ($4\,ft^3\,s^{-1}$) from present-day streamflows (Fig. 9(b), curve 3).

If a target of $0.85\,m^3\,s^{-1}$ ($30\,ft^3\,s^{-1}$) or more is set for streamflow at the Zenith gaging station over a 20 year planning period, this goal could be achieved within the next 3 or 4 years if a 5 km (3 mile) irrigation-pumping moratorium corridor is adopted (Fig. 3(a)) in combination with a 50% reduction in appropriated pumpage (which corresponds to a 28.6% decrease of actual pumpage) throughout the rest of the model area (Fig. 9(b), curve 4). Finally, if all irrigation wells are permitted to pump only half of what they normally pump, this would definitely stabilize and improve streamflows at a level of more than $0.085\,m^3\,s^{-1}$ ($3\,ft^3\,s^{-1}$) over present-day streamflows from 1997 to the end of the planning horizon (2010; Fig. 9(b), curve 2).

Summary and conclusions

This study was undertaken to address concerns with declining streamflows and to explore possible management options to remedy this situation. The approach we followed was to analyze the stream–aquifer system as a unit in two areas of concern: the Akansas River valley from Kinsley to Great Bend, Kansas, and the adjacent lower Rattlesnake Creek watershed. A two-dimensional stream–aquifer model coupled with parameter estimation and optimization modeling was implemented in the study areas, and proved to be an effective and efficient approach in addressing the stream–aquifer problem. The models were field-calibrated for both predevelopment and development periods and were given a limited validation using stresses different from those used in the calibration.

Hydrologic budgets for both predevelopment and developed conditions indicate significant differences in the hydrologic components resulting from development. Such computer simulations provide insight into the changes in recharge and discharge resulting from development. Natural recharge balances natural discharge as baseflow of streams or outflow to springs and wetlands and does not enter the water account for artificial ground-water diversions. Induced recharge and ground-water storage are the two sources of water to balance artificial ground-water withdrawals. The effects of concern to water policy are primarily aquifer drawdown and surface-water depletion. Both are functionally related to pumping rate, aquifer diffusivity, location, and time of pumpage. Thus the natural recharge rate is not directly related to any parameters controlling these primary water policy concerns and should not be used as a measure of the magnitude of ground-water development that will lead to stable, nondepleting ground-water levels. As Bredehoeft et al. (1982) noted, the suggestion that the 'safe yield' of a ground-water basin be defined as the annual extraction of water that does not exceed the average annual ground-water recharge is misleading. As the comparison of the steady-state and transient-state water budgets for both model areas shows, major ground-water development, such as the one in the GMD5 region, significantly changes the recharge–discharge regime with time. The yield of the ground-water basin depends on both the manner in which the effects of withdrawal are transmitted through the aquifer and the changes in rates of recharge and discharge induced by the withdrawals.

We used sensitivity analysis to identify parameters to which the transient-state model was most sensitive. Ground-water pumpage had the largest effect on aquifer water levels and streamflows, followed by recharge, aquifer storativity, and hydraulic conductivity, in order of decreasing sensitivity. These parameters are much more sensitive than stream-related parameters (streambed conductance, Manning's roughness coefficient, stream slope, and stream width).

The calibrated models provide a predictive tool that explains the connections between well-field withdrawals and surface-water depletion. Such causal hydrologic models also link proposed actions to hydrologic effects, as clearly demonstrated by the effects of various management alternatives on the streamflows of the Arkansas River and Rattlesnake Creek. The hydrologic effectiveness of protective stream corridors with restricted ground-water extraction is demonstrated for both study areas, thus providing a possible means of restoring specified streamflows in the area streams.

The results from this study indicate that the present level of ground-water pumpage in both study areas is not sustainable over the long term and that desirable streamflows cannot be maintained unless severe measures along the lines indicated in this study are taken to protect and conserve the water resources of the region. In view of the possible significant impact such studies might have on water management policies in the GMD5 region, the irrigators of the area were organized to protect their rights and contest any unfavorable results from this study. It is hoped that hydrologic studies such as this one will raise people's awareness of hydrologic reality and will encourage open discussion and improve understanding of the important issues we are addressing and their significance to all concerned.

Acknowledgments

US Fish and Wildlife Service funding of the lower Rattlesnake Creek–Quivira marsh study and Kansas Water Office funding of the Kinsley–Great Bend reach of the Arkansas River study are gratefully acknowledged. The cooperation and field assistance of GMD5 personnel is also gratefully acknowledged. Seid Pourtakdoust, a former Kansas Geological Survey (KGS) graduate research assistant, ably assisted during the initial stages of these studies. Alan Stern, a current KGS research assistant, and Jim Mitchell of KGS provided Geographic Information Systems (GIS) support for the project. A. D. Koussis of the Kansas University Department of Geology, as well as R. W. Buddemeier and other colleagues from KGS, provided useful reviews of the manuscript. Two anonymous referees contributed constructive review comments.

References

Bredehoeft, J.D., Papadopulos, S.S. and Cooper, Jr., H.H., 1982. Groundwater — the water-budget myth. In: M. Fiering (Editor), Scientific Basis of Water Resource Management. National Academy Press, Washington, DC, pp. 51–57.

Doherty, J., 1990. MODINV-MODFLOW Parameter Optimization Manual, Version 1.05. Australian Center for Tropical Freshwater Research, Townsville, Qld., 258 pp.

Draper, N.R. and Smith, H., 1981. Applied Regression Analysis, 2nd edn. Wiley, New York, 709 pp.

Fader, S.W. and Stullken, L.E., 1978. Geohydrology of the Great Bend Prairie, south-central Kansas. Kansas Geological Survey, Irrigation Series, 4, University of Kansas Publications, Lawrence, KS, 19 pp.

Latta, B., 1950. Geology and ground-water resources of Barton and Stafford counties, Kansas. Kans. Geol. Surv. Bull., 88, 228 pp.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite difference ground-water flow model. US Geological Survey, Techniques of Water-Resources Investigations, Book 6, Ch. A1. US Geological Survey, U.S. Government Printing Office, Washington, DC.

Prudic, D.E., 1989. Documentation of a computer program to simulate stream–aquifer relations using a modular, finite-difference, ground-water flow model. US Geol. Surv. Open-File Rep., 88-729, Carson City, NV, 113 pp.

Sophocleous, M.A., 1981. The declining ground-water resources of alluvial valleys — a case study. Ground Water, 19 (2): 214–226.

Sophocleous, M.A., 1984. Groundwater flow parameter estimation and quality modeling of the Equus beds aquifer in Kansas. J. Hydrol., 69: 197–222.

Sophocleous, M.A., 1992a. Stream–aquifer modeling of the lower Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge. Kans. Geol. Surv. Open-File Rep., 91-10, 29 pp.

Sophocleous, M.A., 1992b. Modifications and improvements on the lower Rattlesnake Creek–Quivira marsh stream–aquifer numerical model. Kans. Geol. Surv. Open-File Rep., 92-37, 14 pp.

Sophocleous, M.A. and McAllister, J.A., 1987, Basinwide water-balance model with emphasis on spatial distribution of ground-water recharge. Water Resour. Bull., 23 (6): 997–1010.

Sophocleous, M.A. and McAllister, J.A., 1990. Hydrologic-balance modeling of the Rattlesnake Creek watershed, Kansas. Kans. Geol. Surv. Ground Water Ser., 11, 72 pp.

Sophocleous, M.A. and Perkins, S.P., 1993. Stream–aquifer modeling and mineral intrusion analysis of the lower Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge. Kans. Geol. Surv. Open-File Rep., 93-7, 194 pp.

Sophocleous, M.A., Townsend, M.A., Vogler, L.D., McClain, T.J., Marks, E.T. and Coble, G.R., 1988. Experimental studies on stream–aquifer interaction along the Arkansas River in central Kansas — field testing and analysis. J. Hydrol., 98: 249–273.

Sophocleous, M.A., Pourtakdoust, S. and Perkins, S.P., 1992. Stream–aquifer numerical modeling of the Kinsley to Great Bend reach of the Arkansas River in central Kansas — report of second-year results: Kans. Geol. Surv. Open-File Rep., 92-13, 136 pp.