KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 92-37

MODIFICATIONS AND IMPROVEMENTS ON THE LOWER RATTLESNAKE CREEK-QUIVIRA MARSH STREAM-AQUIFER NUMERICAL MODEL

by

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GEOHYDROLOGY

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This report presents the results of further testing and refinement of the stream-aquifer flow model discussed in the Kansas Geological Survey (KGS) Open-File Report 92-6 entitled "Stream-aquifer and mineral intrusion modeling of the lower Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge" by Sophocleous and Perkins (1992). The revised model incorporates changes in (a) aquifer hydraulic conductivities, (b) distribution of ground-water evapotranspiration effects, and (c) estimates of historic ground-water withdrawal rates. The effects of these changes on the model output were evaluated by comparing the values of error variance in the fit between measured and model-estimated ground-water levels, and by qualitative comparison of modeled and measured Rattlesnake Creek streamflows. The revised model results make no qualitative difference in the general conclusions presented in the original report (Sophocleous and Perkins, 1992).

In a review of KGS Open-File Report 92-6, Layne Geosciences Inc. (LGI), representing the Water PACK association headquartered at Macksville, Kansas, raised a number of issues mainly related to (1) the numerical modeling approach, (2) the model or input parameters associated with values of hydraulic conductivity and recharge, and the distribution of ground-water evapotranspiration, and (3) irrigation pumping and irrigation return flows [LGI letter to R. W. Buddemeier, KGS Geohydrology Section Chief, July 7, 1992 (KGS files)]. LGI recommended that the above-mentioned KGS open-file report be revised "to incorporate some of [their] comments and concerns." In a comprehensive response to the LGI letter [KGS letter and accompanying appendix of point by point responses to C. Nuzman, vice-president of LGI, August 4, 1992 (KGS files)] the issues raised were addressed, and additional model runs as per the LGI comments were committed to. The KGS cover letter of that response addressing the major issues enumerated above is considered an integral part of this report and is included as Appendix A. This report summarizes the additional model runs and model modifications following LGI review comments.

The original report (KGS Open-File Report 92-6) sensitivity analysis, which quantifies the effect of all major model or input parameters on the model-predicted ground-water levels and streamflows, provides a basis for evaluating the possible effects of changes in model input values. That sensitivity analysis clearly indicates that ground-water pumpage is the dominant variable on the Rattlesnake Creek-Quivira stream-aquifer system, and that adjusting hydraulic conductivity values, or expanding evapotranspiration zones, will not substantially change the simulated stream-aquifer declining patterns. This message is reinforced by the additional model runs outlined below.

The results of the revised model runs were statistically evaluated to ascertain how closely model-simulated water levels match observed ground-water levels by comparing the error variance of the fit. The estimated error variance and the corresponding standard deviation (i.e., the square root of the error variance) is a measure of overall goodness of fit, that is, how similarly the final simulated water-level (or head) values match the observed values; smaller values of the estimated error variance indicate a better match. If we make the assumption that the ground-water level measurements are normally distributed, then we can say something quantitative about the level of uncertainty pertaining to these estimated head values; that is, the true head values will lie within two standard deviations of the model-estimated values 95 percent of the time.

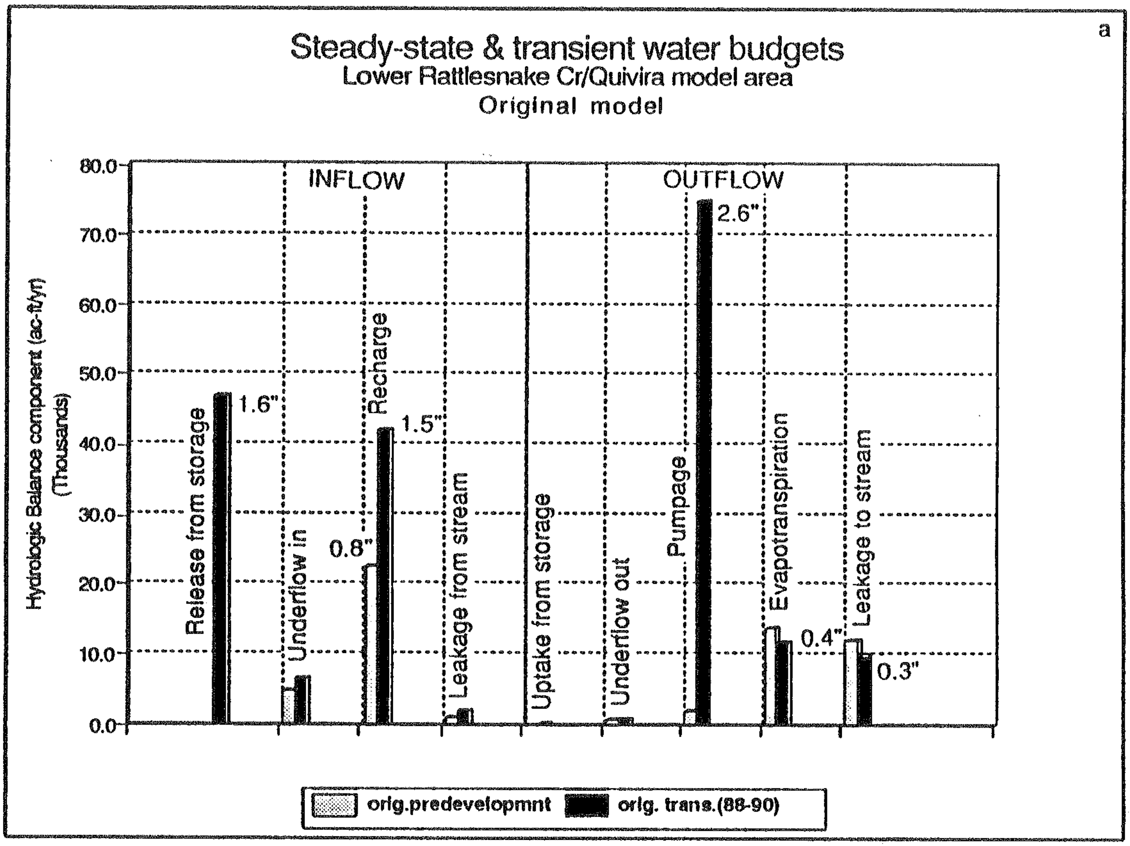
The reported values of measured or estimated hydraulic conductivity for the Great Bend Prairie aquifer, including the highly transmissive Arkansas River alluvium (which is outside the model region), range from 20 to 280 ft/day (Fader and Stullken, 1978; Sophocleous and Perkins, 1992). These values are mostly based on existing irrigation wells that normally tap the most productive parts of the aquifer, so this reported range is probably biased towards the higher values. The model-optimized hydraulic conductivity values for the four hydraulic conductivity zones of the model area in the original study (Sophocleous and Perkins, 1992) range from 10 ft/day (for the region surrounding the Cretaceous bedrock outcrop southwest of the Big Salt Marsh) to 78 ft/day. The resulting standard deviation of the ground-water levels for the predevelopment conditions, based on the optimized hydraulic conductivity values, is 2.84 ft, a relatively small value (compared to the 335-ft difference between the highest and lowest values of observed heads within the model area) indicating a satisfactory fit.

Because the optimized hydraulic conductivity values fell in the lower part of the range of the expected values and because sensitivity analysis (Sophocleous and Perkins, 1992) indicated that the hydraulic conductivity is not a highly sensitive parameter, the optimized values were increased through trial-and-error to the highest degree possible for a stable solution with a satisfactory match to the observed predevelopment water levels. The values for all zones, except the lowest hydraulic conductivity zone by the bedrock outcrop, could be approximately doubled before results became unsatisfactory (i.e., either no model solution or a rapid increase in error variance). These higher values resulted in a slightly worse (ground-water-level standard deviation: 3.08 ft) but still satisfactory fit than in the original predevelopment case. The trial-and-error fit of the four hydraulic conductivity zones of the model area ranged from 11 to 130 ft/day. Effects on post-development model fit are discussed below.

Ground-water evapotranspiration was originally restricted to the lower half of the model region (Sophocleous and Perkins, 1992), where the water table was shallow (less than 6 to 10 ft below ground surface); deeper depths to water-table have minimal or no effect on ground-water evapotranspiration. In order to take into account the riparian zone along the stream banks, the ground-water evapotranspiration zone was expanded by adding a second zone to encompass all model grid cells through which Rattlesnake Creek passes. Incorporating this additional change to the simulation results in a standard deviation of the predevelopment ground-water levels of 3.14 ft, which is still a satisfactory result. Although this model fit is slightly worse than the original simulation, the model fit may be more physically satisfying in that it better represents observational experience; however, because of the coarseness of the model grid (1 mi^2 grid cells) compared to the much smaller dimensions of the riparian-zone area around the stream banks, this refinement may be unnecessary.

The revised hydraulic conductivity values and expanded ground-water evapotranspiration zones were adopted for the transient developed-conditions simulations. We also reduced the actual amount of irrigation pumpage for the transient simulations from 80% of the appropriated amounts to 70%. These combined changes resulted in a significantly improved model fit compared to the original transient simulations. The resulting optimized average value of aquifer specific yield was 18%, which agrees with the expected value for the Great Bend aquifer. The standard deviation of the present-day ground-water levels in the predictive simulation from predevelopment to present-day conditions is only 3.22 ft compared with the original transient simulation fit of 4.27 ft. However, as will be shown later, the revised simulated Rattlesnake Creek streamflows generally overpredict observed flows compared with the original transient simulations, which underpredict observed streamflows.

The following figures make some of the salient features of the revised simulations clearer. Figure 1a depicts the ground-water budget for the original predevelopment and developed-conditions simulations, and fig. 1b displays the same information for the revised simulations. Note that in the original transient simulations it was assumed that the actual pumpage was 80% of the appropriated amounts, whereas for the revised simulations the figure is assumed to be 70%. The hydrologic budgets for both predevelopment and developed conditions indicate significant differences in the hydrologic components resulting from development. For example, the revised predevelopment natural ground-water recharge across the model area was estimated as 1.3 inches per year (0.8 in/yr in the original simulations), while the induced recharge under development conditions was estimated as 1.9 inches per year (1.5 in/yr in the original simulations). These recharge estimates are in agreement with other independent recharge estimates in the region (Sophocleous, 1992). The employed stream-aquifer model treats ground-water recharge as total aquifer replenishment, including irrigation return flows (see also Appendix A for additional information).



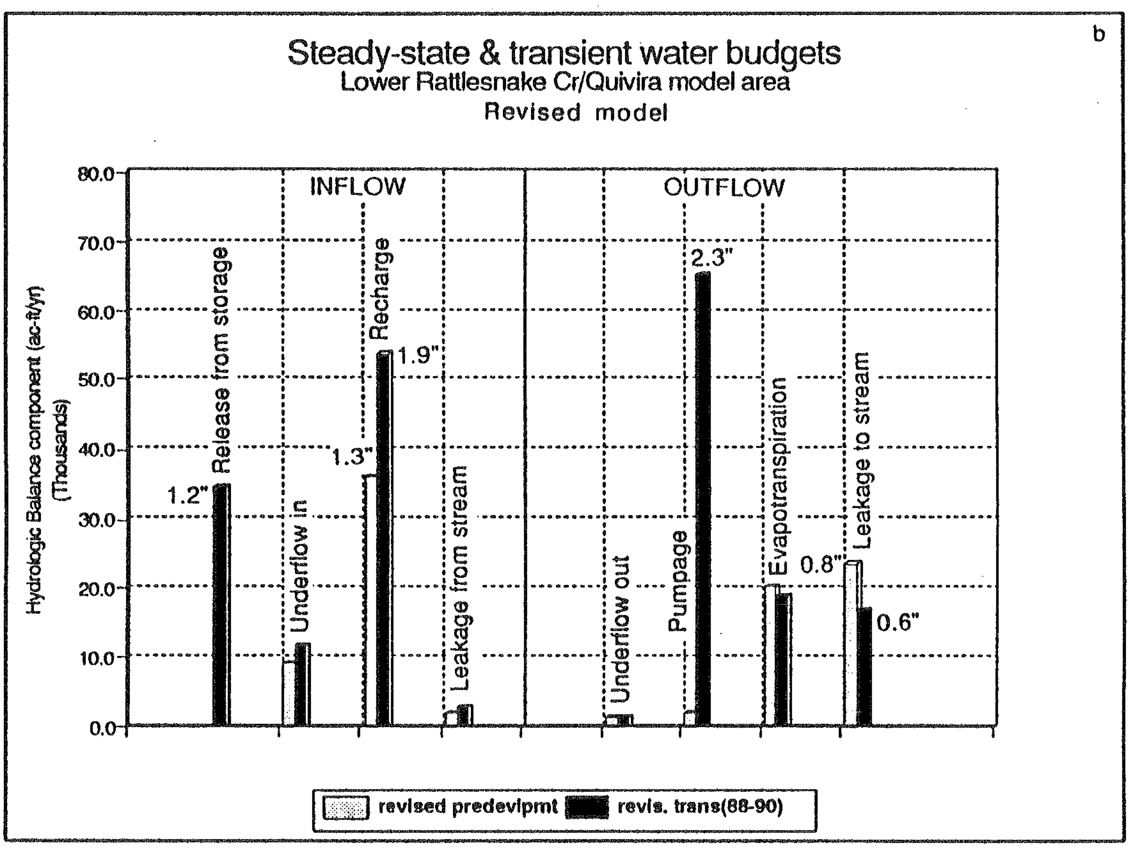


Figure 1. Predevelopment and present-day water budgets for the original (a) and revised (b) simulations of the Rattlesnake Creek-Quivira model area.

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 developed-conditions budgets 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, and others. 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. 1) 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 has been minimal (fig. 2) because of salinity problems, resulting in relatively small decreases in baseflow contributions to streamflow and in evapotranspiration losses (fig. 1).

Figure 3 depicts comparisons of simulated and observed ground-water levels for both predevelopment and present-day conditions using the revised model. Figure 3a and 3b indicate calibrated results from the parameter estimation/optimization program and, fig. 3c is a verification run to check model performance for intermediate years (between the calibrated predevelopment and present-day conditions); the results are satisfactory.

Figure 4 depicts Rattlesnake Creek streamflows at the Zenith gaging station as simulated by the original (a) and revised (b) models. Although, as mentioned earlier, the original simulations usually under predict streamflows and the revised ones usually over predict them, the predicted streamflow trends by both models closely follow the observed ones. This ability to reproduce dynamic behavior lends confidence to the appropriateness of the modeling approach we followed.

Finally, fig. 5 compares streamflow predictions using the original (a) and the revised (b) simulations for the next 20 years at several locations along the Rattlesnake Creek, assuming that

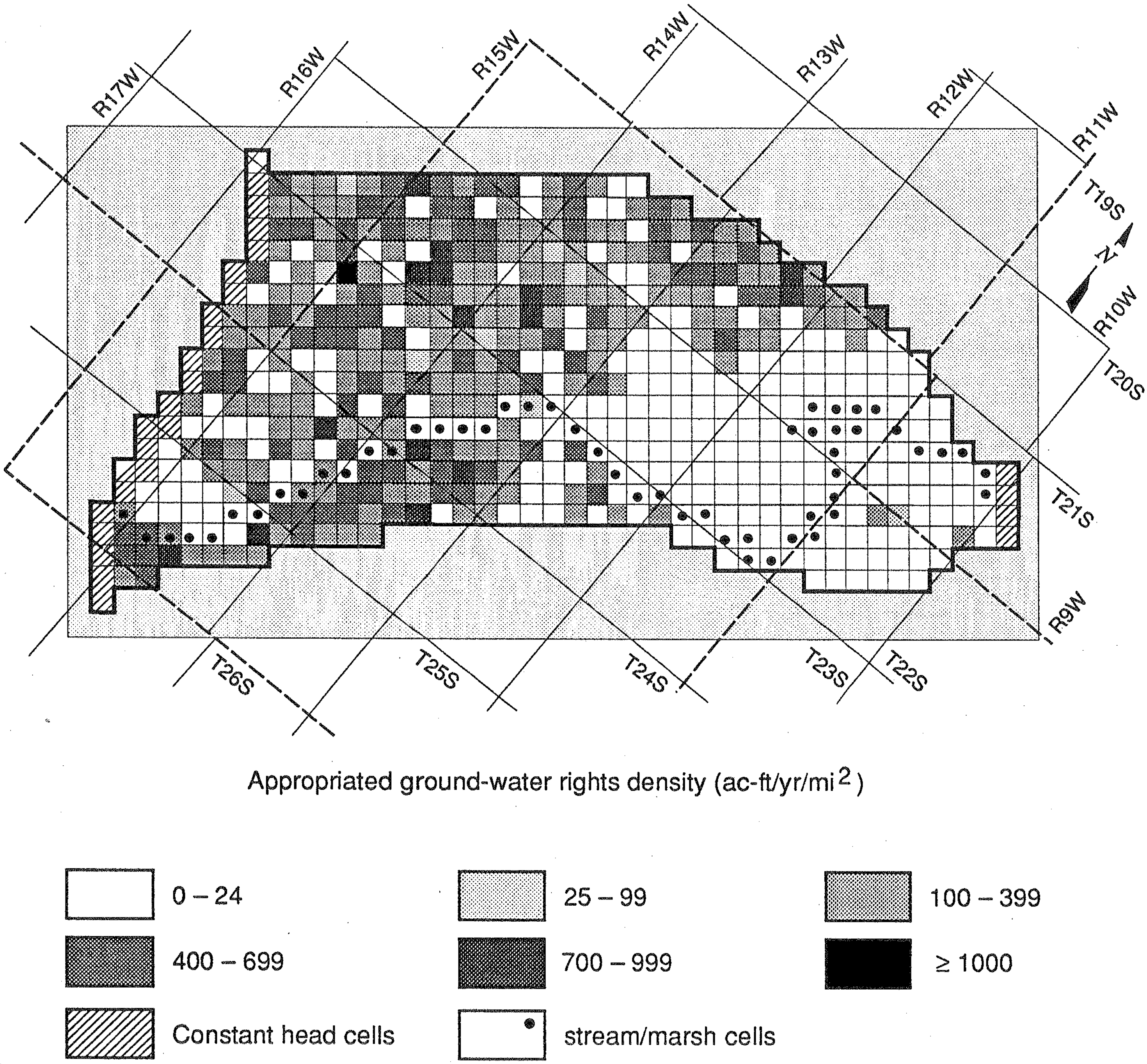


Figure 2. Appropriated ground-water rights density (in acre-ft/year/square mile) throughout the model grid

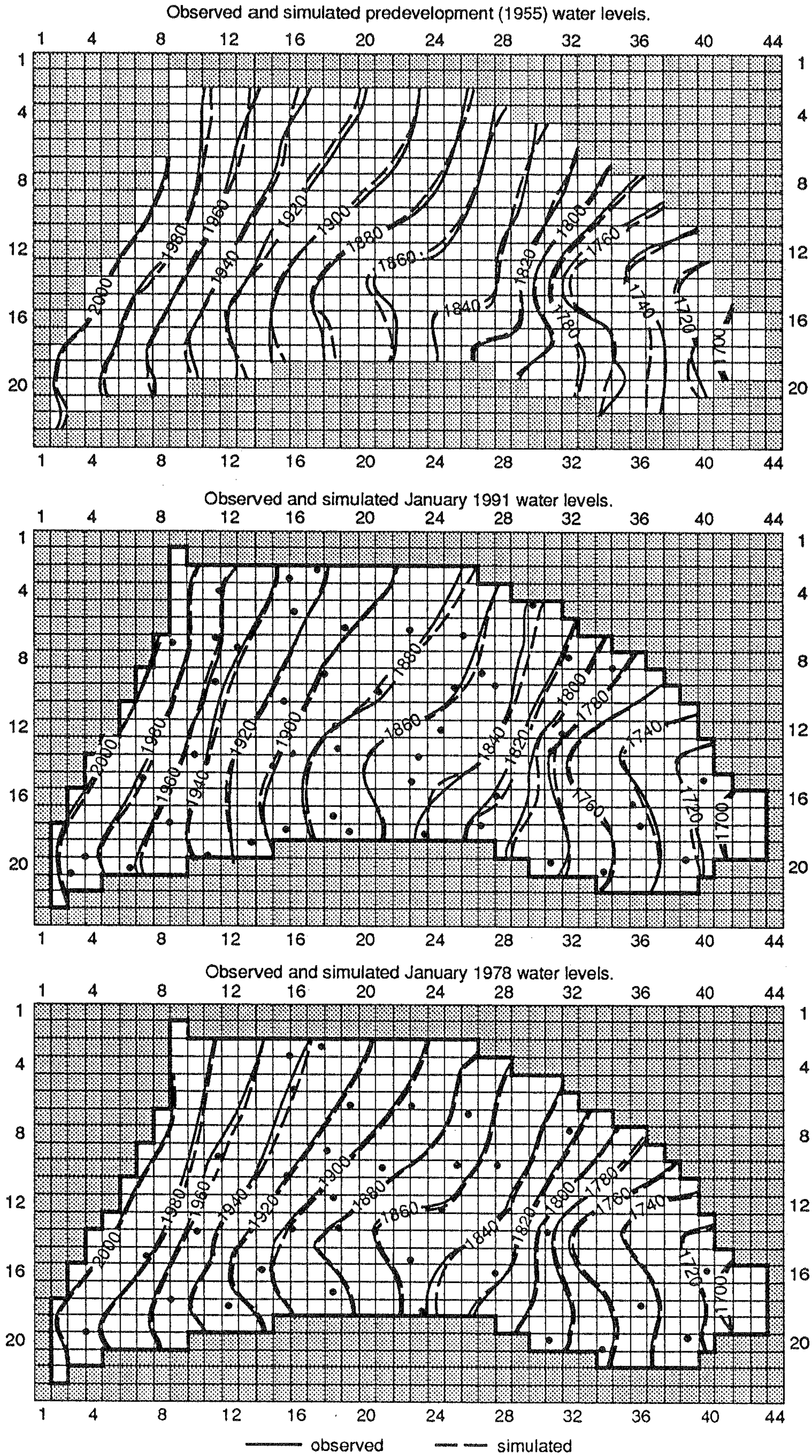
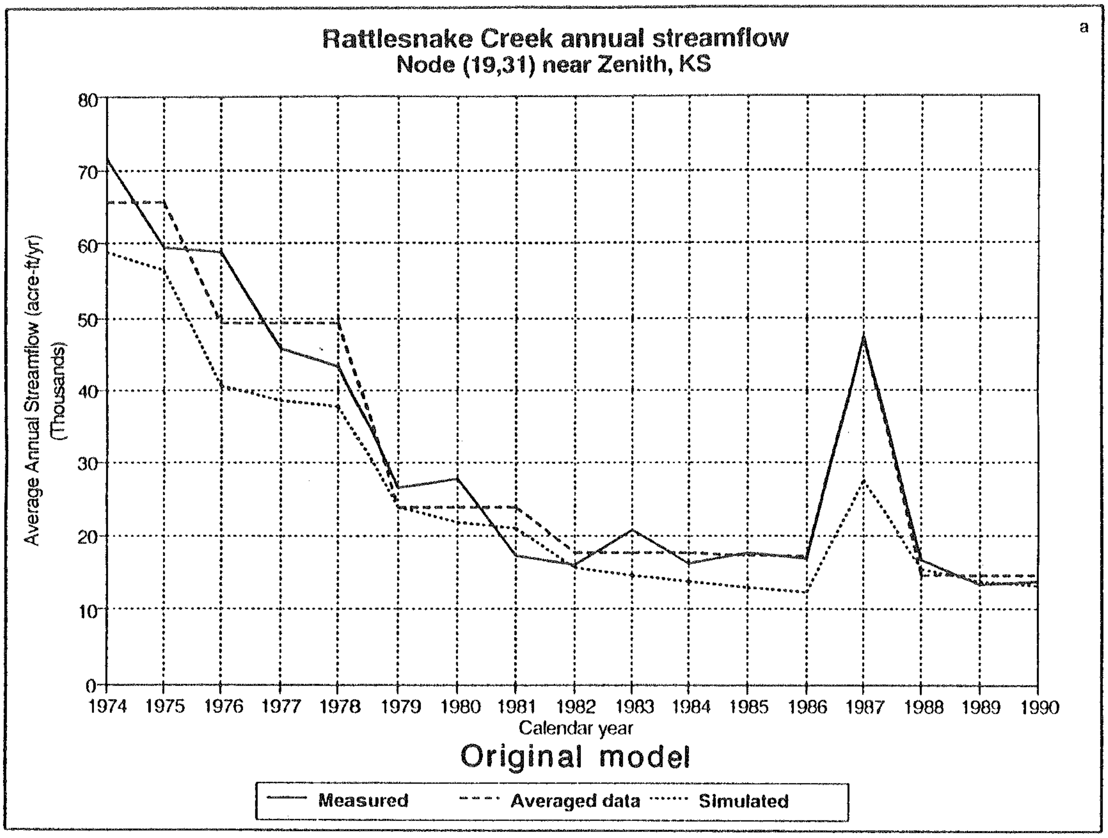


Figure 3. Comparison of revised model results for observed and simulated predevelopment (a) and developed-conditions water table contours for January 1991 (b) and January 1978 (c).



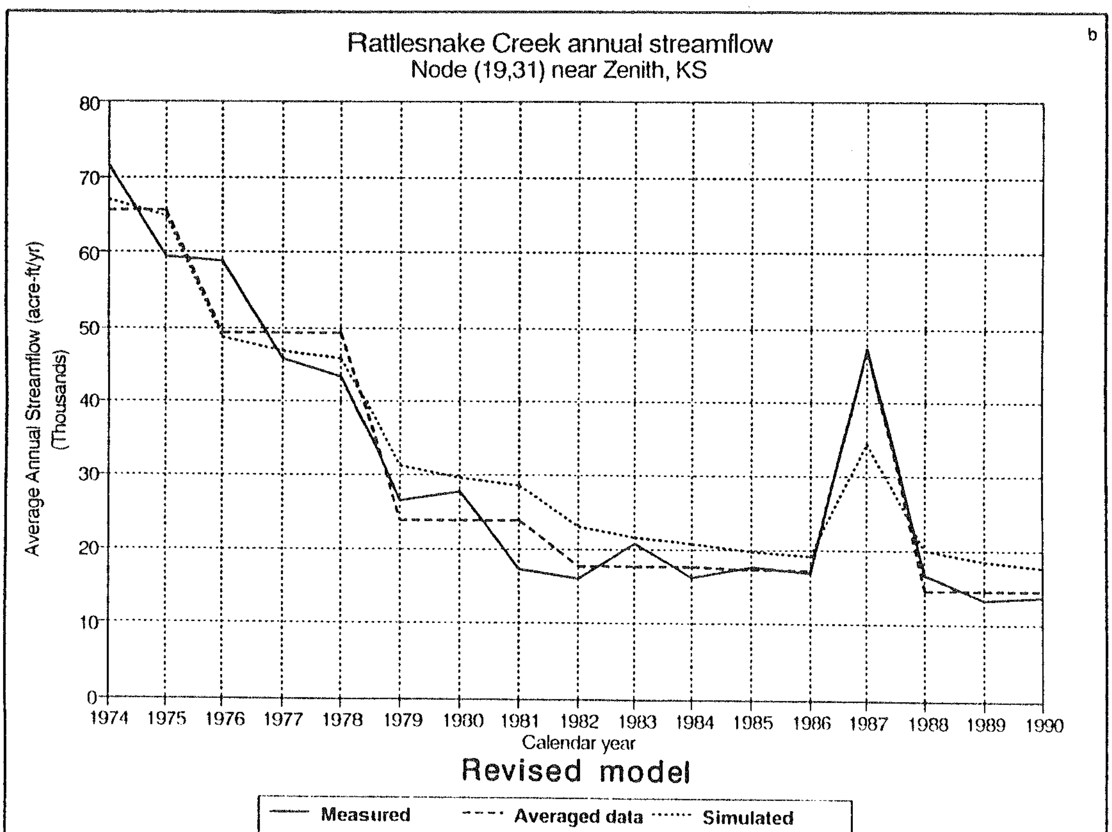
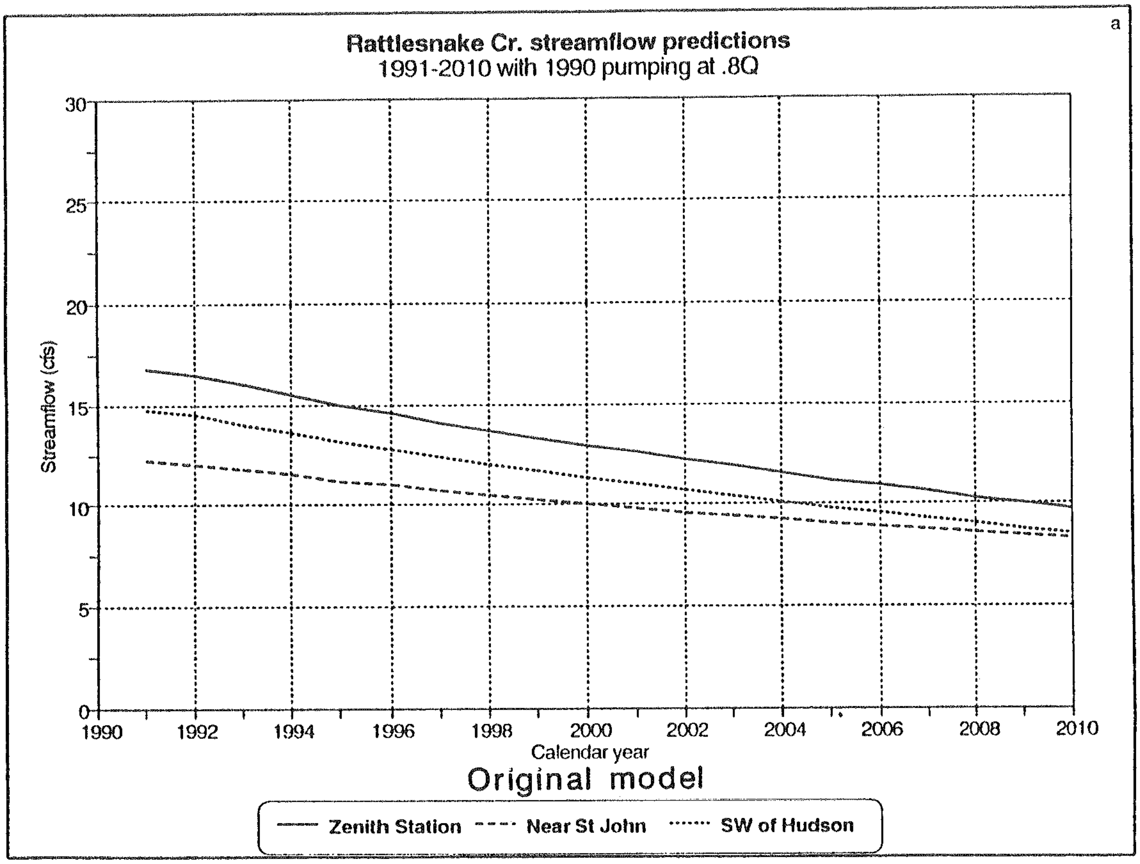


Figure 4. Comparison of measured and averaged (model input) streamflows versus model-simulated streamflows of the Rattlesnake Creek at the Zenith gaging station for the original (a) and revised (b) simulations.



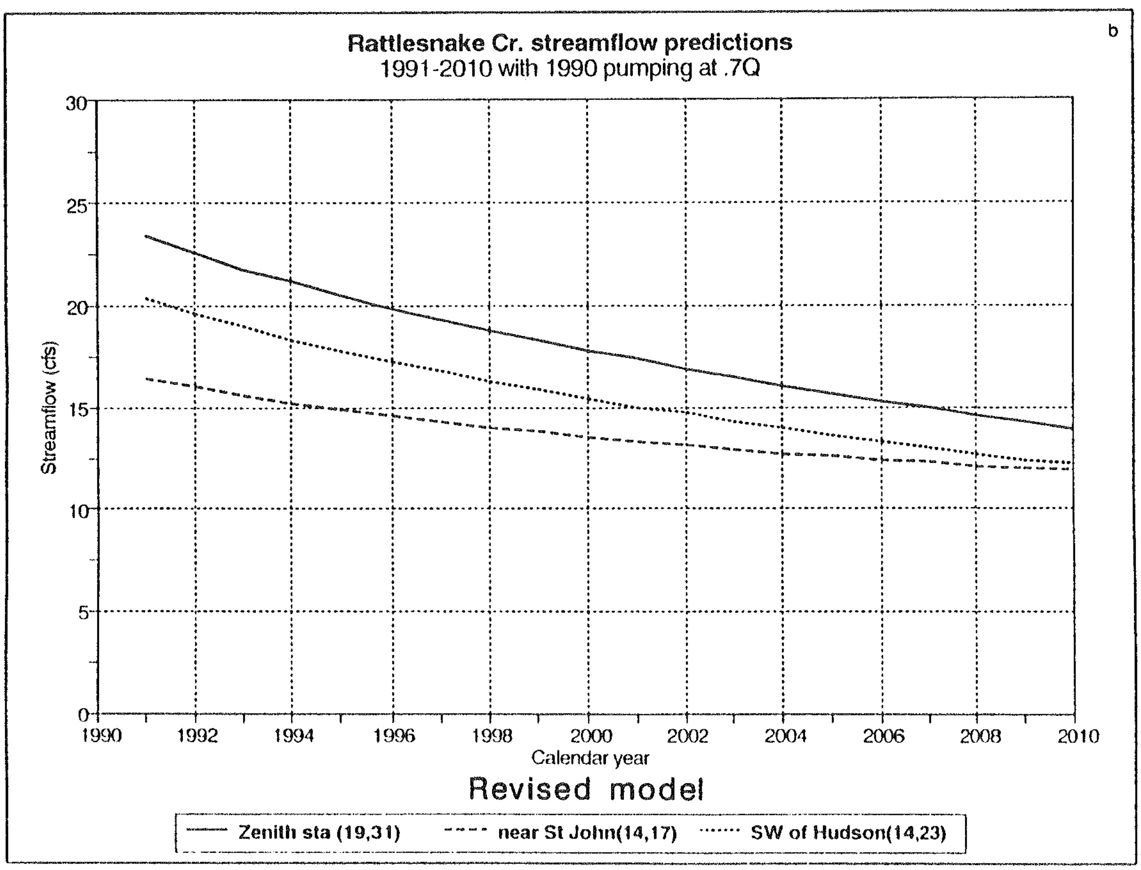


Figure 5. Model-predicted Rattlesnake Creek streamflow declines during the 1991–2000 period for the original (a) and revised (b) simulatons.

present-day climatic and streamflow conditions remain constant and ground-water pumpage stays at current levels. Both simulations predict that the declining streamflow trends observed since the mid-1970's will continue unabated for the entire 20-year prediction period. If undesirable effects of low streamflow are the primary concern, use of the original model will provide more conservative results. On the other hand, use of the revised model can provide an effective estimate of the minimum efforts required to stabilize or increase streamflow (Sophocleous and Perkins, unpublished work in progress).

The results of both the original and revised simulations represent reasonable ranges of possible outcomes and give an approximate measure of the range of uncertainty in model simulations. The revised model results make no qualitative difference in the general conclusions, which demonstrate the reality of stream-aquifer declines and expected declining trends. The original sensitivity analysis is reinforced by the results of the revised simulations and provides an effective way to evaluate model performance. It is highly probable that the "true" values of various parameters fall within the range defined by the original and revised model runs.

Acknowledgments

Sam Perkins, graduate student research assistant, provided able computer modeling assistance. Bob Buddemeier of the Kansas Geological Survey provided constructive review comments on this report.

References

Fader, S. W., and Stullken, L. E., 1978. Geohydrology of the Great Bend Prairie, South-Central Kansas. Kansas Geological Survey, Irrigation Series 4, 19 p.

Sophocleous, M. A., 1992. A quarter-century of ground-water recharge estimates for the Great Bend Prairie aquifer of Kansas (1967–1992). Kansas Geological Survey, Open-File Report 92-17, 22 p.

Sophocleous, M. A., and Perkins, S. P., 1992. Stream-aquifer and mineral intrusion modeling of the Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge. Kansas Geological Survey, Open-File Report 92-6, 208 p.

Appendix A

KANSAS GEOLOGICAL SURVEY

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4 August 1992

Mr. Carl Nuzman
Layne Geosciences, Inc.
610 S. 38th Street
Kansas City, KS 66106

Re: Your review (July 7) of KGS Open File Report 92-6.

Dear Mr. Nuzman:

On behalf of myself and my colleagues, I want to express our appreciation to you and your clients for your review of this document. Your comments will be quite helpful in refining our ongoing and future research, and in pointing out areas where we need to improve our communication. I hope that the combination of your comments and our responses (attached) can start a process of improved communication and understanding concerning the important issues we are addressing.

Before addressing your comments directly, I want to clarify one important point. The document is a progress report of work carried out from March 1991 to April 1992 (including the results obtained under a previous year of the same contract) under contract with the US Fish and Wildlife Service. It is not a final report of that project; the contract is scheduled to be completed in May 1993, at which time a final report will be issued. It also does not provide a comprehensive report of related research being conducted with other support, the results of which will contribute to the final interpretive report. Many of your comments reflect concerns that would be quite appropriate for a final report, and will be addressed in subsequent reports.

In preparing this response I have followed the format of your letter, and for ease of reference have numbered your Appendix A comments (copy attached) so that our responses could be matched to your comments. The points you raised in the body of your letter are addressed below. Report 92-6 has undergone revision subsequent to the draft you received, so the page numbers in the present version do not match yours, although I believe that the figure and table numbers are unchanged. I enclose a copy of the present version and also a copy of 92-10, the "Executive Summary" version, for your information and reference

Modeling approach: We recognize that the inverse modeling is not yet commonly used in the private sector; it is a state-of-the-art approach that has recently been developed (you will have noticed that the key reference is a 1990 publication). While there may be a time lag before its widespread adoption outside of the research community, we feel that it offers some significant advantages over the traditional approach to applied problem-solving. One is that it is possible to be confident that the solution derived is optimum for the specified conditions and methods; another is that it provides quantitative evaluation of the interactions or relatedness of the parameters optimized. However, its greatest virtue may well be its documentability and objectivity. An individual expert may achieve a somewhat better fit of the data, but to the outside observer, the approach is more of a "black box" than the computer optimization. Furthermore, a second expert may achieve a comparable fit with a different set of parameter values, and when the two experts represent different sides in a controversy, suspicions of bias may arise. MODINV (or the general process of which it is an example) is consistent and repeatable, its programs can be reviewed and analyzed, and it was not designed with any specific local issue in mind. We therefore think that the approach will rapidly find favor with policy makers and managers who desire a neutral model output against which to judge conflicting claims.

Hydraulic conductivity values: The 20-280 ft/day range included Values from the Arkansas River alluvium, which are not relevant to the Rattlesnake Creek area. When these are excluded the appropriate range for the productive part of the aquifer is about 20-130 ft/day. The optimized values are toward the lower end of this range, but are not unreasonable. Further, sensitivity analyses (see figures 43-47) indicate that model outputs are relatively insensitive to variations over the magnitude of the value range. However, we are following up on your suggestions and conducting further tests of the model with different assigned values of this parameter.

Recharge (this addresses both the second and fourth paragraphs on page 2 of your letter): Recharge as used here is total recharge, including irrigation return. This is stated on p. 76 (and on p.20 of 92-10): "this irrigation pumpage must be balanced by (1) an increase in aquifer recharge (by increased induced leakage from streams, drainage of the dewatered aquifer sediments, irrigation return flows...." [emphasis added]. It is therefore not surprising that the total recharge for the irrigation period should exceed the predevelopment estimate; and if we neglect the other possible contributors to the increased recharge term, we can estimate the upper limit on the fraction of pumpage returned to groundwater is about 27%. Since this is almost certainly somewhat high, it is in satisfactory agreement with our calculation of probable return flows based on known crop water usage plus irrigation and precipitation records. Thus, both of your concerns have been addressed in the modeling, although not discussed in detail. We will be much more explicit about this in future reports.

Evapotranspiration: Although we believe that any additional ET contributions to the overall water budget will be minor, we are re-running the model with some additional ET areas to test your hypotheses and allay your concerns.

We feel that virtually all of your verifiable comments address issues of clarification and qualification, rather than substantive deficiency. Since distribution of this interim report has been very limited, we will simply send copies of your letter and this response to all past recipients, and include them with any future copies of the report that may be distributed.

We trust this will adequately address your concerns. We welcome any further questions you might have about our responses to the above issues or on Appendix A. Again, I express our gratitude for your assistance in improving our approach to this important problem. Additional modeling runs incorporating some of your suggested changes will be complete within a few weeks; a report of the results will be sent to you and your clients as soon as it is available.

Sincerely yours,

Robert W. Buddemeier, Ph.D.
Chief, Geohydrology Section

cc: Roger Stotts, Water PACK
GMD5
KGS Distribution

Figures