KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 94-31

NUMERICAL MODEL SELECTION CONSIDERATIONS AND DATA COLLECTION PROGRESS REPORT FOR THE RATTLESNAKE CREEK SUBBASIN, KANSAS

FY 94 Kansas Geological Survey Progress Report
to the Division of Water Resources

by

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Disclaimer

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<u>Report Outline</u>

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Model Selection Considerations

Selection of an appropriate analytical or numerical code for analysis of surface and ground-water flow problems requires a thorough analysis of a variety of factors. Some of the factors to be considered are technical (numerical accuracy, efficiency, etc.) and others are less easily quantified. An example of the latter factor is the experience a user may have with a particular code. As code selection is in essence matching a detailed description of the modeling needs with well-defined characteristics of existing models, selecting an appropriate model requires analysis of both the modeling needs and the characteristics of existing models.

Major elements in evaluating modeling needs are: (1) formulation of the scientific and management objectives and the level of technical sophistication and precision required to achieve the objectives; (2) knowledge of the physical system under study; and (3) analysis of the constraints in human and material resources available for the study.

In selecting a code, its applicability to the management problem being studied and its efficiency in solving these problems are important criteria to consider. In evaluating a code's applicability to a problem, a good description of its operating characteristics should be accessible. For a large number of groundwater modeling codes, such information is obtainable from the International Ground Water Modeling Center (IGWMC), which operates a clearinghouse service for information and software pertinent to groundwater modeling (IGWMC, 1994). In addition, there are several other summaries of available ground-water and other modeling codes (van der Heijde et al., 1985; Scientific Software catalog, 1994; Geraghty & Miller Software Newsletter; USGS, 1991).

There are a number of other factors to consider in selecting a model which include but are not limited to:

•Formulation—Is it based upon scientific principles?

•Output—Does it provide results in the form desired?

•Data Availability—Are the data needed to run the model available?

•Processes—Does it include necessary hydrologic or land-use processes?

•Parameters—Can they be easily obtained or determined?

•Ease of Use—Is the effort to use it commensurate with the worth of the results to be obtained?

•Acceptance—Is it in general use, i.e., has it stood the test of time?

As model credibility is a major problem in model use, special attention should be given in the selection process to ensure the use of qualified models that have undergone adequate review and testing. Unfortunately, a standardized review and testing procedure has not yet been widely adopted.

A model used by a large number of people demonstrates significant user confidence. Extensive use often reflects the model's applicability to different types of groundwater systems and to various management questions. It might also imply that the model is relatively easy to use. Finally, if a model has a large user base, many opportunities exist to discuss particular applications with knowledgeable colleagues.

There is probably no such thing as a "best" code for all study purposes and objectives. The determination of adequate code performance is made during the evaluation process. Objective methods of choosing the best model have not yet been developed, so this choice remains a part of the art of hydrologic modeling. Dawdy and Lichty (1968) suggest four general criteria that can be used to choose between alternative models: (a) accuracy of prediction, (b) simplicity of the model, (c) consistency of parameter estimates, and (d) sensitivity of results to changes in parameter values.

Accuracy of prediction of system outputs is obviously very important. It is desirable that models developed by research be tested in such a manner that error statistics are known. All other factors being equal, the model with minimum bias and error variance would be superior. Simplicity refers to the number of parameters that must be estimated and the ease with which the model can be explained to clients or public bodies. Again, all other factors being equal, one should choose the simplest model that is capable of producing the desired output. Consistency of parameter estimates is an important consideration in developing conceptual models using parameters estimated by optimization techniques. If the optimum values of the parameters are very sensitive to the particular period of record used, or if they vary widely between similar watersheds, the model will probably be unreliable. Finally, models should not be extremely sensitive to input variables that are difficult to measure.

One should note that no single existing hydrologic flow and transport code currently includes all the relevant processes and mechanisms of importance to a conjunctive surface-groundwater program. Fortunately, it is not always necessary to have a single code that is capable of simulating all of the many and complicated processes occuring simultaneously in such a system. Most simulation problems can be adequately handled as a group of coupled simpler problems involving subsystems of the entire model region. The subsystem simulations can often be performed conveniently in sequence, each providing input to the subsequent submodel in the simulation sequence. For example, typical subsystems are the soil surface, unsaturated zone, and underlying aquifers. Sequential simulation can, in most cases, also be applied to certain coupled physical processes. For example, soil evaporation is an input to an unsaturated zone simulation, areal seepage or root zone percolation or deep drainage is an input to an aquifer simulation, and spatial and temporal flow velocities are an input to a solute transport simulation. However, when subsystems and processes cannot be sequentially modeled, it will be necessary to select codes that integrate and perform simultaneous simulations.

Acceptance of a model should be based on technical and scientific soundness, its efficiency, and legal and administrative considerations. A model's efficiency is determined by the availability of its code and documentation, access to user support, and by its usability, portability, modifiability, reliability, and economy.

Types of Models

Groundwater models can be divided into various categories, depending on the purpose of the model and on the dynamics of the groundwater system. Apart from spatial resolution (one, two, or three dimensions), and temporal definition (steady-state flow or transport versus time-dependent behavior), models can be distinguished by the process they are designed to simulate (van der Heijde et al., 1985).

Flow models simulate the movement of one or more fluids in porous or fractured rock. One such fluid is water; the others, if present, can be air (in soil) or immiscible nonaqueous phase liquids (NAPLs) such as certain hydrocarbons. A special case of multifluid flow occurs when layers of water of distinct density are separated by a relatively small transition zone, a situation often encountered when salt water intrusion occurs. Flow models are used to calculate changes in the distribution of hydraulic head or fluid pressure, drawdowns, rate and direction of flow (e.g., determination of stream-lines, particle pathways, velocities, and fluxes), travel times, and the position of interfaces between immiscible fluids.

Solute transport models are used to predict movement, concentrations, and mass balance components of water-soluble constituents, and to calculate radiological doses of soluble radionuclides. A solute transport model uses the (piezometric) head data generated by a flow model to generate velocities for advective displacement of the contaminant, while also accounting for additional spreading through dispersion and for possible transformations by chemical and microbial reactions. The transformations considered by so-called nonconservative models are primarily adsorption, radioactive decay, and biochemical transformations and decay.

As groundwater is part of a larger physical system, the hydrologic cycle, many models address in one way or another the interaction between groundwater and the other components of the hydrologic cycle. Increasingly, models are developed that simulate the processes in each subsystem in detail, in addition to the inter-relationships. Two types of models fit this latter category; watershed models and stream-aquifer models (sometimes called conjunctive use models).

Watershed models customarily have been applied to surface water management of surface runoff, stream runoff, and reservoir storage. Traditionally, these models did not treat groundwater flow in much detail, in part because of the wide range of temporal scales involved. The subsurface components in these models were limited to infiltration and to a lumped, transfer function approach to groundwater (El-Kadi, 1986). The inclusion of detailed groundwater flow processes in watershed models increases significantly the complexity of model computations. Differences in temporal scale between surface and subsurface processes add to the complexities.

With the growing interest during the 1970's in the conjunctive use and coordinated management of surface and subsurface water resources by regulatory agencies, a new class of models was developed: the stream-aquifer models, where the flow in both the surface water network and the underlying aquifers could be studied in detail. Their use is expected to increase due to the limited water supplies in many localities and the need to increase supplies by considering both surface and ground-water sources.

The Role of Data

Modeling provides a framework to order and interpret data within the decision-making process. The effectiveness of any model is dependent on the accuracy of the data acquired. In many applications, the lack of data inflicts a severe constraint upon obtaining useful model results. Therefore, the use of computer models in groundwater resource development and protection will continue to be limited mainly by the time and costs incurred in collecting sufficient and accurate hydrologic and geologic data for proper description of groundwater systems and their functional characteristics. This does not mean, however, that some indication of the relative contribution of various processes to a groundwater system's total response cannot be estimated; much of the existing information can be used in a semiquantitative manner (i.e., sensitivity analyses and "worst-case" scenarios).

Rattlesnake Creek Subbasin Water-Related Problems, Present Program Objectives, and Model Selection Requirements

Water-Related Problems in the Rattlesnake Creek Subbasin

Part of the Kansas Water Plan is subbasin planning, the purpose of which is to target state programs to address priority water resource issues within a particular geographic area. The Rattlesnake Creek Subbasin was deemed by the Division of Water Resources (DWR), Kansas State Board of Agriculture as an area with water issues of the highest priority. Three major issues were identified for that subbasin (Kansas Water Plan, 1993): 1. Ground-water declines; 2. Streamflows in Rattlesnake Creek; and 3. Saltwater intrusion.

Regarding ground-water declines, there is a need to evaluate the impacts of ground-water withdrawals on water level changes and baseflow to streams, and implement management policies to achieve "safe yield" management of the ground-water resource based on established criteria. There is also a need to improve municipal and agricultural water use efficiency to prevent waste of water and reduce overall water use.

Regarding Rattlesnake Creek streamflows, there is a need to evaluate the impacts of regional ground-water withdrawals and land use practices on streamflow levels in Rattlesnake Creek and to establish management options to maintain reasonable baseflow levels. Minimum desirable streamflows were designated on Rattlesnake Creek in 1985.

Water quality issues include natural mineral intrusion, pollution from oil and gas production, agrichemical pollution, animal feedlots, unplugged and improperly constructed water wells and other sources. Saltwater intrusion is a concern in the area of the Rattlesnake Creek Subbasin roughly east of U.S. Highway 281 which crosses the subbasin north-south. Thus regarding saltwater intrusion, there is a need to determine its impact on "safe yield" management of ground-water withdrawals in the Great Bend Prairie Aquifer, and to evaluate alternative ground-water management options for addressing natural and artificially induced saltwater intrusion.

Program Objectives and Model Selection Requirements

According to the Division of Water Resources, the purpose of the present program is to develop a comprehensive, long-term water management strategy to implement solutions to water problems within the framework of existing state water law on a proactive basis. It is intended to be holistic, addressing concerns related to, in order of importance, surface water depletions, ground-water declines, and deterioration of the quality of water in the Rattlesnake Creek basin in south-central Kansas caused primarily by saltwater intrusion from underlying formations. A detailed analysis of the impacts of water rights and agricultural and other land use on the water resources of the area are of particular interest to DWR. Therefore, the objective of the present contract is to initiate development of a comprehensive computer simulation of the Rattlesnake Creek watershed and associated aquifers. This model is to be used by the Division of Water Resources of the State Board of Agriculture to evaluate alternative water management strategies in the Rattlesnake Creek basin.

Therefore, the objective in model development is to predict the effects of management decisions on basin water yields with reasonable accuracy. To satisfy this objective, the model should be: (1) Physically based and designed to accept readily available inputs; (2) capable of operating on watershed scale, allowing the basin to be subdivided (soils, land use, management, etc., make subdivision necessary); (3) continuous in time to allow simulation of land management factors such as crop rotations, tillage, etc., and irrigation scheduling; (4) capable of simulating long periods for use in frequency analyses; (5) computationally efficient to allow simulation of a variety of management strategies without excessive costs; and (6) field tested over a wide range of hydrologic regimes.

Given that a separate, Kansas Water Office-funded Mineral Intrusion study is under way in the salt-water intrusion affected area of the Groundwater Management District No. 5, which incorporates a sizable portion of the Rattlesnake Creek watershed, and in order to reduce the already appreciable complexities of the Rattlesnake Creek basin numerical modeling, DWR decided to concentrate on water quantity issues for this contract, and to rely on the mineral intrusion study for consideration of water quality issues.

Study Area Delineation

The Rattlesnake Creek subbasin is not a clearly defined entity. Because of the relative flatness of the topography at the surface, a significant portion of the watershed does not contribute to stream runoff. The picture is even more blurry underground because there is no physical separation of the Rattlesnake Creek subbasin aquifer from that of the rest of the Great Bend Prairie aquifer. To partially solve this problem, one possible approach would be to extend the western subbasin boundary westwards to also include the Arkansas River Valley up to the limits of the aquifer marked by some Dakota outcrops and the western GMD5 boundary from south-west of Kinsley to the confluence with the Rattlesnake Creek. In addition, the area between the Arkansas River and Rattlesnake Creek has the highest irrigation pumpage intensity and ground-water level declines than any other area of GMD5. A flow line boundary on the eastern side of the Rattlesnake Creek basin, where irrigation pumpage is not that intense, would probably suffice. Constant head boundaries at some south and south-western regions of this combined study region would also be appropriate.

However, such a consideration would more than double the study area, and may strain time, personnel, and computer requirements. Given that stream-aquifer interactions are considered the most crucial element of modeling, it was felt that the western Rattlesnake Creek subbasin boundary, which is located several miles away from the stream, would probably have minor impact on streamflows within the planning horizon of this program. DWR suggested that when the turn of the Arkansas River Valley from Kinsley to Great Bend comes for detailed analysis, the model grids of these two regions should be compatible for a possible combined study.

Preliminary Assessment of Selected Stream-Aquifer, Watershed, and Salt-Water Intrusion Models

Here we summarize selected models related to (i) stream-aquifer processes, (ii) physically-based, continuous time simulation, distributed parameter, and agriculturally-oriented watershed analyses, and (iii) salt-water intrusion problems.

(i) Stream-Aquifer Models

1. **MAEP** (Ozbilgin and Dickerman, 1986). **Modified Aquifer Evaluation Program**

Model Summary Description: The Trescott, Pinder, and Larson (1976) two-dimensional finite-difference program USGS-2D Flow[1] (which simulates steady and transient ground-water flow in an irregularly shaped, heterogeneous and anisotropic aquifer that can be a confined or unconfined aquifer or both) assumes that the water level in streams in hydraulic connection with an aquifer are not appreciably affected by the flow between the streams and the aquifer. That model was modified to enable simulation of the interaction between surface water and ground water systems subject to variable rates of stream flow and stage levels. Modifications were designed to allow calculation of surface-water heads and flow either to or from contiguous surface-water bodies in response to imposed stresses; and to allow more convenient data input.

Arrays were added or moved around in the modified program so that recharge, evapotranspiration, inflow to surface-water bodies, number of wells, pumping rate, and duration of pumping could be varied for any time period. The Manning formula was used to relate stream depth and discharge in surface water streams. The interaction between surface water and ground water is represented through the leakage term which is included in both the ground-water flow and surface-water mass balance equations.

The modified program has been tested under a variety of conditions simulated for idealized aquifers. It has been used to develop a field model of a stream-pond-aquifer system in

[1] This model was employed in the modeling of the Great Bend Prairie aquifer by Cobb, Colarullo, and Heidari (1983).

the Beaver-Pasquiset ground-water reservoir in southern Rhode Island. Numerical results from the modified program were in good agreement with published analytical results.

Model Summary Critique: This model is now dated. It is superseded by the actively-supported USGS MODFLOW program with the Streamflow Routing Package (see below). Until recently, the USGS-2D flow model was one of the most used ground-water flow models for two-dimensional problems.

2. **TRACY 2D-FE** (Dunlap et al., 1984) **Two-Dimensional Finite Element Galerkin Model** developed by J.V. Tracy.

Model Summary Description: This model simulates steady and non-steady two-dimensional ground-water flow in an irregularly shaped confined or unconfined aquifer. The aquifer's transmissive and storage properties may be heterogeneous. The model accounts for gains and losses from the river flow in each reach based on the incoming river and tributary flows and the gain from or loss to the aquifer in the reach. With an estimate of river discharge, the river stage is computed for each reach using an input stage-discharge relationship given for each reach. The river-aquifer gains and losses are calculated as a function of streambed area, riverbed leakance, and the head gradient between the river and the aquifer. Evapotranspiration from ground water is estimated using monthly values of precipitation, applied water rate, evapotranspiration demand, the moisture capacity of the soil zone, and depth of root zone. Well discharges can vary monthly. Specified flux and specified head boundaries can be simulated.

A "regular" finite element grid is used in the simulation i.e., the region is subdivided by a given number of columns, each of which has an equal number of elements, where the columns need not be parallel or of the same lengths. The effect is of a deformed rectangular grid. Applying the Galerkin method results in an associated matrix which is solved using a direct method. Mass balances are computed for each time step and the cumulative simulation period. This model has been applied to the Arkansas River Valley in southwestern Kansas.

Model Summary Critique: This model is also dated, with limited or non-existent support. It is superseded by MODFLOW (see below).

3. MODFLOW (McDonald and Harbaugh, 1988). **A Modular Three-Dimensional Finite Difference Ground-Water Flow Model.**

Model Summary Description: MODFLOW is a modular three-dimensional finite-difference flow code developed by the USGS. MODFLOW can simulate fully three-dimensional systems and quasi-three-dimensional anisotropic, heterogeneous and layered systems in which flow in aquifers is horizontal and flow through confining beds is vertical. The code can also be used to simulate flow in two dimensions either in one horizontal layer or in a cross section. The model is based on a block-centered finite difference approach, using variable grid spacing in x-, y-, and z- directions. The model can simulate confined, unconfined, or conditions convertible between the two. The model can also handle layers that pinch out. MODFLOW has been used in numerous applications, many of which are documented in USGS Water-Supply Paper, Professional Papers, and Water-Resources Investigations Reports.

The code permits the user to select a series of packages (or modules) to be used during a given simulation. The packages include three equation-solver packages, stream packages, a recharge package, and packages to simulate pumping or injection wells, drains, and evapotranspiration from the water table.

Options set in an output control module allow the user to specify the print format of the head and/or drawdown arrays and to request printout of the water balance. Water balance output includes a summary statement of total flows to and from the system. If desired, flows to specified head nodes and discharges via pumping and evapotranspiration can also be printed. Preprocessors available for MODFLOW include PM and MODINP from the Scientific Software Group, PREPRO3FLO and PREMOD from GeoTrans, Inc., and Model-CAD from Geraghty and Miller, Inc. Postprocessors include PM and MODGRAF from the Scientific Software Group, POSTMOD from IGWMC, a statistical package from the USGS, contouring packages provided with some versions of the code, and the particle-tracking codes MODPATH (Pollock, D.W., 1989) and PATH3D (Zheng, C., 1991). These particle-tracking codes calculate ground-water paths and travel times in two or three-dimensional flow fields. They can be used to simulate the movement of ground-water and the advection of contaminant solutes in ground-water. In addition a number of parameter estimation packages exist (MODFLOWP, MODINV, and others) that can be used with MODFLOW to improve model construction and calibration.

MODFLOW is written in strict FORTRAN 77. It runs on all computers that have a FORTRAN 77 compiler. It has been run without modification on many different types of mainframes, minicomputers, and workstations. It also has been run without modification on IBM and Apple personal computers and their clones. The allowable size of a problem, as measured by the number of finite-difference cells, depends on the size of MODFLOW's *X* array, which can be set at compilation time. On 8088 and 80286 computers, the practical limit is about 8000 cells Extended-memory versions have no theoretical limits. Because of our interest in stream-aquifer relations, the Streamflow Routing Package (STREAM) of MODFLOW is highlighted here.

The STREAM Routing Package (Prudic, 1989) was written to account for the amount of flow in streams and to simulate the interaction between surface streams and ground water. The Streamflow-Routing Package is an accounting program that tracks the flow in one or more streams which interact with ground water. It permits two or more streams to merge into one with flow in the merged stream equal to the sum of the tributary flows. The program also permits diversions from streams.

Streams are divided into segments and reaches. Each reach corresponds to individual cells in the finite-difference grid used to simulate ground-water flow. A segment consists of a group of reaches connected in downstream order. Leakage is calculated for each reach on the basis of the head difference between the stream and aquifer and a conductance term. It is subtracted or added to the amount of streamflow into the reach. The stage in each reach can be computed using the Manning formula under the assumption of a rectangular stream channel.

The amount of leakage in each reach (either into or out of the aquifer) is incorporated into the ground-water flow model by adding terms to the finite-difference equations. Recharge to the aquifer in a reach ceases when all the streamflow in upstream reaches has leaked into the aquifer and the stream is dry. A stream is permitted to flow again in downstream reaches if the head in the aquifer is above the elevation of the streambed.

Results from the program have been compared to results from two analytical solutions. One assumes time varying areal recharge to the aquifer and discharge only to a stream and the other assumes recharge to the aquifer from a change in stream stage. Results from the program reasonably duplicated the analytical solutions. In addition, several field applications of MODFLOW with the stream package are documented by the USGS and other agencies.

The ground-water flow model with the Streamflow-Routing Package has an advantage over the analytical solution in simulating the interaction between aquifer and stream because it can be used to simulate complex systems that cannot be readily solved analytically.

The Streamflow-Routing Package does not include a time function for streamflow but rather streamflow entering the modeled area is assumed to be instantly available to downstream reaches during each time period. This assumption is generally reasonable because of the relatively slow rate of ground-water flow in comparison with the rate of flow in streams. Another assumption is that leakage between streams and aquifers is instantaneous. This assumption may not be reasonable if the streams and aquifers are separated by a thick unsaturated zone.

Model Summary Critique: MODFLOW is the most widely used and best supported numerical code available at present. Its flexible modular structure can handle a great variety of flow problems.

4. MODBRANCH (Swain and Wexler, 1993). **A Coupled Surface-Water and Ground-Water Flow Model for Simulation of Stream-Aquifer Interaction.**

Model Summary Description: This new coupled ground-water and surface-water model was developed by combining the U.S. Geological Survey models MODFLOW and BRANCH (Schaffranek et al., 1981); the interfacing code is referred to as MODBRANCH. MODFLOW is the widely used modular three-dimensional, finite-difference, ground-water model, and BRANCH is a one-dimensional, numerical model commonly used to simulate unsteady flow in open-channel networks.

MODFLOW was originally written with the River package that calculates leakage between the aquifer and stream, assuming that the stream's stage remains constant during one model stress period. A simple streamflow routing model has been added to MODFLOW, but it is limited to steady flow in rectangular, prismatic channels. To overcome these limitations, the BRANCH model, which simulates unsteady, nonuniform flow by solving the entire St. Venant equations, was restructured and incorporated into MODFLOW. Terms that describe leakage between stream and aquifer as a function of streambed conductance and differences in aquifer and stream stage were added to the continuity equation in BRANCH. Thus, leakage between the aquifer and stream can be calculated separately in each model, or leakages calculated in BRANCH can be used in MODFLOW. Total mass in the coupled models is accounted for and conserved.

The BRANCH model calculates new stream stages for each time interval in a transient simulation based on upstream boundary conditions, stream properties, and initial estimates of aquifer heads. Next, aquifer heads are calculated in MODFLOW based on stream stages calculated by BRANCH, aquifer properties, and stresses. This process is repeated until convergence criteria are met for head and stage. Because time steps used in ground-water modeling can be much longer than time intervals used in surface-water simulations, provision has been made for handling multiple BRANCH time intervals within one MODFLOW time step. An option was also added to BRANCH to allow the simulation of channel drying and rewetting. Testing of the coupled model was verified by using data from previous studies; by comparing results with output from a simpler, four-point implicit, open-channel flow model linked with MODFLOW; and by comparison to field studies of the L-31N canal in southern Florida.

Model Summary Critique: Although this model addresses the dynamic aspects of streamflow, the additional data requirements and the time scale of streamflow modeling, which is of the order of minutes, make its applicability to long-term (multi-year) simulations of interest in our study impractical.

(ii) Watershed Models[2]

1. **BHS** (Green and Pogge, 1973). **Basin Hydrologic Simulator**

Model Summary Description: The Basin Hydrology Simulator is a digital computer model to simulate the hydrology of a stream basin. The model simulates both surface-water and ground-water phases and their interaction by combining the features of the watershed rainfall-runoff model known as the Kansas Water Budget Model (Smith and Lumb, 1966) and of ground-water flow simulators. Input to the model includes precipitation, climatic conditions, boundary and initial conditions, and basin constants. Provision has been made for modeling withdrawals from both groundwater and surface waters for consumptive use. The computer output includes streamflow hydrographs at selected points, groundwater levels, and summaries of important moisture fluxes. The model is designed to be general in nature so that it will be applicable to other basins with similar geographical and geological conditions.

The structure of the model is such that the basin is divided vertically into four layers and a stream network. Provision is also made to subdivide each layer horizontally into grids or subbasins. The groundwater grids are on the order of one-mile square, while the upper layers are divided into a few relatively large subbasins. The surface-layer subbasins are determined by considering topography, soil types, and climatic data.

In the surface layer, precipitation in each subbasin is divided into runoff and infiltration. Runoff is routed to the outflow point of the subbasin using a unit hydrograph for that subbasin. Water infiltrates from the surface layer to an upper soil zone where it is stored for later evapotranspiration or percolation into the lower soil zone. This upper soil zone is assumed to include the root zone of the shallow rooted annual plants.

The lower soil zone provides consumptive water for deeper rooted plants. It also feeds the stream through interflow and loses water to the aquifer through percolation.

The runoff and the interflow from the subbasin are gathered at the out-flow point of the subbasin. At this location water enters the stream network, which consists of nodes and reaches.

[2]Watershed models developed at KSU are not reviewed here, with the expectation that those models, among others, will be reviewed by KSU.

Nodes represent locations where subbasins drain into the stream. The flows are routed through the reaches using the Muskingum routing method.

Water flow in the groundwater layer is assumed to be governed by the linear equation of ground-water flow. The equation is solved using the alternating direction implicit numerical technique.

Model Summary Critique: This model, although pioneering during its development time, is now dated and not maintained nor supported.

2. **SHE** (Abbott et al., 1986) **European Hydrologic System Model** (Systéme Hydrologique Européen)

Model Summary Description: SHE is a physically based, distributed- parameter catchment modeling system. The model considers the major hydrologic processes which govern water movement through a catchment, namely: snowmelt, canopy interception, evapotranspiration, overland flow, channel flow, and unsaturated and saturated subsurface flow. Spatial variability of hydrologic processes is described by using a rectangular grid of (x, y) points in the horizontal plane with vertical variation in properties represented by a series of horizontal planes of various depths.

SHE is applicable to a wide range of hydrologic processes and can be applied to a variety of hydrologic problems, including irrigation schemes, determination of landuse changes, water development studies, groundwater contamination, erosion and sediment transport, and flood prediction.

Model Summary Critique: SHE applications have been performed on mainframe computers. Applications of the program on PCs are limited due to the large number of computations that must be made. Because of its intensive data and computing requirements this model has not been considered suitable for our application.

3. **TOPMODEL** (Beven and Kirby, 1979) **TOPography-Based Hydrologic MODEL**

Model Summary Description: TOPMODEL is a topography-based hydrologic model derived from the variable contributing area theory. The inputs of the model are the hourly rainfall and potential evaporation, and the distribution of the topographical index derived from the digital terrain map of the catchment. The outputs are the hourly average and local soil moisture deficits below saturation, and the hourly discharge, separated into two components (surface runoff on the saturated area, and subsurface flow/groundwater discharge).

Model Summary Critique: Because, in addition to the high temporal resolution input data requirements, vegetation and land management factors have not been explicitly considered in this model it has not been considered further.

4. **HSPF** (Johanson et al., 1980) **Hydrological Simulation Program-Fortran**

Model Summary Description: The Hydrologic Simulation Program - Fortran (HSPF) model simulates both watershed hydrology and water quality. It allows an integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment- chemical interactions. The program provides a time history of runoff rate, sediment load, and nutrient and pesticide concentration, along with a time history of water quality and quantity at specific points in a watershed.

HSPF computes a continuous hydrograph of stream flow at the basin outlet. Input is a continuous record of precipitation and evaporation data. Rainfall is distributed into interception loss, rainfall on impervious areas which contributes directly to runoff, and an infiltrated portion. The infiltration is divided into (1) surface runoff and interflow which moves through the upper soil zone to channel flow and (2) flow into the lower soil zone or groundwater storage which contributes to active and inactive groundwater storage. The model utilizes three soil moisture zones: an upper soil zone, a lower soil zone, and a groundwater storage zone. Rapid runoff is accounted for in the upper zone. Both the upper and lower zones influence factors such as overland flow, infiltration, and groundwater storage. Water that is computed as moving into the lower zone can move into deep groundwater storage, some of which can become base flow to the stream. Total stream flow is a combination of overland flow, interflow, and groundwater flow.

The program user must supply parameters for each of the various processes. More than 20 parameters are needed to describe merely the hydrological parameters, some of which cannot be directly measured (such as the various soil moisture parameters). Without calibration data, it can be difficult to verify the flows computed by this model.

Model Summary Critique: Although this model seems to meet a number of our requirements, it has been mainly applied to urban, as opposed to agricultural watersheds, and that seems to be its strength. A drawback of this model is that several parameters of the model are not physically based, therefore they cannot be estimated from readily available information. In addition, the model is so large that it is more suitable for execution on mainframe computers. For these reasons we have not pursued it further.

5. **SPAW** (Saxton et al., 1974) **Soil-Plant-Air-Water Model**

Model Summary Description: SPAW was developed to provide daily soil water estimates on cultivated cropland in the Midwest. The model computes daily estimates of runoff, actual evapotranspiration and deep percolation. Runoff is estimated using the SCS curve number method. Water added to the soil is distributed based on pressure gradients and unsaturated conductivity of the soil. Potential evapotranspiration is computed using pan evaporation (actual or estimated) and a pan coefficient. Plant transpiration is a function of a canopy cover factor and a phenology factor. Soil evaporation is represented by an inclusion of a separate, thin (1.23 cm), upper boundary layer of soil, also called the evaporation layer. The water is evaporated from this thin layer. The evaporation process is limited by the potential evapotranspiration and the available soil water. A daily estimate of the actual evapotranspiration is computed by adding the interception evaporation, soil water evaporation and soil transpiration components.

Model Summary Critique: This agricultural and soil-physics-based model requires too detailed unsaturated soil physical and plant parameters which are not available, and thus this model is not considered further.

6. **VSMB** (Baier et al., 1979) **Versatile Soil Moisture Budget**

Model Summary Description: VSMB calculates the water budget of the soil within the rooting zone of crops from evapotranspiration, precipitation, and deep drainage. Each day the net loss or gain is added to the water already in the rooting zone. Water is withdrawn simultaneously, but at different rates, from different depths in the soil profile, depending on the rate of potential evapotranspiration, the stage of crop development, the water release characteristic of the soil, and the available water content.

The available water-holding capacity of the soil is subdivided into standard zones representing horizontal layers. These zones contain respectively 5, 7.5, 12.5, 25, 25 and 25% of the available water within the root zone. Adoption of the standard zones facilitates the use of a single set of crop (or root) coefficients for wheat and other crops. The coefficients express the amount of water extracted simultaneously from the different zones as a fraction of the potential evapotranspiration rate.

Apart from a set of crop coefficients, the relationship between available soil water and the ratio of actual to potential evapotranspiration (AET/PET) also depends on the physical characteristics of the soil. The VSMB makes use of standard empirical curves (the so-called Z curves) for this purpose.

Model Summary Critique: This is not a distributed parameter model. Its strength lies in a detailed representation of the root zone processes. It has been implemented on a watershed scale by Sophocleous and McAllister (1987, 1990). However it lacks streamflow routing routines and its surface runoff estimation procedures are crude. Its major advantage is its simplicity.

7. **SWAT** (Arnold et al., 1993) **Soil and Water Assessment Tool**

Model Summary Description: SWAT is a physically based, linked surface-subsurface watershed model. The objective in model development was to predict the effect of management decisions (climate and vegetative changes, groundwater withdrawals, reservoir management, and water transfer) on water, sediment, and chemical yields with reasonable accuracy for river basins. The major processes are: 1) Precipitation; 2) Snowmelt; 3) Infiltration; 4) Evapotranspiration; 5) Surface runoff; 6) Routing; 7) Erosion; 8) Chemical movement; 9) Groundwater flow and lateral flow; 10) Irrigation water transfer; 11) Lake water quality; 12) Reservoir (pond) component.

SWAT was developed by adding some components, e.g., ground- water flow and streamflow routing procedures for large basins, to the spatially detailed, continuous time model, SWRRB (Williams et al., 1985), which was developed by modifying the CREAMS (Knisel, 1980) daily rainfall model for application to large, complex, rural basins.

The model allows considerable flexibility in watershed configuration and discretization, and is operated continuously on a daily time step. Watersheds can be subdivided into subbasins. The divisions may be based on stream network, soils, land use, tillage operations, elevation, temperature, rainfall, etc. Sediment and associated chemicals are then routed to the basin outlet. Each subbasin can use a different rain gage. Also, in the vertical direction the model is capable of working with any variation in soil properties -- the soil profile can be divided into a maximum of 10 layers.

SWAT input and output files are split into separate files by subbasin and data type. There are 12 basin input data files, 7 output files, and 8 to 10 subbasin input data files for each of the subbasins. This input data structure facilitates the use of several subbasins in the modeling and simplifies GIS linkages.

SWAT has also been used by Bureau of Indian Affairs and Texas River Authorities.

Model Summary Critique: SWAT is the state of the art in agricultural watershed modeling. Inputs for the surface water model are easily obtained and weather, soils, crops, and pesticide databases for the USA are supplied to users. Groundwater inputs are also relatively easy to obtain and are similar in similar hydrogeological regions. However, the groundwater aspects of the model are too oversimplified.

8. IGSM (Montgomery Watson Co., 1993). **Integrated Groundwater and Surface Water Model.**

Model Summary Description: The IGSM is a comprehensive basin planning model which includes groundwater, surface water, groundwater quality, and reservoir operation simulations routines. The entire model with its pre- and post-processors may be set-up and executed on a desk-top computer.

There are a number of models which simulate groundwater and surface water. However, no other models encompass the full hydrologic system. This model is designed as a combination of existing models, which integrates the various techniques which have been successfully used in those models.

The IGSM is a finite element quasi-three-dimensional model capable of simulating several aquifer layers. The groundwater portion operates on two basic scientific principles: (1) conservation of mass, and (2) Darcy's law of fluid flow through a porous media. The surface water portion includes hydrologic basin analysis for rainfall percolation, run-off, and evapotranspiration. Stream flow simulation operates on a mass balance system. To integrate the surface and groundwater flow simulations, a soil moisture accounting and unsaturated flow system has been incorporated. This, coupled with runoff and percolation rates for given soils allows interaction between the groundwater and surface water flows. Groundwater flows are simulated using the well-known Finite-Element method of analysis. An additional reservoir operations module is included to derive reservoir releases for stream flow accounting. A basic time step used in the groundwater simulation is monthly. Surface water simulation including streamflow estimation can be performed on either a daily or a monthly basis. Furthermore, water quality simulation is included to track a "plume" through the processes of advection, dispersion, and dissolution.

The IGSM is equipped with several pre- and post- processing routines to assist the user with file management and graphical representations of both the input and output of the model. The pre-processing programs prepare the "raw" data into files formatted for the computer code, and provide graphical representations of the model network, base map, and general features. The post-processing programs summarize model output in both tabular and graphical forms.

The IGSM simulates a free-body using a network of three-dimensional "volume elements". The elements can be grouped together to define subregions for water use summaries of individual water districts and other desired areas. A surface water network is overlain on the groundwater network for stream flow and aquifer interaction. The major data input requirements include not only the constant hydrogeological parameters, but also time-dependent parameters including land use, water demand, rainfall, boundary inflows, and historical water supply. The time independent parameters include aquifer layer dimensions and type, storage capacity, and flow rates through the geological material. These estimated parameters are tested and revised through model calibration. Once the model simulation closely matches observed aquifer responses, the model is deemed calibrated and can be used to run future projections and what-if scenarios.

This model was sponsored by the U.S. Bureau of Reclamation, the California Department of Water Resources, State Water Resources Control Board, and the Contra Costa Water District as it was applied to the Central Valley of California.

Model Summary Critique: This model looks very promising and is now being updated by Montgomery Watson. Because it is a newly developed model, it has not been widely used outside California. No journal papers on this model have been encountered by this author.

(iii) Salt-Water Intrusion Models[3]

1. MERCER SALT (Mercer et al., 1980). **Finite-Difference Model to Simulate the Areal Flow of Salt Water and Fresh Water Separated by an Interface.**

Model Summary Description: The model is capable of simulating ground-water flow of salt water and fresh water separated by an interface. The partial differential equations are integrated over the thicknesses of fresh water and salt water resulting in two equations describing the flow characteristics in the areal domain. The program is designed to simulate characteristics in the areal domain. The program is designed to simulate time-dependent problems such as those associated with the development of coastal aquifers, and can treat water-table conditions or confined conditions with steady-state leakage of fresh water. The program will generally be most applicable to the analysis of regional aquifer problems in which the zone between salt water and fresh water can be considered a surface (sharp interface). The equations are approximated using finite-difference techniques and the resulting algebraic equations are solved for the dependent variables, fresh-water head and salt-water heads using an iterative solution method.

2. SWIFT II (Reeves et al, 1987). **Sandia Waste Isolation Flow and Transport Model for Fractured Media, Release 4.84.**

Model Summary Description: SWIFT II is a three-dimensional model to simulate ground-water flow, heat (energy), brine and radionuclide transport in porous and fractured geologic media. The primary equations for fluid (flow), heat and brine are coupled by fluid density, viscosity and porosity. In addition to transient analysis, SWIFT II offers a steady-state option for coupled flow and brine. The equations are solved using central or backward spatial and time weighting approximations by the finite-difference method. In addition to Cartesian, cylindrical grids may be used. Contaminant transport includes advection, dispersion, sorption and decay, including chains of constituents. Both dual-porosity and discrete-fracture representations along with rock matrix interactions may be simulated. The non-linearities

[3] The critique for the first six models is combined and presented after the summary description of the sixth model under this heading.

resulting from water table and variable density are solved iteratively. Boundary conditions include prescribed value or flux for pressure (flow), heat, brine, and nuclide concentration; variable constraint well injection/production; aquifer influence functions (Carter-Tracy); and freewater surface and recharge. Typical applications include deep well injection of hazardous waste; hazardous waste site characterization and remediation; Pump-and-treat, hydraulic containment and other waste remediation; salt-water intrusion, upconing; aquifer thermal energy storage; high-level radioactive waste performance assessment; fractured media, dual porosity. SWIFT II runs on mainframes and also on 386 and 486-based IBM compatible computers.

3. SUTRA (Voss, 1984). **A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Dependent Ground-Water Flow with Energy Transport or Chemically-Reactive Single Species Solute Transport.**

Model Summary Description: SUTRA simulates two-dimensional, density-dependent flow and transport of either a dissolved solute or heat under variably saturated conditions. It can simulate variable density leachate, salt-water intrusion, thermal energy storage, thermal pollution of aquifers, and problems involving geothermal reservoirs.

SUTRA is intended mainly for the simulation of flow and solute or heat transport in fully saturated systems. The capability to simulate variably saturated flow is included to assist in the analysis of mildly nonlinear problems that also may involve thermal energy or solute transport. SUTRA is not specialized for the nonlinearities of unsaturated flow and consequently requires fine spatial and temporal discretization for simulations involving unsaturated porous media.

SUTRA requires all the input needed for a variably saturated flow model and the input for a companion transport code as well as the density and viscosity of the fluid. It also requires the thermal conductivity of the porous medium and information on boundary and initial conditions to solve the heat-transport equation, if heat transport is simulated.

SUTRA uses a numerical approximation method that combines integrated finite differences and quadrilateral finite elements utilizing either a cartesian or cylindrical coordinate system. SUTRA solves two partial differential equations—one for fluid flow and another for either concentration or temperature. Postprocessing packages include packages developed by the USGS and several consulting companies. SUTRA runs on mainframes and on IBM-compatible microcomputers.

4. MOCDENSE (Sanford and Konikow, 1985). **A Two-Constituent Solute-Transport Model for Ground Water having Variable Density.**

Model Summary Description: MOCDENSE is a two-dimensional, cross-sectional model for the analysis of saltwater intrusion. It simulates conservative solute transport and dispersion of one or two constituents in a ground-water system with density-dependent flow. The model is a modified version of the USGS 2D TRANSPORT/MOC model by Konikow and Bredehoeft (1978), which uses finite-difference methods and the method of characteristics to solve the flow and transport equations, respectively. MOCDENSE solves for fluid pressure rather than hydraulic head because of the inclusions of variable density. The flow and transport equations are solved in a coupled fashion as the density is considered a function of the concentration of one of the constituents. It can handle varying recharge, aquifer in homogeneities, variable aquifer thickness, and complex boundary conditions. MOCDENSE was tested on an idealized seawater-intrusion problem for which an analytical solution exists. The results were nearly identical to those of other numerical models tested on the same problem.

5. HST3D (Kipp, 1987). **Simulation of Heat and Solute Transport in Three-Dimensional Ground-Water Flow Systems.**

Model Summary Description: The Heat- and Solute-Transport in 3 Dimensions program (HST3D) simulates ground-water flow and associated heat and solute transport in three dimensions. The three governing equations are coupled through the interstitial pore velocity, the dependence of the fluid density on pressure, temperature, and solute-mass fraction, and the dependence of the fluid viscosity on temperature and solute-mass fraction. The solute-transport equation is for only a single solute species with possible linear-equilibrium sorption and first-order decay. Finite-difference techniques are used to discretize the governing equations using a point-distributed grid. The flow-, heat-, and solute-transport equations are solved, in turn, after a partial Gauss-reduction scheme is used to modify them.

The basic source-sink term represents wells. A complex well-flow model may be used to simulate specified flow rate and pressure conditions at the land surface or within the aquifer, with or without pressure and flow-rate constraints. Boundary-condition types offered include specified value, specified flux, leakage, heat conduction, an approximate free surface, and two types of aquifer-influence functions. All boundary conditions can be functions of time.

Two techniques are available for solution of the finite-difference matrix equations. One technique is a direct-elimination solver, using equations reordered by alternating diagonal planes. The other technique is an iterative solver, using two-line successive over-relaxation. A restart option is available for storing intermediate results and restarting the simulation at an intermediate time with modified boundary conditions. The program runs in batch mode.

6. **SHARP** (Essaid, 1990). **A Quasi-Three-Dimensional Finite-Difference Model to Simulate Freshwater and Saltwater Flow in Layered Coastal Aquifer Systems.**

Summary Model Description: The program "SHARP" is a quasi-three dimensional finite difference model for simulating freshwater and saltwater flow, separated by a sharp interface in layered coastal aquifers. The model accommodates multiple aquifers, separated by confining layers. The uppermost aquifer can be confined, semi-confined, or unconfined with areally distributed recharge. Temporal variations in recharge and pumping are accounted for by introducing multiple pumping periods. The boundary conditions which can be modeled include prescribed flux boundaries, constant freshwater and/or saltwater head boundaries, mixed type boundary conditions (e.g., induced recharge from streams). Aquifer properties can be both heterogeneous and anisotropic (hydraulic conductivity tensor aligned with Cartesian coordinate axes). The model can be used for both areal (horizontal) and cross-sectional (profile) studies.

For each aquifer the vertically integrated freshwater and saltwater equations are solved. These two equations are coupled by the boundary condition at the interface. Leakage between the aquifers is calculated applying Darcy's law. The resulting system of nonlinear partial differential equations is discretized using an implicit finite difference scheme. The discretized system of equations is solved using the strongly implicit procedure (SIP).

The position of the interface tip and toe, within the discretized finite difference blocks, are tracked using linear extrapolation of the interface elevations calculated at grid points. Steady-state results are obtained by running a transient simulation until it achieves steady-state. The model supports variable grid block lengths in the X-, and Y- or Z-direction. The program runs in batch mode.

Model Summary Critique for all six models under (iii): Although all above models could handle salt-water intrusion problems, they all ignore stream-aquifer interactions in the sense described under subheading (i). The only attempt to remedy this situation is presented below. The three-dimensional salt-water intrusion models are not suitable for large basin-scale simulations mainly because of the excessive data and computer time requirements.

7. SASIAM (Sophocleous and Birdie, 1990). **Stream-Aquifer Sharp Interface Areal Model**

Summary Model Description: The U.S. Geological Survey finite difference model developed by Mercer et al. (1980) simulates areal flow of salt- and fresh-water separated by a sharp interface. Transient fluctuations of the interface as a result of recharge and discharge can be effectively traced by the model. However, important sources of recharge and discharge are streams and ponds, which the Mercer et al. (1980) model is incapable of simulating. To enhance its capabilities, Sophocleous and Birdie (1990) modified the basic Mercer et al. model to permit interaction between variable stage streams and ponds and the aquifer. They also modified the program to reduce the two-fluid freshwater-saltwater model to simulate flow in the aquifer resulting from a single fluid (freshwater) only. This enhanced the versatility of the model, making it capable of simulating the cases of (1) freshwater and saltwater flow in the aquifer with and without streams, and (2) freshwater only flow in the aquifer and without streams. This model was successfully tested against a number of analytical and other numerical models.

Model Summary Critique: As of the present time, this model has not yet been tested in an actual field setting. It is subject to the same limitations as 1) the Mercer et al. (1980) model with regard to sharp interface modeling, including the vertical averaging of aquifer properties (i.e. no vertically-layered systems can be simulated), and 2) the streamflow-routing package of MODFLOW.

Recommendations

Based on the study objectives, model selection criteria, and analysis of model candidates, a combination of watershed and stream-aquifer models is required to address study objectives. Of the models readily available for preliminary assessment for this report, the state of the art in stream-aquifer modeling at scales appropriate to this study seems to be the MODFLOW program with the streamflow routing package. The corresponding state of the art in models reviewed to date for agriculturally-oriented, large scale basin analyses is probably SWAT and IGSM. If SWAT is adopted, a sequential, combination approach of the two models (MODFLOW and SWAT) is recommended. Although a more detailed joint assessment may be required and probably additional models may need to be reviewed, the SWAT-MODFLOW combination should be used as standard for comparison.

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Appendix A: Additional Progress Report Items

Streamflow and baseflow data for Rattlesnake Creek

Available daily streamflow data for the entire period of record for three streamgaging stations on the Rattlesnake Creek were electronically retrieved from the USGS. These stations and the period of record are the following: Macksville (1959–1993), Zenith (1973–1993), and Raymond (1960–1993). These data were subsequently used as input to a USGS hydrograph separation computer program (HYSEP2) which employs three techniques (fixed-interval, sliding interval and local minimum) to separate the ground-water and surface-runoff components of a streamflow hydrograph. Daily baseflow estimates for the entire period of record for all Rattlesnake Creek stations using all three previously-mentioned separation techniques are included in a compressed form in the attached diskette. Annual streamflows and estimated baseflows are listed below for the three gaging stations.

Station 07142300 RATTLESNAKE C NR MACKSVILLE,KS

Water year baseflow annual summary:

year	streamflow (cfs)	fixed	sliding	local min
1960	51.84	36.80	36.25	35.45
1961	30.95	27.82	27.76	27.26
1962	39.27	30.62	30.94	30.26
1963	48.27	32.55	32.82	32.86
1964	21.16	19.61	19.63	19.72
1965	20.91	18.20	18.33	17.91
1966	15.91	14.78	14.73	14.82
1967	11.42	8.28	8.40	7.97
1968	7.48	5.60	5.67	5.51
1969	22.66	11.91	12.58	10.47
1970	16.64	15.20	15.29	15.15
1971	14.90	11.79	11.53	10.56
1972	18.33	11.16	11.22	10.81
1973	109.87	34.11	37.94	29.42
1974	97.74	78.40	78.95	76.80
1975	62.13	43.07	41.36	43.02
1976	39.24	33.08	32.90	32.08
1977	37.81	23.01	23.32	21.72
1978	40.73	26.55	24.35	23.12
1979	18.21	15.30	15.39	14.91
1980	21.37	17.27	17.54	16.90
1981	9.91	8.52	8.59	8.44
1982	8.04	6.63	6.56	6.54
1983	11.78	7.50	7.27	5.59
1984	6.37	5.49	5.47	5.43
1985	4.36	2.88	2.90	2.93
1986	9.72	5.02	5.19	4.58
1987	30.19	19.40	17.82	15.19
1988	15.22	13.61	13.61	13.47
1989	11.63	3.38	3.86	2.84
1990	6.03	4.90	4.92	4.13
1991	1.46	0.71	0.73	0.70
1992	2.84	0.52	0.55	0.34
1993	35.17	14.59	14.89	13.52

Station 07142575 RATTLESNAKE C NR ZENITH, KS

Water year baseflow annual summary:

year	streamflow (cfs)	fixed	sliding	local min
1974	178.66	124.66	125.15	116.91
1975	87.27	63.20	62.22	58.39
1976	81.87	50.85	51.35	46.43
1977	63.87	40.06	40.76	37.71
1978	64.83	43.94	44.03	43.13
1979	35.43	27.60	27.77	26.86
1980	42.53	29.27	30.50	25.52
1981	21.15	13.70	14.02	13.19
1982	25.57	19.08	19.38	18.80
1983	29.24	19.59	19.41	18.36
1984	22.42	15.18	15.27	14.45
1985	17.14	11.14	11.14	9.92
1986	26.92	19.27	18.74	17.20
1987	62.76	34.10	37.20	29.66
1988	29.83	24.82	25.06	24.66
1989	17.64	10.60	10.68	9.54
1990	19.80	13.55	13.40	12.04
1991	6.59	5.24	5.30	5.03
1992	10.34	7.10	6.65	6.58
1993	185.65	46.99	41.30	33.52

Station 07142620 RATTLESNAKE C NR RAYMOND, KS

Water year baseflow annual summary:

year	streamflow (cfs)	fixed	sliding	local min
1961	71.05	49.07	47.52	43.87
1962	71.25	55.10	54.13	48.61
1963	70.65	47.84	45.12	36.89
1964	29.14	20.75	20.73	19.93
1965	55.78	32.00	33.15	27.59
1966	34.10	24.56	25.01	22.06
1967	25.36	17.24	17.43	13.01
1968	11.74	8.96	8.81	7.66
1969	61.63	39.28	39.68	27.06
1970	45.63	33.67	34.76	29.93
1971	23.62	15.29	15.89	13.81
1972	29.37	20.25	20.31	16.85
1973	129.56	91.14	78.74	62.99
1974	189.75	134.81	136.57	124.58
1975	82.28	64.03	63.96	57.37
1976	69.29	51.27	51.34	43.76
1977	43.01	28.03	28.09	26.28
1978	54.89	35.88	37.63	35.26
1979	27.41	22.60	21.68	20.87
1980	54.40	37.49	36.14	27.13
1981	14.89	7.50	8.08	7.26
1982	38.58	27.47	28.29	27.58
1983	38.20	28.14	27.55	23.96
1984	26.50	18.35	18.90	16.71
1985	16.40	9.10	9.71	6.26
1986	24.70	17.87	16.59	17.30
1987	79.44	39.95	43.98	25.05
1988	20.85	15.98	16.31	15.24
1989	13.04	5.72	6.51	5.22
1990	23.76	13.01	12.76	11.01
1991	2.77	2.17	2.20	2.12
1992	6.87	4.78	4.32	3.98
1993	123.55	71.02	63.49	35.18

Available water-level surveys in GMD5

A preliminary search of our published and unpublished records revealed that the following ground-water level surveys of the GMD5 general area are available in computer files.

	No. of points	Source of data[a]
Predevelopment (pre-1960)	1022	KGS Bulletins
1970	54	KCPGWLM[b]
1971	49	"
1972	68	"
1973	334	Fader and Stullken (1976, 1978)
1974	343	"
1975	59	KCPGWLM[b]
1976	61	"
1977	71	"
1978	182	KCPGLM[b] plus GMD5 measurements
1979	298	"
1980	305	"
1981	280	"
1982	277	"
1983	271	"
1985	363	KCPGLM + special KGS-GMD5 survey
1991	389	"
1992	271	"
1993	375	"
1994	338	"

[a]Data from USGS and special area projects are also included.
[b]Kansas Co-op Program of Ground-water Level Measurements