# KANSAS GEOLOGICAL SURVEY
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Evaluation of Wet Walnut Water Supply Availability:
Development and Application of an Integrated Watershed Model

A Year-end Progress Report

BY

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Samuel P. Perkins
GIS assistance from Rogheyeh Eskrootchi

# EVALUATION OF WET WALNUT WATER SUPPLY AVAILABILITY: DEVELOPMENT AND APPLICATION OF AN INTEGRATED WATERSHED MODEL

A Year-end Progress Report

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## I. STUDY OBJECTIVES

The overall objectives of this study are:

1. To develop a comprehensive, continuous simulation watershed model for the Wet Walnut Creek Watershed, Kansas which includes surface-water and ground-water systems and interactions between them.

2. To calibrate and verify the model with historical streamflow at the Albert and Rush Center gauging stations in the watershed, and with ground-water levels in the alluvial aquifer of the watershed.

3. To produce a simulated monthly discharge hydrograph at the outlet of the watershed to compare the amount and distribution of streamflow from the watershed for the period, 1960-1996, with and without watershed structures in the watershed; and

4. To evaluate the influences and impacts of watershed structures on the ground-water supply in the watershed.

This report presents the results of the first year of the KGS subcontract to this study in summary form, covering objectives 1, 2, and part of 3 above.

## II. LOCATION, EXTENT, AND GEOLOGY OF STUDY AREA

Wet Walnut Creek in west-central Kansas has a drainage basin, shown in Fig. 1, of approximately 1,700 square miles, rising in Scott County and flowing through Ness, Rush, and Barton counties before discharging into the Arkansas River approximately four miles east of Great Bend, Kansas. The western part of the basin in Scott and Lane counties crosses the Ogallala Formation. The Ness County portion of the stream generally flows on Cretaceous chalks and shales where the Ogallala has been eroded. Alluvial material along the stream is thin or nonexistent in Scott and Lane counties but alluvium thickens in Ness County enough to support wells for irrigation and municipal

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use. The Rush and Barton County portions of the alluvial valley can have a saturated thickness of 80 feet or more.

Previous hydrogeologic studies that include the Wet Walnut Creek valley were conducted by Gillespie and Slagle (1972) who conducted artificial ground-water recharge experiments in the valley. McNellis (1973) reported on the geology and ground-water resources of Rush County, Jenkins and Pabst (1977) studied the hydrogeology of Ness County, and Latta (1950) reported on a detailed hydrogeologic study of Barton and Stafford counties that included the lower end of Wet Walnut Creek valley. McClain and Shapiro (1987) also reported on Wet Walnut Creek hydrogeology.

A ridge of Dakota Formation capped by as much as 50 feet of loess separates Cheyenne Bottoms and the Wet Walnut Creek Valley. Water in the creek is diverted through this ridge by a diversion dam and a canal north of Great Bend.

The Wet Walnut Creek Valley aquifer is composed of Quaternary alluvium consisting of gravel, sand, silt, and clay deposited by Wet Walnut Creek. Terrace deposits on the sides of the valley are composed of similar material. Both deposits yield water to wells although the valley fill is the predominant aquifer. The alluvial material rests on bedrock of Cretaceous age. It consists of the Greenhorn Limestone, Graneros Shale, and Dakota Formation. Neither the Greenhorn nor the Graneros is an aquifer in the Walnut Valley area. The Dakota Formation is an aquifer and supplies water for domestic and stock uses as well as irrigation, municipal, and industrial use. The Dakota and alluvium are in contact along much of the lower end of the valley.
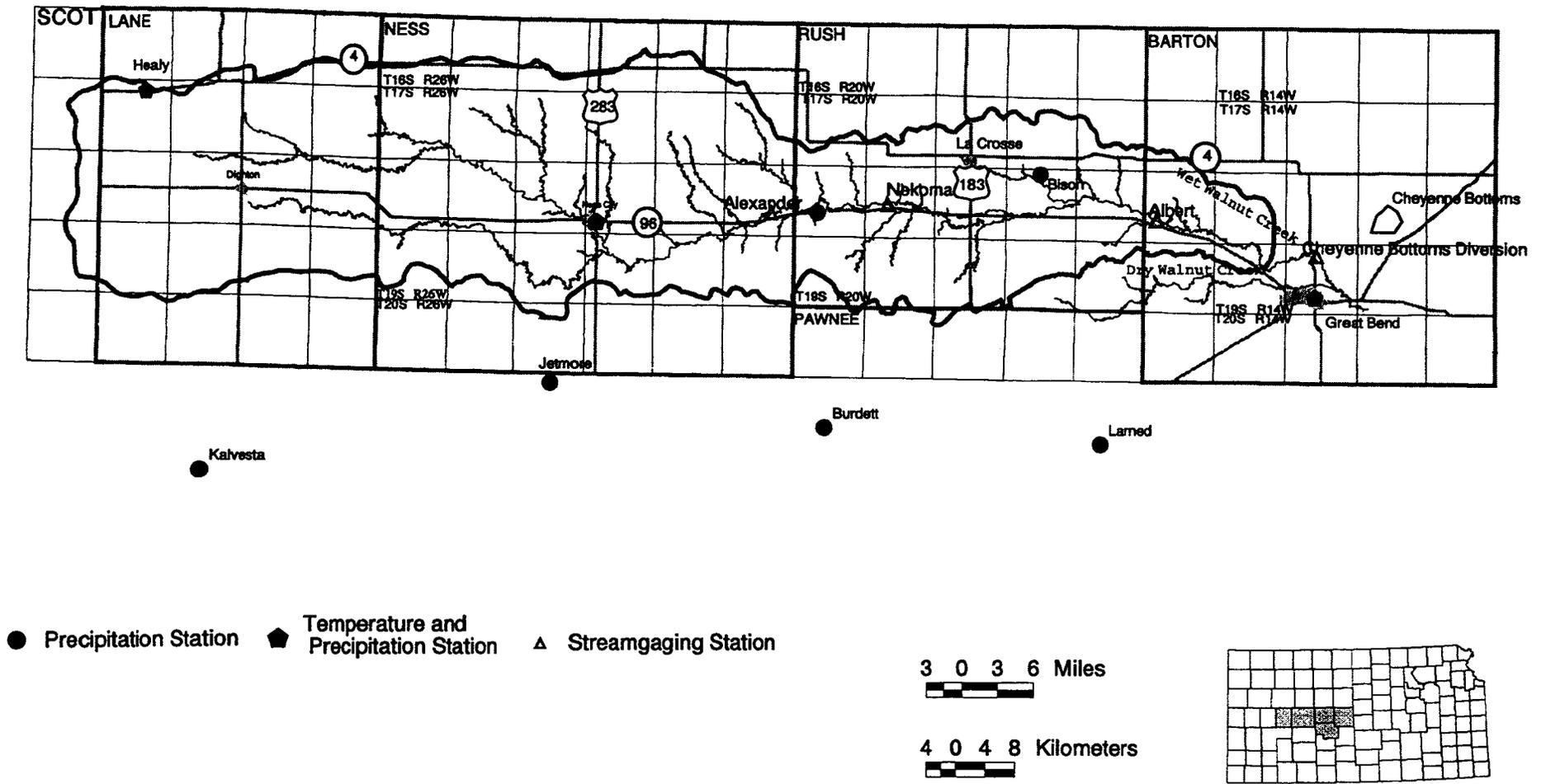
**Figure 1. Wet Walnut Creek basin with climatic and streamgaging stations**

# III. MODELING OF THE WET WALNUT CREEK VALLEY AQUIFER

Numerical modeling is the most commonly used form of ground-water/surface-water analysis. The strength of numerical models is their ability to tie together data and physical principles into a coherent and useful picture of an area.

The first step of a model study consists of <u>collecting and evaluating relevant data</u> on the flow system under investigation. These data are used for

- Problem definition (material properties and geometry of hydraulic units)
- Numerical requirements (initial conditions, boundary conditions, time-stepping conditions, and spatial discretization).
- Modeling requirements (calibration targets, validation targets, and definition of alternate hypotheses and scenarios).

An overview of some of these data is presented in section IV.

The second step in a modeling study is <u>developing a conceptual model</u>. A conceptual model is an idealization of the real world that summarizes the current understanding of area conditions and how the flow system works. It embodies all of the important features of the flow system, while incorporating simplifying assumptions. The purposes of developing a conceptual model are to:

- Develop a better understanding of field conditions and be able to communicate this understanding.
- Define the water problem for development of a numerical model.
- Aid in selecting a suitable numerical model.

Based on information presented in section II, the Wet Walnut Creek Valley aquifer consists of Quaternary alluvium and terrace deposits overlying relatively impervious Cretaceous bedrock. This valley is of the order of 100 miles long, less than 5

miles wide, and of saturated thickness of the order of less than 100 ft. This valley aquifer is therefore modeled as a single layer, unconfined, two-dimensional areal system with vertically averaged hydrogeologic properties. This aquifer unit is only a relatively small portion of the Wet Walnut Creek basin, the remainder being soil-covered bedrock outcrops, representing non-aquifer material. Recharge to the system is primarily a function of precipitation, soil and vegetation cover, land use, and irrigation return flow. Because of the relatively shallow depth to water table in the valley, water percolating beyond the root zone is considered as recharge to the alluvial aquifer. The Wet Walnut Creek is both recharging and draining the alluvial aquifer at different stream segments. Ground-water and surface-water-based irrigation in the valley may be impacting streamflows, especially during drought years. Numerous water control structures in the basin may also be impacting streamflows. Because of data limitations and special interest, only the portions of the valley in Ness, Rush, and Barton Counties up to the Cheyenne Bottoms diversion were modeled in this study (see Fig. 2). As a result, specified head boundaries were assigned along the North and South Forks of Wet Walnut Creek in western Ness County, and at the downstream end of the basin near the Cheyenne Bottoms diversion (see Fig. 3). No-flow boundary conditions were set for the valley walls.

The third step in the modeling process is to select a model code. In our case, we decided to use MODFLOW (McDonald and Harbaugh, 1988) with its STREAM module (Prudic, 1989) as the most appropriate model for addressing stream-aquifer interactions of interest in this study. MODFLOW is the most widely used and best-supported model presently available. MODFLOW is primarily a physically-based, distributed-parameter model, developed by combining the well-known Darcy's law governing fluid movement through saturated porous media, and the mass balance or continuity equation for subsurface flow. It is a modular three-dimensional block-centered finite difference code for layered aquifer systems.
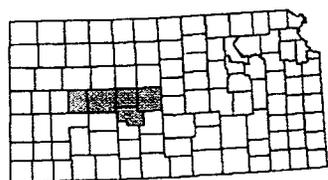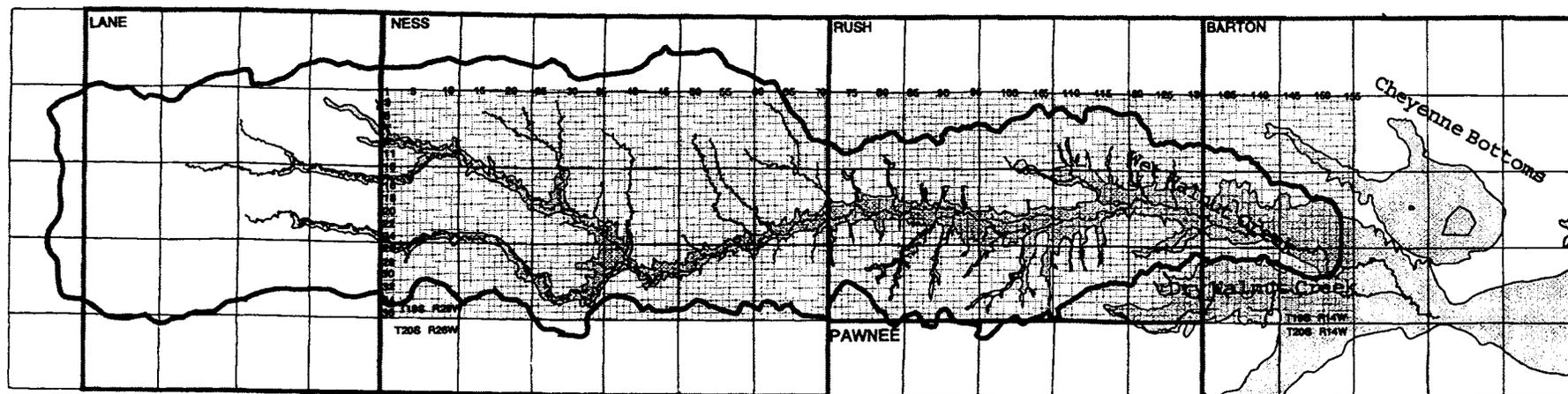
Figure 2. Model area showing Wet Walnut basin boundary, alluvial valley aquifer, and finite difference grid

One of the attractive features of MODFLOW is its modular composition, whereby necessary boundary conditions, aquifer parameters, grid data, and other relevant information are input through separate data files. A summary of the input data required for the Wet Walnut Creek Valley aquifer model is presented in Table 1. All the data items required for each key package of MODFLOW are listed therein. Because MODFLOW is a well-known and widely used code, no further description of this model is presented here.

In order to be able to handle surface water overland runoff to streams, soil profile drainage (recharging the aquifer), plant water uptake, as well as irrigation demand/scheduling, an agriculturally-oriented soil-water hydrologic budgeting model is required. For this purpose, we selected the POTYLDR (POTential YieLD Revised) model (Koelliker, 1994). POTYLDR represents a watershed as a collection of subbasins that are simulated independently on a daily basis to determine runoff, deep drainage, evaporation, and irrigation demand. Pond seepage is also computed for subbasins with watershed storage structures. Transmission losses are simulated by a separate program, CHANET (Govindaraju, 1998, personal communication), and are combined with pond seepage and deep percolation to represent aquifer recharge. The POTYLDR code is to be linked to the MODFLOW stream-aquifer model to form an integrated watershed model. One of the objectives and challenges of this work is to develop the linking routines and other enhancements needed for creating an effective, comprehensive modeling tool. This linking is explained in sections VI and VII. The POTYLDR model and enhancements for this study and related runs are handled by our KSU colleagues, with KGS input, and will not be detailed in this report.

Model setup is the fourth step in the modeling process. Model setup and calibration often constitute the bulk of the total modeling effort. Model setup entails selecting the model domain, discretizing data in space and time, defining boundary and initial conditions, and assembling and preparing model input data.

Input data are referenced in MODFLOW with respect to model grid cells. The model domain is discretized by 36 rows by 156 columns (Figs. 2 and 3), thus forming 5,616 square grid cells, each 0.5-mile by 0.5-mile (0.25 square miles) in area. The half-mile by half-mile discretization was considered necessary because of the narrowness of the Wet Walnut Creek valley, which may reach less than one mile in width in the western parts of the study area (see Fig. 2). However, because of lack of data, the first 11 columns of this grid were not used any further in the modeling. In addition, the top 8 rows did not contain any portion of the alluvial aquifer. Thus less than 700 grid cells actually overlay the alluvial valley aquifer, thus forming "active" cells in the model. Figure 3 shows these "active" cells with 1's and *'s, the latter ones representing specified or constant head boundaries. The 0's represent no-flow or "inactive" cells. The major model input data are outlined in the next section.    The western portion of the basin that overlays the Ogallala Formation is not explicitly modeled in our study. However, results from hydrologic budget modeling of the corresponding western subbasins (using the POTYLDR model) are passed to the adjacent downstream subbasins within the model domain of our study.

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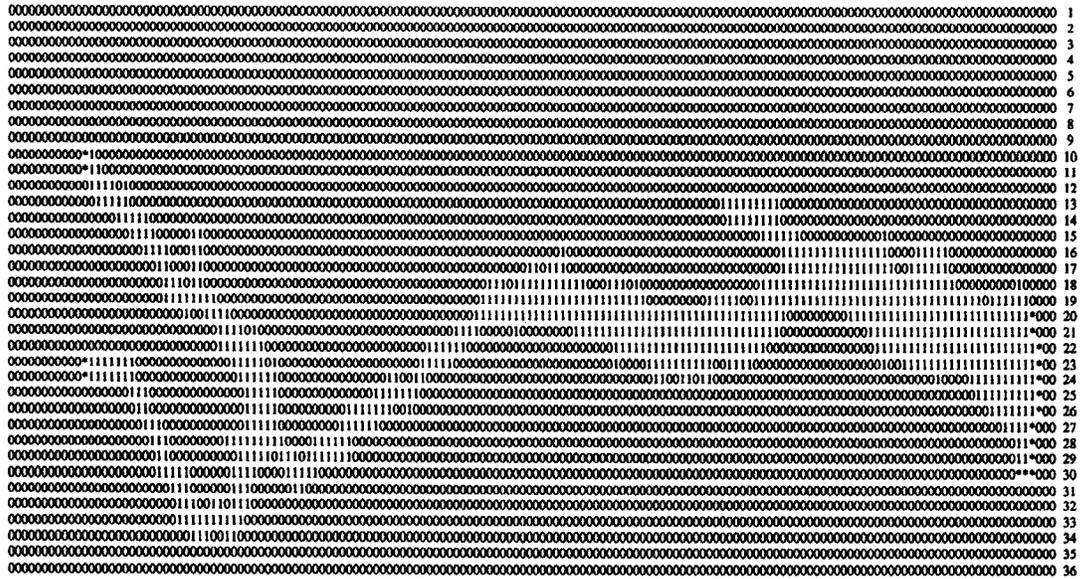
Figure 3. Active (1) and specified head (*) grid nodes in the Wet Walnut Creek valley aquifer model.

**Table 1. Summary of input data required in applying MODFLOW model to Wet Walnut Creek Basin (Numerical solution-related data excluded)**

BASic Package
- Number of layers, rows, and columns
- Number of "stress periods" within which all external stresses are constant
- For each stress period: the length of the period and the number of time steps
- Active, inactive, and constant head boundary nodes
- Initial head for each layer

Output Control Package
- Options for printing/saving head/drawndown
- Specification of time intervals for printing/saving head/drawndown

Block Center Flow Package
    For each layer specify:
- Steady-state or transient simulation
- Layer type code: confined (0), unconfined (1), combination (2 or 3)
- Transmissivity or hydraulic conductivity depending on layer type
- Storage coefficient or specific yield depending on layer type for transient simulations
- Layer bottom elevation for certain layer types
- Leakance (vertical hydraulic conductivity divided by the thickness from a layer to a layer beneath it) if layer is not the bottom layer
- Layer top elevation for certain layer types
- Anisotropy ratio
- Grid spacing along rows and columns

ReCHarge Package
    For each stress period specify spatial distribution (row, column, layer) and amount of recharge

WELl Package
    For each stress period specify layer, row, column, and withdrawal rate

STReam Package
- Number of stream segments (in which streamflow from surface sources are added at the beginning of the segment or subtracted (in the case of a diversion) at the end of the segment), stream reaches (parts of segments that correspond to individual grid cells), and tributary segments
- Layer, row, column of each segment and reach
- Streamflow entering the first reach of each segment
- Stream stage for each reach in a segment
- Streambed hydraulic conductance for each reach in a segment
- Elevation of top and bottom of the streambed for each reach in a segment
- Stream channel width, slope, and Manning's roughness coefficient for each reach in a segment
- Tributaries and diversions for each segment

RIVer Package
- For each stress period specify layer, row, and column of river/pond
- For each stress period specify stage, vertical conductance, and bottom of river/pond

GHB Package
- For each stress period specify layer, row, column, hydraulic head, and hydraulic conductance of river/pond

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## IV. INPUT DATA PREPARATION AND RELATED MAPS AND GIS COVERAGES FOR STREAM-AQUIFER MODELING

The following nine 1:250,000-scale ARC-INFO GIS maps, produced as ARCVIEW projects, were prepared to assist us in the modeling of the Wet Walnut Creek basin. These maps are included in a separate report (Sophocleous and Eskrootchi, 1998)

1.  A GIS coverage and map of the Wet Walnut Creek basin was first prepared for this study (see map 1 titled "Subbasins in Wet Walnut Creek Basin" in Sophocleous and Eskrootchi, 1998). 78 subbasins identified by NRCS are indicated on the map, and their areas specified using GIS tools. Subbasins numbered 54 or greater do not have a water control structure. In addition, all constructed and planned watershed structures are displayed. Figure 3 also displays these subbasins and structures. The GIS map also displays the combined alluvial and terrace deposits, thus outlining the Wet Walnut Creek Valley aquifer to be simulated; the map also displays a reference model grid consisting of 0.5 mile × 0.5 mile grid cells.

2.  An initial condition consisting of an equilibrium ("predevelopment") water table surface is required for modeling. Because such a surface was not available, we decided to create one based on available pre-1980 Kansas Geological Survey publications, mentioned in section II (see map 2 titled "Composite Predevelopment Water Table Map for Wet Walnut Creek Valley" in Sophocleous and Eskrootchi, 1998). Thus, we combined ground-water level data from Latta (1950) for Barton County, measured mainly during 1944, data from McNellis (1973) for Rush County, measured mainly during 1960, and data from Jenkins and Pabst (1977) for Ness County, measured mainly during 1974, to create a GIS

coverage and map of a composite, quasi-equilibrium water table of the valley. The measured wells are also indicated on the map.

3. The base of the alluvial aquifer is also required for modeling. An existing KGS bedrock map compiled by a former colleague (Thomas McClain, personal communication, 1997) was digitized and extended by adding additional bedrock values for the western portion of the study area (based on driller's logs and other data available at KGS). Thus a bedrock coverage and map was created (see map 3 titled "Bedrock Map for Wet Walnut Creek Valley" in Sophocleous and Eskrootchi, 1998).

4. Land surface elevations are also required for this study. A digital line graph (DLG) coverage of land surface elevations for the study area at a scale of 1:100,000 was extracted from the Kansas Data Access and Support Center (DASC) database, and a surface contour elevation map of the Walnut Creek basin was produced.

Modeling however requires discrete values of input data. Thus, the contour maps outlined under items 2 to 4 above were discretized to 0.5 mile × 0.5 mile cells, and cell-center values were obtained using a series of ARC-INFO GIS commands, such as CREATE TIN, GENERATE Fishnet, and TINSPOT (to perform bilinear interpolation).

5. As a result of the above-mentioned discretization procedure, a derivative GIS coverage and map of "predevelopment" aquifer saturated thickness was produced by subtracting the interpolated cell-centered values of the composite "predevelopment" water table from the corresponding bedrock values (see map 4 titled "Predevelopment Saturated Thickness Map for Wet Walnut Creek Valley" in Sophocleous and Eskrootchi, 1998). As can be seen from that map, the aquifer saturated thickness generally increases from west to east, with the greatest aquifer saturated thickness values occurring near the downstream end of the valley.

6.    Detailed stream distribution geometry is also required for modeling. Using GIS tools, this stream geometry and stream reach length within each reference model grid cell, mentioned under item 1 above, were specified. Grid cells where tributaries joined the main stream were also identified. In order to achieve better accuracy with streambed elevations and stream slopes, 7.5-minute USGS quadrangle topographic maps were employed, and all contour intersections with Wet Walnut Creek were identified, and their geographic coordinates were registered. Linear slopes between these points were employed for establishing stream-segment slopes. All these data were used to create the stream-input file for the MODFLOW ground-water model component (see Table 1).

7.    An up-to-date (1997) water rights file for the Wet Walnut Creek Valley was requested and obtained from the Division of Water Resources (DWR), Kansas Department of Agriculture (Brownie Wilson, 1998, personal communication). A GIS coverage and map indicating both surface and ground-water rights in the valley has been created from these data (see map 5 titled "Locations of Water Rights in Wet Walnut Creek Valley" in Sophocleous and Eskrootchi, 1998). The amount of water rights, irrigated area, and reported water use with time in the valley are shown later in Fig. 6.

8.    Hydrogeologic data for the alluvial aquifer were compiled from KGS publications mentioned in Section II and item 2 above. The average hydraulic conductivity of the aquifer based on pumping tests reported in McNellis (1973) is of the order of 250 ft/day, and the specific yield of the aquifer is considered to be 0.15. These are adopted as the initial average values of hydrogeologic parameters for the ground-water model of the valley aquifer.

**Additional maps and coverages**

An unpublished 1981 water table map for the Wet Walnut valley (Thomas McClain, 1998, personal communication) was digitized, and an ARC-INFO coverage and map was produced (map 6 titled "1981 Water Table Map for Wet Walnut Valley" in Sophocleous and Eskrootchi, 1998). By combining this map with the existing bedrock

map of the same area (see item 3 above), a "1981 saturated thickness map for Wet Walnut Valley" (map 7 in Sophocleous and Eskrootchi, 1998) was also produced.

Finally, by combining 1996 annual ground-water level data from the KGS data base with measurements of water levels in the area conducted by DWR-Stafford Field Office personnel, a "1996 water table map for Wet Walnut valley" (map 8 in Sophocleous and Eskrootchi, 1998), and a "1996 saturated thickness map for Wet Walnut valley" map (map 9 in Sophocleous and Eskrootchi, 1998) were produced using Arc-Info.

One of the objectives of this study is to evaluate the impacts of the watershed structures in the numerous subbasins of the Wet Walnut Creek basin. Figure 4 displays these subbasins and watershed structures. The existing climatic stations and streamgaging stations used in this study are displayed in Fig. 1.
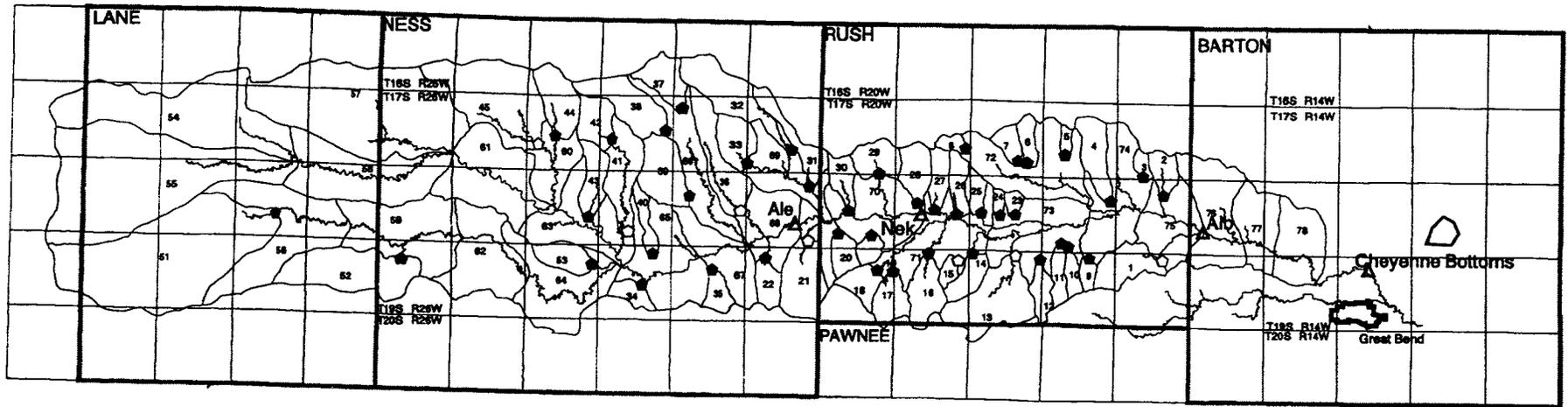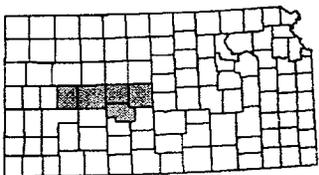
Figure 4.  Wet Walnut Creek subbasins with water-control structures

## V. MODFLOW ENHANCEMENTS (regarding irrigation, streamflow routing, and stream-aquifer interaction) FOR IMPROVED LINKAGE TO ANY WATERSHED MODEL

While our revisions to MODFLOW address specific modeling requirements of the Walnut Creek basin study, they also conform to the modular spirit of MODFLOW's design. In addition, they are based on previous developments that we have applied to models of the Republican River and Rattlesnake Creek basins in Kansas. Our revisions to MODFLOW as applied to the Walnut Creek basin study are encapsulated in the following packages. (Documentation for each of these packages will be available in 1999 as KGS open-file reports.)

MODSWB provides a means of using results from a watershed simulation model, specifically POTYLDR for the Walnut Creek basin, to specify conditions for surface and ground water pumping based on irrigation demand; lateral inflows to Walnut Creek based on storm runoff; and ground water recharge based on soil water percolation, channel transmission losses, and pond seepage.

MODWEL extends the modeling capabilities of MODFLOW's Well package. Diversions from not only ground water but also surface water sources may be specified. If surface water sources are specified, a stream network must also be specified using MODSTR, the modified STREAM package (below) such that each diversion's grid cell location corresponds to a stream reach from which water is diverted. Pumping limits may be specified with respect to both rated pumping capacity and the source, i.e., available stream inflows for surface water diversions and adequate saturated thickness for ground water diversions.

MODSTR is an extension of MODFLOW's Stream package. It has been modified to generalize lateral flow in its routing procedure to include tributary inflow,

surface water diversions, and evaporation along with streambed leakage. Streamflow characteristics (depth, width, wetted perimeter, and others) for trapezoidal and natural channels can also be represented. Streambed conductance may vary with streambed hydraulic conductivity and stream width; hydraulic conductivity may be resolved into components corresponding to bottom and side walls; and leakage due to flooding outside the main channel is characterized as recharge due to percolation instead of coupled stream-aquifer interaction.

The modified Well and Stream packages (MODWEL and MODSTR) may be used independently as in the case of the original packages; or they may be used to take advantage of some added capabilities requiring that both packages be invoked, such as specification of surface water rights to be drawn from streamflow. Similarly, these two packages may be used in conjunction with the MODSWB package, which can specify recharge, tributary inflows, diversions from surface and ground water for irrigation, and evaporation in terms of watershed simulation results.

Three additional packages are used to provide capabilities of the postprocessing variety. These are MODRSD, MODPOST, and MODPLT, which are used as a matter of course with every simulation run of MODFLOW for the Walnut Creek model for the convenience they provide.

MODRSD calculates ground water level residuals, i.e., the errors $e_i = h_{sim} - h_{mea}$, for $i$ from 1 to n observations, where $h_{sim}$ is MODFLOW's hydraulic head solution for a given grid cell and time step, and $h_{mea}$ is an available measurement taken within the grid cell during the time step. MODRSD is set up for use with either annual or, in the case of the Walnut Creek model, monthly time steps.

MODPOST provides functions that are analogous to postprocessors that operate on MODFLOW's standard output or binary "Save" file, but are executed during MODFLOW's simulation run and do not require retaining the output for postprocessing.

Results provided by MODPOST from each simulation of Walnut Creek include hydraulic head solutions for specified time steps in a format for input to surface or contour plotting packages; hydrographs of aquifer heads, streamflow, and streambed leakage for specified grid cells; and volumetric budget summaries. The hydrograph and budget summaries are written in column formats for importing into spreadsheet programs. Budgets may also be calculated for zones, i.e., subsets of the grid model, which may correspond to subbasins represented by a watershed simulation used by MODSWB to specify conditions for MODFLOW's solution in each time step.

MODPLT provides interactive visualization of various aspects of the simulation of each case run for Walnut Creek during execution of the simulation. This can provide useful insight into the simulations that can be difficult to obtain from results after execution. Results shown graphically for each time step include a spatial distribution of change in heads; histograms for change in heads and residuals; hydrographs of ground water heads that can be specified during execution; hydrographs of streamflow at gaging stations; water budget hydrographs; and stream profiles of tributary inflows, surface water diversions, streambed leakage or baseflow, and stream depth. The mouse can be used to point to grid locations to show corresponding geographical locations.

## VI.  LINKING MODFLOW AND POTYLDR MODELS FOR THE WET WALNUT CREEK BASIN

**Organizing an integrated watershed model: Combining POTYLDR with MODFLOW**

The watershed simulation model applied to the Wet Walnut Creek basin links two separate simulation packages.  POTYLDR is used to simulate an agricultural watershed's hydrologic processes.  The hydraulics of ground water flow and stream-aquifer interaction are beyond the scope of POTYLDR.  These processes are simulated by MODFLOW ("Modular 3-D Flow Model", McDonald and Harbaugh, 1988), which solves the equations of flow for ground water (Freeze and Cherry, 1979) and its interaction with streamflow (Prudic, 1989).  On the other hand, MODFLOW lacks a means of specifying conditions on its solution in terms of hydrologic processes at the watershed's surface and in the soil profile, which POTYLDR is used to provide.  Conditions on MODFLOW's solution include inflows to the stream network, ground water recharge, evapotranspiration from shallow ground water, and diversions from surface and ground water rights for irrigation and other water uses.

POTYLDR and MODFLOW simulate their respective components of Walnut Creek basin at different temporal and spatial scales.  POTYLDR operates with daily time steps, whereas MODFLOW takes monthly time steps.  POTYLDR represents spatial heterogeneity within a given subbasin statistically, using the concept of hydrologic response units (HRUs), which are practically homogeneous areas having a distinct hydrologic response, whereas MODFLOW operates on the discrete grid cells into which the subbasin is divided (Fig. 2).

We wrote additional code to meet specific modeling requirements, and to provide an interface between POTYLDR and MODFLOW.  Several conceptualizations were developed and coded in both POTYLDR and MODFLOW.  POTYLDR was modified to represent various subbasin configurations, including the presence or absence of watershed

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storage structures and an underlying alluvial aquifer, as described in previous reports to KWO. Similarly, model refinements with respect to irrigation, streamflow routing, and stream-aquifer interaction were incorporated into MODFLOW, as described in section VII below.

Figure 5 outlines the procedure followed to simulate Walnut Creek basin using POTYLDR and MODFLOW.
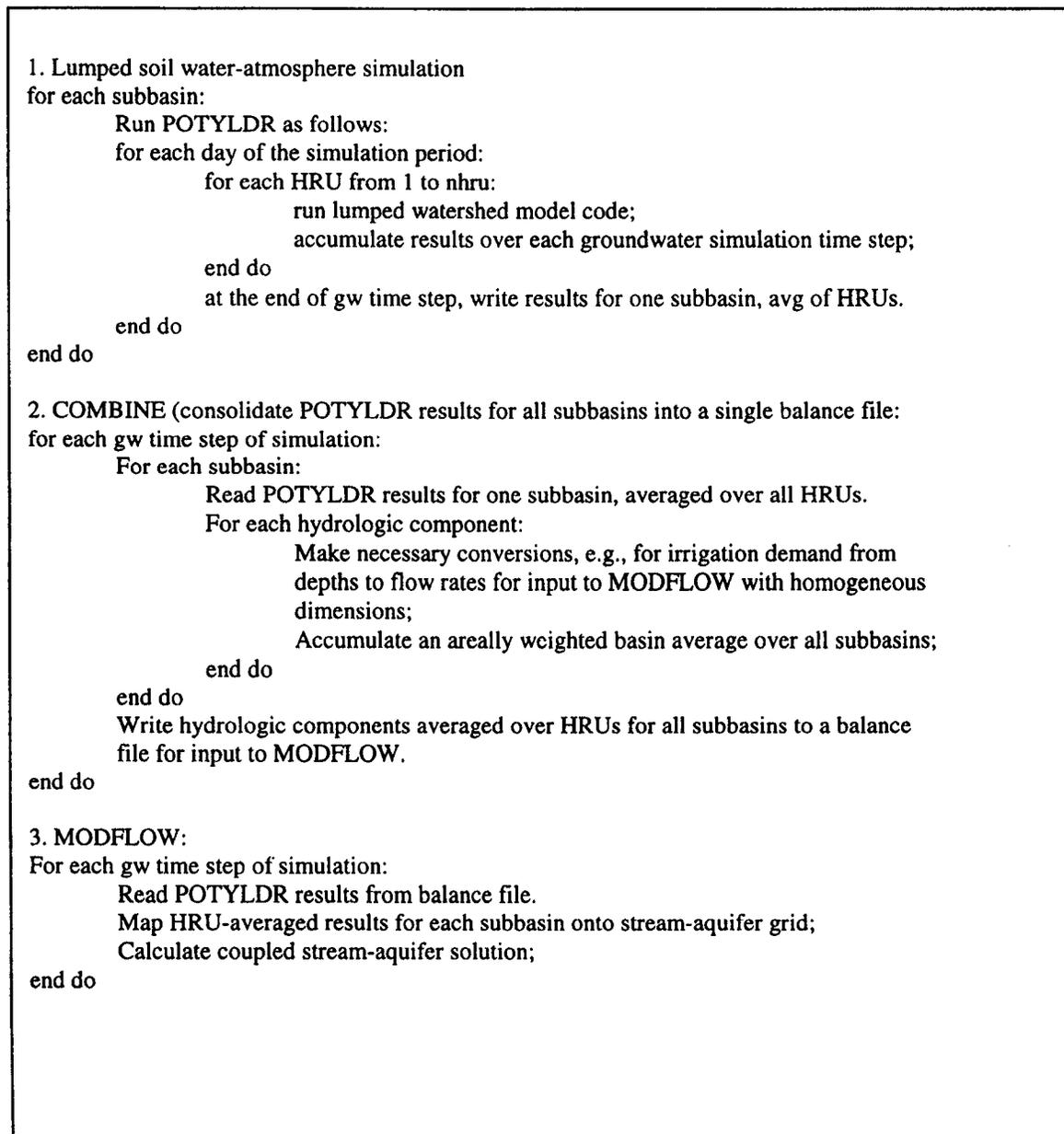
```
1. Lumped soil water-atmosphere simulation
for each subbasin:
        Run POTYLDR as follows:
        for each day of the simulation period:
                for each HRU from 1 to nhru:
                        run lumped watershed model code;
                        accumulate results over each groundwater simulation time step;
                end do
                at the end of gw time step, write results for one subbasin, avg of HRUs.
        end do
end do

2. COMBINE (consolidate POTYLDR results for all subbasins into a single balance file:
for each gw time step of simulation:
        For each subbasin:
                Read POTYLDR results for one subbasin, averaged over all HRUs.
                For each hydrologic component:
                        Make necessary conversions, e.g., for irrigation demand from
                        depths to flow rates for input to MODFLOW with homogeneous
                        dimensions;
                        Accumulate an areally weighted basin average over all subbasins;
                end do
        end do
        Write hydrologic components averaged over HRUs for all subbasins to a balance
        file for input to MODFLOW.
end do

3. MODFLOW:
For each gw time step of simulation:
        Read POTYLDR results from balance file.
        Map HRU-averaged results for each subbasin onto stream-aquifer grid;
        Calculate coupled stream-aquifer solution;
end do
```

Figure 5. Procedure followed in combining POTYLDR and MODFLOW; it requires insertion of intermediate step COMBINE to collect subarea results.

In Step 1, each subbasin of Walnut Creek basin is simulated with a separate execution of POTYLDR. The subbasins are heterogeneous with respect to soils, crops, and land use management. These heterogeneities are represented by POTYLDR as a combination of homogeneous subareas, referred to as hydrologic response units (HRUs), each of which POTYLDR simulates independently and then combines as a weighted average, in which the weighting is given by the HRU subareas. POTYLDR accumulates the HRU-averaged quantities over the days corresponding to each time step and writes the results of its simulation for each subbasin to a separate file.

In Step 2, program COMBINE was written to combine simulation results from POTYLDR into a single input file for MODFLOW, and to convert quantities expressed by POTYLDR variously as depths and volumes into flow rates with units that are consistent with MODFLOW's simulation. The hydrologic depths represent flow rates per unit area integrated over a time step, i.e., $d = Q\Delta t/A$. Converting depths to flow rates involves rearranging this expression into the form $Q = Ad/\Delta t$ for the appropriate areas. In the case of irrigation, the area of irrigation within each subbasin is obtained from water rights appropriation files from DWR.

In Step 3, a geographical correspondence between subbasins represented by POTYLDR and the aquifer grid and stream network represented by MODFLOW is given by input data to the MODSWB package. These data consist of grid cell locations to specify outflows from subbasins to the stream network as tributary inflow, and aquifer grid cells underlying each subbasin. MODSWB uses this correspondence in each time step to determine where runoff from each subbasin enters the stream network; and to which aquifer grid cells percolation, pond seepage, and transmission losses flow as recharge. In addition, MODSWB determines the pumping rates required of both surface and ground water rights in each time step to meet irrigation demand simulated by POTYLDR.

**Hydrologic requirements for the interface, and data transfer from POTYLDR to MODFLOW**

POTYLDR simulates each subbasin individually with daily time steps, and provides a monthly summary of the following results in a separate data file for each subbasin, expressed variously as flow rates, Q, volumes, $V = Q\Delta t$, and volumes per unit area (depth), $d = V/A$ or $d = Q\Delta t/A$. Initial values are given for soil water content [d, in] and pond storage [v, acre-in]. For each time step ($\Delta t = 1$ month), the following hydrologic components are given by POTYLDR.

$d_{pcp}$: Precipitation [d, in] -->[d,ft]

$d_{irr}$: Irrigation demand [d, in] -->[Q, cfs]

$d_{etact}$: Actual evaporation [d, in] -->[d,ft]

$d_{etpot}$: Potential evaporation [d, in] -->[d,ft]

$d_{perc}$: Deep percolation (percolation through soil profile to the aquifer) [d, in] -->[d,ft]

$dv_{trib}$: Surface runoff: tributary inflow toWet Walnut Creek [v, acre-ft] -->[Q, cfs]

$dv_{seep}$: Pond seepage [v, acre-ft] -->[Q, cfs]

sw: Soil water content [d, in] -->[d, ft]

$dv_{pond}$: Change in pond storage volume [v, acre-in] -->[v, acre-ft]

In Step 2, simulation results from POTYLDR for each subbasin are combined into a single file for MODFLOW by program COMBINE, which also applies unit conversions to some of POTYLDR's results to be consistent with MODFLOW's homogeneous set of units. Monthly irrigation demand simulated by POTYLDR is converted into a monthly flow rate for the subbasin according to $Q_{irr} = d_{irr} A_{irr}/\Delta t$. The area of irrigation within each subbasin, $A_{irr}$, is known from analysis of DWR water rights records for each year of the historical simulation period 1960-1996. An associated estimate of annual water use for irrigation, Uirr, was based on analysis of DWR water use reports. From these, an annual irrigation depth, $d = U_{irr} \Delta t /A_{irr}$ is derived.

Water budget terms ($d_{pcp}$, $d_{etact}$, sw, and $dv_{pond}$) were included in these results to be passed to MODSWB in MODFLOW to allow calculating an overall watershed hydrologic balance. The remaining terms are used by MODSWB to specify recharge, evapotranspiration, groundwater pumping, surface water diversions, and tributary inflow for the stream-aquifer model.

In Step 3 (above), the MODSWB package reads an input file (denoted as the SWB file) to initialize the associations between the subbasins with the stream network and aquifer grid. Then in each time step, MODFLOW reads the results of POTYLDR simulations from the data file written by COMBINE (which is denoted as the balance file).

The SWB file contains the following data:
Ibshed: a 2-d integer array in standard MODFLOW format containing subbasin codes to associate each grid cell with a subbasin; instructions for the Ibound integer array in MODFLOW's Basic package apply to Ibshed.
For each subbasin index i from 1 to 78 (refer to Fig. 4 for subbasin numbering system):
   A flag to indicate whether (y=1,n=0) results are given for a subbasin corresponding to
      index i (because the numbering system for the Walnut Creek subbasins is not
      continuous).
   Grid location (row, column) where runoff from the subbasin enters the Wet Walnut
      Creek stream network represented by MODFLOW's STREAM package.
   Area of the subbasin.
   Fraction of the subbasin area that is underlain by the alluvial aquifer.

# VII. IMPLEMENTATION OF MODFLOW ENHANCEMENTS TO WET WALNUT BASIN INTEGRATED MODEL

The following describes how the MODFLOW enhancement items described in section V fit together in the context of our integrated model.

## 1. Irrigation limits applied to ground and surface water sources

Annual irrigation water use along Walnut Creek Basin's alluvial valley was estimated on the basis of water rights records and annual water use reports from DWR for the period 1960-1997. Water use reports from a small fraction of water rights holders were available beginning around 1966; the reporting fraction increased to nearly one by the early 1990's. Water rights records included appropriated area of irrigation, A (acres), annual volumetric limit, V (acre-ft), and maximum pumping rate, $Q_r$ (cfs). Annual water use reports included volume of water used, U (acre-ft). Annual irrigation depth was calculated from reported water use and corresponding appropriated irrigation area, i.e., d = U/A, for reporting water rights within each subbasin for each year of available water use reports 1966-1997. The fraction of total appropriations reporting water use was taken to be representative of the remaining non-reporting appropriations; i.e., the total appropriated area for irrigation was assumed to be irrigated at the depth calculated from the water use reports. Figure 6 displays the appropriated irrigated area (acres) and irrigation volume (acre-ft) as cumulative totals with time. It also displays the estimated irrigation depth (ft) based on reported water use, and also on appropriated amounts.
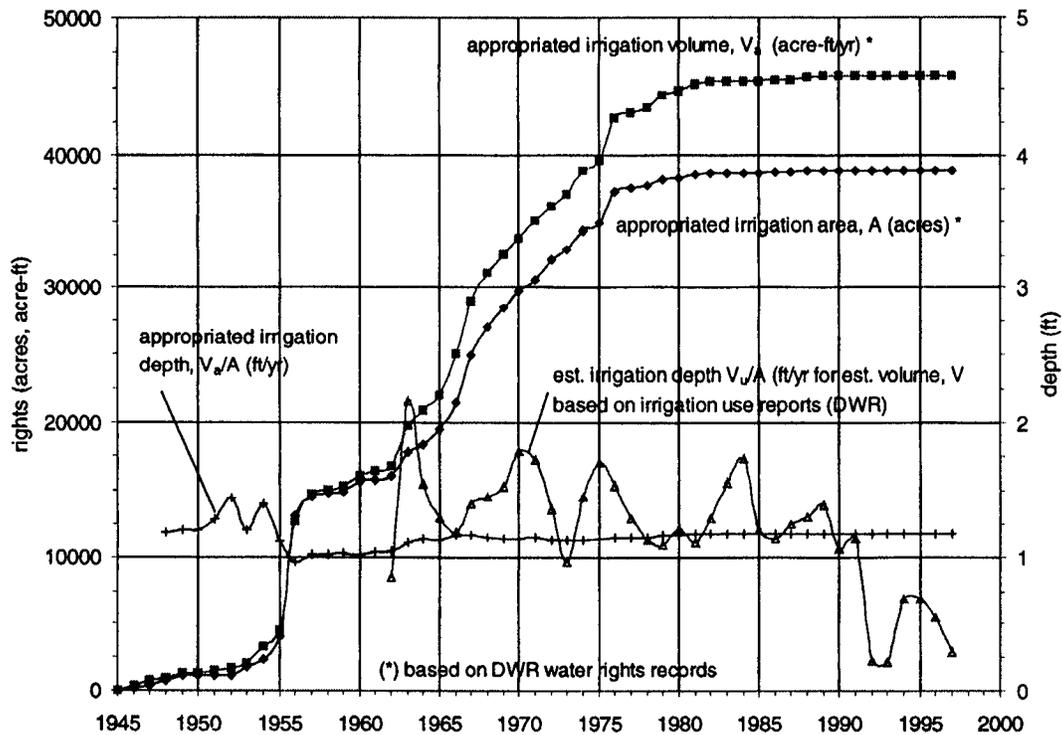
appropriated irrigation volume, V, (acre-ft/yr) *

appropriated irrigation area, A (acres) *

appropriated irrigation
depth, $V_a/A$ (ft/yr)

est. irrigation depth $V_u/A$ (ft/yr for est. volume, V
based on irrigation use reports (DWR)

(*) based on DWR water rights records

rights (acres, acre-ft)

depth (ft)

1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000

Figure 6. Cumulative appropriated irrigated area and irrigation volume since 1945, and estimated annual irrigation depth based on appropriated and water use reports

Estimated annual irrigation depth for each subbasin was used as an annual maximum irrigation depth in daily hydrologic simulations by POTYLDR. Appropriated irrigation area as a fraction of subbasin area was used by POTYLDR to represent the relative importance of irrigation as a land use within the subbasin. Irrigation depth was simulated by POTYLDR for each subbasin and accumulated for each month. This depth was converted to a flow rate, $Q_i = d*A/dt$, by program COMBINE, which serves to consolidate simulation results from POTYLDR for all subbasins and convert the results into appropriate units to be used as input to MODFLOW's MODSWB package.

MODFLOW's stress periods were used to represent calendar years, so that in each calendar year the corresponding appropriated water rights could be specified according to DWR's water rights records. For each stress period, either annual or monthly time steps

may be taken, based on either annual or monthly hydrologic summaries from POTYLDR. Our simulations with MODFLOW are based on monthly time steps.

Because both ground and surface water are appropriated for irrigation, Modflow's Well package was modified to represent both sources, using DWR's "G" and "S" designations to distinguish them. The modified Well package also allows specifying the type of use; DWR's "Use Made of Water" code "IRR" or corresponding index 3 identifies irrigation rights. The location of a surface water diversion is specified in the Well package input file as a grid cell (layer, row, and column), the same as for ground water diversions. Non-irrigation water rights were also simulated.

Monthly irrigation simulated by POTYLDR for each subbasin was used to specify pumping rates in MODFLOW by applying a scaling factor, s, to the annual appropriation of each individual irrigation water right. The scaling factor is given by $s = \eta \, Q_{irr}/Q_{app}$, where $Q_{irr}$ = total simulated pumping rate (cfs) for irrigation summed over all subbasins; $Q_{app}$ = total appropriation of all irrigation water rights summed over all subbasins; and evaporative losses (irrigation efficiency) are represented by the factor $\eta = 1/(1-f_e)$, where $f_e$ = fraction of irrigation pumping lost to evaporation.

As an example, consider an irrigation water right that is appropriated 724 acre-ft/yr, a volume corresponding to 724 acres with a depth of 1 ft ($V = d \cdot A$) and a flow rate $Q_{app} = 1$ cfs ($V = Q\Delta t$). To use the entire appropriation in one month, water must be pumped at a rate approximately $s = 12$ times higher than the appropriation expressed as an average annual flow rate, i.e., $Q_{irr} = 12$ cfs.

The scaling factor, s, is necessarily nonzero only during months when irrigation is applied according to POTYLDR simulations; during the months of heaviest irrigation, s was found to be as large as 8. By comparison, converting rated pumping capacity and annual appropriation according to DWR water rights records to common units, e.g. cfs, their mean ratio was found to be approximately 16 for ground water sources and 32 for

surface water sources. For a second comparison, if a water right's entire annual appropriation were used in a single month with no evaporative losses, the scaling factor s would be approximately 12; with 15 percent evaporative loss, the scaling factor in this case would be approximately 14.

In meeting the monthly demand specified by POTYLDR with pumping from ground and surface water, limits on both pumping capacity and supply were considered. The pumping capacity limit was taken to be twice that given as the appropriated maximum in the DWR water rights records. For water rights with no maximum pumping rate given (i.e., specified as zero in the DWR water rights records), a maximum rate was determined from an average rated capacity as a fraction of appropriatons for the corresponding source. By including the factor of two, this operating limit was rarely reached, with the intended effect that a limit on the supply source would instead be affected. The limit on supply is represented by saturated thickness for ground water sources, and by the sum of channel and lateral surface inflows to a stream reach in the case of surface water diversions.

The saturated thickness limit for ground water sources is represented as follows. Two saturated thickness limits are specified; for the current base case, these limits are set at 10 and 15 ft. Above the upper limit, the appropriated pumping rate  scaled by the factor s is unaffected; below the lower limit, the pumping rate is set to zero. For a saturated thickness between these limits, the pumping rate is scaled linearly between these two extremes.

2. Streamflow routing: tributary inflows and surface water diversions

The specification of surface water diversions requires that a stream network also be specified. MODFLOW's Stream package was modified to accommodate surface water diversions specified for the modified Well package.

First, a grid cell array, Idxstr, was introduced to provide an index from each grid cell to the corresponding stream reach as specified by input to the Stream package. This index array allows the location (layer, row, column) specified for a surface water diversion to directly refer to the corresponding stream reach from which water is to be diverted; without Idxstr, a time-consuming search for the corresponding stream reach would be required.

Second, the stream routing procedure was modified to generalize lateral flow to include not only baseflow (or its negative, streambed leakage), but also terms for evaporation from the stream surface and for lateral inflow from surface water sources. This change is employed to include both tributary inflows, based on simulated runoff, and surface water diversions, represented by negative inflows. The modified stream routing procedure constrains surface water diversions from a given stream reach to not exceed the sum of channel and lateral surface inflows to the reach.

Tributary inflows are related to the stream network by specifying grid cell locations for outflows from each subbasin; these locations also refer to corresponding stream reaches directly by way of the Idxstr array. The lateral inflow term of the routing procedure was further generalized to include a component to represent evaporation from the stream surface, based on potential evaporation, stream surface area, and time step.

3. Streamflow characteristics: depth, width, and area

The Stream package was modified to allow representing either a trapezoidal channel or a natural stream channel. In the case of a trapezoidal channel, a side slope is specified, and Manning's equation is used to evaluate stream depth, $y$, which determines

stream width, $B$, wetted perimeter, $P$, and transverse area of channel flow, $A$. For a natural stream channel, power functions based on measurements at USGS gaging stations can be used to represent these characteristics. In the case of Walnut Creek, measurements from USGS gaging stations at Albert, Nekoma, and Alexander were examined and compared. Streamflow characteristics for the Albert gaging station were found to represent streamflow at the other gaging stations adequately, and were consequently used to represent all stream reaches of the network. The characteristics $y$, $B$, and $A$ were approximated by power functions of flow rate, $Q$, of the form

$$u(Q) = aQ^b,$$

where $u(Q)$ represents any of the characteristics $y(Q)$, $B(Q)$, and $A(Q)$. For relatively shallow streams such as Walnut Creek, the wetted perimeter can be approximated by the stream width; i.e., for $B \gg y$, $P \approx B$. An example of depth-discharge, y(Q) relationship for the Albert gaging station is shown in Fig. 7, where power function approximations were superimposed on USGS measurements.
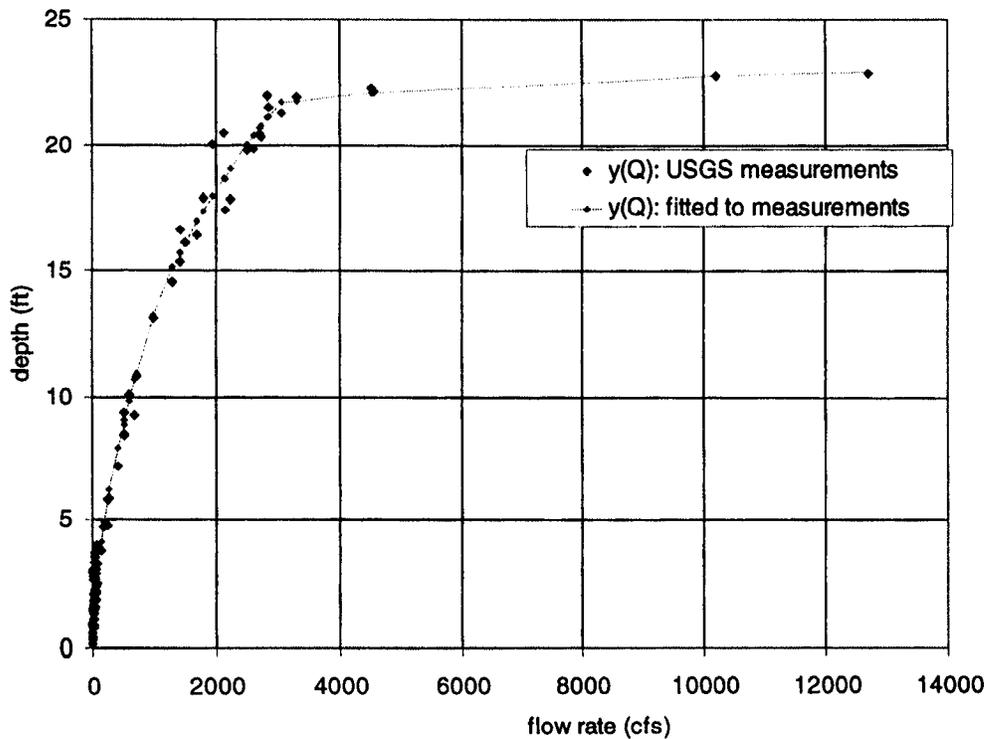


Figure 7. Depth-discharge rating curve of Wet Walnut Creek at Albert gaging station

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4. <u>Streambed leakage</u>

Streambed leakage, $Q_l \equiv q_l \Delta x$, is evaluated according to Darcy's law,

$$q_l \Delta x = -K_s P \Delta x (dh / dl),$$

where $\Delta x$ = reach length, $K_s$ = hydraulic conductivity, $P$ = wetted perimeter, and $dh/dl$ = hydraulic gradient across the streambed. This is represented in the Stream package as $Q_l = C(z_s - h)$, where $C$ = streambed conductance, $z_s$ = stream stage, and $h$ = aquifer head or streambed bottom elevation, $z_b$, whichever is higher; if $z_b, > h$ for a given stream reach, the streambed leakage is treated as recharge and does not depend on the hydraulic head, $h$. Streambed conductance is given by $C = K_s P \Delta x / (z_t - z_b)$, where $z_t$ = streambed top elevation, $z_b$ = streambed bottom elevation, and $(z_t - z_b)$ = streambed thickness.

In MODFLOW's standard STREAM package, conductance is specified as an input; variations in conductance with respect to hydraulic conductivity and wetted perimeter are neglected.

$\Delta h$ = hydraulic head across streambed, and $\Delta l$ = streambed thickness. The STREAM package was further modified to refine its model of streambed leakage, in part to represent different flow regimes with respect to this cross section.

First, the STREAM package was modified to allow specifying saturated hydraulic conductivity for the streambed, so that conductance, C = Ks*L*W/(ztop - zbot), can be calculated in each time step, rather than specifying C as input for each reach and stress period.

Second, two values of hydraulic conductivity were specified: a lower value, taken to represent a presumably silted main channel, with a width specified to be up to 40 ft; and a higher value to represent side channels, which are involved only during high flows.

Finally, the model used to represent the hydraulic gradient across the streambed was refined for the rare case of flood flows overtopping the side channels into the flood plains. In this case, the width of hydraulic contact is limited to the stream's maximum

width within its banks. For this width, streambed leakage is based on a composite hydraulic conductivity and a hydraulic head measured from the stream stage elevation to the water table. Outside this in-bank width, a second, decoupled component of streambed leakage is calculated, based on a hydraulic head corresponding to the depth of water covering the flood plain plus an assumed saturation zone given by the streambed thickness.

## VII. CALIBRATION AND VERIFICATION OF THE INTEGRATED WATERSHED MODEL

Model calibration is the process of varying uncertain model input over likely ranges of values until a satisfactory match between simulated and observed data is obtained. Calibration is needed to account for unmeasured, unknown, or unrepresented conditions or processes, and for uncertainty in measured data. Model verification or corroboration is the process of demonstrating that the calibrated model is an adequate representation of the physical system. Owing to uncertainties in the calibration, the set of parameter values used in the calibrated model may not accurately represent field conditions.

### Calibration targets

Our calibration targets were measured monthly streamflows at the Albert and Nekoma USGS gaging stations, measured ground-water levels across the valley at different time periods, and reported water use for irrigation. Using available hydrogeologic data, and 1960 initial conditions (assumed to be near-equilibrium conditions) we run the combined model on a monthly time step until 1990. (A square grid mesh of 0.5-mile by 0.5-mile cells was employed throughout the valley.) The data for the period of 1991 to 1996 was reserved for verification of the calibrated model.

As mentioned earlier, from estimated annual water use information, $U_{irr}$, from DWR water-use reports, and from irrigated area information for each subbasin from DWR water appropriation files, an annual irrigation depth is derived as $d_{ann} = U_{irr} \Delta t / A_{irr}$. POTYLDR uses this estimate of annual irrigation depth for the basin as an upper limit on its daily simulation of irrigation demand within each subbasin. Program COMBINE

applies the irrigation depths simulated by POTYLDR, $d_{irr}$, to the irrigated subbasin areas, $A_{irr}$, to determine irrigation demand as a monthly flow rate for each subbasin, to be supplied by both surface and ground-water diversions in MODFLOW. Thus annual irrigation water use, $U_{irr}$, provides a calibration target to be compared with pumping rates simulated by MODFLOW to supply annual irrigation.

Calibration procedure

A preliminary sensitivity analysis was conducted to evaluate the impact of various model input parameters on the model output results. We focussed our efforts on the impact of the following hydrogeologic parameters: aquifer hydraulic conductivity, aquifer storativity, and streambed hydraulic conductivities of both the main channel and side channel slope. These parameters were changed one at a time (within expected ranges), and the resulting mean and standard deviation of the ground-water level residuals (i.e. the differences between simulated and observed water levels) were examined, as well as the simulated and observed cumulative streamflows at the downstream gaging station at Albert. The parameters that resulted in the smallest mean residuals and standard deviations, as well as the best matched cumulative streamflows at the Albert gaging station were adopted as the calibrated values for the 1960-1990 simulation, hereafter referred to as the base case. Additional attempts to subdivide the valley into regions of different hydrogeologic parameters resulted in only marginal improvements in the results. In this study, we followed the principle of parsimony in selecting our final, calibrated results, that is, among equally likely alternatives, the simplest one is preferred.

Calibration/verification results

The results of our calibrated base case ( referred to as 'Potyldr11' in the figures) for ground-water levels are presented in Fig. 8, where it can be seen that the mean residual (i.e., the difference between simulated and measured water levels) is 1.51 ft, and the standard deviation is 6.59 ft, based on 1218 measured ground-water-level values over the 1960-1990 period, available in the KGS KIWI data base, and 502 interpolated values in each active grid cell obtained from a 1981 water table contour map (see section IV). The mean residual for the 1991-1996 verification period is 0.53 ft with a standard deviation of 8.22 ft, based on 509 measured depths to water table available from the

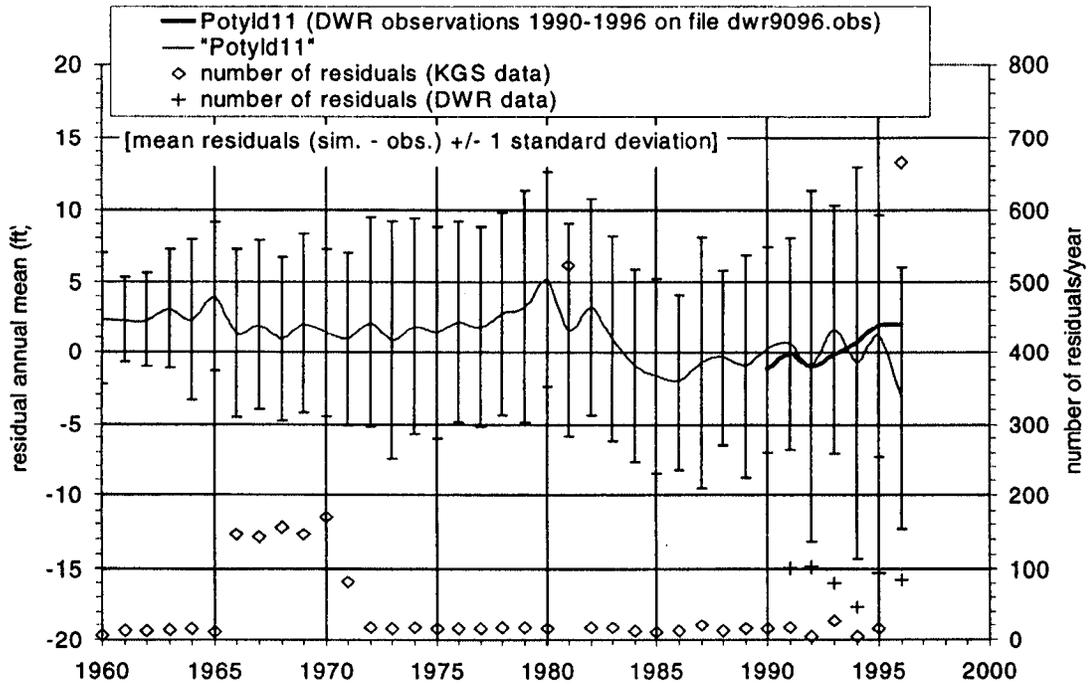DWR water use data base, and land surface elevations obtained from 7.5-minure USGS quadrangle maps).



Figure 8. Ground-water-level residuals (differences between simulated and measured values) and error bars of ±1 standard deviation for the calibration and verification cases

The calibrated hydrogeologic parameters are: K(aquifer)=250 ft/d, S(aquifer)=0.20, K(main channel)=2 ft/d, and K(side channel)=5 ft/d, where K and S represent hydraulic conductivity and storativity, respectively. (A value of S=0.15 resulted in slightly smaller ground-water-level residuals but slightly larger streamflow residuals at both Nekoma and Albert gaging stations.) In evaluating Fig. 8, it should be kept in mind that the highest density of measured water-level data points, employed in the model, occurred during the years 1966-1971, 1981, and 1990-1996.

Figure 9 displays a comparison of reported irrigation use and simulated irrigation use based on POTYLDR irrigation scheduling. In order to simulate irrigation system

efficiency (generally considered to be 85%), a 15% irrigation loss (evaporation) was implemented, which in effect means that 15% more water is pumped to satisfy the determined irrigation demand and account for system losses. The simulated results closely reproduce the reported water use.
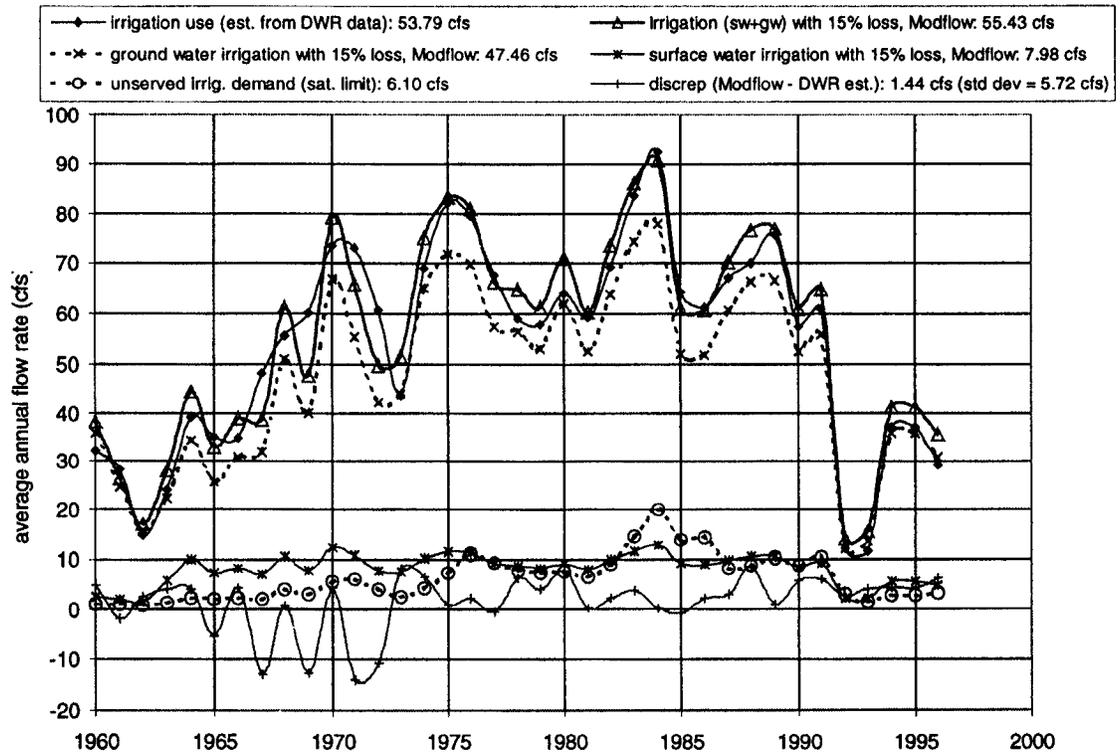


Figure 9. Comparison of reported and simulated irrigation use based on POTYLDR irrigation scheduling. Unsatisfied irrigation demand due to limited aquifer saturated thickness (less that 15 ft) is also shown

Figures 10 and 11 show annual and cumulative monthly comparisons of measured and simulated streamflows at the Albert gaging station, respectively; figures 12 and 13 show the same items but for the Nekoma gaging station. Overall the results are satisfactory with a mean absolute discrepancy (difference between simulated and observed monthly streamflows) of 1.5 cfs at the Nekoma station, and 7.1 cfs at the Albert gaging station. The overall statistics of streamflow comparisons since 1970 (when both

Albert and Nekoma gaging stations are operational) for the entire 1970-1996 period, and for both the calibration and verification periods are shown in Table 2.
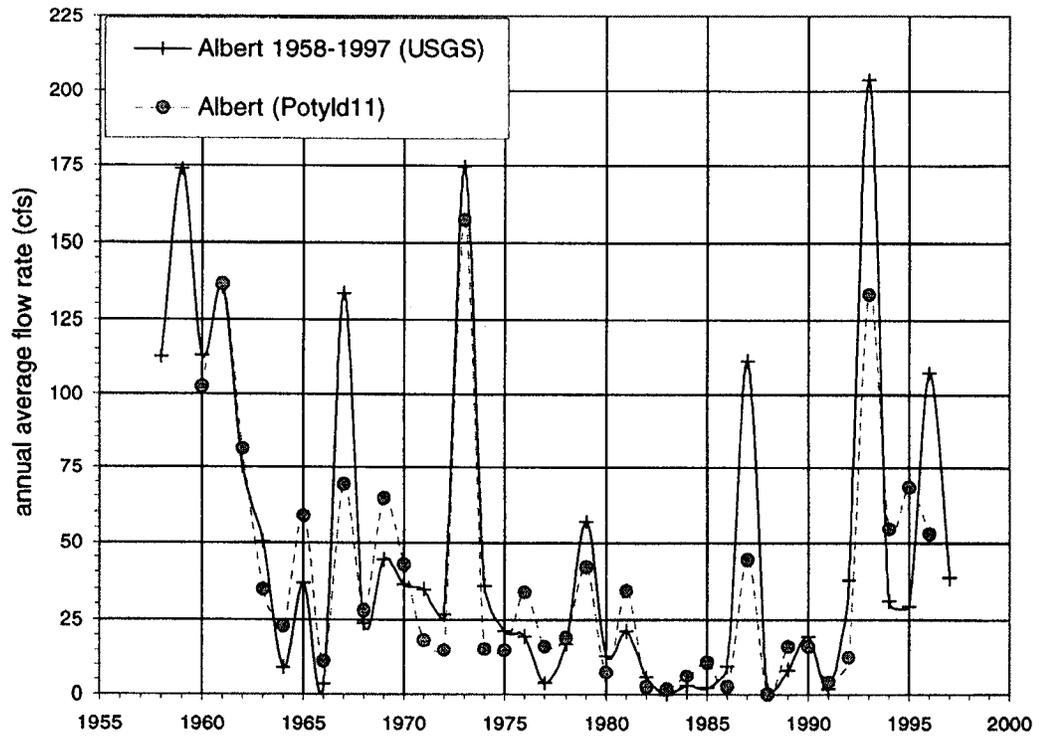


Figure 10. Comparison of annual measured and simulated Wet Walnut Creek streamflows at Albert gaging station
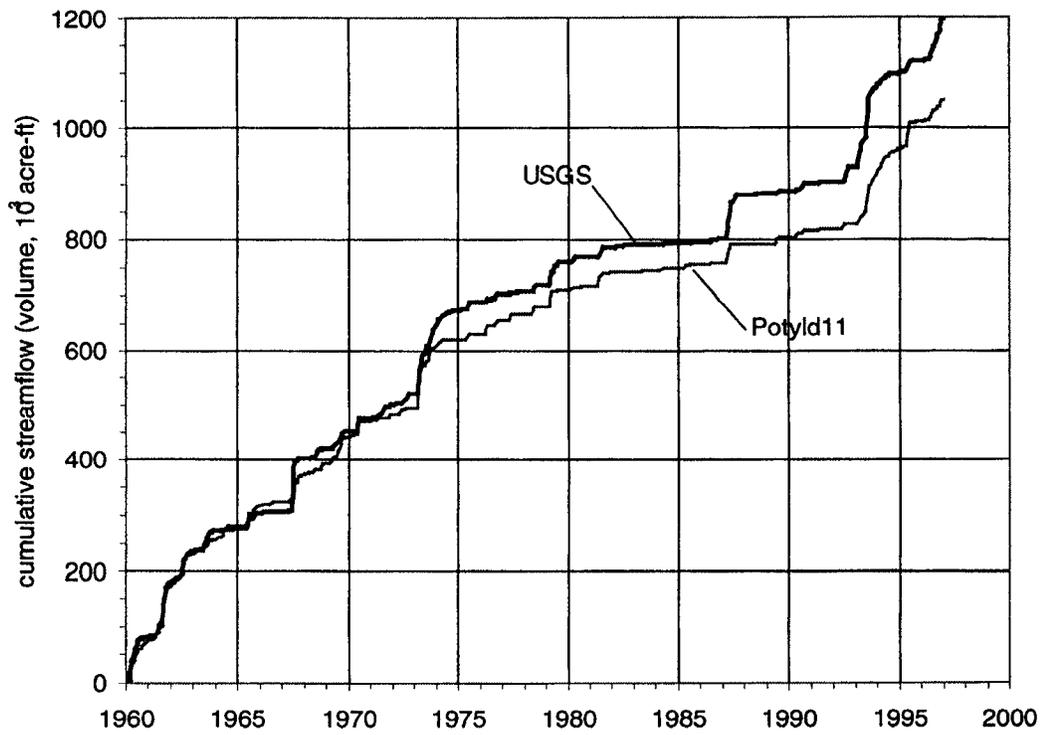
Figure 11. Comparison of cumulative measured and simulated Wet Walnut Creek
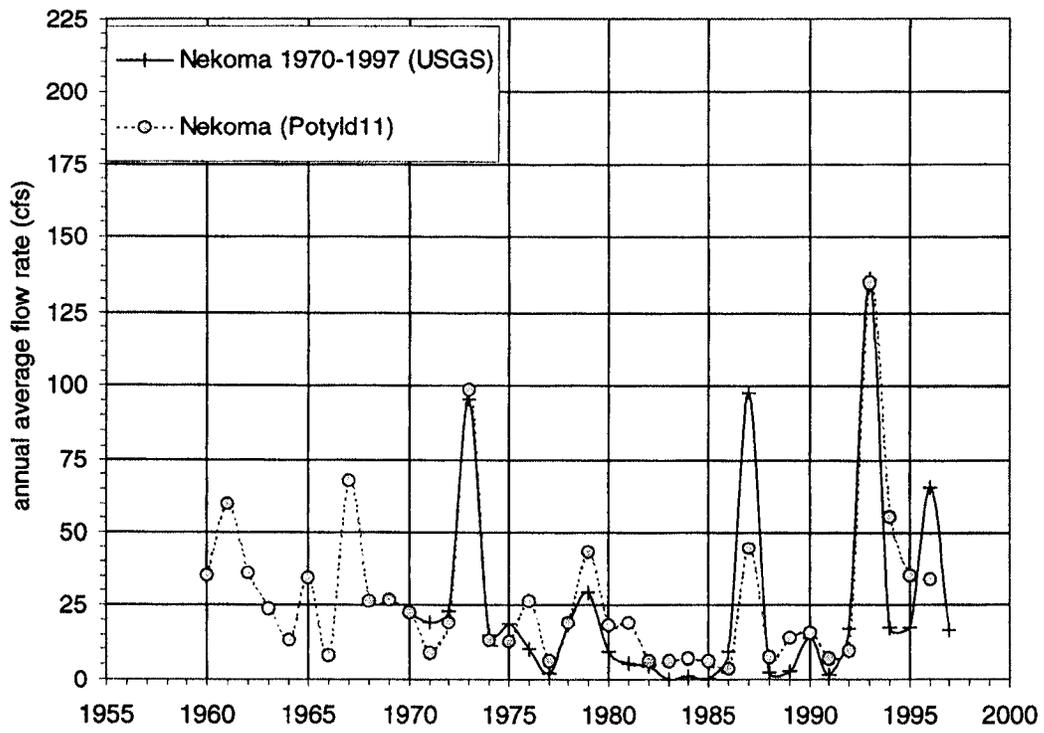streamflows at Albert gaging station

Figure 12. Comparison of annual measured and simulated Wet Walnut Creek
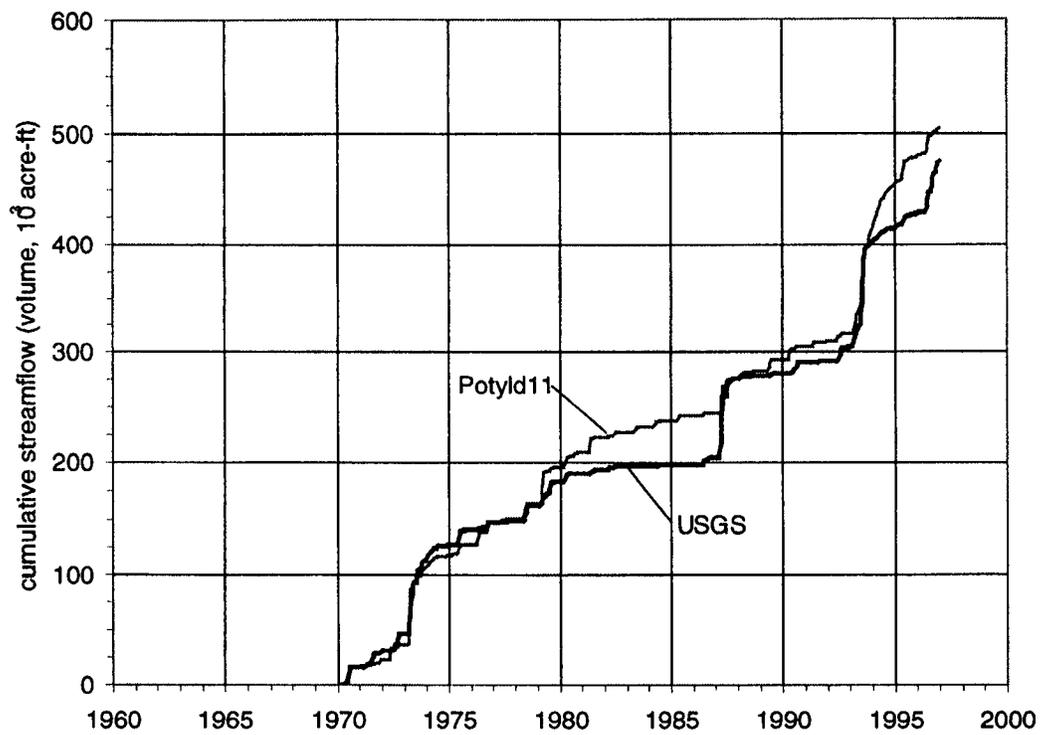streamflows at Nekoma gaging station

Figure 13. Comparison of cumulative measured and simulated Wet Walnut Creek
streamflows at Nekoma gaging station

Table 2. Statistics on comparison of simulated and observed streamflow
(All values in cubic feet per second)

| Period | Statistic (cfs) | USGS meas. Nekoma | Albert | Simulated (Potyld11) Nekoma | Albert | Discrep. (sim. - obs.) Nekoma | Albert |
|---|---|---|---|---|---|---|---|
| 1970-1996 | | | | | | | |
| | median | 1.65 | 1.57 | 1.49 | 0.08 | 0.00 | 0.00 |
| | mean | 24.22 | 38.09 | 25.70 | 31.01 | 1.48 | -7.08 |
| | std dev. | 76.88 | 101.58 | 73.95 | 100.55 | 58.30 | 79.81 |
| 1970-1990 | | | | | | | |
| | median | 0.45 | 0.86 | 0.93 | 0.00 | 0.00 | 0.00 |
| | mean | 19.07 | 29.54 | 19.95 | 24.45 | 0.89 | -5.09 |
| | std dev. | 59.18 | 84.59 | 69.09 | 91.56 | 56.82 | 75.27 |
| 1991-1996 | | | | | | | |
| | median | 11.93 | 15.41 | 14.88 | 9.70 | 0.85 | 0.00 |
| | mean | 42.26 | 68.00 | 45.81 | 53.98 | 3.56 | -14.03 |
| | std dev. | 118.66 | 143.08 | 86.44 | 125.17 | 63.57 | 94.26 |

## VIII. 1960-1996 CUMULATIVE WATER BUDGET FOR THE WET WALNUT VALLEY

The stream-aquifer system budget is shown in fig. 14 on a cumulative basis since 1960. The significant recharge impact of the major floods of 1973, 1987, and especially 1993 is clearly visible. The figure shows that Wet Walnut Creek was a net gaining stream from the beginning of the simulation period (1960) up to the mid to late 1960's, but since the late 1960's it became a net losing stream to the alluvial aquifer. By the early to mid-1980's, the stream network system became the major source of recharge to the aquifer, exceeding precipitation- and pond-seepage-based recharge. The model simulation shows that the 1993 flood restored aquifer storage back to the early-1960's aquifer-storage levels.

The average 1960-1996 recharge to the aquifer (which also includes pond seepage from the watershed structures and irrigation return flow, in addition to precipitation percolation) was estimated at 1.9 inches/year; however, it ranged widely from less than 0.05 in/yr to more than 16 in/yr during the 1993 flood year (which represents the

maximum simulated recharge over the 1960-1996 period). In comparison, the average

pumpage from the aquifer over the same period was 4.0 in/yr. The average net stream

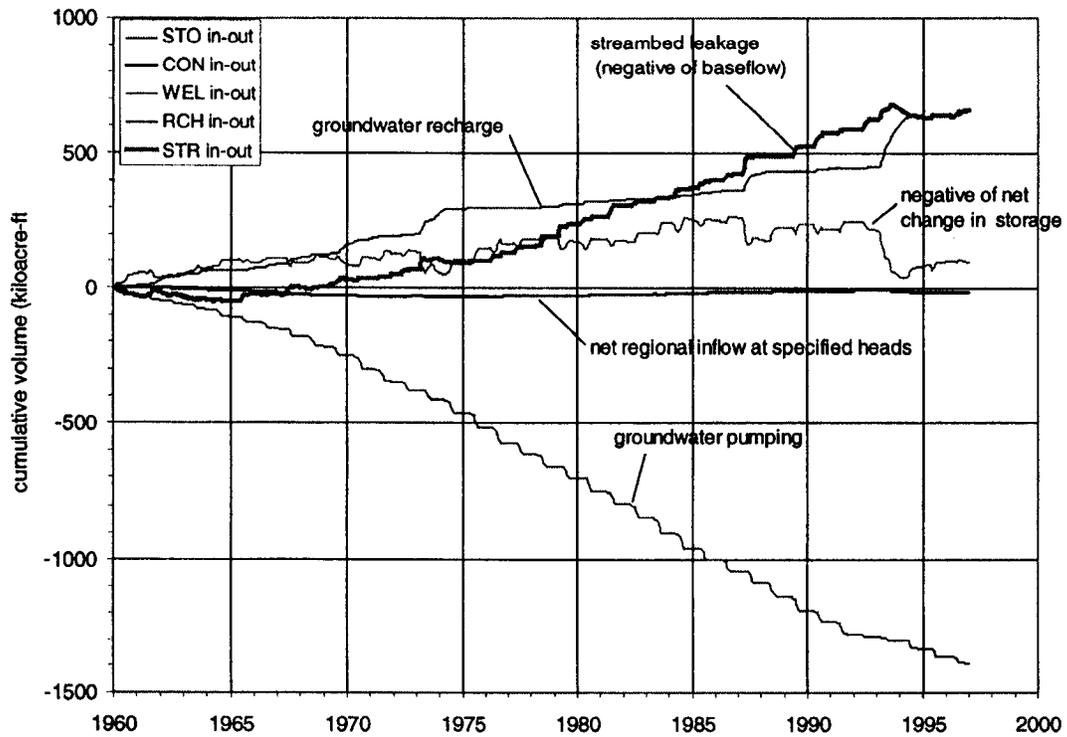seepage to the aquifer (i.e. stream seepage minus baseflow) was estimated at 1.9 in/yr.



Figure 14. 1960-1996 simulated cumulative water budget components for the Wet
Walnut Creek aquifer

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