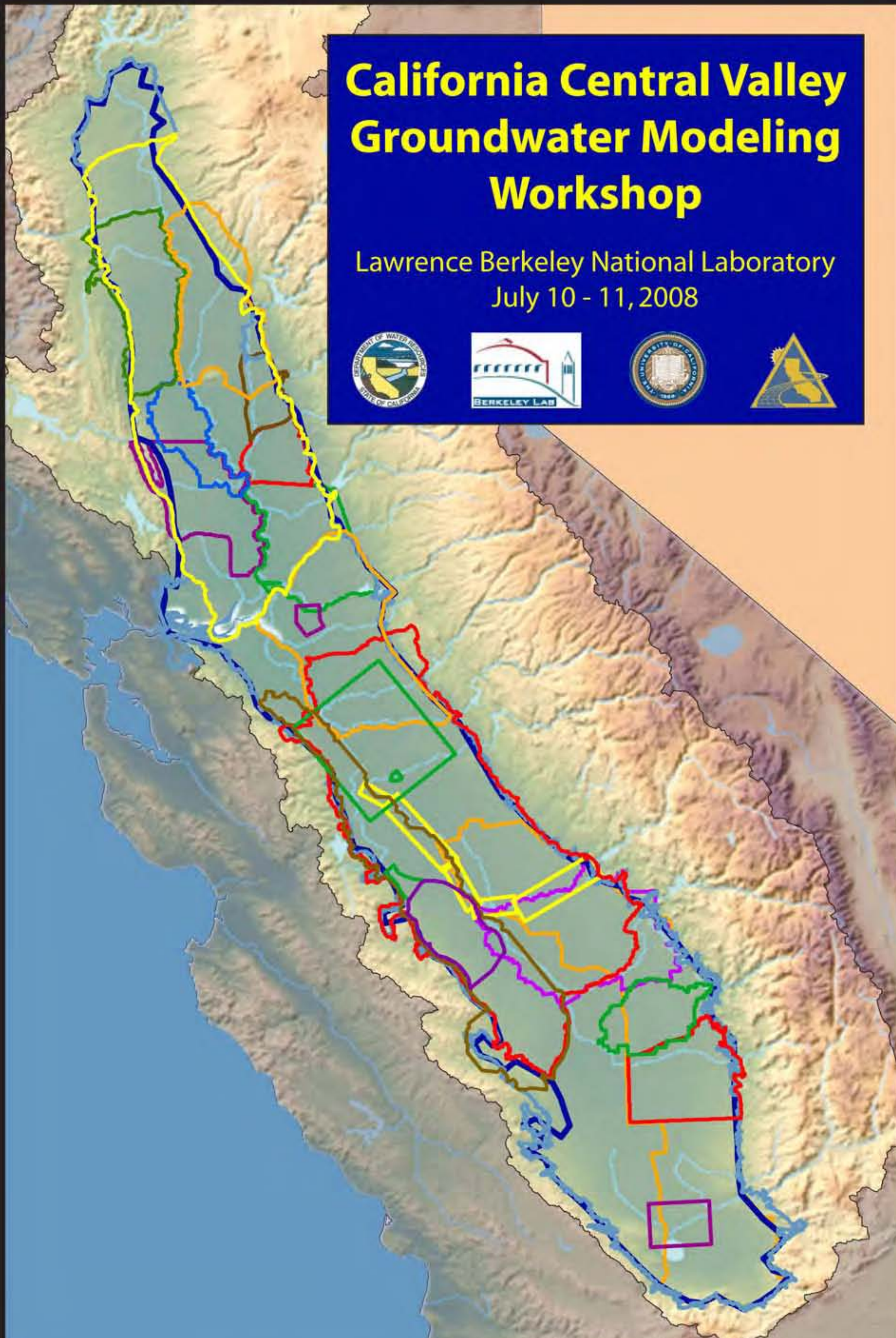
California Central Valley Groundwater Modeling Workshop

Lawrence Berkeley National Laboratory

July 10 - 11, 2008



Proceedings of the California Central Valley Groundwater Modeling Workshop

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Lawrence Berkeley National Laboratory, Berkeley, CA

Sponsors

California Department of Water Resources

U.C. Berkeley Water Center

California Water and Environment Modeling Forum

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Organizers: Charlie Brush, Norm Miller, and Rich Satkowski

California's Central Valley is currently home to over 6 million people, and generates over $20 billion in agricultural crops each year. An intricate surface water distribution system routes water from surrounding watersheds to the Central Valley, the Central Coast and Southern California. The Central Valley's aquifers have historically provided water for agricultural and urban use, and are increasingly being used as a buffer for fluctuations in surface water supplies. Current scientific and management challenges include understanding the aquifer's response to drought and climate change, protecting the quality of groundwater, limiting subsidence caused by groundwater pumping, and implementing aquifer storage and recovery programs.

This workshop will be a gathering of researchers, consultants, administrators and others interested in learning about how groundwater models have been applied to address scientific and resource-management questions in the Central Valley. The workshop follows the Computational Methods in Water Resources XVI International Conference, being held in San Francisco July 6-10. Workshop presentations will increase our understanding of the groundwater flow system at both the local and regional scales.

The workshop will begin with a dinner gathering July 10th at Looney's Barbeque in Berkeley. Members of the original USGS Central Valley Regional Aquifer System Analysis team will give a presentation on the history of groundwater modeling in the Central Valley. The meaning of the term 'groundwater model' has changed over the years, from a set of painted wooden dowels representing well logs, to analog models created with resistors and capacitors, to the current digital computer models.

On Friday, we will meet at Lawrence Berkeley Laboratory to see twenty presentations on groundwater models developed for the Central Valley. The morning session will include four groundwater flow models in the Tulare Basin and five in the San Joaquin River Basin. The afternoon session will include four more models in the San Joaquin River Basin, three in the Sacramento River Basin, and will close with four presentations on Valley-wide modeling efforts.

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California Water and Environment Modeling Forum

Schedule

Looney's Barbeque, 2190 Bancroft Avenue, Berkeley, July 10, 2008

7:00 PM	**HISTORY OF GROUNDWATER MODELING IN THE CENTRAL VALLEY** **Dave Prudic**

Toll Room, Alumni House, University of California, Berkeley, July 11, 2008

7:30 AM REGISTRATION

8:00 AM	**OPENING**
8:00 AM	Opening remarks - Norm Miller and Charlie Brush
8:10 AM	Welcome - James Hunt and Susan Hubbard
8:20 AM	Introduction - Francis Chung

8:30 AM	**TULARE BASIN**
8:30 AM	Ground water dating and flow-model calibration in the Kern Water Bank, California **Laurent Meillier**, Hugo A. Loaiciga and Jordan F. Clark
8:50 AM	Water management and estimation of groundwater pumping as closure to the water balance of a semi-irrigated agricultural basin: Tule River Basin (southern Tulare County) **Thomas Harter,** Nels Ruud, Jay Lund, Guilherme Marques and Marion Jenkins
9:10 AM	Numerical groundwater flow model for the Kaweah Delta Water Conservation District, southern San Joaquin Valley, California **Nels Ruud**, Peter Leffler, and Larry Dotsun
9:30 AM	Integrated Modeling: An Analytical Tool for Integrated Regional Water Management Plan Development – Application to Kings Basin **Reza Namvar**, Elias Tijerina, and Ali Taghavi

9:50 AM 20-minute break

10:10 AM	**SAN JOAQUIN RIVER BASIN – 1**
10:10 AM	High resolution groundwater models of the San Joaquin River riparian zone for evaluation of surface water/groundwater interactions under alternate river flow regimes **Deborah L. Hathaway**, Gilbert Barth, and Karen MacClune
10:30 AM	Development of regional and nested local-scale ground-water models for study of the fate of agricultural nitrogen, Merced County, California **Steven P. Phillips**, Christopher T. Green, Karen R. Burow, Jennifer L. Shelton, and Diane L. Rewis
10:50 AM	Comparison of simulated travel time distributions and age tracer concentrations in samples from an alluvial fan aquifer, San Joaquin Valley, California **Christopher Green** and Barbara Bekins
11:10 AM	WESTSIM: Integrated groundwater/surface water, conjunctive use, agricultural drainages, and wetland return flow simulation on the west-side of the San Joaquin Valley Nigel W. T. Quinn and **Jafar A. Faghih**
11:30 AM	Hydrogeosphere application in multi-scale hydrological/ecological processes in San Joaquin River Basin, and HGS-CalSim: A tool to conjunctively and dynamically simulate hydraulic processes and multi-reservoir systems for evaluation of climate change impacts **George Matanga**, Mary Kang, Jeff Randall, Don DeMarco / **Mary Kang**, Varut Guvanasen and Kirk Nelson

NOON	**LUNCH**

Schedule – continued

Toll Room, Alumni House, University of California, Berkeley, July 11, 2008

1:00 PM	**SAN JOAQUIN RIVER BASIN – 2**
1:00 PM	San Joaquin County DYNFLOW model **Brian J. Heywood** and Brandon Nakagawa
1:20 PM	City Wide Groundwater Modeling for Remediation and Management – City of Lodi **Varinder S. Oberoi**, Michael Chendorain, Patrick B. Hubbard, Richard Prima, Wally Sandelin, and Charles Swimley
1:40 PM	Impact of climate change on crop water requirements, groundwater and soil salinity in the San Joaquin Valley, California Gerrit Schoups, **Jan W. Hopmans**, and Edwin P. Maurer
2:00 PM	Sustainable root zone salinity in the context of shallow perched water table, and attenuation: Land retirement demonstration project in the west San Joaquin Valley **Purnendu Singh** and Wes Wallender

2:20 PM	**SACRAMENTO RIVER BASIN**
2:20 PM	Applications of the Sacramento County Integrated Groundwater and Surface Water Model **Jim Blanke**, Jon Traum, and Ali Taghavi
2:40 PM	Butte Basin IWFM model **Brian J. Heywood**, Karilyn J. Heisen , and Kristen H. McKillop
3:00 PM	SACFEM: A Land Use Based Transient Finite-element Groundwater Flow Model of the Sacramento Valley **Peter Lawson**, Heather Perry, Lee Bergfeld and Walter Bourez

3:20 PM 20-minute break

3:40 PM	**CENTRAL VALLEY**
3:40 PM	Integrated Hydrologic Models in the Central Valley, California **Ali Taghavi**
4:00 PM	Application of MODFLOW's Farm Process to California's Central Valley **Claudia C. Faunt**, Randall T. Hanson, Wolfgang Schmid, and Kenneth Belitz
4:20 PM	Simulating the historical evolution of the Central Valley hydrologic flow system with the California Central Valley Groundwater-Surface Water Model **Charles Brush**, Emin C. Dogrul, Michael Moncrief , Jeff Galef, Steven Shultz, Matt Tonkin, Dan Wendell, Tariq Kadir, and Francis Chung
4:40 PM	California Central Valley Drought Scenario Sensitivity Analysis Using C2VSIM **Norm Miller**, Charles Brush, Larry Dale, Sebastian Vicuna, Tariq Kadir, Emin C. Dogrul, and Francis Chung

5:00 PM	**CLOSING**
5:00 PM	Closing remarks – Charlie Brush and Norm Miller
5:10 PM	**ADJOURN**

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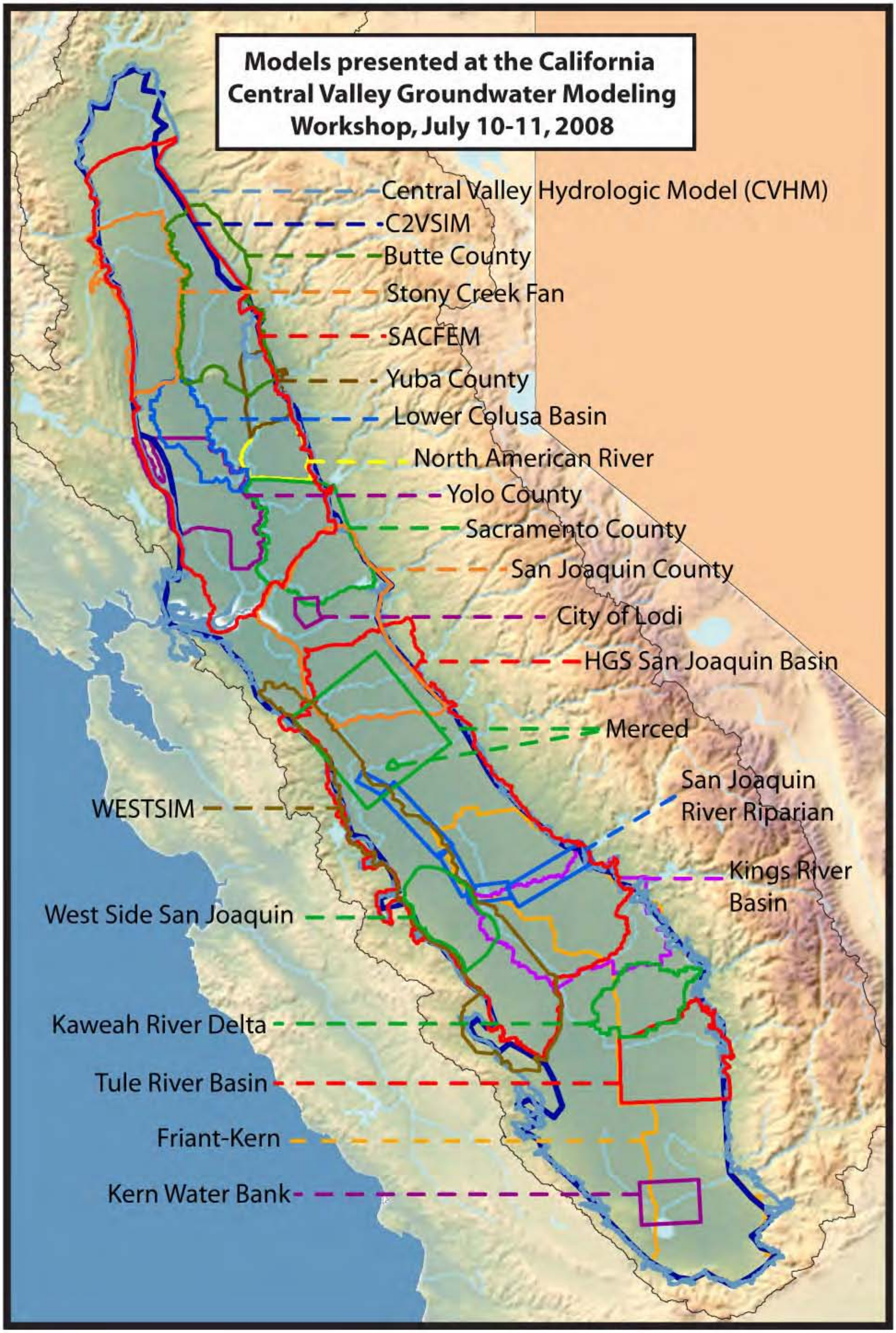
Models presented at the California Central Valley Groundwater Modeling Workshop, July 10-11, 2008
Central Valley Hydrologic Model (CVHM)
C2VSIM
Butte County
Stony Creek Fan
SACFEM
Yuba County
Lower Colusa Basin
North American River
Yolo County
Sacramento County
San Joaquin County
City of Lodi
HGS San Joaquin Basin
Merced
San Joaquin River Riparian
WESTSIM
Kings River Basin
West Side San Joaquin
Kaweah River Delta
Tule River Basin
Friant-Kern
Kern Water Bank

Ground water dating and flow-model calibration in the Kern Water Bank, California

Laurent Meillier, Hugo A. Loáiciga and Jordan F. Clark

This research summarizes ground water chemistry characteristics and dating in the Kern Water Bank (Figure 1), California. The scientific information memorialized in this thesis written toward the Master of Science in Geology was partly collected in January and August 2000. This work describes the development of a calibrated ground water numerical model (Figure 2) for the Kern Water Bank's (KWB) aquifer. The integrated study also produced a calibrated flow model that can be used in predicting the effects of future recharge and ground water-extraction operations in an important recharge and recovery operation.

The KWB is a 78 km2 artificial storage recovery operation located in the Kern River alluvial fan. Groundwater samples were collected at 10 and 13 locations from a shallow and deep monitoring well. The CFC-based method for dating ground water applied in this work assumes that percolating water recharging an aquifer is in equilibrium with tropospheric air at the time of recharge. The CFC data indicate that the relatively young groundwater (<15 yr) is found in the northern and central regions of the KWB at shallow depths. An intermediate aged (15 to 40 yr) groundwater component is encountered in the deeper wells of the northern and central regions. The oldest water (> 50 yr) is found in the southern and western areas.

A hydrogeologic model was developed using the Visual Modflow™ Software. The model is composed of three layers (total thickness 226 m), representing the aquifer structure and permeability. Each layer is built on a 58 columns, 39 rows grid consisting of 1935 active cells ranging in size from 0.16- 0.65 km2 and 327 inactive cells located in southwestern corner of the grid. The California Department of Water Resources hydrogeologic data sets were transferred into the model. Field data entered into the model for simulation included: (i) the initial groundwater surface in spring 1994, (ii) the 1994 – 2000 artificial recharge rates at the KWB, (iii) 1994 – 2000 hydraulic heads records at 26 monitoring wells and (iv) 1994 – 2000 pumping rates at productions wells. The calibrated model was run over a 7-year simulation period (1994 - 2000) in a transient mode, with twelve time steps for each stress period. Calibration carried out with the PEST optimization module. The most noticeable improvements observed were in the values of Kx and Ky. The average mean absolute error over the twenty six wells modeled and the seven years modeling period equaled 4.48 m. The root mean squared (RMS) error average over the KWB equaled 8 m and ranged between 3.00 and 21.66 m. The largest RMS error was detected in the northern areas where post-1990 artificial recharge has been most active.

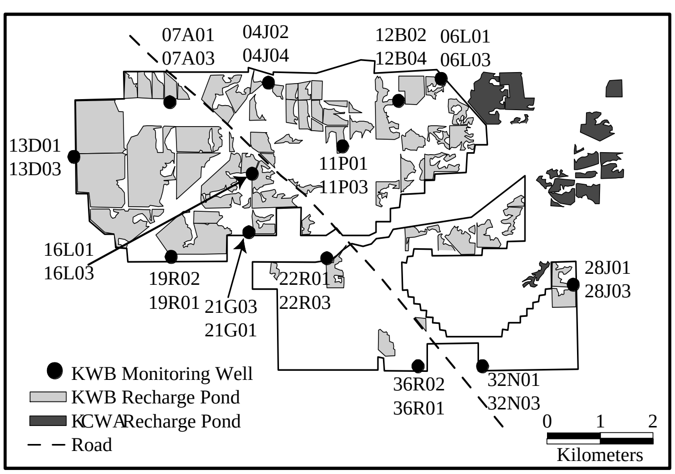

Figure 1. Map of the Kern Water Bank.

From a groundwater model standpoint, this study determined that an optimal set of hydrogeologic parameters was identified, which, in conjunction with recharge data, boundary- and initial-condition data, and a hydrogeologically-based finite difference grid, were integrated into a calibrated ground water flow model useful for predicting recharge and stress impacts in the Kern Water Bank. However, the identification of CFC sources and concentrations in the Kern Water Bank would allow a more accurate calculation of ground water age within its aquifer. Once these sources are identified, the calibration of the numerical ground water model could be built based on observed hydraulic heads and on CFC data. The study identified the need for more accurate record keeping of the location, amount, and timing of artificial recharge in the Kern Water Bank. This is desirable for the management and accounting of its ground water and to for continued improvements in ground water model calibration.

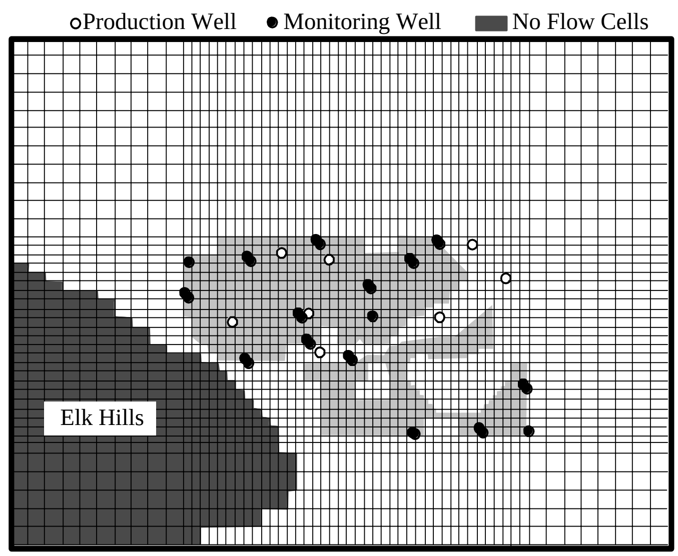

Figure 2. Numerical grid used in the Kern Water Bank ground water-flow model.

You may find additional information on this work at the following bibliographic references:

Paper to be published in 2009 as Meillier, L, Loaiciga, H.A., Clark, J.F at the Journal of Hydrologic Engineering (in press).

Electronic file of the thesis memorializing this work may be available upon request from Laurent Meillier.

Water Management and Estimation of Groundwater Pumping as Closure to the Water Balance of a Semi-Arid, Irrigated Agricultural Basin: Tule River Basin (Southern Tulare County)

Thomas Harter, Nels C. Ruud, Jay F. Lund, Guilherme R. Marques, Marion Jenkins

Groundwater pumping is frequently the least measured water balance component in semi-arid basins with significant agricultural production. We present a GIS-based water balance model for estimating basin-scale monthly and annual groundwater pumping and apply it to a 2,300 km^2 semi-arid, irrigated agricultural area in the southern San Joaquin Valley, California (Tule River basin). Both annual groundwater storage changes and pumping are estimated as closure terms. The local hydrology is dominated by distributed surface water supplies, limited precipitation, and large crop water uses; whereas basin-scale runoff generation and groundwater-to-surface water discharges are negligible. Groundwater represents a terminal long-term storage reservoir with distributed inputs and outputs. To capture the spatio-temporal variability in water management and water use, the study area is delineated into 26 water service areas and 9611 individual fields or land units. The model computes conveyance seepage losses external to districts; seepage losses within districts; and net applied surface water of each district. For each land unit, the model calculates the applied water demand; its allotment of delivered surface water; the groundwater pumping required to meet the balance of its applied water demand; and aquifer recharge resulting from deep percolation of applied water and precipitation. These spatially distributed components are aggregated to the basin scale. Estimated annual groundwater storage changes compared well to those computed by the water-table fluctuation method over the 30-year study period, providing an independent verification of the consumptive use estimation. Pumping accounted for as much as 80% of the total applied water in 'Critical' water years and as little as 30% in 'Wet' years. Pumping estimates are most sensitive to estimation uncertainty of soil available water. They show little sensitivity to estimation errors in effective root depth, irrigation efficiencies, and intra-district seepage losses, although the cumulative sensitivity is significant. Model results also illustrate monthly field-by-field pumping and recharge rates and seasonal recharge and pumping patterns within and between irrigation and water districts.

Introduction

The Friant Division is a dynamic, highly developed system. Intense agricultural development has relied in the use of both surface and groundwater supplies, which are commonly stored, sold, and transferred among users for mutual benefit and profit. The often uncoordinated use of groundwater and surface water supplies has led to aquifer overdraft and related problems in most of the region. This project develops simulation tools to aid in examining water issues within the Tulare Basin and Friant Division and in examining the effects of external water management issues on Tulare Basin activities. The project combines detailed groundwater simulation with economically-driven simulation techniques to provide an integrated modeling approach able to represent the dynamics behind users' decisions and their impact in the system.

The model development includes two major reports. Report 1 – "A Conjunctive Use Model for the Tule Groundwater Sub-Basin Area in the Southern-Eastern San Joaquin Valley, California" describes the conceptual basis and development of a hydrology model applicable for the hydrologic conditions in the Friant Division of the Tulare Basin. It includes a surface-water supply model, an unsaturated zone water budget model and a groundwater model. The report also describes the implementation of this hydrology model for the Tule River sub-basin including computation of spatio-temporally distributed groundwater pumping and groundwater recharge; groundwater model development, model calibration and validation; and provides all relevant data. An extension of the hydrology model to the Kaweah Basin just north of the Tule Basin has been completed by the Kaweah Delta Water Conservation District (see Ruud et al., this conference proceedings). The second report – "Modeling of Friant Water Management and Groundwater" includes the description of improvements on a water management model and links the water management model with the hydrology model.

Approach

A two-pronged approach was used:

1. Hydrologic modeling provided the basis for the development of a regionally calibrated physical groundwater - surface water model for the Tule-Kaweah basin, which includes almost two dozen Friant Kern contractors.
2. A water management and economic model for the Friant-Kern Unit allowed for a quantitative assessment of changes in deliveries and system reliabilities in response to changes in water operations, environmental restrictions, water prices, and other regulations.

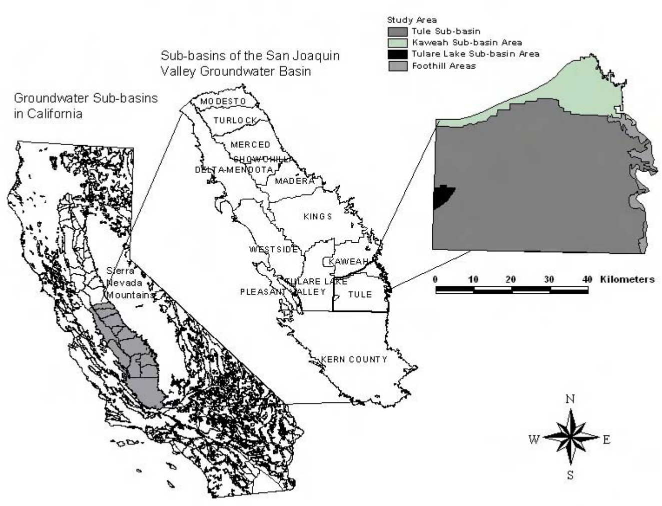

Figure 1. Location of the project and modeling area.

Hydrology Model

We developed a GIS-based sub-basin scale conjunctive use model for a semi-arid agricultural area in the eastern part of the southern San Joaquin Valley, California. The base period are the fiscal water years of 1970-99. The study area is 541,580 acres in size, and consists of 9,114 land units and 26 water service districts. The conjunctive use model consists of three sub-models: 1) a surface water supply (SWS) model, 2) an unsaturated zone water budget (UZWB) model, and 3) a groundwater flow model.

The SWS model calculates the surface water balance for the source and diversion channels in the conveyance network supplying surface water to individual districts. Its primary outputs are monthly surface water deliveries to each district and the monthly seepage andand evaporative losses from the modeled channels. The surface water deliveries become input for the UZWB model and the channel seepage are input into the groundwater flow model as a localized source of aquifer recharge.

The subsurface of each land unit is conceptualized as consisting of a soil root zone and a deep vadose zone overlying the aquifer system. For each land unit, the UZWB model calculates the monthly applied water demand; its allotment of delivered surface water; the groundwater pumping required to meet the balance of its applied water demand; and any aquifer recharge resulting from deep percolation of surface applied water and precipitation. Its primary outputs are the diffuse recharge to the aquifer system from surface applied water and precipitation, and the groundwater pumping demand from the aquifer system.

The diffuse aquifer recharge and groundwater pumping become input into the groundwater flow model. Its purpose is to calculate the hydraulic head and groundwater storage changes in the aquifer system subject to transient groundwater recharge and pumping stresses. The main model output is the simulated hydraulic head distribution in the modeled area for each stress period. A post-processing routine calculates the cumulative annual groundwater storage changes over each district and the entire study area. An automated calibration of the transient groundwater flow model was performed from 1970-85. The model was then validated from 1986-99. Using the calibrated model, we computed the annual inter-district groundwater fluxes between adjacent districts.

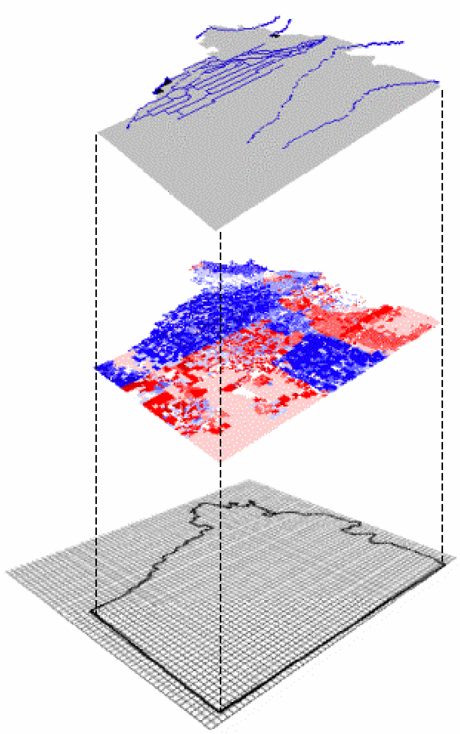

Figure 2. Overlay of channel seepage and land unit recharge and pumping GIS coverages onto MODFLOW finite-difference grid via Argus ONE™.

Water Management Model

The water management model – FREDSIM – simulates water operations in the Friant Division as a system driven by economicperformance at the irrigation district level. The model uses a computer based decision support system based on a capacitated network flow approach for simulation and optimization of water resources systems (MODSIM).

Land use and water demand data provided by the hydrology model is used to develop water penalty functions at the irrigation district level with the SWAP (Statewide Agricultural Production) model. Penalty functions are integrated into the water management model to represent economic decisions on water use by irrigation districts.

Groundwater data from the hydrology model is used to delineate groundwater reservoirs and identify their connection with the irrigation districts that pump groundwater. The groundwater model is used to develop response parameters (hydraulic conductance) so that groundwater flows can be calculated and groundwater reservoirs head tracked based on storage variation. Groundwater pumping costs are updated every time step based on head changes.

Results

Hydrology Model

The Tule Sub-basin study area is 541,580 acres in size and contains the entire Tule groundwater sub-basin and parts of the Kaweah and Tulare Lake groundwater sub-basins. The incorporated land in the study area is divided into 26 water service districts: 21 irrigation, water, or public utility districts; 2 major cities; 2 private contractors; and 1 water company. These districts are either completely or partially located within the study area. The study area is further delineated into 9,114 individual land units from a 1985 land use survey of Tulare County. Agriculture is the largest land use, comprising 72% of the study area. Native and urban land use comprise 22% and 4% of the study area, respectively. Semi-agricultural and special conditions (i.e. fallow) land use each comprise 1%. Twelve crops account for 95% of the area under agricultural production. Cotton, grain & grass hay, citrus, vineyards, and alfalfa individually represent 20.3, 18.6, 13.6, 13, and 10.3% of the total productive acreage, respectively.

The total imported surface water for 1970-99 from the CVP and the Success Reservoir are 13,329,262 and 4,653,501 acre-feet (af), respectively. The SWP and the Kings River imported the lesser amounts of 88,625 and 7,332 af, respectively. Annual CVP diversions varied from 125,970 af in 1977 to 679,298 af in 1993 with a 30-year annual average of 444,309 af. The Tule River and Pioneer Ditch both receive regulated releases from Success Reservoir. Tule River annual imports varied from 11,034 af in 1977 to 607,154 af in 1983 while the Pioneer Ditch varied from 3,445 af in 1973 to 5,874 af in 1990. The total natural runoff from the Deer Creek and White River from 1970-99 were 703,444 and 219,098 af, respectively. Deer Creek runoff varied from4,082 af in 1992 to 103,716 af in 1983 while the White River runoff varied from 422 af in 1977 to 37,985 af in 1998.

From 1970-99, a total of 15 million af of surface water was applied by the service districts in the study area. The applied surface water varied from a low of 135,482 af in 1977 to a high of 708,293 af in 1996. The Lower Tule River Irrigation District and the Delano-Earlimart Irrigation District together account for 59% of the total applied surface water while occupying approximately 40% of the incorporated area in the study area. Over the 30-year base period, an estimated total of 3.5 million af of seepage conveyance loss occurred in all surface water channels. Seepage in the Tule River, Deer Creek, and White River accounted for 85% of the total seepage. Total annual seepage varied from a low of 8,128 af in 1977 to 467,084 af in 1983.

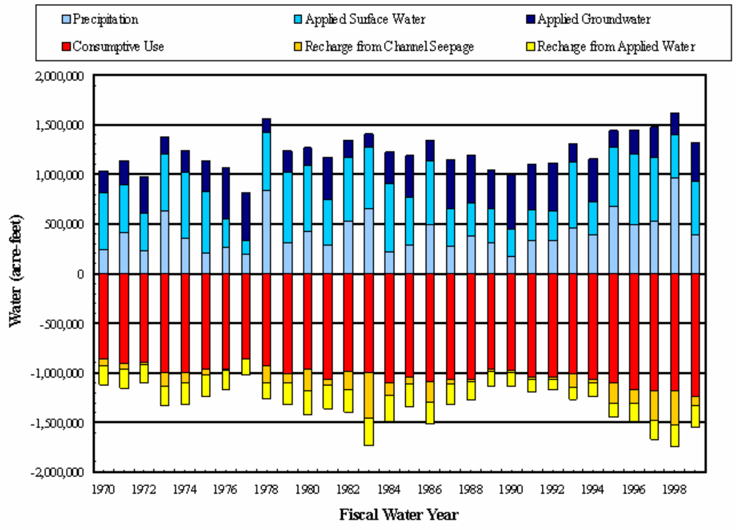

Figure 3. Annual water balance components (acre-feet) for the fiscal water years of 1970-99: precipitation, applied surface water, applied groundwater, consumptive use, diffuse recharge from applied water, and localized recharge from channel seepage.

The total annual agricultural and urban consumptive use ranged from 872,100 af in 1970 to 1,250,700 af in 1999. The estimated total pumping ranged from 143,100 af in 1978 to 560,600 af in 1990. As expected, pumping was heaviest during the droughts of 1975-77 and 1987-92, and lightest during the wet years of 1973, 1978, 1982-83, 1995, and 1998. Precipitation totals varied from 176,500 af in 1990 to 967,400 af in 1998. Diffuse recharge from surface applied water ranged from 110,000 af in 1992 to 270,100 af in 1983.

The trends in cumulative annual groundwater storage changes computed from the water balance and the water table fluctuation (WTF) method from 1970-99 were quite similar. The minimum and maximum differences between them were 28,479 af (1996) and 1,027,693 af (1991), respectively. From 1970, the maximum amount of groundwater accumulation occurred in the spring of 1987 with the WTF method and the water balance estimating positive storage changes of 1,146,286 and 907,155 af, respectively. The maximum groundwater overdraft occurred in 1993 with the WTF method estimating a negative storage change of 1,610,210 af while the water balance method maximum overdraft was 992,906 af in 1995. The 1987 and 1993 fiscal water years marked the beginning and ending of a major 6-year drought in California, respectively. Details of the seasonal, field-by-field pumping and recharge computations can be found in Ruud et al, 2004.

Three different conceptual models of the aquifer system horizontal hydraulic conductivity, Kh, structure were evaluated in the calibration process: 1) Kh as an exponential function of the specific yield, Sy, distribution, 2) Kh as a linear function of the saturated hydraulic conductivity of the soil survey mapping units, and 3) division of the model domain into square zones of uniform size. The models were calibrated against both spatially distributed hydraulic head targets and cumulative groundwater storage change targets for seven of the largest districts. The discretization of the model domain into uniform square zones provided the most robust Kh structure and produced the most reasonable estimates of hydraulic head and district groundwater storage changes from the three conceptual models over the 1971-85 calibration period. The calibrated model was then used to compute the annual net inter-district groundwater fluxes between adjacent districts. In general, groundwater flux directions were consistent with the large-scale hydraulic gradients. Annual inter-district net fluxes between adjacent districts ranged from negligibly small (< 100 af) to as much as 50,000 af (e.g. net flux from Lower Tule River ID to Pixley ID). Net interdistrict fluxes were generally a function of the local transmissivity,

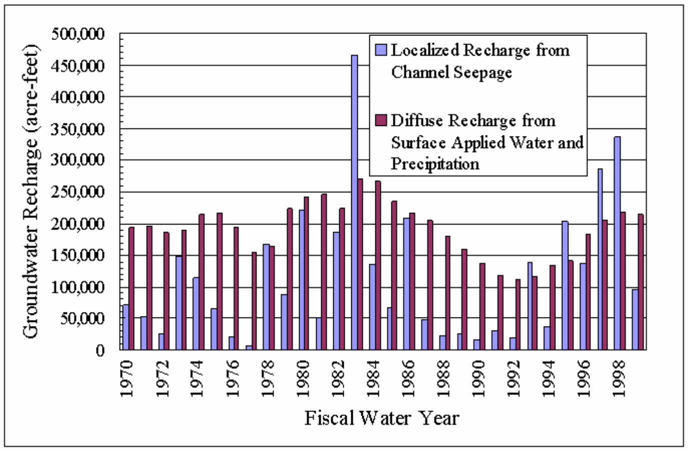

Figure 4. Annual localized recharge from channel seepage and diffuse recharge from surface applied water and precipitation (acre-feet) from 1970-99.

the length of the shared border between adjacent districts, and the differences in their surface water supplies.

Water Management Model

The water management model was run for three initial alternatives. A FPlow run (original groundwater pumping costs), a FPhigh run (updated groundwater pumping costs based on new head data, and a VP run (variable groundwater pumping cost). Multiple runs were made under the VP alternative with varying surface water and energy prices. The higher groundwater pumping costs on runs FPhigh and VP resulted in reduction in groundwater pumping, reduction in overdraft and increase in scarcity and scarcity costs (Table ES-1). The lower groundwater pumping cost run (FPlow) results in 21 maf of total overdraft over 73 years and a $19 million/yr average penalty in scarcity costs. Avoiding this overdraft would require reducing groundwater pumping by either cutting back in production or acquiring supplemental non-local surface supplies averaging 288 kaf/yr. The groundwater pumping curtailment seen in VP run could reduce the overdraft to 9.2 maf at a cost of $24 million/yr in scarcity costs, if no supplemental surface supply is available. To eliminate the 9.2 maf overdraft 126 kaf/yr average of supplemental surface supplies would be needed.

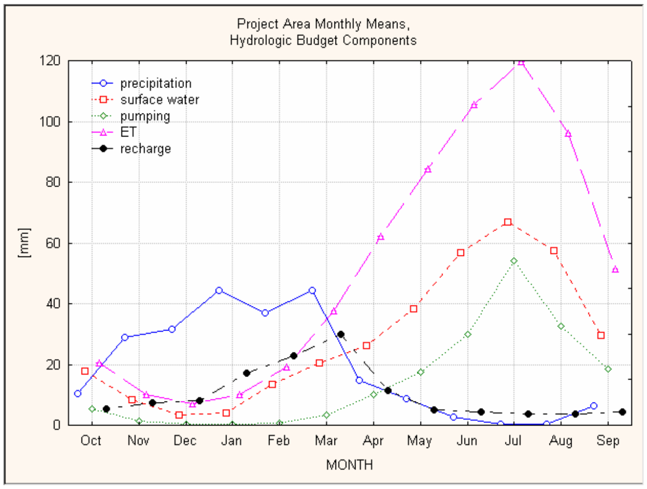

Figure 5. Average monthly water balance components for the fiscal water years of 1970-99: precipitation, applied surface water, applied groundwater, evapotranspiration, and diffuse recharge from applied water and precipitation.

Reduction of this overdraft requires reduction of groundwater pumping. In terms of surface water this is equivalent to 33% of contract surface supplies that would be required as non-local transfers. Without additional surface supplies, a 49% reduction in overdraft (9.8 maf) would cost an additional $5 million/yr average in scarcity costs, a 26% increase.

Uses

Results from the models developed provide better understanding of the groundwater system under Friant Division, particularly the important role of irrigation and pumping in driving the dynamics of the groundwater system. The model points towards significant groundwater exchanges among districts. The non-uniqueness of the groundwater model calibration provides the basis for defining future data needs. The integration of this information into the management model enables it tosimulate operational changes consequence of management policies modifying surface water and energy prices.

Conclusions

Users change supply sources and quantities, and transfer water reacting to variations in water and energy price, economic value and water availability. Groundwater is a critical component of the system and the differences in the approaches used to model it demonstrate that efforts dedicated to evaluate it accurately are important in modeling the Friant system.

Significant increases in surface water prices are seen to compromise current conjunctive use operations. The historical overdraft pattern is still occurring despite the increase in groundwater prices and it is a consequence of the irrigation districts economic decisions. Reduction of this overdraft requires reduction of groundwater pumping. In terms of surface water this is equivalent to 33% of contract surface supplies that would be required as non-local transfers. Without additional surface supplies, a 49% reduction in overdraft (9.8 maf) would cost an additional $5 million/yr average in scarcity costs, a 26% increase

High spatial and temporal variability in groundwater pumping was found by processing data from the groundwater model for use in FREDSIM. This variability is included as a constraint in the simulation model to enable a better characterization of present conditions when the model optimizes the water allocation for a given time step.

Recommendations

Recommendations to address some of the model limitations include:

3. Combine the Lower Tule River groundwater model with the Kaweah Basin model and complete database for unmodelled areas between and around these modeling basins

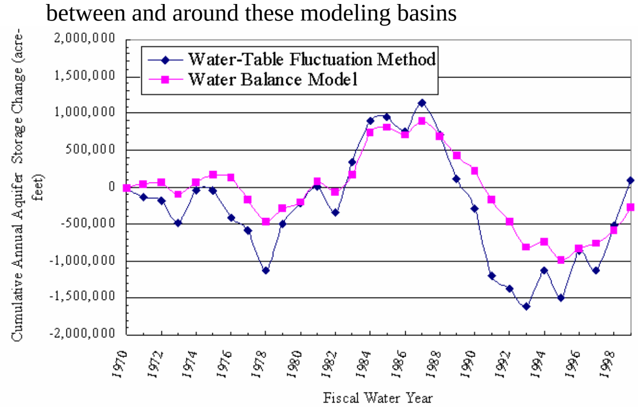

Figure 6. Water-table fluctuation method versus the modeled water balance: cumulative annual groundwater storage changes (acre-feet) for the study area for the fiscal water years of 1970-99.

4. Collect field data on groundwater hydraulic conductivity and incorporate into the groundwater model
5. Include carry-over value functions for surface and groundwater storage
6. Improve information regarding applied water demands and evapotranspiration.
7. Implement sensitivity study on the coupled hydrology-water management model to determine interdependency between input data to the hydrologic model and the output from the water management model.

The model should also be applied in further investigation of conjunctive use operations and water-market scenarios in the region. Currently only non-contract water is allowed to be exchanged among irrigation districts.

References

(see also: http://groundwater.ucdavis.edu/gw_203.htm)

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Table ES-1. Overall average results, all FRIANT contractors.

	Variable pmp cost FPlow run		Fixed pmp cost VP run	
Totals (taf/yr avg)		% Total		% Total
Demand	2,984	100.0%	2,984	100.0%
Total Supply	2,891	96.9%	2,865	96.0%
Scarcity	93	3.1%	119	4.0%
Total Supply	2,891	100.0%	2,865	100.0%
Surface contract supply	867	30.0%	1,004	35.0%
Surface other supply[1]	613	21.2%	613	21.4%
GW supply	1,411	48.8%	1,248	43.6%

[1]Excluding artificial recharge

Numerical Groundwater Flow Model for the Kaweah Delta Water Conservation District, Southern San Joaquin Valley, California

Nels Ruud, Peter Leffler, Larry Dotson

The Kaweah Delta Water Conservation District is an intensively irrigated agricultural area located in the eastern part of the southern San Joaquin Valley. Overall, the District is approximately 340,000 acres in size; with agriculture accounting for about 285,000 acres, urbanized areas for 40,000 acres, and undeveloped lands for 15,000 acres. Many farmers in the District depend on both surface water and groundwater resources to meet their crop water needs. Urban demands are met almost entirely with groundwater. On average, the District uses approximately 880,000 acre-feet per year (afy) of surface water and groundwater with irrigated agriculture consuming about 95 percent of this total. The major sources of surface water are: 1) Lake Kaweah via the St. Johns and Lower Kaweah rivers, 2) Millerton Reservoir via the Friant-Kern Canal, and 3) Pine Flat Dam via the Kings River.

In this study, we developed a three-dimensional numerical groundwater flow model for the District. The model was based on the conceptualization of the aquifer system hydrogeology from the Water Resources Investigation (WRI) for the District (Fugro West, Inc., 2003) and the recalculation of the major recharge and discharge components of the hydrologic balance at the land unit scale of the land use survey. The groundwater model covered the same base period of 1981 to 1999 as the WRI. The objective of the calibrated model was to calculate the hydraulic head and groundwater storage changes in the aquifer system subject to historical transient groundwater recharge and pumping stresses in the District. The model was used to evaluate the potential impacts and benefits of five different future agricultural and urban water use management and supplemental water supply scenarios on the groundwater resources of the District:

Model Scenario 1 – 2 Percent Annual Urban Growth Rate: This scenario evaluated a 2 percent urban growth rate for the cities of Visalia and Tulare over a 19-year simulation period from 2000 through 2018.

Model Scenario 2 – 3 Percent Annual Urban Growth Rate: This scenario evaluated a 3 percent urban growth rate for the cities of Visalia and Tulare over a 19-year simulation period from 2000 through 2018.

Model Scenario 3 – Water Management Basins: This scenario evaluated the recharge of supplemental surface water into eight additional water management basins located predominantly east of the City of Visalia.

Model Scenario 4 – Conceptualized Delta View Improvement District: This scenario evaluated the diversion and delivery of supplemental CVP surface water supplies to the conceptual Delta View Improvement District, located within the northwestern region of the District and within the northeast region of the Kings County Water District.

Model Scenario 5 – City of Visalia Stormwater/Recharge Basins: This scenario evaluated recharge of supplemental surface water into 13 City of Visalia stormwater/recharge basins located in and around the City of Visalia.

Overall, the results demonstrate that the calibrated groundwater flow model for the District is well-suited for simulating scenarios of the geographic scope and magnitude (of changes to the hydrologic budget) implemented in this study. The model could be applied to many other such scenarios to help guide implementation of groundwater management strategies or to evaluate impacts of various patterns of urban growth. However, model limitations related to the model grid (1,000 by 1,000 foot grid squares) and large size of the model domain most likely preclude use of the model for small scale simulations such as individual residential developments or individual recharge basins. Nonetheless, smaller scale models that may be needed for particular problems may benefit by incorporating District model results into their boundary conditions.

Introduction

The Kaweah Delta Water Conservation District (District) is an intensively irrigated agricultural area located in the northern portion of Tulare County and generally in the eastern part of the southern San Joaquin Valley (Plate 1). During 2003, Fugro West Inc. (Fugro) completed a detailed Water Resources Investigation (WRI) for the District and documented its findings in a comprehensive report (Fugro, 2003). The WRI consisted of the collection and organization of existing data describing the District geology, hydrogeology, surface water processes, and groundwater quality. This data was used in the WRI to develop a conceptual model of the local hydrogeology, and to estimate a hydrologic balance and safe yield for the aquifer system underlying the District. In addition, the WRI also recommended that a basin-scale groundwater model be developed as a quantitative groundwater management tool for the District. Consequently, during 2004 and 2005 a numerical transient groundwater flow model was developed by Fugro and used to evaluate five different future scenarios of water supply and demand in the District (Fugro, 2005). This proceedings paper provides a summary description of the results from that groundwater modeling study.

Background and Setting

For the purposes of the hydrologic and geologic analyses in the WRI, the District was divided into six hydrologic units (Plate 2). Each of the hydrologic units contained all or portions of the approximate 37 service areas (i.e., irrigation districts, water districts, ditch companies, riparian users, and other miscellaneous service areas) either fully or partially located within the District (Plate 3). The District also includes three major incorporated urban areas: Visalia, Tulare, and Farmersville. Overall, the District is about 340,000 acres in size; with agriculture accounting for about 285,000 acres, urbanized areas for 40,000 acres, and undeveloped lands for 15,000 acres (Plate 4). The ground surface topography has low relief, with variations rarely exceeding 10 feet except in natural channels. Elevations across the District vary from about 500 feet above sea level near the eastern boundary to 200 feet along the western boundary. The surface grades approximately 10 feet per mile in the northeast to southwest direction.

Many farmers in the District depend on both surface water and groundwater resources to meet their crop water needs (Plate 5). Urban demands are met almost entirely with groundwater. On average, the District uses approximately 880,000 acre-feet per year (afy) of surface water and groundwater with irrigated agriculture consuming about 95 percent of this total. The major sources of surface water are: 1) Lake Kaweah via the St. Johns and Lower Kaweah rivers, 2) the Central Valley Project-owned Millerton Reservoir via the Friant-Kern Canal, and 3) Pine Flat Dam via the Kings River. Surface water from these sources enters the District boundaries and is distributed to the respective entitlement holder service areas through a network of hydraulically inter-connected natural and constructed channels.

Study Objectives

The construction of the groundwater model was based on the conceptualization and characterization of the hydrologic balance and the aquifer system hydrogeology presented in the WRI. The base period of the model was from 1981 to 1999. The objective of the groundwater flow model was to calculate the hydraulic head and groundwater storage changes in the aquifer system subject to historical transient groundwater recharge and pumping stresses in the District. The model was calibrated by adjusting the hydraulic conductivity distribution until the simulated groundwater levels reasonably matched historical measurements. A calibration sensitivity analysis and a prediction sensitivity analysis were then performed on the calibrated model subject to ASTM standards (ASTM, 1994). The application of the model was to evaluate the potential impacts and benefits of five different future agricultural and urban water use management and supplemental water supply scenarios on the groundwater resources of the District.

Model Scenario 1 – 2 Percent Annual Urban Growth Rate: This scenario evaluated a 2 percent urban growth rate for the cities of Visalia and Tulare over a 19-year simulation period from 2000 through 2018.

Model Scenario 2 – 3 Percent Annual Urban Growth Rate: This scenario evaluated a 3 percent urban growth rate for the cities of Visalia and Tulare over a 19-year simulation period from 2000 through 2018.

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Model Scenario 5 – City of Visalia Stormwater/Recharge Basins: This scenario evaluated recharge of supplemental surface water into 13 City of Visalia stormwater/recharge basins located in and around the City of Visalia.

Water Balance and Conceptual Model of Hydrogeology

In the WRI, the District was divided into six hydrologic units and an annual hydrologic balance was computed from 1981 to 1999 for each hydrologic unit and for the District as a whole using an inventory method (Table 1). Annual changes in groundwater storage were estimated as the differences between the aquifer system recharge and discharge components. The major groundwater recharge components were identified as: 1) horizontal subsurface inflows through the District boundary, 2) deep percolation of precipitation, 3) river streambed percolation, 4) ditch conveyance losses, 4) percolation in recharge basins, 5) deep percolation of irrigation return flows, and 6) percolation of urban wastewater. Conversely, the major groundwater discharge components were: 1) horizontal subsurface outflows through the District boundary, 2) groundwater pumping, 3) extraction of groundwater by phreatophytes, 4) evaporative losses from surface water bodies, and 4) surface water exports.

Cumulative annual changes in groundwater storage were estimated for the entire District using the inventory method. Those results were compared against estimates by the specific yield method and are displayed in Figure 1 and summarized in Table 1. Over the entire base period, the cumulative change in storage was small. However, in the intervening years storage changes varied from an accumulation of 693,300 af in 1983 to a deficit (relative to the 1981 base year) of 1,934,100 af in 1994 (Figure 1), as computed by the inventory method. The annual safe yield was estimated by the inventory and specific yield methods as 615,900 and 602,300 af, respectively. Since annual discharge frequently exceeds annual recharge, the District experienced an annual overdraft ranging from about 17,800 to 36,100 af over the base period.

Characterization of the local hydrogeology was based on an analysis of available well logs (Plate 6) and on the work of Croft and Gordon (1968) and Davis et al. (1957). A regional geologic map of the District is displayed on Plate 7 and a hydrogeologic cross section of the aquifer system in the east-west direction is given on Plate 8. The base of the permeable water-bearing sediments is the contact between the unconsolidated deposits and the consolidated marine deposits (QTc) throughout much of the District, and between the unconsolidated deposits and the granitic and metamorphic basement rocks (pT) along the extreme eastern boundary of the District. The base of the permeable water-bearing sediments generally defines the lower boundary of the aquifer system. As displayed on Plate 8, the thickness of the aquifer system varies from 450 feet along the eastern boundary to 1,200 feet along the western boundary.

In the western half of the District, the aquifer system is conceptualized as three hydrogeologic units: 1) an unconfined aquifer, 2) an aquitard, and 3) a confined aquifer. In the eastern half of the District, the aquifer system is conceptualized as a single, thick unconfined aquifer. Four different unconsolidated sedimentary continental deposits were identified in the aquifer system: 1) young alluvium, 2) oxidized older alluvium, 3) reduced older alluvium, and 4) lacustrine and marsh deposits. The most significant zone of lacustrine and marsh deposits is the Corcoran Clay Member of the Tulare Formation (QTl). The Corcoran Clay forms the aquitard that is located in the western half of the District (Plate 8).

Groundwater Model Development and Calibration

The numerical groundwater model was developed in MODFLOW-2000 (Harbaugh et al., 2000) using a MODFLOW graphical-user-

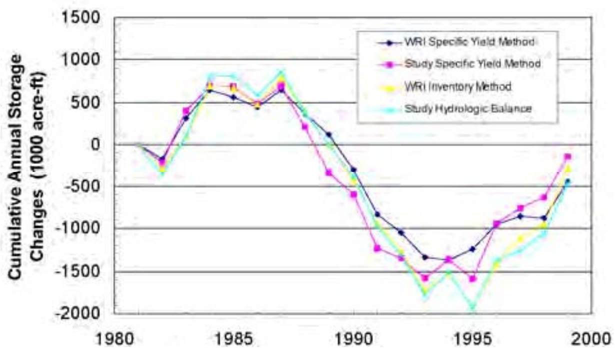

Figure 1. Comparison of cumulative spring-to-spring groundwater storage changes in the Kaweah Delta Water Conservation District.

interface (GUI) (Winston, 2000) developed for Argus ONE (Open Numerical Environments) (Argus Interware Inc., 1997). The groundwater model was calibrated and validated against historical water levels over the base period using the PEST (Parameter ESTimation) software (Doherty, 2002). The major aquifer recharge and discharge components from the WRI were recalculated at the land unit scale for input into the groundwater model. The aquifer system was modeled using three MODFLOW model layers. The finite-difference grid in the horizontal direction consists of 134 rows and 200 columns, with uniform cell lengths of 1000 feet. The base period of 1981 to 1999 consisted of 38 six-month stress periods. The transient model was calibrated from 1981 to 1993 and validated from 1994 to 1999. Spring-measured hydraulic heads for 1986, 1990, and 1993 were used as calibration targets.

Five different sources of vertical aquifer recharge were prepared for input into the groundwater model: 1) percolation of precipitation, 2) percolation of irrigation return waters, 3) artificial recharge in percolation basins, 4) streambed percolation from the two major rivers, and 5) ditch seepage conveyance losses. All recharge sources, except for streambed percolation in the two rivers, were estimated at the land unit scale and combined into a single GIS land use survey map that was imported into Argus ONE and overlain on model layer 1 of the finite-difference grid. The groundwater pumping demand in model layer 1 was then subtracted from the recharge rate in model layer 1 to yield a net recharge rate for model layer 1. The resulting net recharge was modeled in layer 1 using the MODFLOW Well Package.

A GIS land use survey map containing the groundwater pumping demand for each stress period for each land unit was imported into Argus ONE and overlain on the finite-difference grid. As mentioned above, the groundwater pumping demand in model layer 1 was subtracted from the recharge rate in layer 1 to obtain a net recharge rate per stress period for layer 1. The groundwater pumping demands for model layers 2 and 3 were also modeled using the MODFLOW Well Package. The proportion of groundwater pumping taking place above and below the Corcoran Clay aquitard was estimated by analysis of available screen location information in drilling well logs. East of the Corcoran Clay aquitard, the percentage of the total pumping demand in model layers 1, 2, and 3 were chosen to be 60 percent, 10 percent, and 30 percent, respectively.

River streambed percolation was estimated for each of the 13 reaches comprising the St. Johns and Lower Kaweah rivers (Plate 5). The stress period percolation rate for each reach was imported into Argus ONE as a GIS map of line objects and assigned to the cells that intersected the line objects. River reach percolation was then modeled using the MODFLOW Recharge Package

Three different conceptualizations of the spatial structure of the horizontal hydraulic conductivity distribution were evaluated in the model calibration. Estimation of the horizontal hydraulic conductivity distribution as an exponential function of the specific yield

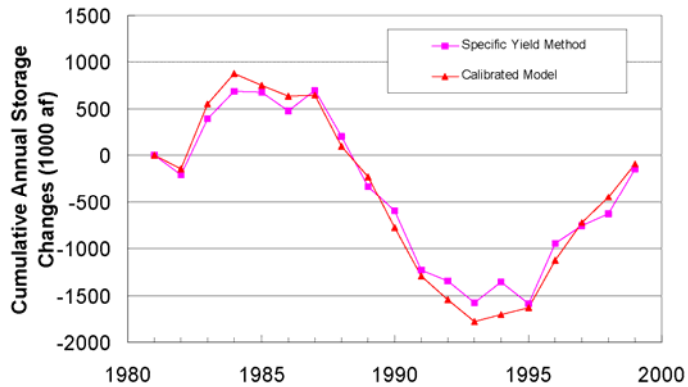

Figure 2. Specific yield method versus modeled cumulative spring-to-spring groundwater storage changes in the Kaweah Delta Water Conservation District.

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distribution provided the best calibration and most geologic-based structure for the horizontal hydraulic conductivity in both the unconfined and confined aquifers. Horizontal hydraulic conductivity estimates ranged from approximately 50 to 235 feet/day in the unconfined aquifer and from 30 to 105 feet/day in the confined aquifer. More than 70 percent of the hydraulic head residuals (i.e., measured minus modeled hydraulic heads) for 1986, 1990, and 1993 were less than the 18-foot residual criterion. This criterion was determined using the rule-of-thumb that the absolute value of the calculated hydraulic head residuals should be within 5 percent of the range of measured hydraulic heads over the District. For the District, 5 percent of the range of measured hydraulic heads is approximately 18 feet. In addition, the agreement between the specific yield method and the modeled storage changes over the base period at the District and the hydrologic unit scales were quite good (Figures 2 and 3).

Future Scenarios Analysis

The purpose of the scenarios analysis was to use the calibrated model to evaluate five scenarios of future water use and water supply in the District. Much of the input data for the future scenarios is identical to that of the calibrated model. Like the calibrated model, the simulation period for the future scenarios is 19 years in length and extends from 2000 to 2018. For comparison purposes, a base case future scenario was also simulated in addition to the five future scenarios. The base case future scenario for the 19-year simulation period used the same climatic conditions (i.e., reference ET, spatial and temporal distributions of precipitation) and the same surface water balance components (i.e., diversions, river seepage losses) for generating model inputs as the calibrated model. Unless specified otherwise, the agricultural and urban water demands over the 19-year simulation period for the base case scenario and the five future scenarios are defined using only the 1996/1999 land use survey, as opposed to the three different land use surveys (i.e., 1981/1986, 1991/1993, 1996/1999) that were used to generate the inputs for the calibrated model. Generally, the five scenarios involve specific isolated changes in future water supplies or future water demands in the District, but otherwise use the same model input data as the base case future scenario.

Scenario 1

Scenario 1 evaluated a 2 percent urban growth rate for the cities of Visalia and Tulare over a 19-year simulation period from 2000 through 2018. A map displaying the differences in groundwater levels between Scenario 1 and the base case scenario at the end of the 19-year simulation period is displayed on Plate 9. For this scenario, groundwater levels relative to the base case scenario (i.e., no future changes in water supply and demand) were higher in and around the cities of Visalia and Tulare over the simulation period. However,

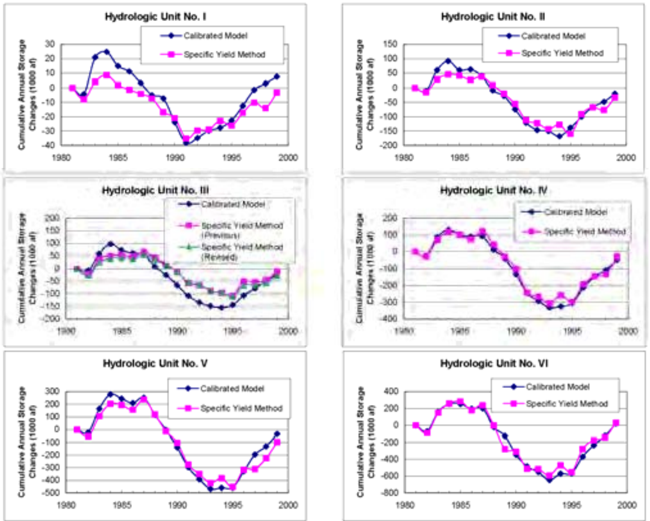

Figure 3. Cumulative spring-to-spring groundwater storage changes in Hydrologic Units I through IV, Kaweah Delta Water Conservation District.

groundwater levels overall continued their pattern of a historic decline. In effect, urban growth at a 2 percent rate serves to reduce the amount of groundwater level decline that would otherwise occur. This result was due to a steady decrease in local water demands resulting from the conversion of agricultural lands to urban land uses, and the concentrated application of surface water diversions in the reduced service areas of Modoc Ditch Company (DC), Goshen DC, Evans DC, Persian/Watson DC, and Oakes DC (Plate 3). Decreases in net water demands were 420,200 acre-feet (af) over the 19-year simulation period, or an average of 22,115 af per year. Groundwater storage increased by 96,000 af and accounted for 23 percent of the water demand decreases, while the remaining 77 percent, or 324,200 af, of the conserved water left the District as subsurface outflow via the general-head boundary conditions. The positive net subsurface outflows through the District boundaries are attributable to higher water levels in areas northwest of the City of Visalia and west of the City of Tulare.

Scenario 2

Scenario 2 evaluated a 3 percent urban growth rate for the cities of Visalia and Tulare over the 19-year simulation period. A map displaying the differences in groundwater levels between Scenario 2 and the base case scenario at the end of the 19 year simulation period is displayed on Plate 10. For this scenario, the groundwater levels were higher than those for the base case scenario, but were lower than those in Scenario 1 due to the assumption of a 3 percent annual growth rate in urban populations rather than the 2 percent growth rate used in Scenario 1. Increases in groundwater storage were 68,000 af over the 19-year simulation period and the decrease in net water demand between Scenario 2 and the base case scenario was 356,500 af. Increases in groundwater storage reflect 19 percent of the reductions in net water demands with the remaining 81 percent, or 288,500 af, of conserved water leaving the District through the general-head boundary conditions. Again, urban growth at 3 percent helps to reduce the amount of groundwater level decline that would otherwise occur assuming the surface water supplies from converted agricultural lands are still applied locally, although the net benefit is less than Scenario 1.

Scenario 3

Scenario 3 evaluated the recharge of supplemental surface water into eight additional water management basins located predominantly east of the City of Visalia. A map displaying the differences in groundwater levels between Scenario 3 and the base case scenario at the end of the 19 year simulation period is displayed on Plate 11. The source of the supplemental supplies derived from 4,250 af per year of Central Valley Project (CVP) surface water available through an exchange agreement between the District and the Ivanhoe Irrigation District and from captured surface water spills from the Tulare Irrigation District, Consolidated Peoples DC, and Cross Creek systems. The increase in groundwater storage relative to the base case scenario over the 19-year simulation period was 16,000 af compared to the 408,571 af of supplemental CVP supplies and captured spills recharged into the basins. Many of the basins are located in the eastern portion of the District in close proximity to the District perimeter boundaries. Increases in water levels due to recharge in the management basins were limited by significant subsurface outflows through the District boundaries via the general-head boundary conditions. The supplemental surface water is applied only during the water years in which it is available. The application during these years creates considerable mounding beneath the management basins leading to radial flow of groundwater outward from the basins, including across District boundaries. During the intervening years between recharge events, the water level rises subside as the groundwater system returns to a more equilibrium condition.

Scenario 4

Scenario 4 evaluated the diversion and delivery of supplemental CVP surface water supplies to the conceptual Delta View Improvement District, located within the northwestern region of the District and within the northeast region of the Kings County Water District (KCWD). The supplemental CVP supplies totaled 20,000 af per water year and were assumed available during 11 of the 19 years of the future simulation period. A map displaying the differences in groundwater levels between Scenario 4 and the base case scenario at the end of the 19 year simulation period is displayed on Plate 12. The increase in groundwater storage relative to the base case scenario was 52,000 af over the 19-year simulation period, compared to the 220,000 af of supplemental surface water diverted into the District for delivery to the Delta View Improvement District. Changes in groundwater storage reflect the decreases in groundwater pumping in the Delta View Improvement District and also the supplemental CVP supplies that enter the aquifer system as either river seepage losses, ditch system seepage losses, or deep percolation of applied water.

Scenario 5

Scenario 5 evaluated recharge of supplemental surface water into 13 City of Visalia stormwater/recharge basins located in and around the City of Visalia. The supplemental surface water totaled 8,000 af per water year and was assumed available during 11 of the 19 water years of the simulation period. A map displaying the differences in groundwater levels between Scenario 5 and the base case scenario at the end of the 19 year simulation period is displayed on Plate 13. The increase in groundwater storage relative to the base case scenario was 31,000 af over the 19-year simulation period, compared to the 88,000 af of surface water diverted for recharge into the city basins. Changes in groundwater storage therefore reflect 35 percent of the supplemental surface water recharged into the city basins, with the remaining recharge leaving the District through the general-head boundary conditions.

Conclusions

The study results show that impacts on groundwater storage and water levels are dependent on the location, magnitude, and timing of the future changes in water supply and demand associated with each scenario. In terms of magnitude and timing, Scenarios 4 and 5 considered the application of supplemental surface water supplies for either intentional recharge purposes or to meet applied water demands for 11 of the 19 water years of the simulation period. These supplemental supplies resulted in increased groundwater levels during the years in which these supplies were available. However, during the intervening years the water levels in the aquifer system slowly declined (from the increased levels caused by supplemental water) due to subsurface outflows through the District boundaries. Nonetheless, dry year water levels and groundwater storage were modestly greater than if the scenario were not implemented.

In terms of location, Scenario 3 considered the application of recharge in water management basins located in close proximity to the eastern boundary of the District. This resulted in significant subsurface outflows of the recharge via the general-head boundary conditions through the northern and southern boundaries in this region. Therefore, the impacts of the recharge on groundwater levels within the District boundaries were less effective due to the locations of these basins. Consequently, locating recharge basins away from District boundaries and closer to the middle of the District will maximize the benefits of an artificial recharge program.

The most significant increases in groundwater storage relative to the base case scenario occurred for Scenarios 1 and 2. These increases were due in part to a steady annual reduction in net water demands over the 19-year simulation period from the conversion of agricultural areas to urban land uses. To achieve the most significant impacts on groundwater storage, it appears that changes in water supplies and demands must be implemented consistently from year to year, to the extent possible.

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Table 1. Major recharge and discharge components of the Hydrologic Balance and Groundwater Storage Changes for the District from 1981-1999.

Year	Rainfall		Components of Inflow						Components of Outflow						Total Inflow	Total Outflow	Change in Storage		Cumulative Change in Storage	
									Groundwater Pumpage											
	Inches	% of Average	Subsurface Inflow	Wastewater Inflow	Streambed Percolation and Conveyance Losses	Percolation of Recharge Basins	Percolation of Irrigation Water	Percolation of Precipitation	M & I	Irrigated Agriculture	Total Net Extraction	Extraction by Phreatophytes	Evaporative Losses	Subsurface Outflow			Inventory Method	Specific Yield Method	Inventory Method	Specific Yield Method
1981	8.4	77%	73.6	8.3	122.6	1.5	217.7	60.1	37.6	682.3	719.9	0.4	1.0	42.2	483.7	763.5	-279.8	-172.4	-279.8	-172.4
1982	13.7	126%	64.5	8.5	327.6	89.0	202.8	76.5	38.0	326.3	364.2	0.6	1.0	28.6	768.9	394.4	374.5	486.8	94.7	314.4
1983	16.1	148%	61.8	8.8	408.4	376.4	177.3	149.5	40.0	496.0	536.0	0.7	1.0	45.8	1,182.1	583.5	598.6	329.1	693.3	643.5
1984	6.1	56%	87.0	9.1	259.6	95.3	248.8	22.3	44.5	668.5	713.0	0.2	1.0	32.2	721.9	746.5	-24.5	-87.0	668.8	556.5
1985	7.2	66%	47.1	9.4	162.8	21.3	224.7	55.9	45.3	657.4	702.7	0.3	1.0	12.3	521.1	716.3	-195.2	-118.2	473.6	438.3
1986	13.9	128%	45.1	9.6	303.0	121.0	198.9	113.1	48.0	408.7	456.6	0.5	1.0	19.0	790.8	477.1	313.7	209.6	787.3	648.0
1987	8.2	75%	54.3	10.0	71.3	8.8	218.3	77.9	50.0	779.6	829.6	0.3	1.0	5.6	440.6	836.5	-395.8	-279.3	391.5	368.7
1988	9.4	86%	35.9	10.2	95.7	6.9	222.7	46.9	49.5	750.9	800.3	0.4	1.0	7.4	418.2	809.0	-390.8	-246.5	0.7	122.2
1989	8.3	76%	36.8	10.6	83.8	0.4	221.8	53.8	52.1	756.9	809.1	0.3	1.0	21.8	407.0	832.3	-425.2	-426.0	-424.6	-303.8
1990	5.8	53%	53.5	10.6	39.1	0.0	226.8	63.8	54.4	850.1	904.5	0.2	1.0	7.9	393.8	913.7	-519.9	-528.1	-944.5	-832.0
1991	8.7	80%	59.9	10.9	92.0	0.9	222.9	83.4	54.2	729.6	783.9	0.4	1.0	17.9	470.0	803.1	-333.1	-222.6	-1,277.6	-1054.6
1992	9.2	84%	62.9	10.5	43.8	0.9	210.7	57.9	56.8	774.1	830.8	0.4	1.0	8.8	386.6	841.0	-454.5	-285.8	-1,732.0	-1340.4
1993	12.7	117%	48.1	11.1	252.9	49.2	200.0	131.4	57.0	412.9	469.9	0.5	1.0	12.3	692.7	483.7	208.9	-37.7	-1,523.1	-1378.1
1994	7.8	72%	36.6	11.8	67.7	0.4	207.2	59.0	63.1	715.9	779.0	0.3	1.0	13.3	382.7	793.7	-411.0	132.1	-1,934.1	-1246.0
1995	17.6	161%	59.8	12.2	314.7	149.6	180.6	163.9	63.6	287.6	351.2	0.7	1.0	12.4	880.8	365.3	515.5	288.4	-1,418.6	-957.5
1996	11.5	106%	71.5	12.1	299.0	60.7	202.5	96.5	65.7	336.4	402.1	0.4	1.0	34.1	742.3	437.6	304.7	100.7	-1,113.9	-856.9
1997	11.2	103%	68.6	12.5	267.8	138.8	204.5	76.6	69.5	491.4	560.9	0.5	1.0	48.8	768.9	611.2	157.7	-23.7	-956.3	-880.5
1998	22.1	203%	49.2	12.6	320.2	192.0	146.5	251.9	63.2	210.5	273.8	0.9	1.0	23.4	972.3	299.1	673.3	439.4	-283.0	-441.1
1999	9.2	84%	39.5	13.4	168.3	35.4	186.7	121.3	71.0	517.7	588.7	0.4	1.0	29.2	564.6	619.2	-54.6	-244.6	-337.6	-685.7
Maximum	22.1	203%	87.0	13.4	408.4	376.4	248.8	251.9	71.0	850.1	904.5	0.9	1.0	48.8	1,182.1	913.7	673.3	486.8		
Minimum	5.8	53%	35.9	8.3	39.1	0.0	146.5	22.3	37.6	210.5	273.8	0.2	1.0	5.6	382.7	299.1	-519.9	-528.1		
Average	10.9	100%	55.6	10.6	194.7	71.0	206.4	92.7	53.9	571.2	625.1	0.4	1.0	22.3	631.0	648.8	-17.8	-36.1		
% of Total			9%	2%	31%	11%	33%	15%	8%	88%		0%	0%	3%						

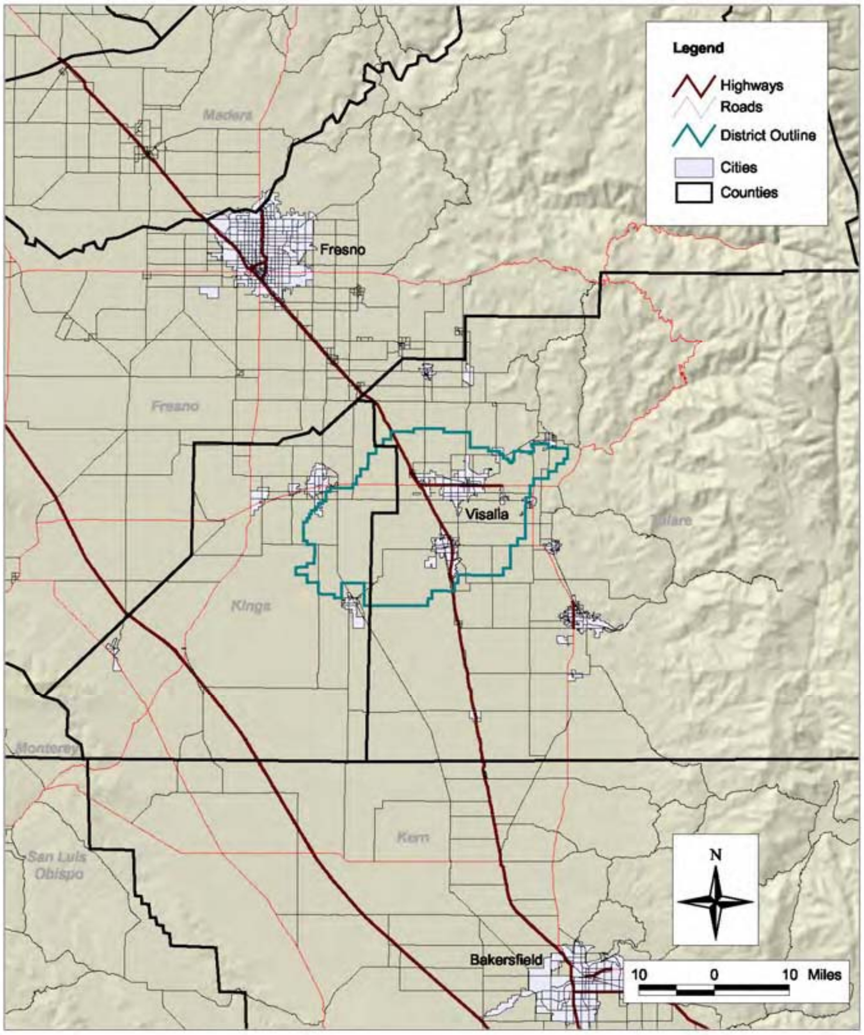

Plate 1. **Study area location map, Kaweah Delta Water Conservation District.**

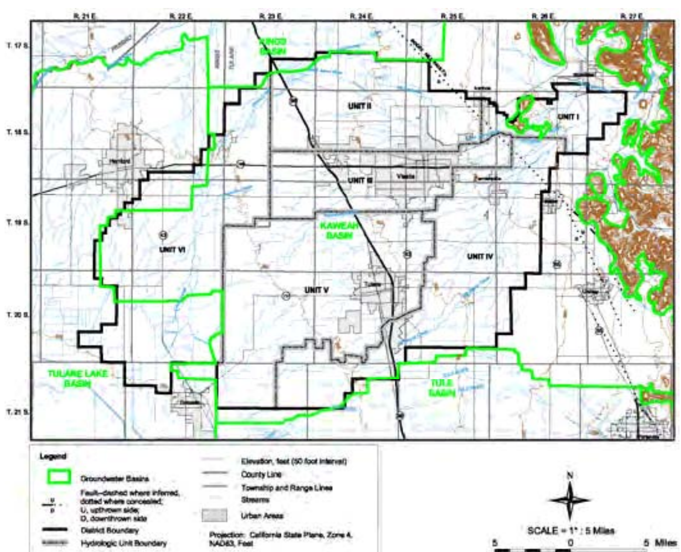

Plate 2. **Study area map, Kaweah Delta Water Conservation District.**

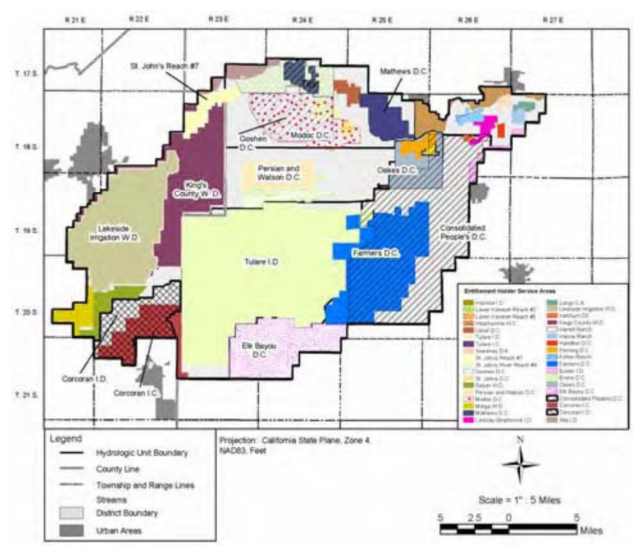

Plate 3. **1999 entitlement holder service areas, Kaweah Delta Water Conservation District.**

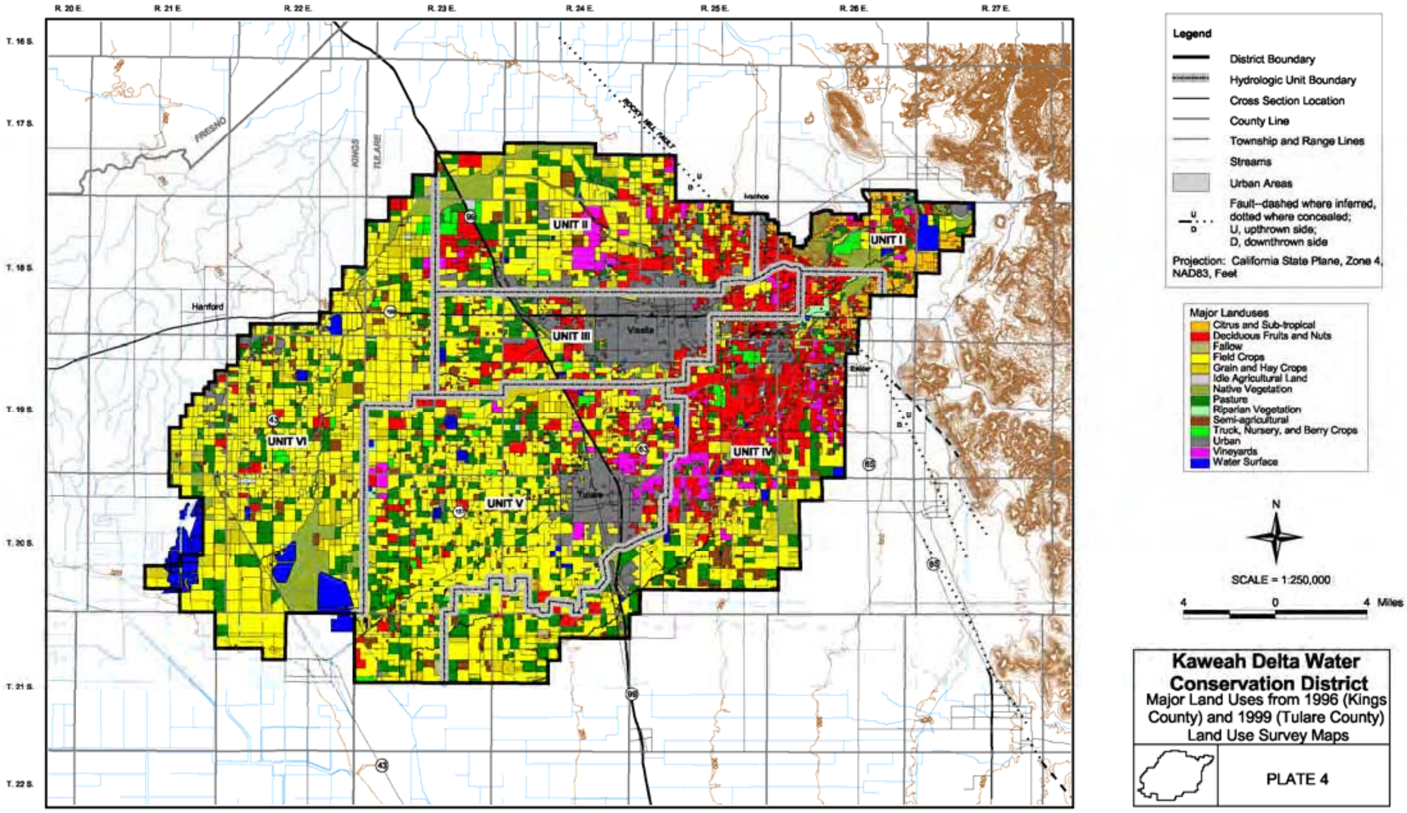

Plate 4. Major land uses from 1996 (Kings County) and 1999 (Tulare County) land use survey maps, Kaweah Delta Water Conservation District.

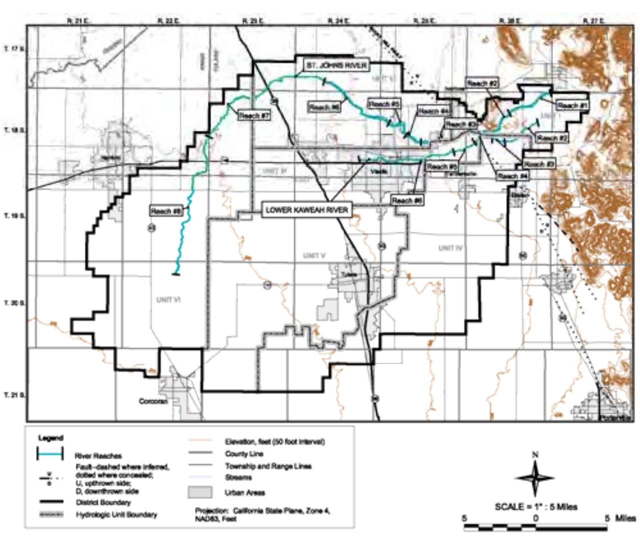

Plate 5. Reaches of the St. Johns and Lower Kaweah Rivers, Kaweah Delta Water Conservation District.

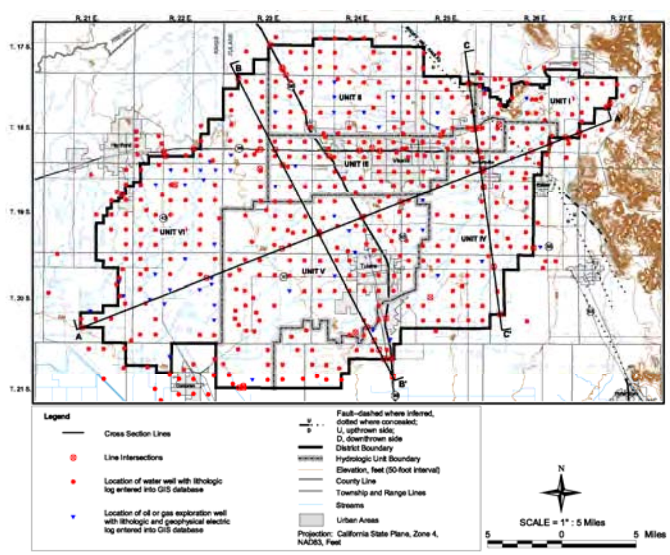

Plate 6. Well database and cross section location map, Kaweah Delta Water Conservation District.

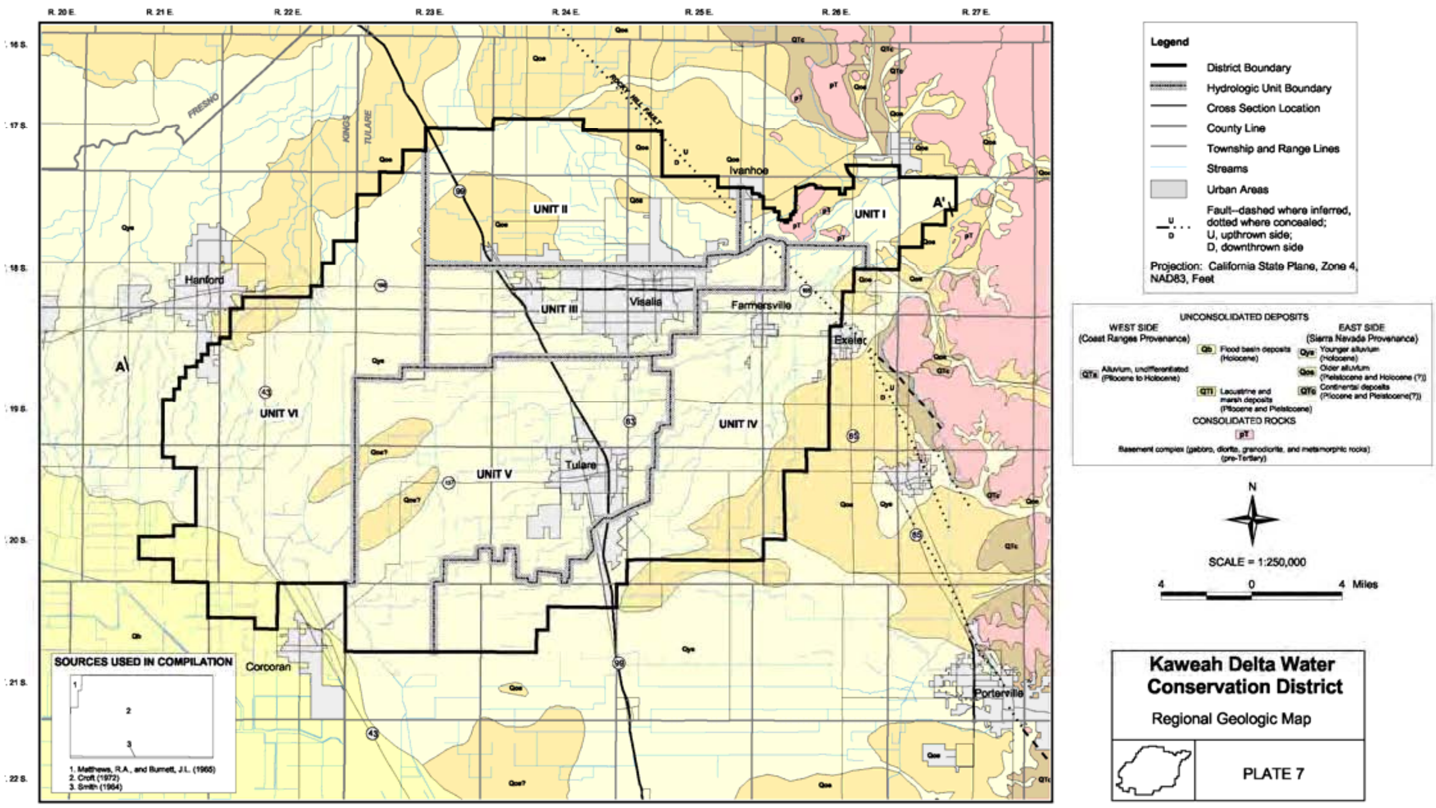

Plate 7. **Regional geologic map, Kaweah Delta Water Conservation District.**

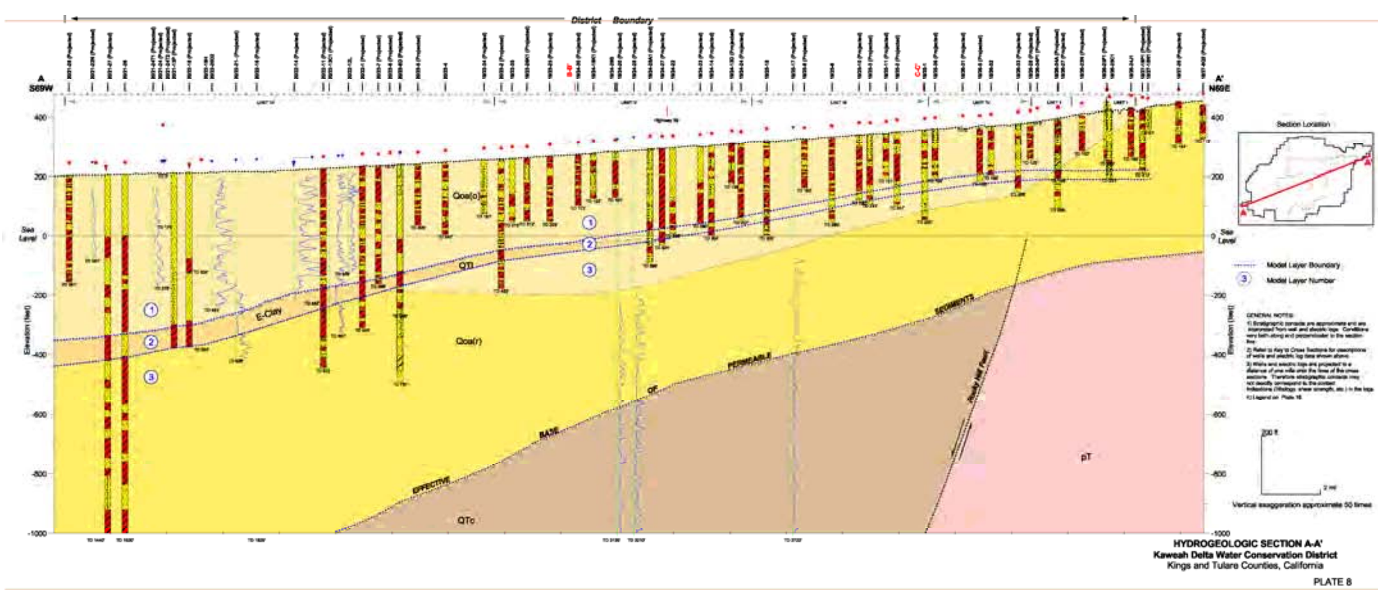

Plate 8. **Hydrogeologic section A-A', Kaweah Delta Water Conservation District.**

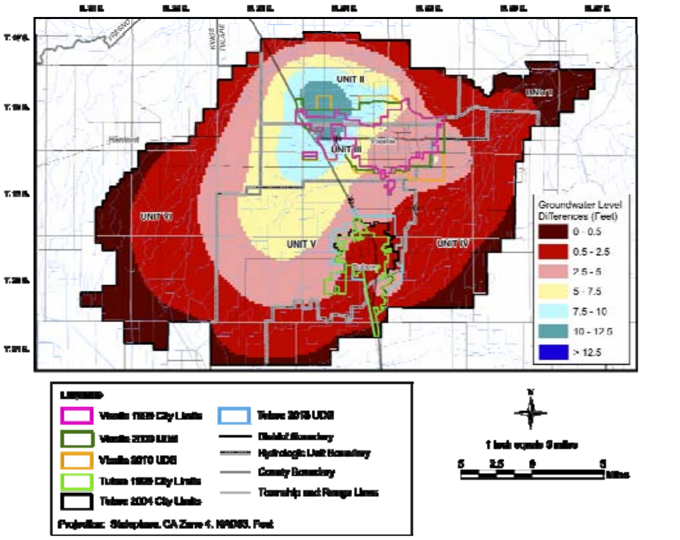

Plate 9. Differences in groundwater levels between Scenario 1 and Base Case at the end of the 19-year future scenario period, Delta Water Conservation District.

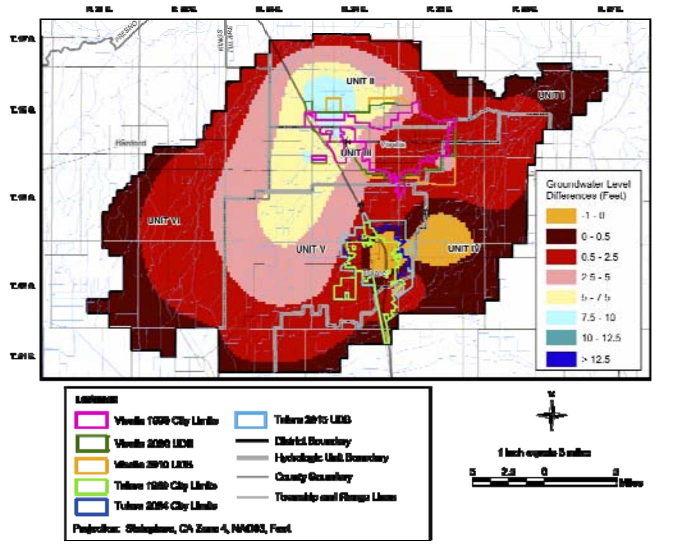

Plate 10. Differences in groundwater levels between Scenario 2 and Base Case at the end of the 19-year future scenario period, Delta Water Conservation District.

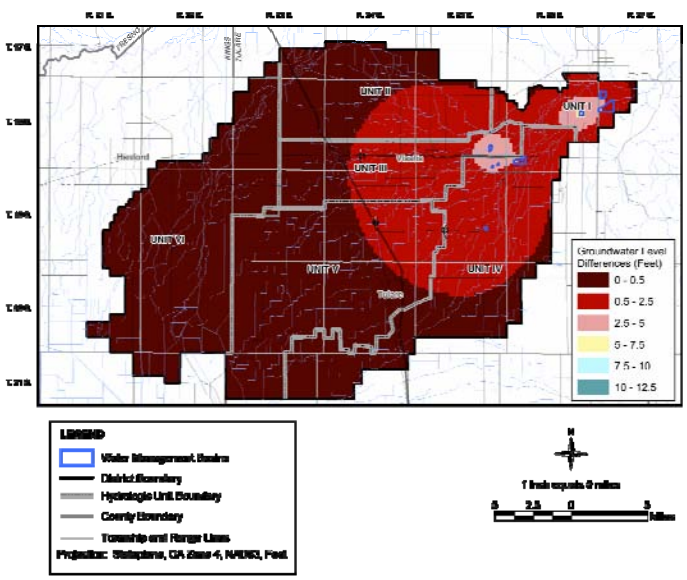

Plate 11. Differences in groundwater levels between Scenario 3 and Base Case at the end of the 19-year future scenario period, Delta Water Conservation District.

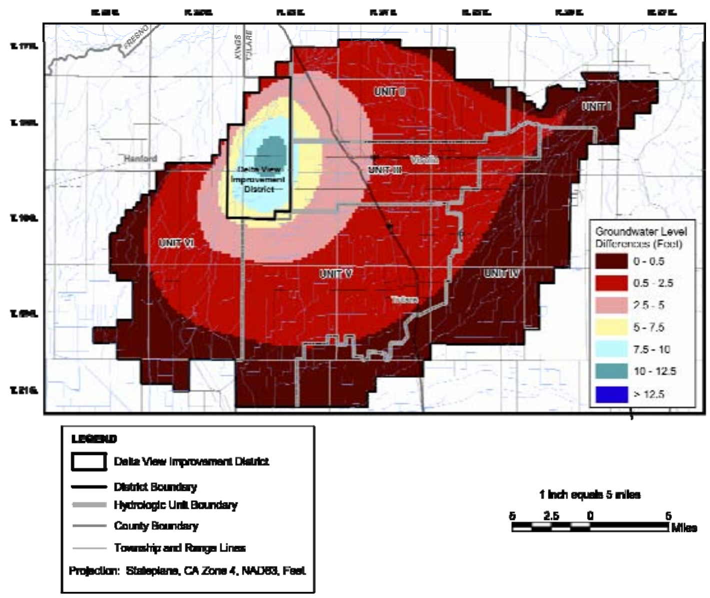

Plate 12. Differences in groundwater levels between Scenario 4 and Base Case at the end of the 19-year future scenario period, Delta Water Conservation District.

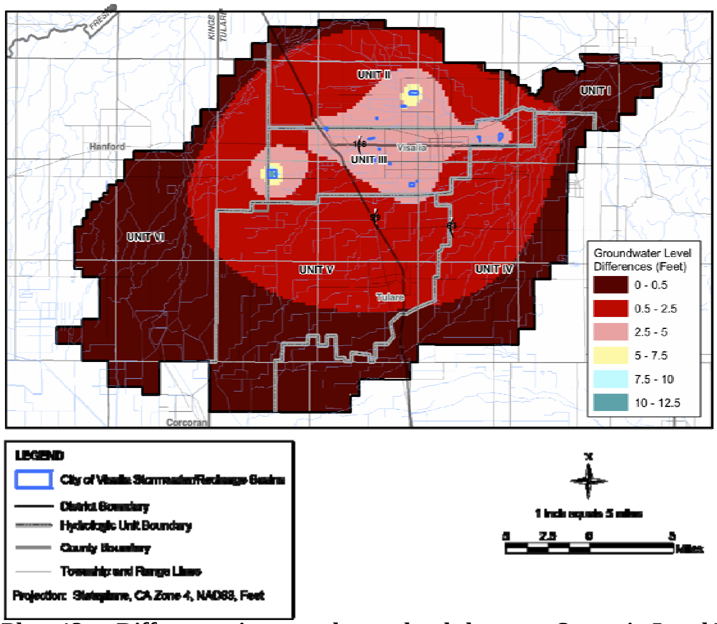

Plate 13. **Differences in groundwater levels between Scenario 5 and Base Case at the end of the 19-year future scenario period, Delta Water Conservation District.**

Integrated Modeling: An Analytical Tool for Integrated Regional Water Management Plan Development – Application to Kings Basin

Reza Namvar, Ph.D., P.E., Elias Tijerina, and Ali Taghavi, Ph.D., P.E.

An Integrated Groundwater and Surface water Model (IGSM) was developed as an analytical tool for development of Kings Basin Integrated Regional Water Management Plan (Upper Kings IRWMP). Kings Basin covers an area of about 1,600 square miles. Water use in this basin consists of approximately 2,700 TAF agricultural and 170 TAF urban water use which is met by 1,800 TAF of groundwater and 1,070 TAF of surface water. Kings River, with an average annual stream flow of 1,600 TAF, is the primary source of surface water for the basin. This analytical tool will be used to evaluate IRWMP project alternatives and water management strategies. The project alternatives include regional groundwater direct and in-lieu recharge projects and regional groundwater banking. The model development and calibration is discussed briefly, and model past and potential future applications are presented.

Introduction

This paper documents the development and calibration of the Kings Basin Integrated Groundwater and Surface water Model (Kings IGSM). The Kings IGSM model was developed to support the planning analysis required for the Upper Kings IRWMP (WRIME, 2007b). The Upper Kings Basin Water Forum (Water Forum) recognized the need for a tool to quantitatively evaluate the nature and extent of the water resources problems in the Kings Groundwater Basin (Figure 1); evaluate and compare potential future conditions and project effects; aggregate the available data; and ensure the scientific and technical merit of analysis.

The development of the Kings IGSM was coordinated by the Technical Analysis and Data Work Group (TAD Work Group) of the Water Forum. The Kings IGSM development process included a series of steps, each of which was conducted and completed in cooperation with the TAD Work Group which provided technical review, guidance, and coordination to the Kings IGSM modeling team. TAD Work Group made decision regarding the technical assumptions, analysis approach, and data used in the Kings IGSM development; and reviewed interim results. The development of the model was supported by a series of technical studies that were reviewed by the TAD Work Group (WRIME, 2006 and 2007).

The City of Fresno (City) is updating its Metropolitan Water Resources Management Plan (Metro Plan) to guide the development and management of the available water supplies needed to meet

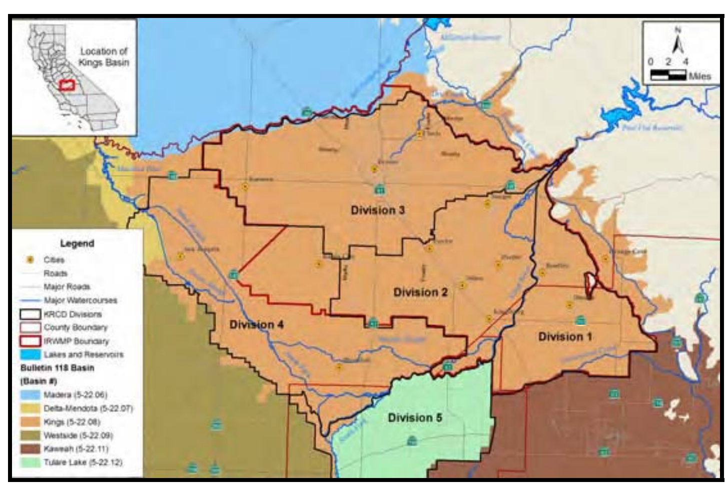

Figure 1 **Location of Kings Groundwater Basin, Kings IGSM, and IRWMP**

current demands and future growth through 2060. The City is using the Kings IGSM as an analytical tool for development and analysis of the Metro Plan and supported the enhancement of the model in and surrounding the City. Detailed model input data and analysis of model results for Fresno area are presented in the Kings IGSM report (WRIME, 2007c).

Model Area and Calibration Period

The Kings IGSM is a regional model that covers the entire Kings Basin as defined by the California Department of Water Resources in Bulletin 118 (Figure 1). The Kings IGSM simulates the surface water and groundwater systems of Kings Basin, and is the first comprehensive model of the Kings Basin that incorporates the past four decades of detailed historical conditions of the Kings Basin. Hydrogeologic conditions, land use, crop pattern, major diversions of King River and major canals in Kings Basin are included in Kings IGSM. The Kings IGSM was calibrated using a representative 41-year period from 1964 to 2004. This period was selected because it contains an array of representative wet and dry periods and includes the operations of Pine Flat Reservoir under the final agreements as coordinated by the King River Water Association (KRWA).

A wide array of data was collected from local, state and federal sources for the Kings Basin. This data was analyzed and processed to create input files for to the Kings IGSM development (WRIME, 2007c). To reflect the geologic and hydrologic interconnection of the Kings Region with surrounding areas, the readily available data on the neighboring areas adjacent to Kings Basin were collected and analyzed to develop the Kings IGSM.

Model Subregions and Grid

Kings IGSM model area is subdivided into 32 water and land use management areas called subregions. The subregions are used to enable independent analysis of water budgets and hydrologic conditions for each management area. In addition, the subregions allow for the proper development of model input data, especially water supply and demand data. The Kings IGSM subregions represent urban areas sphere of influence, individual water districts, irrigation districts, or other organized and/or unorganized areas within the model.

The Kings IGSM model grid consists of 4,689 elements and 4,266 nodes. The model area covers approximately 1,627 square miles, with an average element size of about 222 acres and minimum and maximum sizes of 9 acres and 965 acres, respectively. The hydrogeology in the Kings Basin is modeled as a 3-layer aquifer system.

Model Data

The model input data consists of seven major categories: geohydrology, hydrology, land use, water use, aquifer parameter,

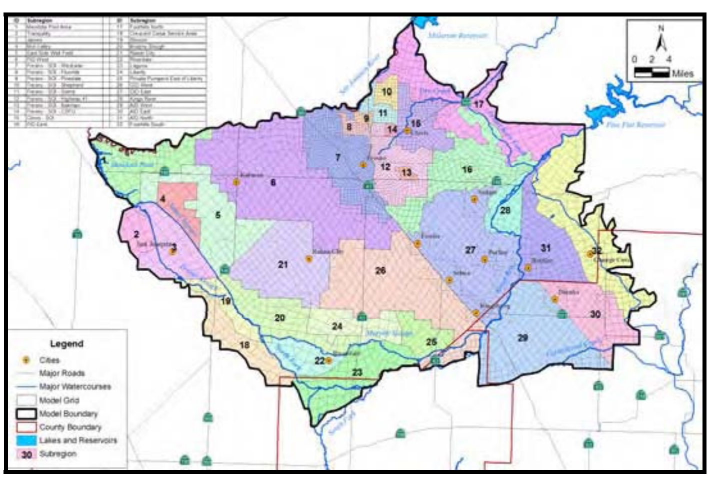

Figure 2. Model Grid and Subregions

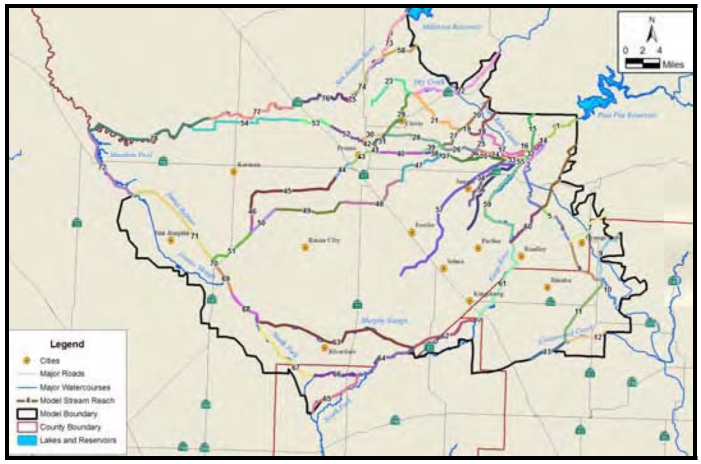

Figure 3. Model Surface Water System

initial conditions, and boundary conditions. The Kings IGSM provides simulation of flows and stream-aquifer interaction for Kings and San Joaquin Rivers and nine smaller creeks (Figure 3). The flow in fourteen major canals and deliveries of eight additional canals are also simulated in the Kings IGSM as part of the surface water flow system. A general head boundary condition is used for all model layers at the northern, western, and southern boundaries. Small watershed boundary conditions are used for the eastern boundary of the Kings IGSM.

Model Calibration

The Kings IGSM was calibrated using the water budgets, groundwater levels, and streamflows. In order to evaluate the performance of the Kings IGSM during dry, average, and wet hydrologic conditions, Fall 1977, Spring 1983, and Spring 2004 periods were used to match the groundwater levels. The Kings IGSM simulates groundwater elevations at 240 wells (Figure 4). The modeled groundwater levels at these wells were compared with corresponding observed values for long-term trends as well as seasonal fluctuations. The performance of the Kings IGSM calibration exceeds the calibration targets (Figures 5, 6, and 7).

Sensitivity Analysis

Sensitivity analyses were performed for the Kings IGSM for hydraulic conductivity, specific yield, storage coefficient, streambed hydraulic conductivity, groundwater pumping, and leakance between model layers 1 and 2. The results of the sensitivity analysis for the Kings IGSM indicate that the model is a stable and it responds in the expected manner to changes in aquifer parameters and input data

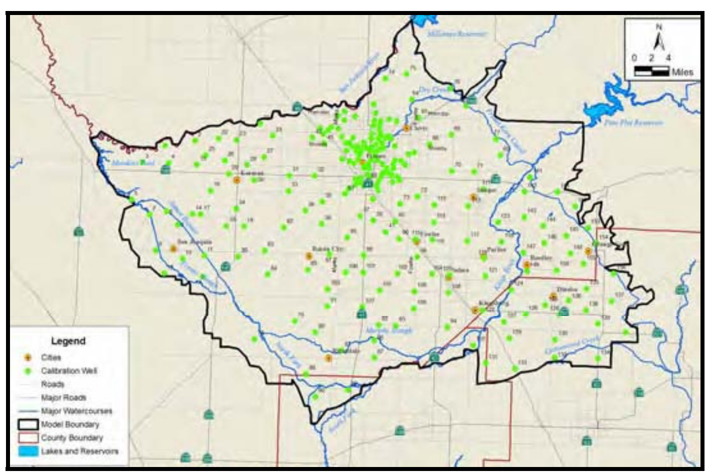

Figure 4. Calibration Wells

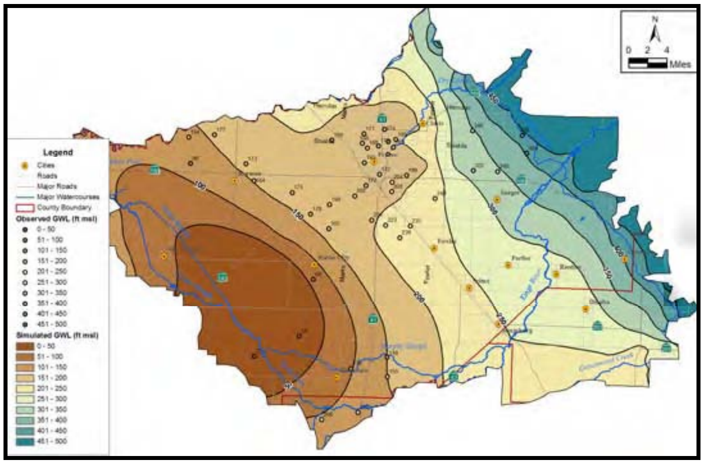

Figure 5. Observed and Simulated Groundwater Levels (Spring 2004)

Anticipated Uses and Application of the Kings IGSM

The Kings IGSM is expected to be used extensively for water resources planning and management in the Kings Basin. KRCD will continue to coordinate the use and application of the model. The model was used to conduct a Baseline Analysis for development of the Kings IRWMP. It is anticipated that the Kings IGSM will be used to further support the Water Forum in sizing capital projects and evaluating the IRWMP alternatives. The Kings IGSM may also be applied to any circumstances which require quantification of project or program benefit and effects and comparison of alternatives..

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WRIME, 2006a. Kings Basin Integrated Hydrologic Modeling – Modeling Objectives and Strategy. Technical Memorandum. Prepared for the Upper Kings Basin Water Forum and the Kings River Conservation District with support from the California Department of Water Resources. Sacramento, CA.

WRIME, 2006b. Analysis of Water Demand in the Kings Basin. Technical Memorandum, Phase 1, Task 3. Prepared for the Upper Kings Basin Water Forum and the Kings River Conservation District with support from the California Department of Water Resources. Sacramento, CA.

WRIME, 2006c. Analysis of Water Supplies in the Kings Basin. Technical Memorandum, Phase 1, Task 4. Prepared for the Upper Kings Basin Water Forum and the Kings River Conservation District with support from the California Department of Water Resources. Sacramento, CA.

WRIME, 2007a. Water Quality Standards, Conditions and Constraints. Technical Memorandum. Prepared for the Upper Kings Basin Water Forum and the Kings River Conservation District with support from the California Department of Water Resources. Sacramento, CA.

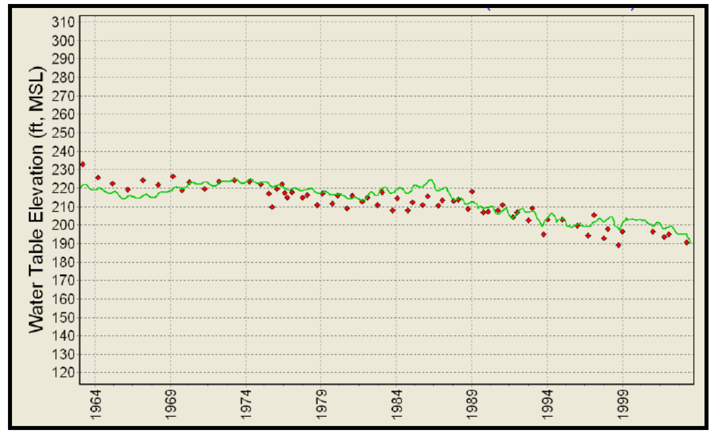

Figure 6. Simulated and Observed Groundwater Elevation for Calibration Well 53

WRIME, 2007b. Upper Kings Basin Integrated Regional Water Management Plan (IRWMP). Prepared for the Upper Kings Basin Water Forum and the Kings River Conservation District. with support from the California Department of Water Resources. Sacramento, CA.

WRIME, 2007c. Kings Basin Integrated Groundwater and Surface water Model (Kings IGSM) – Model Development and Calibration. Prepared for Upper Kings Basin Water Forum, Kings River Conservation District, and City of Fresno in coordination with the California Department of Water Resources.

Figure 7. Simulated and Observed Groundwater Elevation for Calibration Well 104

High Resolution Groundwater Models of the San Joaquin River Riparian Zone for Evaluation of Surface Water/Groundwater Interactions under Alternate River Flow Regimes

Deborah L. Hathaway, Gilbert Barth and Karen MacClune

Efforts are underway to evaluate and implement actions to restore 150 miles of the San Joaquin River downstream of Friant Dam and to reintroduce previously extirpated spring- and fall-run Chinook salmon. Among planned actions is the augmentation of river flow to achieve restoration hydrographs that vary in shape and volume according to a degree of "wetness" or, water year type, reflecting the basin water supply. High resolution groundwater models of the San Joaquin River riparian zone have been developed and applied to evaluate surface water/groundwater interactions associated with the restoration hydrographs. Model cells are 300 by 50 feet in size; the shallow groundwater within about one half mile to each side of the river is modeled in multiple layers, with boundary conditions specified to reflect deeper aquifer conditions and lateral regional boundary conditions. Initially developed in 2000, the models for San Joaquin River Reaches 1, 2 and 4 were re-structured and re-parameterized in 2005 and used to evaluate seepage losses under a range of conditions. The Reach 1 and 2 models were re-calibrated using available flow and alluvial monitoring well data from the 2004 to 2005 period, including data collected during the large flood releases in May of 2005. The models are implemented in MODFLOW with river boundary conditions specified using HEC-2 model-generated water surface profiles. The models can evaluate near-river groundwater and groundwater/surface water interaction at high spatial and temporal resolutions.

Detailed transient modeling analyses of the riparian groundwater environment adjacent to the river indicate that numerous physical processes bear on the magnitude and timing of river seepage losses, and that the seepage losses may be impacted by changes that will be associated with river restoration. The analyses indicate that river seepage losses will vary seasonally and with flow levels as a function of regional groundwater conditions, riparian vegetation type and density, geomorphic changes affecting the hydraulic properties of the river bed and antecedent conditions. Model sensitivity results illustrate the dynamic and transient nature of surface water/groundwater interactions. The models provide a platform capable of assessing the transient seepage losses under restoration conditions planned for the San Joaquin River to support water acquisition and to monitor the effectiveness of water operations in meeting the target hydrographs. The predictive accuracy of the models can be further evaluated and improved as additional data are collected through expanded monitoring programs.

Introduction

Storage and diversion of water for various uses in the Central Valley have decreased the flows of the San Joaquin River over the past century. In 1999, entities represented by the San Joaquin River Riparian Habitat Restoration Program (SJRRHRP) desired a tool for assessing the mechanism of river losses/gains and groundwater conditions under various flow regimes. Five high-resolution, contiguous groundwater flow models, Figure 1, were developed for this program by S.S. Papadopulos & Associates, Inc. (2000), under a contract to the U.S. Bureau of Reclamation, to qualitatively explore the hydrologic dynamics that occur within the riparian zone in response to changes in river flow conditions and regional groundwater conditions. The riparian groundwater models incorporate river conditions (river width and depth) corresponding to specific flow levels as calculated using HEC-2 surface-water models. In 2005, the models were updated for three of the reaches, Reach 1, 2 and 4 (Hathaway, 2005). As part of the update, the models were restructured to use MODFLOW 2000 (Harbaugh et al, 2000) and significant new data were reviewed and incorporated into model re-calibration. The groundwater models can be used to evaluate water-level conditions in the riparian zone relevant to riparian habitat restoration along specific reaches of the river, and to evaluate river gains and losses under alternative hydrologic or land use conditions. The models have been applied to assess loss conditions in Reaches 1 and 2 under hypothetical restoration hydrographs (Hathaway, 2005).

Model Development

Model Structure

MODFLOW (Harbaugh et al. 2000) was used to simulate groundwater conditions. With some modification, this model can represent all of the processes that are important for simulating groundwater conditions in the riparian zone and can incorporate the HEC-2 surface-water model results. The finite difference grid for each modeled river reach contains up to a maximum of 495 rows, 795 columns (Table 1). Preliminary models utilized between 10 and 13 model layers to allow for detailed evaluation of potential impacts of vertical heterogeneity; updated models utilize only 3 layers, as field data to support the more detailed characterization do not exist. In the lowermost model layer, regional groundwater conditions are represented by constant head groundwater elevations at the boundary cells.

Within this framework, active cells are designated within about ½ mile on either side of the river. The fine-mesh spacing of approximately 300 feet by 50 feet allows accurate representation of

Table 1. Number of Model Rows, Columns for Modeled Reaches

Model Reach	Rows	Columns
Reach 1: Friant Dam to Gravelly Ford	495	795
Reach 2: Gravelly Ford to Mendota Dam	237	561
Reach 3: Mendota Dam to Sack Dam	277	525
Reach 4: Sack Dam to Bear Creek	488	657
Reach 5: Bear Creek to Merced River	178	387

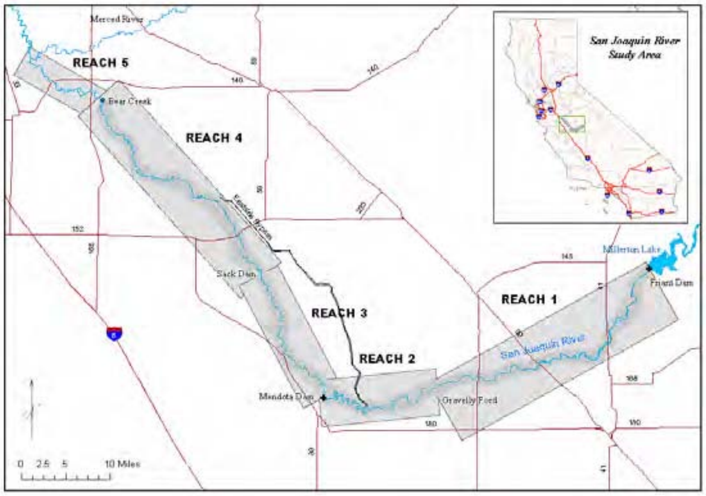

Figure 1. Location of San Joaquin River Riparian Groundwater Models, Friant Dam to Merced River

the stream geometry, changes in stream geometry with river stage, and the lateral position of the stream within the riparian zone.

River Conditions

Output from existing HEC-2 surface-water models (1-D step backwater model for open channel flow, COE, 1990) of the 150-mile stretch of the San Joaquin River (Mussetter Eng., Inc., 2005a, 2005b) were used to develop MODFLOW river conditions. The HEC-2 models are used to generate river stage and width at cross-sections located approximately every 500 feet along the river for a series of flow profiles. Flow profiles at the 5%, 20 – 30%, and 60% exceedence levels were initially selected to represent low, mid-range and high flow conditions for initial model development and sensitivity analyses. In subsequent work, HEC-2 model output was used to develop river width and stage for flow levels of 200, 500, 1,000, 2,000, 4,000, and 8,000 cfs. For each of these flow profiles, an input file for the MODFLOW River Package identifying inundated cells and the corresponding stage was prepared. The River Packages structured for each of these flow levels can be used in sequence, to match a given hydrograph as a step-function and to simulate changes to the river boundary condition during a transient simulation.

Soil Texture And Hydraulic Parameters

Geologic logs from over 300 wells drilled in the upper 100 feet of the aquifer were evaluated to obtain an idealized representation of the nature of the floodplain deposits. A soil texture analysis was conducted to characterize the lithology observed in wells and to develop representative conditions for various model sub-areas. Initial assignment of hydraulic conductivity values using the soil texture representation was conducted, drawing on studies specific to the San Joaquin Valley and other relationships. Parameters were adjusted during calibration for reaches where suitable data were available. Vertical hydraulic conductivity was based on an assumed vertical to horizontal anisotropy ratio of 1:10 in upper layers and 1:100 for the lowermost layer. In the preliminary models, soil moisture accounting was incorporated as an option into the MODFLOW analysis to represent soil moisture storage and depletion above the active water table. Parameters required for the vadose zone option were developed using the soil texture analysis of lithologic logs (Blum, Israel, and Larson, 2001). This feature was not applied in the updated models, as the shallow alluvial materials appear to be sufficiently permeable such that model results are not sensitive to this process at a time-scale spanning weeks and months, that is, over the course of a seasonal hydrograph.

The updated models were calibrated, to the extent possible, using ground water elevations and seepage loss rates observed during selected time periods, including the spring 2005 flood pulse. Hydraulic conductivity in the updated models ranges from 60 to 120 feet per day for layers 1 and 2, representing the upper 60 feet of alluvial material in the river corridor; to 3 feet per day in the lowest layer. A specific yield of 0.20 was assigned to the water table layer, and specific storage of 1×10^{-5} per foot was assigned to lower layers. Riverbed conductance is based on vertical hydraulic conductivity of 5 to 25 feet per day (for a corresponding thickness of one foot), decreasing downstream in reaches 1 and 2.

Regional Groundwater Elevations and Boundary Conditions

Regional groundwater conditions can be broadly assessed using the mapped information published bi-annually by the California Department of Water Resources. This information provides sufficient detail for setting regional boundary conditions on the riparian groundwater models for a specific time period or for hypothetical periods that might be characterized by average, high or low groundwater elevations. Alternately, specific boundary conditions for a future projected condition could be developed using a regional groundwater model. In the lowermost model layer, regional groundwater conditions are represented by constant head groundwater elevations at the boundary cells.

Groundwater conditions vary greatly along the 150-mile stretch of the San Joaquin River, with groundwater conditions associated with the occurrence of river losses being prevalent in upper reaches and with the occurrence of river gains more common in lower reaches. However, the spatial and temporal pattern of groundwater elevations and stream gains and losses can be complex and is influenced by numerous conditions and processes.

Evapotranspiration

Evapotranspiration (ET) rates for the riparian groundwater model have been assigned based on general classifications of riparian communities mapped from aerial photographs. Evaporation rates have been assigned to each general class, or zone, using a class multiplier and a potential evaporation rate for the time frame of interest. A seasonal model reflecting maximum evapotranspiration, to which the multipliers for vegetative class are applied, was derived using data for the Firebaugh area, obtained from the California Irrigation Management Information System. The derived relationship results in a potential ET rate averaging about five feet. The MODFLOW ET package is employed using an array of evapotranspiration potential rates and an extinction depth of ten feet. An alternate approach for ET handling is included in the vadose option (Blum, Israel, and Larson, 2001).

Sensitivity Of Riparian Zone Conditions To Regional Groundwater Elevations And River Operations

Preliminary model simulations were made to evaluate the sensitivity of riparian zone conditions to regional groundwater levels and to river operations (S.S. Papadopulos & Associates, Inc., 2000). For these simulations, three conditions were defined for the regional boundary condition and for the river condition, each representing a low, medium or high range condition. Combinations of these conditions were evaluated for each reach to illustrate the sensitivity of riparian conditions to variation in these parameters. These analyses are briefly summarized below.

- *Alternate river flow conditions*: A change in river conditions had a significant impact on simulated groundwater levels. In some cases, the low flow scenario resulted in hydraulic disconnection of a previously connected channel and in significant dewatering of the shallow riparian zone. Conversely, the high flow scenario resulted in shallow water depths across a significant area of the riparian zone. Seepage rates under alternate flow conditions varied significantly, and these differences varied widely by reach.
- *Alternate antecedent river conditions*: Seepage rates for a given hydrograph are impacted by antecedent river conditions and

corresponding groundwater levels. The sensitivity of seepage to antecedent flow conditions depends on reach lithology and other factors. The persistence of this sensitivity is dependent on the antecedent and subsequent flow magnitude: for example, a high peak flow of extended duration may "erase" the antecedent condition effect, but, a short-duration flow peak will incur greater than expected losses if it follows a below-average period.

- *Alternate river boundary conditions*: A change in the representation of regional groundwater levels at the model boundary, within ranges seen over recent years, can change seepage rates by a factor of 2; in some sub-reaches, regional boundary condition changes can shift river sub-reaches from gaining to losing conditions. The sensitivity of riparian zone water levels and seepage rates to changes in regional boundary conditions is more pronounced under low flow conditions, when less water is available to recharge and maintain head conditions in the riparian zone.

Application of Model for Riparian Water Management

The riparian groundwater models for the San Joaquin River riparian zone provide a tool to assess river losses/gains and groundwater conditions under alternate flow regimes, within the backdrop of regional land use and water development conditions. The general steps for applying the models to evaluate alternatives are to identify the hydrologic (i.e., regional water-level and river flow) and land use conditions (i.e., changes in riparian coverage or consumptive use rates); to update or refine the reach-specific hydrogeologic model arrays; to analyze the river restoration alternative and quantify the resulting groundwater elevations and river seepage; to check the calculated model seepage against surface-water modeling seepage assumptions; and to adjust and iterate, if necessary, to achieve reasonable balance between assumed surface-water model losses and calculated groundwater losses. The results obtained from this process can be used to quantify and characterize changes in riparian groundwater conditions and seepage losses that may be associated with river restoration alternatives.

The model has been applied to evaluate seepage losses associated with various proposed restoration hydrographs (Hathaway, 2005) under alternate regional groundwater and antecedent river flow assumptions. Among various restoration hydrographs considered, channel seepage losses ranging from 62,000 acre-feet per year to over 144,000 acre-feet per year have been calculated, with differences attributable to the magnitude and duration of flow, previous year conditions and regional groundwater condition assumptions. Greater variability is seen on a shorter time scale; for example, high losses are observed for high flow peaks of durations less than a week, particularly when occurring during a dry period.

Model uncertainty can be reduced through additional data collection and subsequent model refinement. Data useful in this process would include additional lithologic and hydraulic data from observation wells in and near the riparian zone at multiple transects within each model reach of interest; additional seepage runs for specific sub-reaches; and, updated riparian vegetation mapping.

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Development of Regional and Nested Local-Scale Ground-Water Models for Study of the Fate of Agricultural Nitrogen, Merced County, California

Steven P. Phillips, Christopher T. Green, Karen R. Burow, Jennifer L. Shelton and Diane L. Rewis

Regional- and local-scale models of steady-state ground-water flow were developed as part of a study of the transport and fate of nitrate from application of nitrogen fertilizers along a well-instrumented, 1-km transect near the Merced River (Phillips and others, 2007). A three-dimensional local model (17 square km) is nested within a regional model (2,700 square km) bounded by the Stanislaus, San Joaquin, and Merced Rivers and the foothills of the Sierra Nevada in northeastern San Joaquin Valley, California (fig. 1). The regional model provides hydrologically reasonable boundary conditions for the nested local model; both were developed using MODFLOW-2000.

The heterogeneity of aquifer materials was incorporated explicitly into the regional and local models. Three-dimensional kriging was used to interpolate sediment texture data from about 3,500 drillers' logs in the regional model area (Burow and others, 2004). The resulting distribution of sediment texture (fig. 2) was used to estimate hydraulic parameters for each cell in the 16-layer regional model.

Sediment texture data within the local model domain were used to generate multiple transition-probability-based realizations, using TProGS (Carle and Fogg, 1996), of textural distributions for the 110-layer local textural and flow models, which shared the same grid. Explicit depiction of textural heterogeneity in the local model (fig. 3) effectively incorporates macro-scale hydrodynamic dispersion into the flow model, allowing more direct comparison of particle-tracking results to tracer-derived estimates of ground-water age.

Water levels measured in multi-depth wells along the 1-km transect were used to calibrate the local model. The median error between simulated and observed values at 11 well locations was 0.12 m, less than 3 percent of the observed range along the transect. The calibration was evaluated using independent estimates of ground-water inflow to the Merced River and ground-water age estimates from concentrations of sulfur hexafluoride. The calibrated local model has been used to estimate source areas for water and nitrate sampled from the multi-depth wells, and as the basis for a reactive transport model used to better understand the transport and fate of nitrate in the aquifer system.

A report (Phillips and others, 2007) describing the development of the regional and local models can be downloaded from: http://pubs.usgs.gov/sir/2007/5009/.

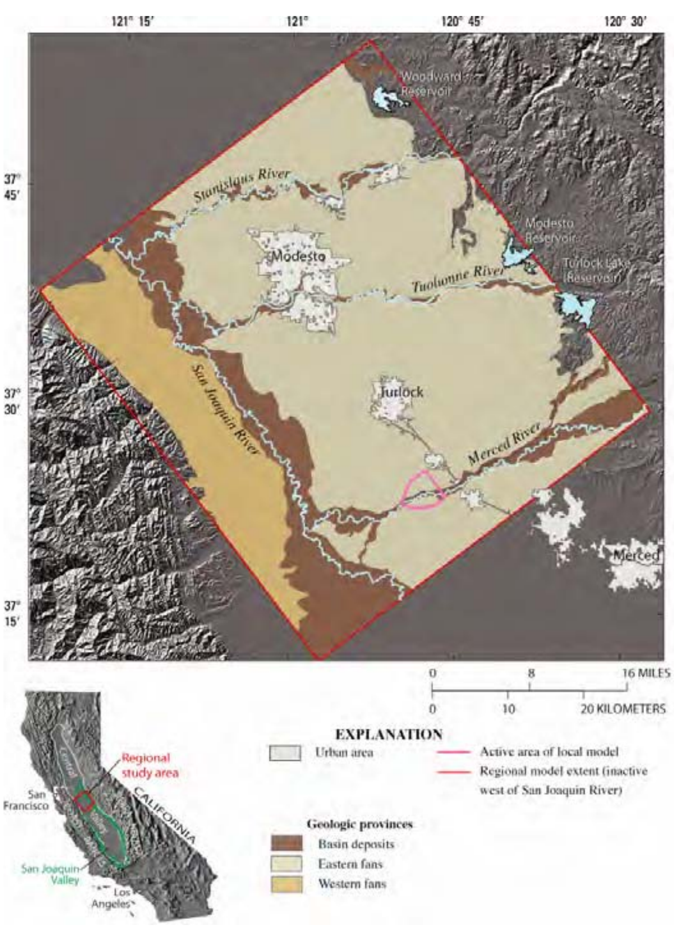

Figure 1. Study location.

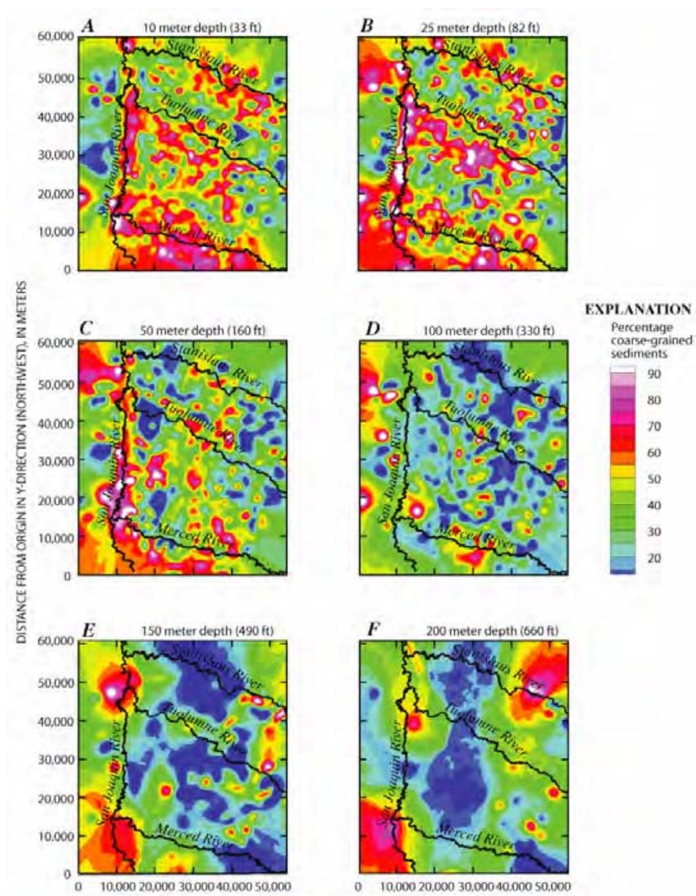

Figure 2. Two-dimensional slices through three-dimensional model of sediment texture.

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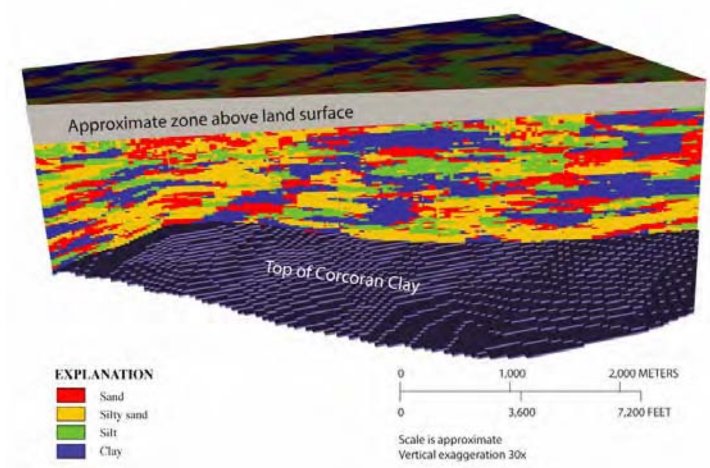

Figure 3. Vertical section roughly parallel to the Merced River showing distribution of sediments for one of 200 equally probable realizations.

Comparison of simulated travel time distributions and age tracer concentrations in samples from an alluvial fan aquifer, San Joaquin Valley, CA

Christopher T. Green and Barbara A. Bekins

A calibrated model of flow and transport was used to investigate the effects of heterogeneity on travel time distribution and age tracer concentrations in a ground-water sample. The study site included a 1-km transect of multi-level well nests near the Merced River at Delhi, CA, installed as a part of the US Geological Survey's National Water Quality Assessment Program. The model domain included a rectangular area of 24.6 km^2 and a depth of 55 m, discretized into a domain of 140 (x) by 110 (y) by 110 (z) cells. Multiple geostatistical realizations were created of subsurface geological features in pre-Holocene alluvial fans and Holocene alluvium using geophysical logs, drilling cores, and published maps of geological features. The distribution of hydrofacies in each geostatistical model was used to populate the hydraulic parameters in a 3-D flow model by assigning uniform values to each sedimentary category. Using artificial constant head boundary conditions, average flow was simulated three times for the x y and z directions, for all 200 realizations. The realizations were ranked based on average flow properties across the domain in the x, y, and z-directions, and six realizations were selected to represent mid-range and extreme cases of average hydraulic properties for further modeling studies. A site-specific 3-D flow model was made using MODFLOW with boundary conditions interpolated from the results of a regional model that included the transport model domain. Transport of age tracers was simulated with backward random walk particle tracking (RWHet). Using a parameter estimation routine (PEST) hydraulic conductivity, porosity, and dispersivity were calibrated in the flow and transport models to obtain a best fit between observed and modeled heads and concentrations of age tracers including sulfur hexafluoride (SF_6) and dichlorodifluoromethane (CFC-12). Calibrated models were used to estimate distributions of travel times in samples from existing ground-water wells and to simulate concentrations of additional, hypothetical age tracers for comparison of multiple tracer concentrations in individual samples. Results show that heterogeneity strongly influences the distribution of ages and the inferred ages of ground-water samples. Travel time distributions were strongly skewed and often multimodal. Near-surface heterogeneity in the recharge zones strongly influenced the characteristics of travel time distributions. As observed in previous studies, the inferred ages obtained by assuming piston flow were consistently lower than the arithmetic average of the travel time distributions, and this difference increased with the age of the sample. Inferred ages based on a single solute should be used with care, as the travel time distributions underlying them are complex and depend on highly variable local geologic features. Use of multiple age tracers can be used to parameterize lumped parameter models to correct bias due to mixing of travel times in a ground-water sample.

Introduction

Atmospheric age tracers provide estimates of recharge dates and travel times that are important for many ground-water studies. Recharge dates can be used, for example, to estimate the history of flux concentrations at the water table of non point source contaminants such as NO_3^- in agricultural areas (Böhlke, 2002). Estimates of travel time from the water table to the sample location (also known as "ground-water age") can be used along with other chemical data to estimate rates of reactions in ground water (see references in Green et al., 2008). Age tracer concentrations also serve as observations for calibration and validation of ground-water flow and transport models (Phillips et al., 2007).

Though inference of recharge dates and travel times from atmospheric age tracers has become increasingly common, available methods of interpretation remain in development. Some commonly used approaches are "lumped parameter models" such as the piston flow model, exponential model, and the exponential-piston model, which allow quick estimates based on assumptions of simplified spatial dimensions and homogeneous flow and transport properties (Cook and Böhlke, 2000). The piston flow model assumes that all water in a sample recharged simultaneously. The exponential model assumes that the ground-water age distribution in a sample is an exponential function. Exponential-piston models are intermediate between the piston and exponential models, with the shape of the curve determined by a parameter, ξ (Fig. 1). This model results from the analytical solution for 2-D advective flow in hypothetical scenarios where a well or discharge point samples a volume of water that originated from a distant recharge area. The exponential portion of the distribution results from the assumption of uniform, distributed recharge, and the piston flow offset is created by advective flux below the water table from the recharge zone to the sample location. For realistically complex scenarios in heterogeneous aquifers, relatively little work has been done to investigate the effects of flow and dispersive transport on the inference of ground-water ages from atmospheric tracers (Weissmann et al., 2002), or to use these simulation methods in combination with the lumped parameter methods to explore improved methods for interpreting age tracer concentrations.

In this study, a direct simulation approach was used to study the effects of mixing due to geological heterogeneity on age tracer concentrations and the feasibility of using lumped parameter approaches to correctly infer mean ages from tracer concentrations. For individual ground-water samples from a heterogeneous alluvial fan aquifer in the San Joaquin Valley, California, realistic age distributions were generated from calibrated flow and transport simulations. The distribution of ages in each sample was used to determine the simulated average age. To evaluate the effects of geological variability on the interpretation of age tracer data, simulated average ages were compared to ages inferred by applying the piston flow model to simulated tracer concentrations. Simulated age tracer concentrations were also analyzed with the exponential-piston model to explore the feasibility of using this model to interpret age tracer concentrations in heterogeneous geological settings.

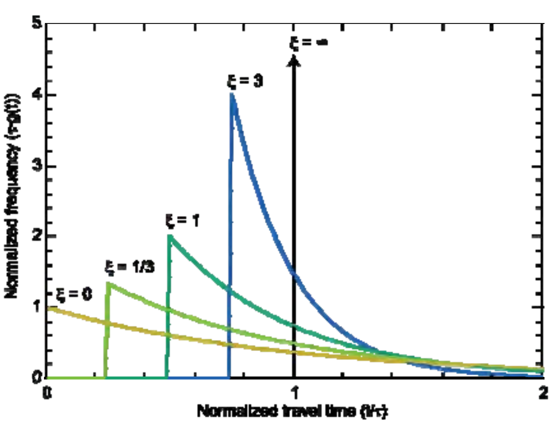

Figure 1. Lumped parameter models of hypothetical ground-water age distributions in a sample. The function g(t) is the age frequency distribution, τ is the average age, and t is time. The variable ξ corresponds to x*/x in Cook and Böhlke (2000). The curves show forms of the exponential-piston models for various values of ξ. At ξ = 0, the function is equivalent to the exponential model. As ξ approaches ∞, the distribution function approaches the piston flow model.

Methods

Instrumentation And Sampling

A 1-km transect of 11 nested monitoring wells was installed north of the Merced River at Delhi, California in the summer of 2003 in corn fields and almond orchards (Fig. 2). Wells were installed using air hammer and mud rotary methods. Monitoring wells were constructed of 5 cm diameter PVC with 60 cm long screens at depths of 8 to 30 meters below ground surface. Water levels were measured with steel tapes and pressure transducers equipped with data loggers.

At the end of the 1-km transect, 20, 5 cm diameter PVC monitoring wells were installed in or near the Merced River at depths of 0.3 to 2.8 meters. Screen lengths were 15 to 30 cm. Three of the 2.8 m-depth wells were selected for inclusion in this study on the basis that the samples did not appear to be strongly influenced by surface water as indicated by major ion chemistry and did not appear to have degassed or to be under-pressured with respect to the atmosphere based on dissolved gas analyses.

Water samples were collected for dissolved gas and age-tracer analysis in late June and early July, 2004. Sampling procedures are described by Capel et al. (2008, supplementary material). Concentrations of age tracers were analyzed by the USGS CFC-laboratory in Reston, VA. SF6 concentrations were obtained for 11 transect wells and 3 in-stream wells.

Only one apparently reliable CFC-12 concentration was obtained for one transect well. Many CFC samples appeared to be contaminated or degraded. As described in Green et al. (2008), age tracer

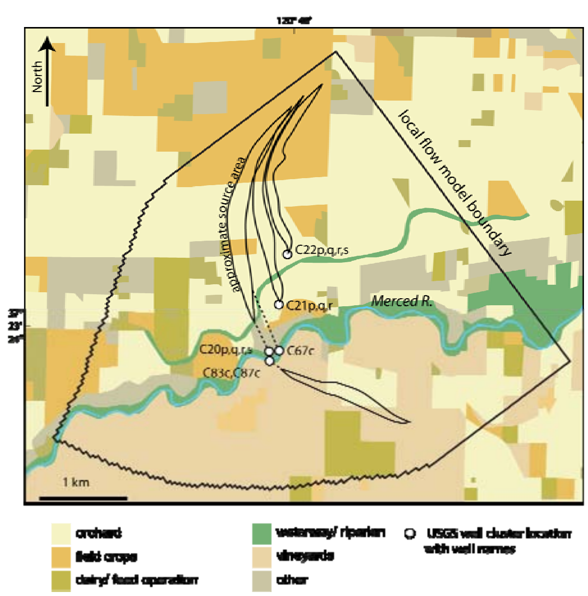

Figure 2. Site location map showing land use, model domain boundaries, monitoring well locations, and approximate source areas as determined by backwards random walk particle tracking.

concentrations were adjusted to account for dissolution of entrapped air bubbles, as indicated by dissolved gas analyses.

Simulation Methods

Two-hundred Transition Probability Geostatistics (TProGS, Carle and Fogg, 1996) realizations were generated for the model study area. The model domain included a rectangular area of 24.6 km^2 and a depth of 55 m. Realizations were discretized at a scale of 40 m in the X- and Y- directions and 0.5 m in the Z-direction. The realizations were ranked according to their domain-scale hydraulic properties. Using MODFLOW2000 (Harbaugh et al., 2000), the domain-scale hydraulic conductivity was calculated for each realization in the x, y, and z directions using simulations of flow with uniform hydraulic gradient in the direction of flow and no flow boundaries on the sides of the domain perpendicular to flow.

Six realizations were selected from unidirectional flow simulations for conducting simulations with realistic boundary conditions. The six realizations were chosen to represent a range of isotropic hydraulic properties (i.e. minimum, maximum and median of X + Y + Z flow), and anisotropic hydraulic properties (i.e. maximum and minimum and upper quartile of (Z/(X+Y)) flow). For the steady-state local flow models, constant hydraulic properties were assigned to each of the four hydrofacies (clay, silt, silty sand, sand) in the realizations. Boundary fluxes on vertical faces of the local flow models were assigned by distributing fluxes from adjacent cells in a regional model. The flux assigned to each local model cell was weighted by the cell's hydraulic-conductivity. Recharge to the water table was specified for individual parcels on the basis of estimated crop demands and irrigation methods. These details and additional information about the regional and local flow models are described by Phillips et al. (2007).

Transport modeling was done using RWHet (LaBolle et al., 2000). One-thousand particles were introduced at each of 14 screen locations and backward tracked with random walk simulated dispersion to the water table or local-domain boundaries. Scenarios were run with particles assigned along the full length of the well screen and at a single point at the center of the screen. The age of each particle at the time of sampling was assigned based on the travel time between the well screen and the water table. For a small number of particles that arrived at the local model boundary, the total travel time was calculated as the dispersive travel time to the boundary cell, plus an advective travel time from that boundary cell to the regional model water table. Advective travel times were determined using MODPATH (Pollock, 1994). Such adjustments only occurred for particles with travel times greater than 40 years, which tended not to strongly influence calculated concentrations, and occurred for only about 1-2% of the particles in the domain.

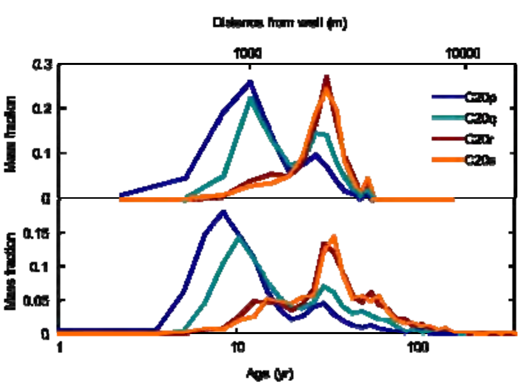

Figure 3. Graphs of the mass fraction of water as a function of the distance between the recharge location and the sample location (upper figure) and the mass fraction of water as a function of ground-water age (lower figure) in ground-water samples from well cluster C20 in one realization.

Modeled concentrations corresponding to sample concentration data were computed using a program module with inputs of travel times of each particle in each sample, as provided by the RWHet simulations. Concentrations of SF_6 and CFC-12 were assigned to each particle based on the calculated equilibrium with water of the historical atmospheric concentration of these atmospheric contaminants when the particle was at the water table (Busenberg and Plummer, 2000). The concentration in each sample volume was set equal to the average of the sample's particle concentrations.

The combined flow and transport models were calibrated using PEST (Doherty, 2004), a numerical code for nonlinear parameter estimation. The porosity, dispersivity, and vertical hydraulic conductivity of the underlying semi-confining layer were adjusted to minimize the error between modeled and measured observations of hydraulic head and age tracer concentrations. The conductivity values of other hydrofacies in the model had been calibrated previously (Phillips et al., 2007) and were not adjusted for this study.

Results and Discussion

Calibrations achieved a reasonable fit between simulated and measured age tracer concentrations and hydraulic heads. Among the six realizations, the root mean square errors (RMSE) of SF_6 estimates were in the range of 0.5 to 1.0 parts per trillion by volume (pptv), which corresponds to +/- 5 to 10 years for water recharging after 1980. For CFC-12, RMSEs were 20 to 60 pptv among the six realizations, which corresponds to +/- 1 to 3 years for water recharging between 1970 and 1990. Hydraulic head RMSE ranged from 0.3 to 1.0 meters. Estimated values of porosity were between 0.38 and 0.40, similar to the average of measured values of aquifer material, which was 0.38. Estimated isotropic dispersivities were between 0.001 and 0.008 m. Because the 3-D model accounts for macrodispersion explicitly by incorporating grid-scale heterogeneity, these dispersivity values represent dispersion below the scale of the 40 m x 40 m x 0.5 m grid cells.

Results show that travel time distribution in a sample was strongly skewed and often multimodal. Figure 3 shows examples of ground-water travel time distributions for samples taken from monitoring wells near the Merced River. In the graph of mass fraction of water versus ground-water age, shallow wells C20p and C20q have two peaks at about 10 and 30 years. The distributions for deeper wells C20r and C20s have one major peak at about 30 years, coinciding with the second peaks for C20p and C20q. The plots illustrate that ground-water age distribution in a sample is complex, and are not consistent with the assumption of a single uniform age for an entire sample.

As also indicated in Figure 3, heterogeneity influences the distribution of ages and the inferred ages of ground-water samples. The shape of the age distributions match the curves in the upper plot of mass fraction of water versus the distance from well to the recharge location. The similarity between the age and recharge location distributions indicates that the shape of the age distributions are controlled by the locations of recharge. Recharge tends to travel faster where coarser sediments are present at the water table. Additional comparisons of source areas with geology at the water table (not shown) further indicate that geological features near the water table influence the source areas and travel time distributions of each ground water sample.

Errors associated with inferring age from atmospheric age tracer concentrations in mixed samples are shown in Figure 4. Each point on the graph is a simulated sample from one of the six realizations. The X-axis shows the average age of the ground water in the sample, equal to the arithmetic mean of the particle ages. The Y-axis shows the inferred age determined by comparing the simulated concentration of age tracer in the sample to theoretical curves derived from the historical atmospheric concentrations of SF_6 and CFC-12. Filled points use the piston flow assumption that all water in a sample recharged simultaneously. For SF_6 using the piston flow assumption, inferred ages are similar to average ages for samples recharged within the last 20 years. For samples older than 20 years, the inferred age is younger than the average age because the atmospheric concentration curve is non-linear, with a slope that approaches zero for ages older than 40 years. For CFC-12, inferred and average ages are similar for samples recharged approximately 20 years ago. Younger samples are subject to error due to recent decreases in atmospheric CFC-12 concentrations that result in multiple interpretations of a single concentration. Older samples are subject to the same bias as SF_6 because of the similar shape of the atmospheric concentrations curves. This result for CFC-12 has been previously observed at another site in the Central Valley, California, by Weissmann et al. (2002).

A calibrated exponential piston model (EPM), was able to predict mean ages from tracer concentrations without bias. Figure 4 shows inferred ages based on an EPM model with ξ = 0.6. The value of ξ was determined by comparing simulated concentrations of SF6 and CFC-12 in each sample from all six simulations. When compared to the simulated average age, the EPM estimates of average ages (empty symbols) are equally distributed above and below the 1:1 line. With additional simulation-based studies of ground-water ages, it will be possible to explore whether EPM can be applied in a variety of geological and hydrologic settings.

It is important to note that the EPM is used in this study as an empirical distribution and not as an analytical solution for a particular advective transport scenario. The physical meaning of ξ from previous analytical solutions stems from the assumption that the age distribution is controlled by simple geometric features such as screen length. In contrast to the EPM model, particle simulations with heterogeneous hydraulic conductivity showed that mixing in the screened interval had a negligible effect. Simulations with particles introduced at a single point at the center of the screen yielded nearly identical results to simulations with particles introduced along the full length of the screen. Therefore, ξ estimates should account for dispersive effects, for example by calibrating to multiple age tracers.

Conclusions

Based on simulations of flow and transport in an alluvial fan aquifer near Delhi, California, the distributions of ages in a ground-water sample appeared complex and depended on highly variable local geological features. Ground-water age distributions were strongly skewed and were often multimodal. The exact shape of a distribution appeared to be largely controlled by the location of recharge areas

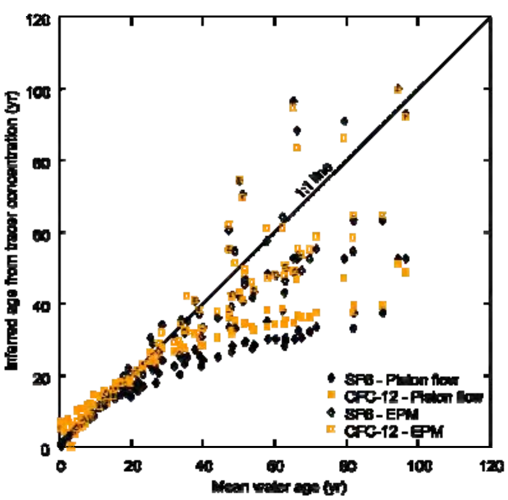

Figure 4. A comparison of mean ground-water age to inferred age from tracer concentrations. Each point represents a single, simulated sample. Points on the graph are from simulations using all six realizations of the geology. Inferred ages are based on CFC-12 and SF_6 concentrations using an assumption of piston flow or exponential-piston model (EPM) distributions of ages.

contributing to the well sample. Because of the complexity of the age distribution and the non-linear changes in atmospheric age tracer concentrations over time, the piston flow age inferred from tracer concentrations did not match the average ages of the ground water sample. This bias depended on dispersive characteristics of the aquifer as well as the particular age-tracer, so inferred ground-water ages from a single age-tracer should be used with care, especially for cross-site comparisons. As demonstrated by comparisons of simulated CFC-12 and SF_6 concentrations, lumped parameter models can be calibrated using multiple tracers to correct the bias in age estimates. Additional work with numerical simulations of ground-water age will help to explore the possibility of establishing parameter values for lumped parameter models across a variety of geological and hydrologic scenarios to improve simple estimates of ground-water ages from atmospheric age tracer concentrations.

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WESTSIM: Groundwater conjunctive use, agricultural drainage and wetland return flow simulation on the west-side of the San Joaquin Basin

Nigel W.T. Quinn and Jafar A. Faghih

WESTSIM is a detailed groundwater and surface water simulation model of the west-side of the San Joaquin Valley covering the entire federal service area. WESTSIM differs from previous regional groundwater models of the west-side of the San Joaquin Basin in its detailed depiction of irrigation hydrology, the use of a monthly time step to improve simulation of aquifer recharge and subsurface drainage and simulation of seasonally managed wetlands in the model domain. WESTSIM was the first application using the new IWFM model code, developed within California Department of Water Resources. WESTSIM results to date have demonstrated that the evapotranspiration (ET) values used in current hydrologic models of the west-side of the San Joaquin Basin are too high and fail to account for deficit irrigation practices on certain crops – it is impossible to produce realistic tile drainage estimates that match field data unless calculated ET values are reduced by up to 20%. A unique groundwater data management tool, named SHEDTOOL, which allows entry, storage, retrieval, and presentation of groundwater and surface water data, was enhanced to allow WESTSIM simulation results to be interpreted by a wide spectrum of stakeholders. Customized post-processing spreadsheet tools were also developed to elicit interaction with agency staff and water district managers.

Background

In early 2003 a model peer review of the Integrated Groundwater Surface Water Model (IGSM) code (Boyle Engineering Inc. 1990) by the California Water and Environmental Modeling Forum (CWEMF) revealed deficiencies in the code related to the linearization of the groundwater flow equations and the computation of subsurface tile drainage. An improved model code (IGSM2) was released publicly in early 2004 which addressed these and other deficiencies together with comprehensive theoretical documentation and a user manual. The model code was renamed IWFM (Integrated Water Flow Model) in September 2005 to reduce confusion with the original model code and subsequent improved versions of the original model code made by some of the original contributors to IGSM. The author of IWFM, Dr. Can Dogrul (DWR) was awarded the Fischer prize by CWEMF in 2003 for his work on the new model.

The WESTSIM application of the IWFM model code uses finite element techniques to simulate the hydrologic cycle's various components and how these components interact. The most important components are the stream/aquifer interaction, subsurface drainage simulation and soil moisture accounting. The model also simulates phenomena such as surface water reuse and seasonal wetland hydrology that have hitherto been ignored by regional groundwater models of the Basin. The model consists of 61 sub-regions that include both water districts and wildlife refuges (Table 1). The model is unique in its resolution at the water district level, the attention devoted to developing accurate land-use data and the graphical user interface and data management system

Model Applications

The WESTSIM model was developed by U.S Bureau of Reclamation (Reclamation) for a number of applications that could not be addressed by existing regional groundwater models these applications included :

Impacts of Reductions in Contract Water Deliveries on Aquifer Subsidence.

The Central Valley Project (CVP) and State Water project (SWP) were authorized in the 1960's to address pumping-induced aquifer subsidence throughout large areas within the western San Joaquin Valley. Surface water deliveries from the Delta began to reverse the rate of decline of pieziometric heads and helped to stabilize the irreversible decline in aquifer storage brought about by consolidation. The current regulatory climate and recent decline in annual snowpack storage have encouraged greater use of groundwater with the attendant increased risk of renewed subsidence. WESTSIM is being applied to determine the areas most vulnerable to subsidence impacts.

Increased Competition for Water – Impacts to Stream Flow in the San Joaquin River

During dry and critically dry years flow in the San Joaquin River from east-side tributaries is significantly diminished and the role of groundwater contributions to the River becomes more important both in terms of the total flow volume at Vernalis and water quality. Low flows in the San Joaquin River create irrigation diversion problems in the South Delta due to insufficient head above the pumps, low flows through the Stockton Deep Water Ship Canal are the cause of low dissolved oxygen in the late summer. WESTSIM is being used to calculate the impact of groundwater conjunctive use on groundwater accretions to the San Joaquin River.

Climate Change Impacts on Water Supply Reliability

Climate change studies have suggested a trend of reduced annual Sierra snowpack, earlier snowmelt and increased winter season runoff due to increased atmospheric CO2 levels and warmer mean temperatures. WESTSIM and the basin-wide C2VSIM model (DWR) are being linked to CALSIM-II and CALSIM-III models to better understand the regional impacts of climate-induced changes in the hydrology of the San Joaquin Basin and resultant impacts on State and Federal water allocation. Since climate impacts affect the east-side tributaries and the east-side water districts that rely on river diversions as well as project water pumped from the Delta – WESTSIM shows the impacts on potential groundwater pumping patterns on the west-side of the San Joaquin Valley. Climate change will also impact the 180,000 acres of seasonal wetlands within the San Joaquin Valley. DWR is collaborating with Reclamation in improving the algorithms for both seasonal wetlands and rice hydrology (since they both require the ponding of water above the land surface). At the present time the Lake routine in IWFM is used to create wetland impoundments which are regulated using a weir structure that is simulated at the outlet of each Lake. A time series of weir elevations controls monthly surface drainage from each impoundment.

Technical Assistance to Water Districts and Refuges Facing Salt, Boron and DO TMDL's

Reclamation's partner in WESTSIM development, MWH Americas Inc. (MWH), developed a spreadsheet post-processing tool, which works much like the MODFLOW zone-budget post-processor, and parses IWFM output from each simulation run into individual water district water budgets. The design of these water budget spreadsheets was development in partnership with two west-side water districts in order to convey the maximum of information in an intuitive format. These spreadsheets have been used by managers within Reclamation's Water Conservation Program to compare to water budgets required of Reclamation contactors as part of the Contract renewal process.

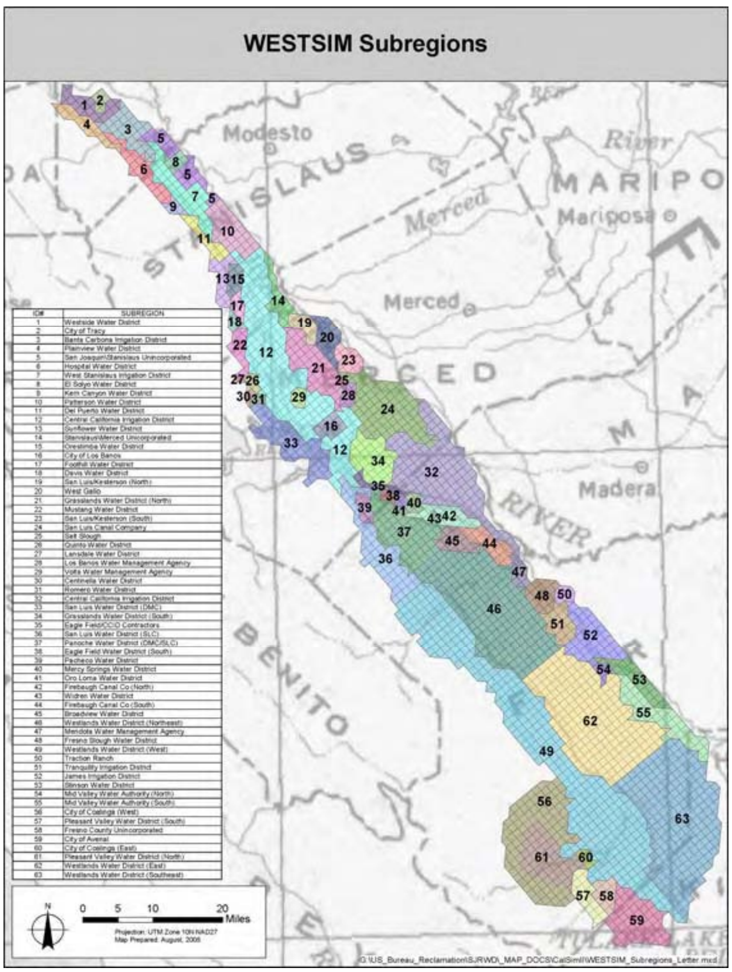


Figure 1. Water districts are represented as individual WESTSIM subregions. In the case of large water districts such as Central California Irrigation District (CCID) and Westland Water District (WWD) the area is subdivided into component subregions according to water delivery (in the case of CCID) and water allocation and drainage conditions in the case of WWD.

Model Development

One of the most frustrating aspects of regional groundwater modeling is the desire of most groundwater analysts to create their own unique model mesh and aquifer discretization while using the same basic information to develop their models. This makes direct comparisons of model performance very difficult. This tendency was resisted on the WESTSIM development project given that Reclamationhad spent more than 8 million dollars since the San Joaquin Valley Drainage Program in 1986 on USGS groundwater research which included the initial development and refinement of a regional groundwater model of the south-west San Joaquin Basin (initially published by Belitz et al., 1993 and revised later by Brush et al., 2006). Reclamation determined that the USGS dataset was better than any other dataset for the area of common coverage.

Reclamation's resources during the development of WESTSIM were therefore applied to working collaboratively with the USGS improving and extending the existing model datasets (Brush et al, 2006). These included more attention to accurately representing water deliveries and diversions, improved accounting of crop acreage by water district which has led to more accurate estimates of crop evapotranspiration. WESTSIM has used the same six layer aquifer layering as used by the first update to the original Regional Groundwater Model (Belitz et. al., 1993) which divided the above-Corcoran aquifer into 5 distinct layers, (20ft, 50ft, and a ratio of 2:3:5 for the remainder of the semi-confined aquifer above the Corcoran Clay) with a single aquifer layer below the Corcoran Clay. In WESTSIM, a seventh aquifer layer was added to represent the Corcoran (Clay). IWFM simulates the hydraulic properties of both aquifers and aquitards whereas MODFLOW simulates only aquifers and uses an aquifer leakance parameter to describe flow between adjacent aquifers.

WESTSIM used the same general alignment as the original Belitz et al (1993) model and has incorporated the texture based aquifer hydraulic properties first developed by Belitz and Phillips (1992) and later described in Brush et al. (2004) which were used in a revision to the original (Belitz et al, 1993) model. The alignment of the model to the north-east correctly follows the axis of the Basin and regional groundwater flow is roughly orthogonal to this alignment. Datasets for federal water deliveries, irrigation stream diversions, water district cropping and crop evapotranspiration were developed jointly and common datasets used in WESTSIM and the updated USGS south-western San Joaquin Basin model.

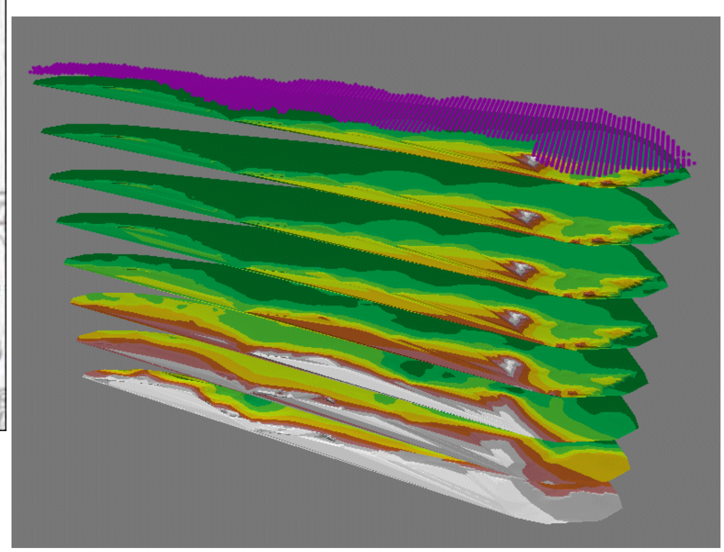


Figure 2. Aquifer texture-based hydraulic conductivity (white – highest) for the 7-layer WESTSIM model.

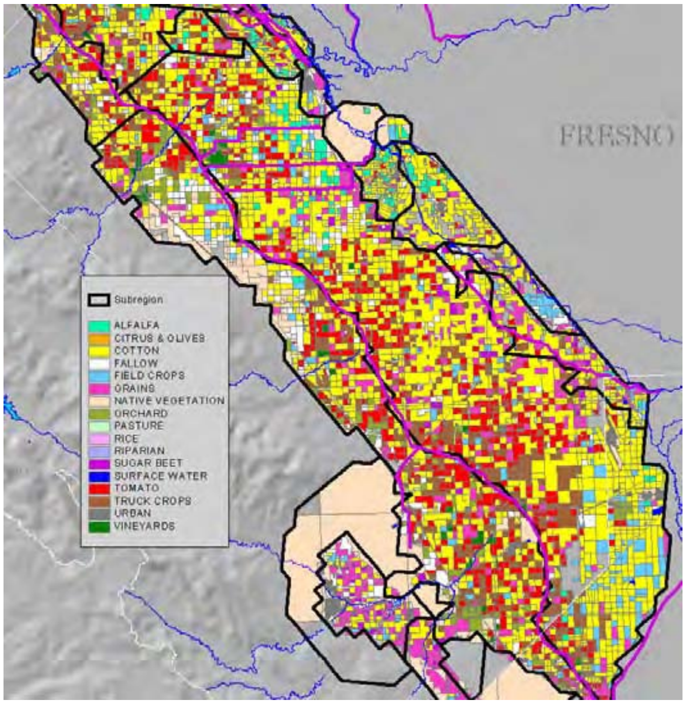


Figure 3. Cropping maps developed by DWR for the Central Valley on a 5-7 year cycle.

WESTSIM Crop-Based Water Requirements

One of the most significant features of WESTSIM has been its use of detailed water district crop data to improve monthly estimate of aquifer recharge and crop evapotranspiration. Crops were lumped into 19 proxy crop categories based on seasonal water requirements. These categories included fallow land and both seasonal and permanent wetland categories. Each proxy crop was assigned a mean monthly water consumptive use estimate based on historic data. The proxy crop category was typically estimated by the crop grown most widely in the WESTSIM model domain. Because DWR and Reclamation have different crop categories – these were independently associated with the proxy crop categories.

Data was obtained from Reclamation archives and directly from water districts. There were often discrepancies between the two estimates. Water districts provide Reclamation with provisional cropping estimates ahead of each growing season – these estimates can be changed at the time of planting. Although the Water Districts update their records this is not typically done within Reclamation – hence there can be errors in Reclamation database. Records for crops planted during the early 1970's are very poor or non-existent from both Reclamation archives and local water districts. These data were estimated, where necessary using 5 year average cropping data or by emulating cropping trends from adjacent water districts.

Every 5-7 years from the 1980's onwards DWR has obtained remote sensing imagery and has developed cropping estimates on a 1 mile grid over the entire Central Valley. These data were used to verify the Reclamation and local water district data – these were used preferentially for the year in which the surveys were taken if there were large discrepancies.

Surface Drainage – Rivers And Streams

Surface drainage in the model study area is complex given the number of ways surface water can be intercepted as it flows across the Basin towards the San Joaquin River. In Westlands Water District (which has no drainage outlet) and in the Grasslands agricultural areas there has been a moratorium on surface drainage leaving each farm field since the late 1980's (in the case of WWD) and since the Grassland Bypass Project, which commenced in 1996 (in the case of the Grasslands agricultural area). Tailwater is typically collected in sumps located at the lowest corner of each field and returned to the head ditches for blending with surface water supply. The initial approach to determining surface drainage within the Basin utilized the Digital Elevation Model (DEM) data. A robot was developed within GIS which queried surrounding raster cells, within a defined search radius, finding the most likely flow path and the natural drainage of the region (Figure 4) based only on elevation data.

The Stream Characteristic File that was initially developed using this approach was subsequently modified after it was determined that this early termination of the west-side ephemeral streams, although physically accurate, caused problems with routing of the stream flow and with convergence of the groundwater model. Hence, each of the ephemeral stream reaches was extended to intersect the San Joaquin River, creating a more complete stream network. These extended reaches were assigned high streambed hydraulic conductivity to encourage the percolate into the groundwater, rather than contributing any significant amount of surface water to the San Joaquin River.

Subsurface Drainage

Maps of subsurface tile drainage show the greatest density of drains in the vicinity of the west-side alluvial fans which extend eastwards from Little Panoche Creek, Panoche/Silver Creek, Cantua Creek, Salt Creek and Los Gatos Creek on the west-side of the San Joaquin Valley. Only the alluvial fans of Panoche and Little Panoche Creek are underlain by tile drains (Figure 5) that discharge into sumps and through drainage canals into the san Joaquin River. One of the most valuable data sets that has been developed in the past decade has been the subsurface drainage monitoring database for the Grasslands agricultural area. Sumps were monitored for both flow and EC weekly in all seven participating water districts including Panoche, Pacheco, Broadview, Widren, Charleston, Firebaugh Canal and the Camp 13 portion of CCID. This data set has been invaluable in WESTSIM initial calibration and has helped to point out some possible flaws in the way ET is estimated for some west-side agricultural crops which results in

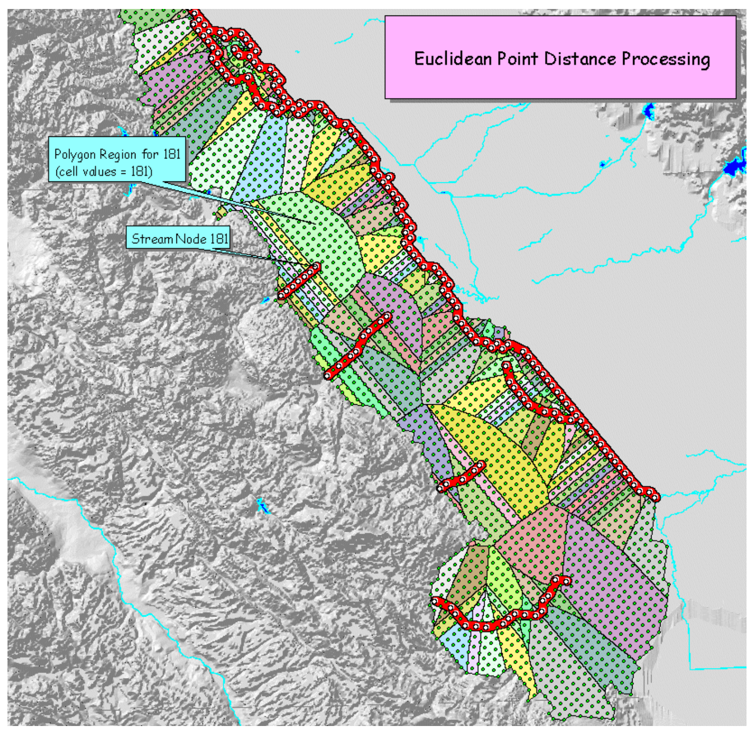


Figure 4. Euclidian point distance processing using a "robot" to determine likely surface drainage flow paths. In WESTSIM every point in the watershed is connected to a river node.

lower than expected deep percolation rates within water districts in the Grasslands sub-basin and in WWD.

Model Calibration

WESTSIM model calibration is ongoing. Initial model calibration was completed in two phases : first water budget calibration, followed by groundwater level and streamflow calibration. The first phase was intended to ensure that the model was accurately simulating the key components of the groundwater basin's hydrologic water balance. This concept simply states that inflow minus outflow to the basin is equal to the change in storage within the groundwater basin. WESTSIM tracks the movement of all of the primary sources of water coming into and leaving the basin, including rainfall, streamflows, applied water, consumptive use, and subsurface inflows and outflows. The model output that is reviewed during this phase of calibration includes annual and monthly water budgets for groundwater, streamflow, soil moisture, and land and water use for the entire modeled area and selected subregions.

The water budgets developed for the project to encourage stakeholder review of the model have been especially useful in eliciting feedback from water district managers who would have difficulty digesting one of the typical IWFM output files but can relate to spreadsheet outputs such as water table rise/fall expressed in acre-ft/acre or drainage outflow summed for the entire water district in acre-ft/month. Figure 6 illustrates the water budget designed for stakeholder review.

The preliminary water budget was further refined during the course of the study to take advantage of a revised hydraulic conductivity averaging algorithm applied to the USGS regional MODFLOW model of the southwest San Joaquin Basin. These revised hydraulic conductivity parameters, helped to improve the deep percolation of water – which was found to be insufficient to generate the required volumes of tile drainage. Secondly, the crop efficiencies, ET, soilmoisture, specific yield, and porosity were all refined to better reflect physical conditions and to improve the overall water balance. Another model feature was to improve the representation of reuse water in WESTSIM – which required that changes be made to the IWFM code. Reuse of both surface and subsurface drainage water has become an important part of irrigation management since the late 1980's and any model that attempts to realistically simulate irrigation hydrology needs to include this additional resource. In previous versions of IWFM, reuse water was simply taken as a constant percentage of return flow. However, the eventual destination of this water was not clear in the original code. A clearer definition of irrigation reuse was developed and reuse was added as a time series variable allowing WESTSIM to simulate improvements in reuse technology over the 1970-2000 simulation period.

Significant Findings

Significant findings to date include evidence that the crop coefficient-based ET estimates, commonly used in groundwater simulation models of the Basin, seem to over-predict evaporation losses by as much as 20%. This finding was confirmed through conversations with Jerry Robb (Westlands Water District) who has been reviewing ET estimates made using the SEBAL method within the District. The conclusions drawn from analysis of remotely sensed thermal data was that much of WWD was practicing deficit irrigation – essentially growing crops with lower volumes of water than the scientific literature suggests is needed. The WESTSIM finding, previously reported to DWR, was later confirmed by CH2M-Hill, who were tasked to calibrate the C2VSIM model. They discovered, what our team discovered during calibration – that the model generated insufficient deep percolation to allow the production of tile drainage.

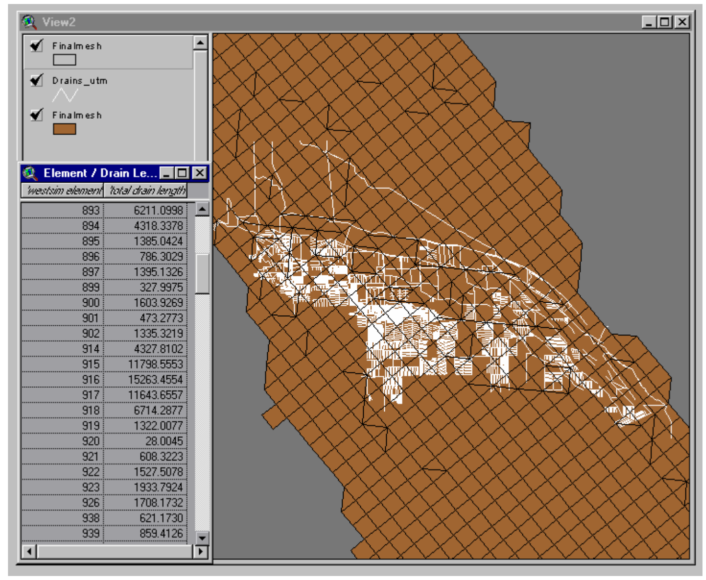


Figure 5. Subsurface tile drainage laterals in the Grasslands agricultural area and WWD as of 1990. Most tile systems were installed in the 1960's and 1970's as a means of controlling soil salinity and to help reclaim soils to allow the cultivation of salt sensitive crops.

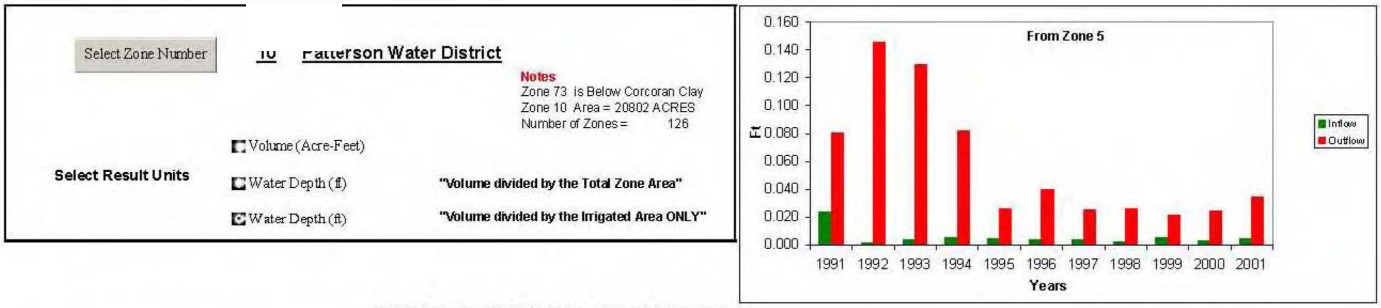
Current continuing model calibration is attempting to develop a deficit irrigation factor that can be applied in a consistent manner over the watershed to attempt to improve the model water balance. DWR has officially requested and received the current WESTSIM model and have made commitments to assist in further calibration efforts through the use of the PEST Inverse Modeling software. C2VSIM has undergone calibration using the same approach.

The WESTSIM database has been extensively used in the development of the CALSIM III hydrology for the San Joaquin Basin. The mapping of drainage outflow from individual elements within each water district to the San Joaquin River has had great utility in reworking the more detailed CALSIM-III model network.

Groundwater Data Management GUI

WESTSIM model development was facilitated through the application of a unique groundwater data management tool, developed within MWH, named SHEDTOOL. SHEDTOOL recognizes that groundwater management depends on data accessibility and data sharing between models and analytical tools. SHEDTOOL is a stand-alone application, developed by Jonathan Goetz, which allows entry, storage, retrieval, and presentation of groundwater and surface water data, recognizing that groundwater data are generated in many forms, stored in various formats, and maintained by numerous private, local, state, and federal agencies. SHEDTOOL is being used by others such as the Sacramento Groundwater Authority to implement the objectives from its Groundwater Management Plan where the collected data is used to assess the progress of its various management projects and programs.

Having the model interface with data analysis and storage, empirical relationships based on historical data can be used to develop, calibrate, and update groundwater models. Various improvements were made to the SHEDTOOL, such as the compiling of DWR, USGS, and Reclamation groundwater data in the region. Improved model interface features were added as well as other graphical data management tools. Also added was a "Z-Budget" Summary spreadsheet tool, that would display the output from DWR's "Z-Budget" post-processor, in a graphical and tabular spreadsheet. These data were summarized in a way that were more user-friendly than the raw Z-Budget output, therefore they would be easier for water managers that were most concerned with the "bottom-line" and needed to make decisions based on the model's recommendations,



IGSM2 ZONE BUDGET IN Ft FOR ZONE 10

Inflow	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	AnnuAvera
Streams Loss to GW	1.43	0.79	0.51	0.49	0.14	0.43	0.17	0.19	0.16	0.26	0.18	0.43
Tile Drains	-	-	-	-	-	-	-	-	-	-	-	-
Subsidence	-	-	-	-	-	-	-	-	-	-	-	-
Net Deep Percolation	6.27	3.07	3.32	3.78	0.75	2.13	1.48	1.37	1.77	1.22	1.37	2.41
General Head BC	0.03	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
Small Watershed Baseflow	-	-	-	-	-	-	-	-	-	-	-	-
Diversion Recoverable Loss	-	-	-	-	-	-	-	-	-	-	-	-
Bypass Recoverable Loss	-	-	-	-	-	-	-	-	-	-	-	-
Lakes(Wetland)Loss to GW	-	-	-	-	-	-	-	-	-	-	-	-
Pumping by Element	-	-	-	-	-	-	-	-	-	-	-	-
From Zone 5	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
From Zone 7	1.14	0.30	0.25	0.20	0.08	0.13	0.11	0.12	0.13	0.14	0.15	0.25
From Zone 11	0.69	0.33	0.31	0.19	0.07	0.17	0.18	0.20	0.19	0.22	0.22	0.25
From Zone 12	0.51	0.35	0.31	0.19	0.06	0.09	0.05	0.05	0.07	0.06	0.05	0.16
From Zone 73	0.13	0.23	0.16	0.06	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.06
Total	10.23	5.09	4.89	4.93	1.13	2.98	2.01	1.95	2.34	1.91	1.99	3.59

Outflow	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	AnnuAvera
Streams Gain From GW	1.51	1.60	1.38	0.75	0.46	0.73	0.58	0.59	0.69	0.74	0.67	0.88
Tile Drains	-	-	-	-	-	-	-	-	-	-	-	-
Subsidence	-	-	-	-	-	-	-	-	-	-	-	-
Net Deep Percolation	-	-	-	-	-	-	-	-	-	-	-	-
General Head BC	2.12	2.43	2.10	1.38	0.58	0.80	0.63	0.66	0.66	0.68	0.69	1.16
Small Watershed Baseflow	-	-	-	-	-	-	-	-	-	-	-	-
Diversion Recoverable Loss	-	-	-	-	-	-	-	-	-	-	-	-
Bypass Recoverable Loss	-	-	-	-	-	-	-	-	-	-	-	-
Lakes(Wetland) Gain From GW	-	-	-	-	-	-	-	-	-	-	-	-
Pumping by Element	-	-	-	-	-	-	-	-	0.02	-	0.02	0.00
To Zone 5	0.08	0.15	0.13	0.08	0.03	0.04	0.03	0.03	0.02	0.02	0.03	0.06
To Zone 7	0.08	0.19	0.14	0.10	0.03	0.05	0.03	0.03	0.02	0.02	0.03	0.07
To Zone 11	0.01	0.03	0.02	0.02	0.01	0.01	0.00	0.00	0.00	-	0.00	0.01
To Zone 12	0.05	0.05	0.05	0.06	0.03	0.05	0.05	0.07	0.06	0.07	0.10	0.06
To Zone 73	0.27	0.03	0.04	0.04	0.02	0.04	0.04	0.05	0.06	0.07	0.07	0.07
Total	4.13	4.48	3.86	2.44	1.15	1.71	1.36	1.43	1.53	1.61	1.62	2.30

Storage	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	AnnuAvera
IN	1.34	1.32	0.93	0.25	0.46	0.42	0.38	0.41	0.43	0.43	0.44	0.62
OUT	7.44	1.93	1.97	2.73	0.45	1.68	1.03	0.93	1.25	0.73	0.82	1.91
Change	6.10	0.61	1.03	2.49	(0.01)	1.26	0.65	0.52	0.81	0.30	0.38	1.29

Soil Budget	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	AnnuAvera
Agricultural Area (1000 Acres)	4.1	3.1	3.6	5.9	14.2	10.6	14.3	14.4	14.7	14.7	14.7	10.39
Precipitation	0.61	0.58	0.82	1.51	0.80	1.02	1.11	0.94	1.68	0.86	0.80	0.98
Runoff	0.23	0.16	0.25	0.44	0.10	0.19	0.15	0.16	0.45	0.07	0.12	0.21
Prime Applied Water	12.46	17.11	14.37	9.98	3.69	5.06	3.79	3.45	3.38	3.23	3.42	7.27
Reused Water	6.81	10.56	8.52	5.41	0.31	1.42	0.34	0.24	0.43	0.24	0.20	3.14
Return Flow	5.80	10.21	7.81	4.15	0.08	0.38	0.08	0.06	0.11	0.06	0.05	2.62
Actual ET	4.10	4.42	4.30	4.12	3.21	3.69	3.18	3.03	2.80	2.82	2.84	3.50

Figure 6. Water budget spreadsheet customized for Reclamation Water Conservation Office use and to elicit review by San Joaquin Basin water district managers.

without having to sift through lines of data. This tool is useful for the user of the model as it provides a quick way to identify potential and obvious problems.

Another analytical tool developed within SHEDTOOL is the Hydrograph Analysis Tool. This is a summary spreadsheet that can take actual groundwater elevation data stored in the SHEDTOOL and compare it against modeled groundwater elevations. This tool is essential for calibration and it brings together the main capabilities of SHEDTOOL, data management and model interface. The user is able to view individual hydrographs of groundwater elevations as well as comparing the statistical performance of the model versus the historical data. The model user can see if the model is performing within "acceptable" standards.

Summary

The WESTSIM model was developed to address a need within Reclamation to recognize the increasing importance of groundwater conjunctive use in meeting agricultural, wetland and municipal contract water supply requirements. Although WESTSIM is a water quantity model – developing a quantitative understanding of groundwater flow and water balance is a precursor to any comprehensive model of surface and groundwater quality. Water quality is becoming increasingly important constraint to all reclamation planning decisions in the State of California. Accomplishments to date of the WESTSIM development initiative include :

- WESTSIM simulations and water balance analyses suggest that evapotranspiration estimates within current water allocations and groundwater simulation models is too high leading to lower computed deep percolation beneath irrigated land on the Westside – particularly in the Grasslands agricultural area and Westlands Water District and unrealistically low subsurface drainage volumes.
- The SHEDTOOL application was completed with WESTSIM to improve Reclamation's management of well log, water level and water quality data and allow more rapid processing of the data necessary for modeling purposes. The water balance post-

processor was developed to be consistent with the format used by the Water Conservation Office - providing the Water Conservation Office with an enhanced tool for evaluating water district-level water conservation programs.

- Private wetlands are being considered for the first time in any west-side groundwater model as distinct sub-regions within the WESTSIM model. Inclusion of wetlands results in a more realistic simulation of San Joaquin Basin hydrology and improves the simulation of stream-aquifer interactions and groundwater contribution to the San Joaquin River. A steady-state monthly wetland operations spreadsheet model (WETMANSIM) was developed and used to provide target hydrology for WESTSIM. The current WESTSIM model treats wetlands as small lakes – future work will add more control of wetland levels to better simulate wetland operations and allow year-to-year changes in wetland operations to be simulated.
- The new hydrology for CALSIM is utilizing WESTSIM hydrology. WESTSIM has established the drainage flow paths to the San Joaquin River which has allowed correct assignment of drainage flows to the new CALSIM nodes for the San Joaquin Basin. The new CALSIM hydrology has incorporated WETMANSIM to simulate wetlands in the San Joaquin Basin. It is envisaged that in the next hydrology upgrade of CALSIM output from WESTSIM will be used to replace the code based on WETMANSIM.
- Reclamation was invited to make a presentation on WESTSIM at the annual conference of the California Groundwater Association.

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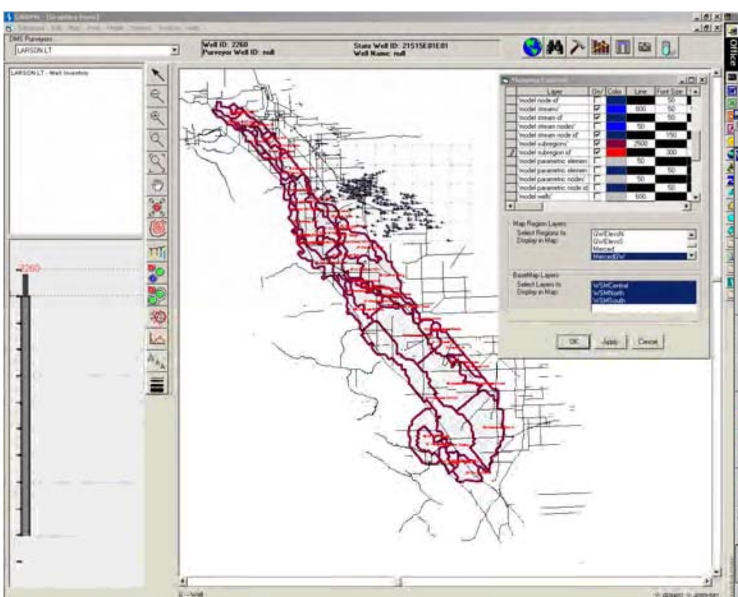

Figure 7. Representation of WESTSIM within SHEDTOOL. Native GIS within SHEDTOOL allows overlay of various parameter files as well as monitoring well locations.

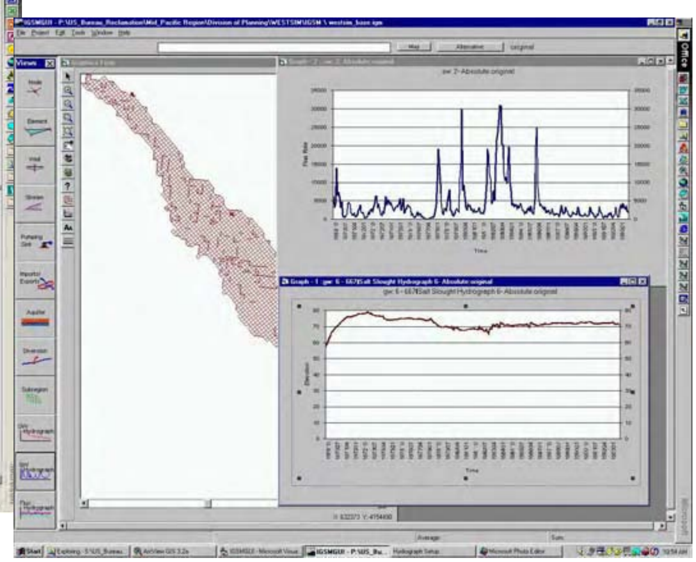

Figure 8. Time series plot of 30 years of Salt Slough flow and stage data as depicted within SHEDTOOL.

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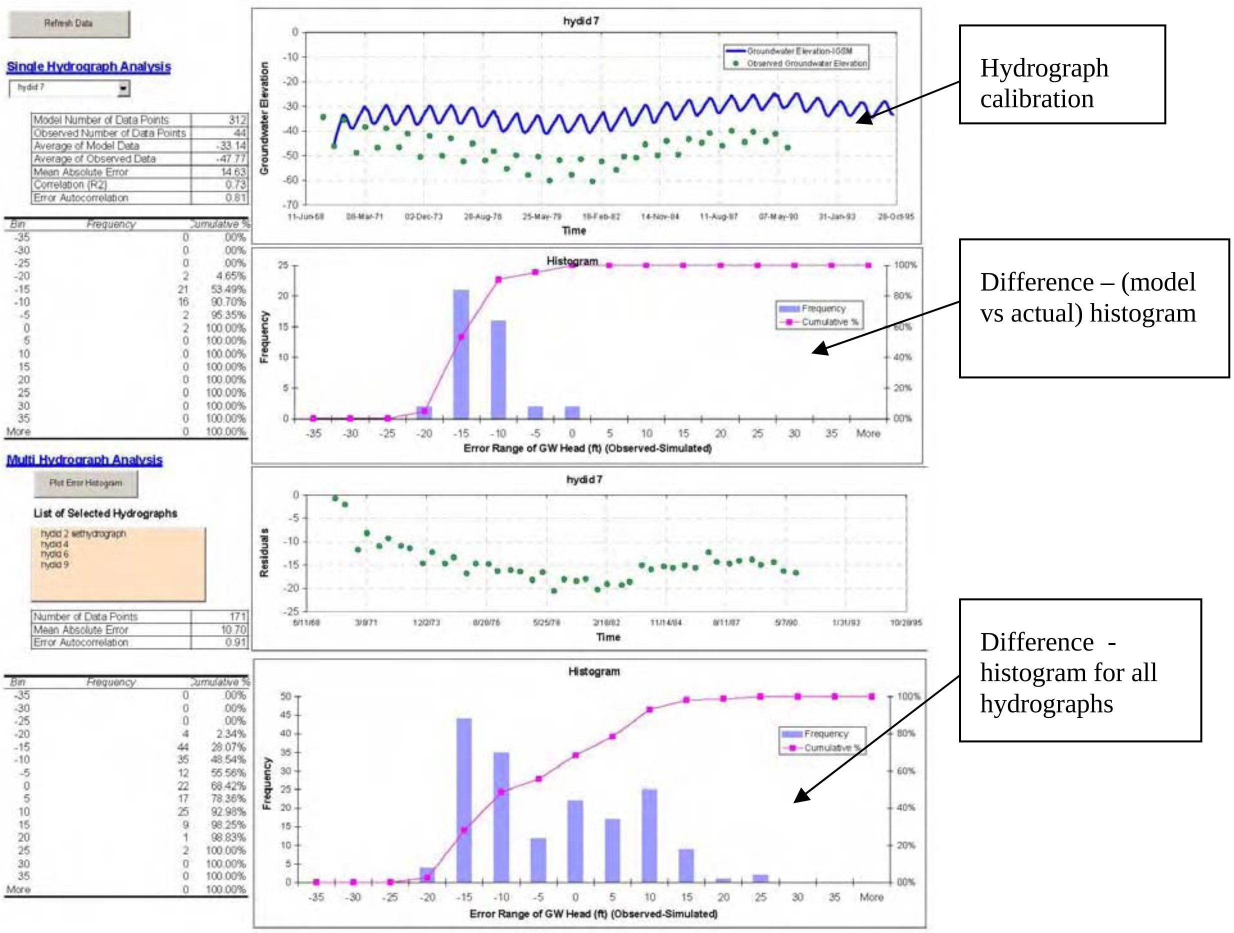

Figure 9. **Use of SHEDTOOL Hydrograph Analysis Tool for both single hydrograph and multiple hydrograph analysis. This allows the statistical performance of the model to be plotted against historical data.**

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Table 1. WESTSIM Model Characteristics

Characteristic	Number
Model Area	1,550,874 acres
Subregions (Water Districts, Irrigation Districts, Cities, Refuges)	63
Elements	2,602
Groundwater Nodes	2,716
Crop Types	16
Aquifer Layers	7
Streams	11
Stream Nodes	351

HydroGeoSphere Application to Evaluate Multi-Scale Hydrological / Ecological Processes in San Joaquin River Basin

George Matanga, Mary Kang, Jeff Randall and Don DeMarco

Optimal management of water resources at a basin scale requires consideration of comprehensive restoration and long-term protection of complex subsurface and surface-based ecosystems. The surface-based ecosystems are closely interconnected and include aquatic habitats (stream channels, wetlands, vernal pools, lakes, periodic floods and other surface-water bodies); riparian zones; lowlands (valley floor); and uplands (mountains). From a hydrological perspective, the surface-based ecosystems (surface water regimes) are known to closely interact with the subsurface ecosystems (subsurface water regimes). In this work, the surface water regimes are treated as two-dimensional systems, while the subsurface water regimes are handled as three-dimensional systems. The two- and three-dimensional water regimes can be integrated into a single system by using geospatial technologies.

The riparian zones are generally small in area in comparison to the landscapes of lowlands and uplands. Therefore, in order to accurately evaluate the hydrological processes at a basin scale, in terms of process simulation, it may be necessary to apply a small scale (refined model grid) for the stream channels and riparian zones and a large scale (coarse model grid) for the lowlands and uplands. Therefore, appropriate numerical models for hydrological analyses require the capability to account for multi-scales in management of water resources in a basin. Geospatial technologies such as geographic information systems (GIS) can easily support both large and small scale data integration within the model. Success of predictive and conjunctive analyses of hydrological processes in integrated surface and subsurface water systems depend on availability of robust numerical models, with capability to account for hydrological processes within and at the interfaces of the surface and subsurface water regimes.

A sub-gridding scheme has been incorporated into HydroGeoSphere to facilitate grid-refinement over a surface or volume of an element and is being tested in a model of the San Joaquin River Basin currently under development. This model accounts for variably-saturated subsurface flow, precipitation, irrigation, river inflows, subsurface extractions, evapotranspiration, surface water, surface-subsurface water interactions, and exchange flux at the surface/subsurface interface. The subsurface system includes discrete layers representing surficial sediments, unconsolidated overburden I, Corcoran clay (where present), and unconsolidated overburden II.

Introduction

In the management of California's State Water Project (SWP) and the federal Central Valley Project (CVP), there is an increasing emphasis on problems that require conjunctive analyses of surface/subsurface hydrologic and water-quality processes, as well as their interactions along the surface/subsurface interface. For example, the conjunctive use of surface and subsurface water resources is increasingly becoming an important component of the optimal management of limited water resources (Lund, 2003). The potential impacts of long-term phenomena, such as climate change, greatly exacerbate the challenges of sustainable water-resource management and also increase the necessity of conjunctive use strategies. A critical element in adaptation to these changes will be an increased reliance on artificial recharge of aquifers or water banking during wet periods. With respect to climate change, impact analysis will require hydrologic and water-allocation models that are driven by meteorological data (e.g., air temperature, precipitation and radiation). Furthermore, the success of predictive, conjunctive analysis of surface and subsurface water regimes will depend on the availability of robust fully-coupled surface/subsurface hydrologic numerical models that accurately account for flow and transport processes within and at the interface of surface and subsurface water regimes.

In California, issues of concern include efficient use of water resources, water quality, and ecosystem health in an integrated manner. CalSim is the most widely-used water-allocation or planning model for assessing efficient use of water resources under different management scenarios. However, it has been noted that, while CalSim does contain adequate representation of operational and regulatory environment of the CVP/SWP system, CalSim is not designed for exploring the impacts of future climate change. This is because of its reliance on a 73 year historic record of streamflows for its primary hydrologic input (Dracup et al., 2004). There is a need to adapt CalSim for climate change scenarios by linking it to a surface/subsurface hydrologic model that is driven by meteorological data as forecasted by generally accepted hydroclimate numerical models such as those developed by NCAR and others internationally. This linkage will render CalSim valuable for climate change studies and improve representation of flow and transport processes in the linkage. A robust fully-coupled surface/subsurface numerical model, HydroGeoSphere, is suitable for linkage to CalSim.

Another critical group of problems includes the transport of dissolved contaminants at multi-scales in surface and subsurface water systems. Management of nutrient loads in rivers contributing to the surface-water bodies, such as California's Bay-Delta, may involve field and modeling studies which are capable of representing nutrient sources as well as key fate and transport processes. However, modeling has not yet captured nutrient fate and transport processes in a way that is satisfactory for management purposes. The ability to understand nutrient processes at the watershed scale is an emerging national and state need as federal and state agencies begin to address TMDL (Total Maximum Daily Load) issues in the river basins. These kinds of analyses will require comprehensive flow and transport simulators with appropriate schemes for loading digital information (DEMs, soil maps, land-use information, subsurface geology, etc.).

Historically, surface and subsurface water interactions have been analyzed independently, with source/sink assumptions providing a lumped estimate of the water budget components that are not directly simulated or linked in a scientifically defendable manner, either physically or computationally. For instance, surface-water flow and transport models neglect or highly conceptualize the subsurface interactions, whereas subsurface flow and transport models are driven by groundwater recharge estimates and treat the surface features, such as lakes and streams, as input or discharge locations (boundary conditions) for water and contaminants. Snowmelt-runoff models generally neglect subsurface flow processes or ET from non-snow covered zones, and sediment transport models often use highly simplified hydrodynamics. This is an inadequate situation from a scientific perspective given the computational tools that are available today.

Within the framework of conjunctive management of scarce water resources or of water quality impacts affecting multiple flow domains, an integrated model is required that accounts for all known processes within all domains in a physically-based manner. A major step towards that end is the development of HydroGeoSphere as a joint undertaking between HydroGeoLogic Inc., the University of Waterloo, Laval University and the Bureau of Reclamation.

Hydrogeosphere Background And Existing Capabilities

On-going work with HydroGeoSphere is directed towards providing a practical tool for multi-scale simulation of conjunctive surface/subsurface flow, and solute and heat transport, and sedimentation in management of water-resource systems. Numerical models currently available to federal and state agencies do not rigorously consider processes of surface/subsurface water flow, water quality and erosion/sedimentation together in a fully-integrated manner.

HydroGeoSphere is a fully-integrated surface/subsurface numerical flow and transport model recently developed for water-resource analysis, planning and management. It is among a relatively small class of physically-based, spatially distributed models designed to address surface and subsurface water regimes and their interactions. The most important feature that distinguishes HydroGeoSphere from most other models is that the surface and subsurface flow and transport equations are solved in a fully integrated, rather than iterative (integrated) or sequential (linked) manner. This in turn greatly improves the ability of the model to accurately simulate the complex physics of hydrologic systems that have strong interactions between the surface and subsurface hydrology, and articulates itself in the lack of mass balance problems and much greater computational efficiency. In its current form, HydroGeoSphere accounts for water flow and solute/heat transport in 2-D surface water, 1-D irrigation systems and tile drains, and 3-D variably-saturated subsurface.

Enhancement Of Hydrogeosphere

Incorporation of snowmelt-runoff processes into HydroGeoSphere will expand its capabilities to encompass all major components of the hydrologic cycle, and in combination with CalSim provide a complete simulator that is driven by meteorological inputs. Moreover, snowmelt processes through their impact on water temperature are important in addressing ecological impacts.

HydroGeoSphere has had capability to simulate heat transport in the subsurface since its development. Extension of the heat transport equation to the surface domain has recently been accomplished. The temperature module is currently being tested. This module will greatly expand HydroGeoSphere's capability to address temperature sensitive issues such as health of fish and other ecological indicators. The energy balance equation will also be coupled with the snowmelt equations to account for the effect of snowmelt on water temperatures.

Dissolved oxygen and major nutrients such as nitrogen and phosphate are among the most important water quality characteristics. The transport equations that describe the physical transport and mixing of these components are already in HydroGeoSphere. There is therefore a need to focus on incorporating reaction modules that account for the biochemical interactions between the components, including denitrification, fixation/sequestration due to biological growth, and associated oxygen depletion. In the case of phosphate, which is strongly sorbed to soil particles, the transport module will account for movement of phosphate adsorbed to sediment particles and linked to the sediment transport module. A general biochemical reaction module will be developed that can account for either equilibrium or kinetic reactions, with temperature-dependent rate constants linked to the heat transport module to account for the effect of water temperature on reaction rates.

Sediment transport routines will be added to the model. Sediment transport follows the contaminant transport mass balance equation in that sediments are transported via the mechanisms of advection and dispersion. The transport equations in HydroGeoSphere will need only slight modification to accommodate transport of sediments. The source / sink terms for sediments (erosion and deposition), however, are functions of the flow velocity, turbulence, particle size and type. These functions will be included in the surface water flow (2-D) and channel flow (1-D) domains of HydroGeoSphere to accommodate interactions with a wide variety of cohesive and non-cohesive sediments within and among the surface-water regimes. Kinetic or equilibrium adsorption of contaminants to sediments will also be incorporated to include effects of adsorbed chemicals on the suspended sediment load as a dominant transport mechanism for contaminants. This enhancement of HydroGeoSphere will allow for rigorous simulation of complex interactions of chemicals as they are transported within surface and subsurface regimes, interacting closely with losing and gaining stream conditions and with other contaminants and sediments within surface and subsurface regimes, as well as at the interface.

Sub-timing and sub-gridding techniques have been incorporated into HydroGeoSphere to improve its computational efficiency and thereby broaden its utility. The sub-gridding technique allows a relatively coarse numerical finite element or finite difference grid to be used for the entire model domain with finer grid resolution only where needed. This three-dimensional technique achieves optimal spatial grid resolution throughout the model domain to maximize simulation efficiency. For instance, the overland flow domain can use a finer resolution in regions of steep slopes or around topographical features of importance (see Figure 1), while the subsurface domain can use finer resolution only in regions of differing material properties, faults, or around wells. Sub-timing allows different time-step sizes to be used for different parts of the modeling domain, in a fully implicit fashion. Smaller time steps may be used for surface water flow, with larger time steps for subsurface flow. This technique results in a large increase in computational speed for long term simulations, while still maintaining full coupling between surface and subsurface flow and transport processes. The sub-gridding and sub-timing techniques are undergoing testing against field data and conditions from San Joaquin River Basin in order to acquire a benchmark of the computational efficiency of the model.

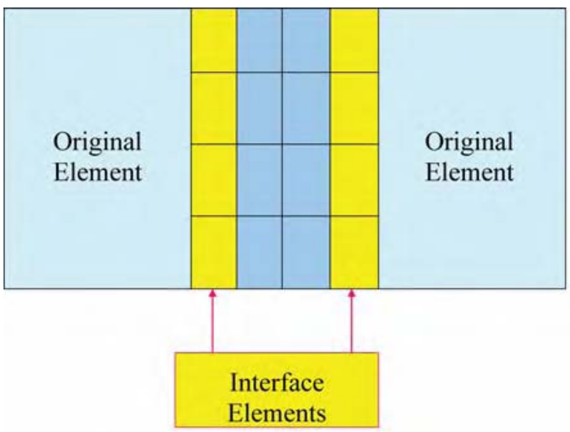

Figure 1. Schematic representation of localized grid refinement.

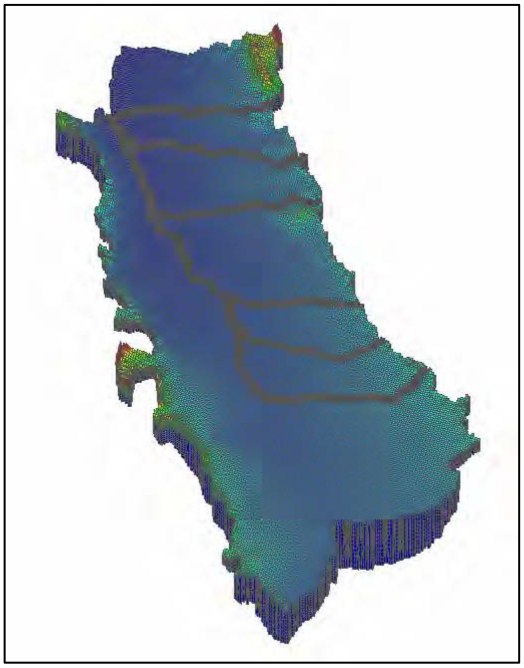

Figure 2. Rectangular mesh with sub-gridding along major rivers

Application To San Joaquin Valley And The Northern Portion Of Tulare Basin

The sub-gridding scheme incorporated into HydroGeoSphere is being tested in a model of the San Joaquin River Basin currently under development. This model covers all of the San Joaquin Valley and a northern portion of the Tulare Basin as shown in Figure 2. This model accounts for subsurface flow (variably-saturated flow, subsurface extractions, evapotranspiration, tile-drain flow, micropore flow, etc); surface flow (overland flow, stream flow, precipitation, irrigation, evapotranspiration) and interactions of flow processes within and at interfaces of flow regimes. The subsurface is characterized by discrete layers representing surficial sediments, unconsolidated overburden I, Corcoran clay (where present), and unconsolidated overburden II. This system is represented using 11 layers and approximately 300,000 coarse elements (i.e. cells without subgrids) with a grid spacing of 800m. As shown in Figure 2, sub-gridding is used to incorporate finer resolution information around major rivers including the San Joaquin, Fresno, Chowchilla, Merced, Tuolumne, and Stanislaus. A comparison of Figures 3 and 4 show how the additional grid refinement is needed to capture the details of the surface water features. The level of discretization used to represent the river reach shown in Figure 3 can create discontinuities that do not exist when topographical information at a finer level of discretization is used. Finally, preliminary model results presented in Figure 5 show that the model captures regional trends of subsurface water flow trending towards the Bay Delta region.

Linkage Between Hydrogeosphere And Calsim

Methodology for linking HydroGeoSphere to CalSim will be developed (Kang et al., 2008). The general approach is to replace the 73 year historic sequence of flows (that currently represent the primary hydrologic input for CalSim) with HydroGeoSphere computed flows (based on meteorological data). CalSim will then provide reservoir releases and allocated water at predetermined points, determined by its optimization engine and a given set of operating rules and constraints, as input to HydroGeoSphere. HydroGeoSphere will undertake all routing of water through the system. Thus, the hydrology and hydrodynamics of the flow domain will be completely evaluated by HydroGeoSphere and the hydrologic/hydraulic conditions required for the water allocation decision-making process will be passed on to CalSim for the purpose of allocating water.

HydroGeoSphere will require future time series of rainfall and temperature for definition of boundary conditions (flux and evapotranspiration) for surface and subsurface water systems. These time series may be evaluated by means of hydroclimate numerical models and statistical/stochastic approaches. This will render the HydroGeoSphere/CalSim linkage valuable for evaluating impact of climate change on the water resources, and will enhance the current form of CalSim.

Conclusion

CALFED agencies have been in partnership with stakeholders and local water/irrigation districts in dealing with water supply, quality and management, environmental mitigation and other water related issues for the Central Valley of California. HydroGeoSphere is valuable for this type of work due to its capability to conjunctively simulate flow and transport in the fully coupled surface and subsurface water systems, and following model enhancement, to conjunctively simulate temperature in the fully-coupled surface and subsurface water system. In this work, we will demonstrate application of HydroGeoSphere, a state-of-the-art hydrological model, to undertake a comprehensive simulation of flow and transport in the Central Valley.

(a)

(b)

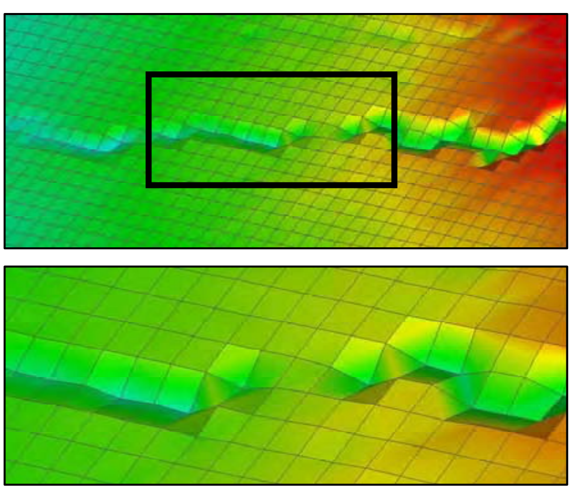

Figure 3. Mesh without subgridding along a major river, where (b) shows the area within the black rectangle in (a).

(a)

(b)

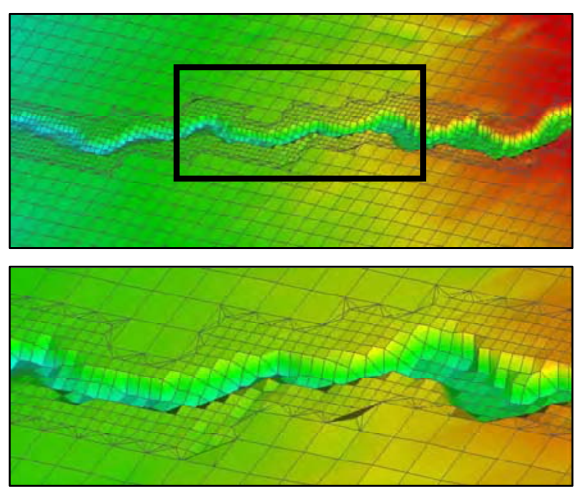

Figure 4. Mesh with subgridding along the same reach of the major river shown in Figure 3, where (b) shows the area within the black rectangle in (a).

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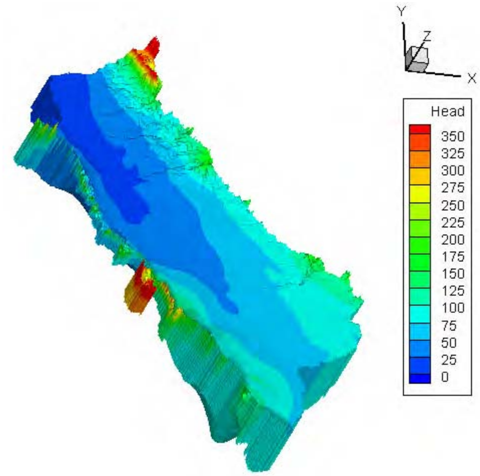

Figure 5. Head output at the end of the December stress period.

HGS-M: A Tool to Conjunctively and Dynamically Simulate Hydraulic Processes and Multi-reservoir Systems for Evaluation of Climate Change Impacts

Mary Kang, Varut Guvanasen and Kirk Nelson

Computer models are frequently used to guide decisions pertaining to the operation, planning and management of the State Water Project (SWP) and the federal Central Valley Project (CVP) water storage and conveyance systems. CalSim, developed by California Department of Water Resources and the U.S. Bureau of Reclamation (BOR), is the standard reservoir-river basin simulation model for studies relating to the SWP/CVP system. HydroGeoSphere (HGS), developed by the University of Waterloo, Laval University, HydroGeoLogic, and BOR, is a distributed-parameter, fully-integrated surface-subsurface numerical model that accounts for three-dimensional variably-saturated subsurface flow and two-dimensional overland/stream flow or overland flow into one-dimensional stream channel. HGS is well suited for physically-based predictions of the impacts of climatic change with regard to surface-subsurface temperature, hydrology and water quality, and has been successfully applied at regional scales to the Central Valley.

To benefit from functionalities of both HGS and CalSim, a dynamic linkage between HGS and CalSim is being developed to facilitate conjunctive simulation of hydrologic processes and multi-reservoir systems without oversimplified representation of key physical processes. The linked HGS-CalSim model provides a comprehensive tool for evaluating the impact of climate change on California's water resources in addition to analyzing water supply, water quality and ecosystem health issues in an integrated and optimal manner. Potential applications include major river restoration, ecosystem-health and water resource management, climate change studies, and CALFED Bay-Delta Programs.

Introduction

Water supply reliability, water quality, and ecosystem health are key issues impacting water resources in California, and pose challenges for sustainable water resource management. These challenges continue to be threatened by current and future anthropogenic activities and exacerbated by climate change. To address water resource management issues in California, various federal and state agencies including the U.S. Bureau of Reclamation (BOR) and the California Department of Water Resources (DWR) have utilized modeling to gain further insight into hydrological and operational dynamics.

Currently, CalSim, developed by DWR and BOR, is the standard reservoir-river basin simulation and operational model for studies relating to the State Water Project (SWP) and the federal Central Valley Project (CVP) system. The CVP/SWP system consisting of dams, reservoirs, and canals has been constructed over the past century as a strategy to meet mounting demands and provide flood protection. The management and operation of the CVP/SWP system, currently performed by BOR and DWR, directly impact many hydrological processes and can aid in addressing water supply reliability, water quality, and ecosystem health concerns. To find mitigative strategies including those that have potential to avert climate change impacts, representation of hydrological processes such as interaction between surface and subsurface water regimes and evapotranspiration should be physically-based and simulated in conjunction with the CVP/SWP system. However, in the latest available version of CalSim, CalSim-II, pre-run CVGSM (Central Valley Ground-Surface Water Model) simulations (an application of IGSM to the Central Valley) using historical data are used to represent hydrological processes (DWR, 2002). In CalSim-III, a successor of CalSim-II, C2VSIM [California Central Valley Groundwater-Surface Water Simulation Model, an application of IWFM (DWR, 2007) in the Central Valley] is being used to represent subsurface hydrological processes in a more dynamic manner (Dogrul, 2008). Nevertheless, the interactions between surface and subsurface water are simplified and reliance on historical data, at the expense of realistic predictions, continues.

HydroGeoSphere (HGS) is a comprehensive, fully-integrated, physically-based and distributed numerical model, that accounts for 3-dimensional variably-saturated subsurface flow and 2-dimensional overland/stream flow or overland flow into 1-dimensional stream channels and is capable of modeling transport processes for non-reactive, reactive chemical species, and heat in the associated surface and subsurface flow fields. In addition, sub-gridding and sub-timing techniques have been incorporated into HGS to improve its computational efficiency and the representation of small-scale processes. As a result, HGS is well suited for physically-based predictions and analyses of climatic change impacts with regard to surface-subsurface temperature, hydrology and water quality. HGS has been successfully applied at regional scales to the Central Valley with model extents covering the Sacramento Valley, the San Joaquin Valley, and the northern portion of the Tulare Basin. Through ongoing collaborative research and development between the BOR, University of Waterloo, Laval University, and HGL, HGS has emerged as a robust and accurate hydrologic simulation model with advanced capabilities that position users to effectively address challenging water resource planning and management issues. However, it currently does not possess the ability to perform water allocations.

Therefore, there exists a gap between multi-reservoir system simulation models with simplified hydrology and physically-based hydrological models without explicit representation of multi-reservoir systems. To fill the knowledge gap, a linkage between CalSim and HGS is being developed to provide a tool that facilitates conjunctive and dynamic simulation of hydrologic processes and operation of multi-reservoir systems.

In this paper, the foundation for code development and modifications required for creating the linkage between HGS and the Water Resources Integrated Modeling System (WRIMS), the engine of CalSim, is established. The resulting system, referred to as the HydroGeoSphere-Management (HydroGeoSphere-M or HGS-M) system, will provide the capability to assess issues related to water supply reliability, and water quality and ecosystem health in an integrated and optimal manner under changing climatic conditions with various water management scenarios. The HGS-M development strategy, presented in Figure 1, consists of assessing simulation requirements, evaluating linkage approaches, and implementing linkage methodology are presented along with potential applications.

Methodology

The premise behind the HGS-M system is to have water routing processes simulated in HGS and water allocations performed within WRIMS. In other words, the system is designed to provide a platform for dynamic water allocation based on responses observed in hydrologic simulations. Water allocation is typically performed using optimization methods (Wurbs, 1993; Labadie, 2004) for which an objective and constraints must be specified. Therefore, the responses observed in hydrologic simulations must be provided in terms of the relationship between stressors and responses. To determine these relationships, multiple hydrologic simulations representing different hydrologic conditions must be run. These hydrologic simulations should be carried out using a time step appropriate for accurate representation of physical processes; while water allocations should be performed for time intervals typically considered in management and operational practices. These time intervals, hereafter referred to as the decision period (Δt), are generally larger than the time step required to accurately represent physical processes. They correspond to the time period for which hydrologic simulations are conducted to provide information for water allocations. Figure 2 outlines the general schematic of HGS-M, where t and $t + \Delta t$ represent the beginning and the end of decision periods, respectively.

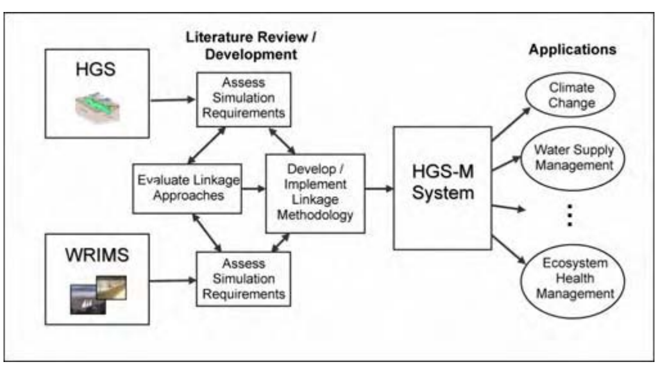

Figure 1. HGS-M system development strategy

As shown in Figure 2, there are four main engines in HGS-M: HGS-MI, HGS, HGSCompile, and WRIMS. HGS-MI (HydroGeoSphere-Management Interface) is the main user interface through which a user can specify the problem to be run. It is assumed that the batch of HGS runs representing various hydrologic conditions and the corresponding WRIMS project files have been created during separate model development efforts. The interface in HGS-MI allows the user to start HGS-M which involves initiating pre-defined HGS runs, HGSCompile, and a WRIMS project. All three engines require some form of initialization and therefore, for added efficiency, HGSCompile and WRIMS are initiated simultaneously with HGS runs.

HGS

The first of these engines to run in the simulation process is HGS, in which all hydrological processes such as stream routing are performed. The M version of HGS will contain modifications required to incorporate water allocation decisions into HGS runs and to communicate outputs to the water allocation engine. The corresponding schematic emphasizing the steps required for inclusion of water allocation is presented in Figure 3. The steps for communication to the water allocation engine are governed by HGS_O controls, which specifies decision times and decision time outputs such as flows and heads. These decision time outputs require

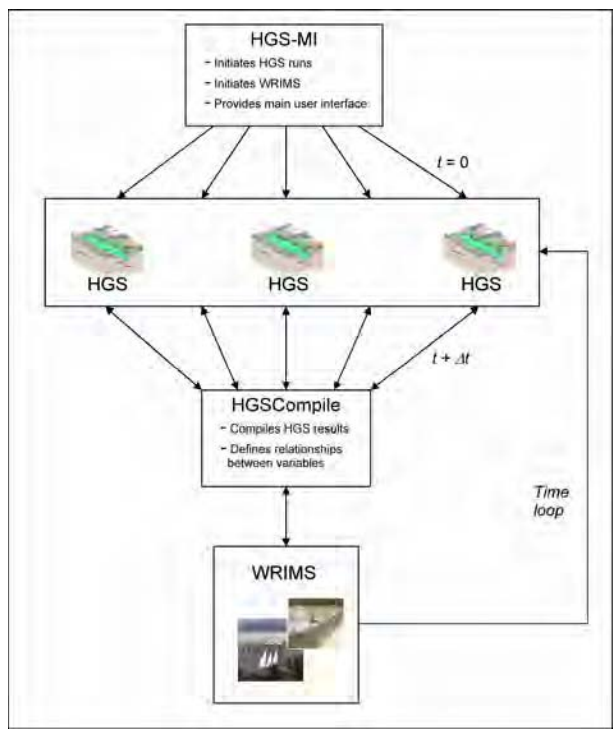

Figure 2. HGS-M: General schematic

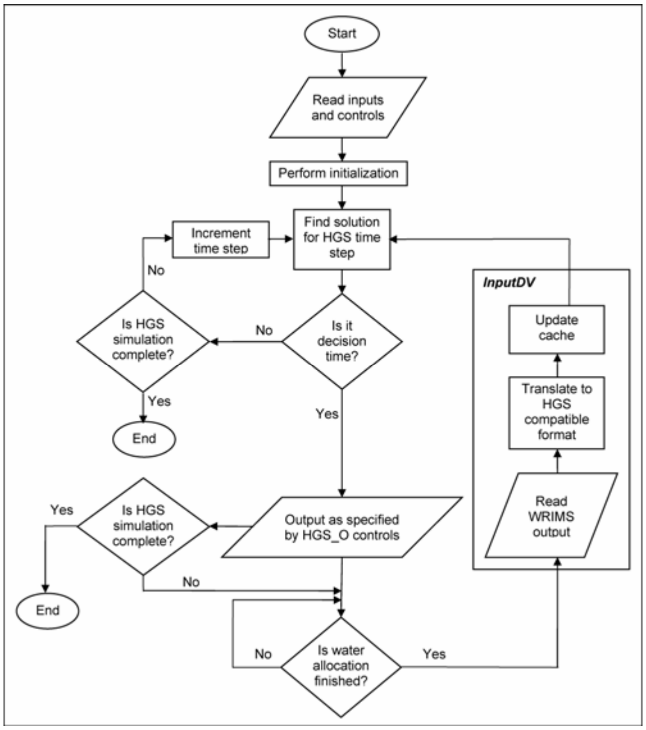

Figure 3. Schematic of HGS.

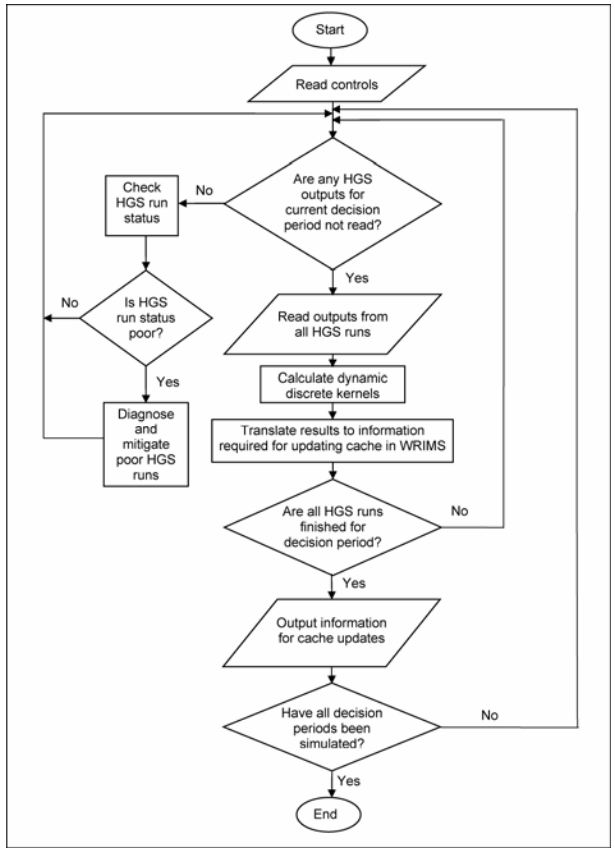

Figure 4. Schematic of HGSCompile.

the specification of a spatial reference point, which matches the corresponding water allocation network. Once the decision time outputs have been produced, HGS waits for water allocation decisions to be provided by WRIMS. These decisions are processed through a new internal HGS module called InputDV. InputDV performs the function of reading the WRIMS outputs, translating it into HGS initial conditions for the decision period, and performing the corresponding updates to the HGS cache. The translation of WRIMS outputs, which are averaged over the decision period, to HGS initial/boundary conditions will be performed utilizing a statistical/stochastic approach. However, if information regarding the distribution of outputs within a given decision period are available, the translation will be based on this distribution and statistical/stochastic approaches will be used only as a supplemental option. Upon the completion of the InputDV, HGS is continued until the next decision time. The completion of the HGS run can coincide with or occur later than the last decision time however, it cannot occur prior to the last decision time.

HGSCompile

Communication to the water allocation engine, WRIMS, is performed via a two-step process: (1) output values from each HGS run, and (2) compile outputs from HGS and translate it into information required by the water allocation engine. The first step is internal to HGS and has been described above. The second step is performed using the HGSCompile engine, which is initiated by HGS-MI. Controls for HGSCompile are a function of the water allocation network component, which dictates how outputs from HGS will be compiled and translated. HGSCompile is designed to run in tandem with the HGS runs and read in the results as they become available as shown in Figure 4. As information from HGS runs becomes available, HGSCompile can generate dynamic discrete kernels and produce information required for updating caches in WRIMS. In the water allocation engine, a mixed integer programming (MIP) solver is used (Draper et al., 2004); correspondingly, a linear relationship must be defined. Therefore, the dynamic discrete kernel / response functions approach (Fredericks et al., 1998) is used to segmentally linearize the combined response of multiple stresses. The combined responses of multiple stresses are also temporally averaged over the decision period to be compatible with WRIMS using statistical approaches. The statistical approaches and associated parameters are dictated by HGSCompile control options, which can be varied depending on the stress. The dynamic discrete kernel / response functions approach assumes that the average responses, including those from non-linear processes, are approximately linear over the decision period. An advantage of this method is that individual stresses can be simulated independently and linearly combined under the principle of superposition, thereby reducing the number of hydrologic conditions to simulate. HGSCompile also functions as a quality controller of the HGS runs and continuously monitors the status of ongoing runs. If required, mitigative measures such as change in the magnitude of the stress and solver parameter values are implemented. Therefore, the behavior of the HGS-based hydrological model should be well understood so that mitigative measures can be predetermined. Once all HGS runs have successfully simulated the entire decision period and the outputs have been compiled and processed, communication with WRIMS is performed to transfer data and restart the WRIMS engine.

WRIMS

The main executable of the WRIMS engine is the wrapper. The schematic of the wrapper with inclusion of steps required for linkage to HGS is illustrated in Figure 5. The linkage necessitates creation of communication processes to check for the completion of HGSCompile, pass decision variables, and initiate HGS runs. Decision variables to be passed include releases at control structures, deliveries, and groundwater pumping rates. Additional code modifications include the development of the module, ReadHGS, and controls in the WRIMS engine specific to the linkage with HGS. ReadHGS is designed to accept variables passed from HGSCompile and update the caches, which contain all decision and state variables, with utilities in WRIMS. (Additional utilities may need to be added to streamline the cache updating process.) The HGS-M specific controls in WRIMS dictate the decision times at which all decision variables are passed to HGS runs.

With the completion of water allocation for a given decision period, HGS runs for the next decision period are commenced. The

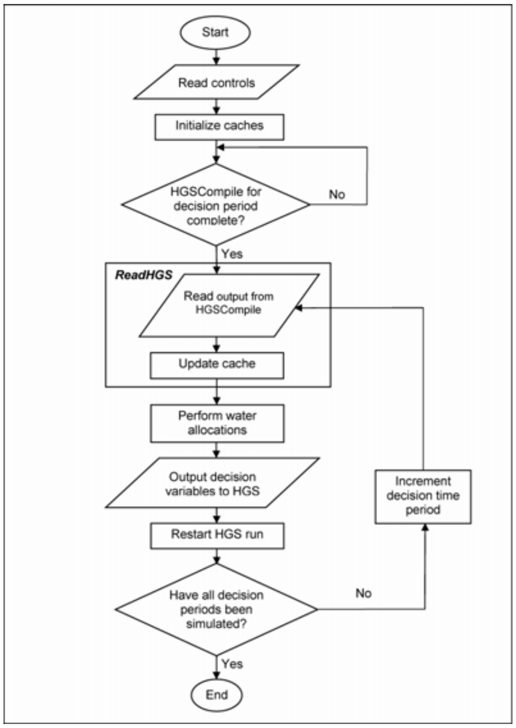

Figure 5. Schematic of wrapper in WRIMS with linkage to HGS.

three engines are paused and run for each of the specified decision periods in the order presented in Figure 2. HGS-M will be designed to run on multi-nodal supercomputing systems to facilitate multiple simulations in a computationally-efficient manner.

Future Directions

Upon the development of the HGS-M system, verification and validation will be performed using the operational and regulatory environment in the latest version of CalSim and an HGS application to the Central Valley. Development of the conceptual model for the entire Central Valley and the verification and validation of the corresponding HGS-based numerical model is being performed under numerous initiatives. Nevertheless, verification of the HGS-M system containing validated and verified HGS-based models will be conducted using field data while validation of HGS-M will be carried out by simulating management scenarios undertaken in the past. The ability of HGS-M to investigate short-term responses not reflected at the temporal scale of the decision period will provide valuable insight in the validation and verification process.

Numerous research and development initiatives for HGS and HGS-M are on-going and plans for more exist. For example, one initiative involving HGS-M development is the establishment of a methodology for the inclusion of future data as they become available. This functionality will play a crucial role in simulating of climate change scenarios driven by predicted hydrometeorological data.

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San Joaquin County DYNFLOW Model

Brian J. Heywood, P.E., and Brandon Nakagawa, P.E.

An integrated groundwater/surface water flow model developed for San Joaquin County Flood Control and Water Conservation District (San Joaquin County) has been applied to numerous studies to aid in water resources planning. The groundwater model utilizes the fully 3-D finite element DYNFLOW simulation code. This model is capable of simulating groundwater/surface water interaction, groundwater pumping, and complex land use-based (i.e., agricultural) water demands.

San Joaquin County is currently home to approximately 650,000 people and sustains a $1.75 billion agricultural economy. The population is expected to increase to over 1.17 million by 2030. Water demand countywide is approximately 1,600,000 acre-feet per year, 60 percent of which is supplied by groundwater. The California Department of Water Resources (DWR) has declared the Eastern San Joaquin Groundwater Basin "critically overdrafted," indicating that the current rate of groundwater pumping exceeds the rate of recharge and is not sustainable.

The county's DYNFLOW model has been used for numerous studies to evaluate many projects aimed at improving the condition of the groundwater basin. The DYNFLOW model was used during the development of the San Joaquin County Water Management Plan (WMP) in 2001 by simulating alternative water management scenarios. These alternatives attempt to improve the "overdraft" condition in the basin by increasing recharge to the basin either through direct or in-lieu processes. Changes in groundwater levels and saline groundwater migration simulated by the model were used to assess the alternatives. In addition to use in support of the WMP, the DYNFLOW model was used in 2005 to support the Environmental Impact Report (EIR) for the City of Stockton Delta Water Supply Project (DWSP).

The DYNFLOW model was used in 2007 for the preparation of the Eastern San Joaquin Integrated Regional Water Management Plan (IRWMP). Simulations of alterative water management scenario, including a no-action alternative, were simulated and presented in the IRWMP. Again, changes in groundwater levels in relation to target levels were a major metric used to evaluate each alternative. The model is currently being used to support the EIR for San Joaquin County's Integrated Conjunctive Use (ICU) Program as evaluated in the IRWMP, and also to explore the potential for an inter-regional conjunctive use project with the Mokelumne River Forum, a stakeholder group comprising water management agencies in the Mokelumne River Watershed.

Introduction

San Joaquin County is located at the northern end of the San Joaquin Valley. The county is currently home to approximately 650,000 people and sustains a $1.75 billion agricultural economy. The population is expected to increase to over 1.17 million by 2030. Water demand county-wide is approximately 1,600,000 acre-feet per year, 60 percent of which is supplied by groundwater. The California Department of Water Resources (DWR) has declared the Eastern San Joaquin Groundwater Basin "critically overdrafted," indicating that the current rate of groundwater pumping exceeds the rate of recharge and is not sustainable.

The San Joaquin County Flood Control and Water Conservation District (San Joaquin County) contracted with to develop a Water Management Plan (WMP) to advance the understanding of county water resources on a regional scale. As part of this study plan, CDM developed an integrated groundwater/surface water model for the region. The model was developed using the DYNFLOW numerical modeling code.

The San Joaquin County DYNFLOW (SJC DYNFLOW) model has been used to support numerous water management studies. The initial application of the model was in the development of the WMP. Subsequently, the model was used to support Environmental Impact Report (EIR) documentation for the City of Stockton's Delta Water Supply Project (DWSP), San Joaquin County Integrated Regional Water Management Plan (IRWMP), and the EIR for the Integrated Conjunctive Use (ICU) Program.

Model Development

Several groundwater models had been developed for the San Joaquin County area prior to the SJC DYNFLOW model. These models include the Central Valley RASA (Williamson 1989) and CVGSM (Montgomery Watson 1990) models. Additional local modeling was also performed by other consultants. One of the models developed for the region was created utilizing the IGSM model code. This IGSM model was used as a basis to develop the SJC DYNFLOW model as part of the SJCWMP.

The DYNFLOW numerical code used to develop the SJC model has been developed over the past 25 years by CDM engineering staff and is used for large-scale basin modeling projects and site specific remedial design investigation. The code has been applied to over 200 model studies worldwide. DYNFLOW is a fully three-dimensional model capable of simulating conditions in the San Joaquin County area. DYNFLOW can simulate saturated groundwater flow, route surface water flows, allow for groundwater/surface water interaction, and simulate the complex water movement resulting from agricultural processes.

Basic Model Characteristics

A few of the basic components of the SJC DYNFLOW model are presented here. A more complete description of the model can be found in the SJCWMP (CDM 2001).

Model Domain and Grid

The SJC DYNFLOW model encompasses portions of San Joaquin, Calaveras, Sacramento, and Stanislaus counties. Figure 1 shows the domain of the SJC DYNFLOW model. The model does not include the portion of San Joaquin County west of the San Joaquin River. The finite-element grid consists of 1,892 triangular elements connected by 3,520 nodes at the vertices.

Model Stratigraphy and Conductivity.

The SJC DYNFLOW model consists of three active layers bounded by five levels at the top and bottom of each layer. The model layers represent the Victor, Laguna, Merhten, and Valley Springs formations underlying the county. However, because there is no clear definition of the contacts between these general. The top layer of the model, representing the Victor Formation and shallow alluvial materials, is represented by horizontal hydraulic conductivities that range from 10 to 150 feet per day. The second layer from the top represents the Laguna and Merhten Formation with conductivities from 10 to 100 feet per day. The layer representing the Valley Springs Formation underlies the Laguna and Merhten. This layer is represented with conductivities between 1 and 40 feet per day.

Land Use

Three types of land use are input into the model: urban, agricultural, and native. Historic urban land use was imported from the previous IGSM model. The model assumed a linear rate of growth from 2000 to 2030 with the assumption that the urban spheres are fully urbanized in 2030. Similarly, historical agricultural land area and the distribution of different crops were also imported into the SJC DYNFLOW model. The growth of urban land resulted in the conversion of agricultural land to urban land. Native areas within the mode domain were also incorporated as appropriate.

Applied Hydraulic Stresses

Groundwater recharge and discharge, along with surface water interaction, were simulated in the SJC DYNFLOW model. Historic pumping—representing municipal, industrial, and domestic groundwater pumping—was incorporated into the model based on data from the IGSM model. Recent data was used to supplement the existing dataset.

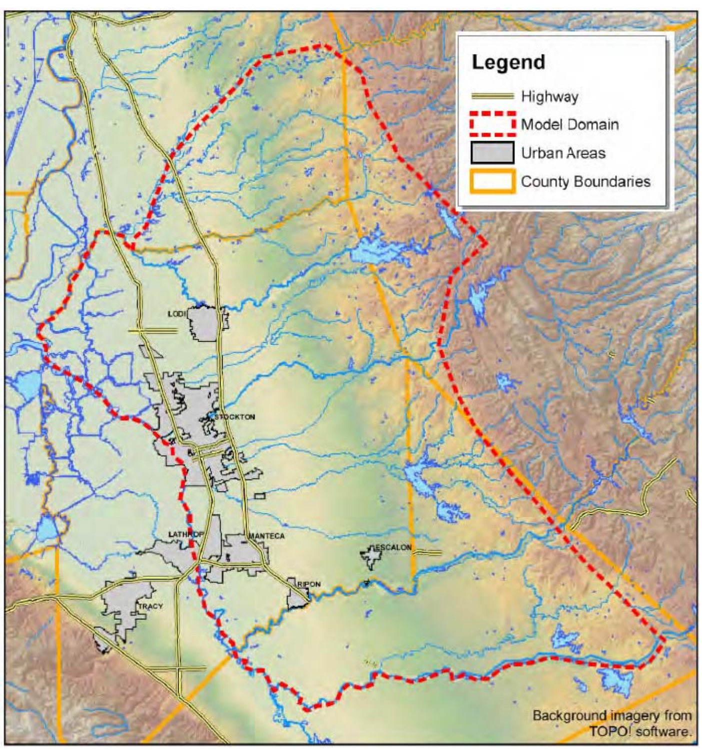

Figure 1. SJC DYNFLOW Model Domain

Agricultural pumping was calculated by the SJC DYNFLOW model based on the data assigned at the ground surface. The amount of agricultural pumping calculated by DYNFLOW was based on crop evapotranspiration patterns, irrigation efficiency, soil runoff characteristics, and surface water irrigation rates and locations.

The San Joaquin, Tuolumne, Stanislaus, Calaveras, Mokelumne, and Consumnes rivers, along with Dry Creek, are modeled explicitly in this model. DYNFLOW calculates the amount of flux passing to or from the stream based on the position of the groundwater table and surface water levels. As mentioned previously, the irrigation of agricultural crops with surface water is also simulated. The points of diversion, diversion rates, and area irrigated are all specified in this model.

Model Calibration

The SJC DYNFLOW model was calibrated in both steady-state and transient modes. The steady-state calibration was performed for water year 1970. After an acceptable calibration was achieved, a transient calibration from water year 1970 to 1993 was performed. Figure 2 shows the results of the steady-state simulation. This figure also shows the transient calibration results at a few of the locations that were considered during calibration.

Model Application

Following model calibration, the model was initially used in developing the SJCWMP. The model was subsequently used by the City of Stockton during the development of the EIR for the DWSP. Most recently the SJC DYNFLOW model was used in preparing the IRWMP. The model is currently being used to support the EIR for the ICU Program as evaluated in the IRWMP.

Water Management Plan

The SJC DYNFLOW model was initially used to provide quantitative assessments of the relative benefits derived from each of the components discussed in the SJCWMP. Each of the components of the plan was simulated utilizing 1970 to 2000 hydrology.

The water management plan components that were simulated included: re-operation of New Hogan Reservoir, the South County

Water Supply Project, the Farmington Project, fully exercising SEWD and CSJWCD's water rights at New Melones Reservoir, and the Freeport Groundwater Banking Project.

The results of the SJCWMP simulations primarily focused on the simulated changes in water levels associated with each component of the SJCWMP. These simulated changes in water levels were then evaluated with respect to the volume of water associated with each component. The SJCWMP process resulted in the acknowledgment that multi-party discussions were necessary to work on groundwater system issues. Consequently, the Northeastern San Joaquin County Groundwater Banking Authority (GBA) was organized in 2001 and provided a consensus-based forum to local, state, and federal water interests to work cooperatively to study, investigate, plan, and develop locally supported groundwater banking and conjunctive use programs.

Stockton DWSP

The city of Stockton's water supply needs are met by a combination of groundwater and surface water. The DWSP was developed to provide Stockton additional supply, replace temporary surface water supplies, and reduce reliance on the over-drafted aquifers beneath San Joaquin County.

The SJC DYNFLOW model was used in support of the EIR for the City of Stockton DWSP. The modeling was used to identify the project's potential impacts and/or benefits to the groundwater system in the San Joaquin County area. The impact of the DWSP on groundwater levels, groundwater/surface water interaction, and other components of the groundwater system were evaluated using the SJC DYNFLOW model, similar to the work on the SJCWMP. Figure 3 shows a set of water level results from the DWSP simulations presenting simulated water levels with and without the DWSP in place.

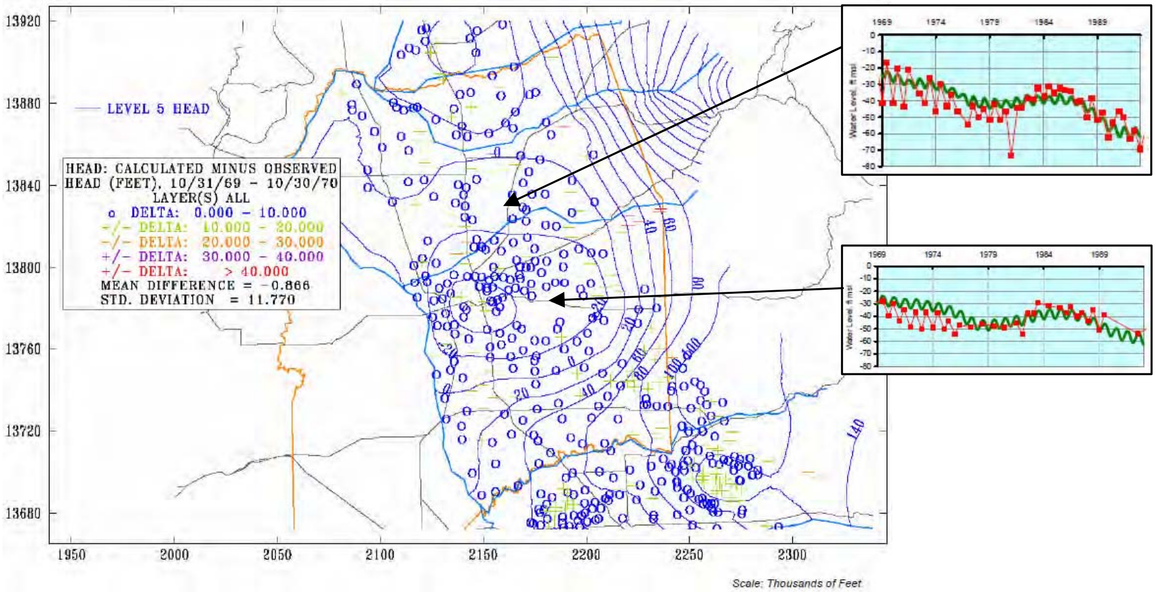

Figure 2. Sample Calibration Results.

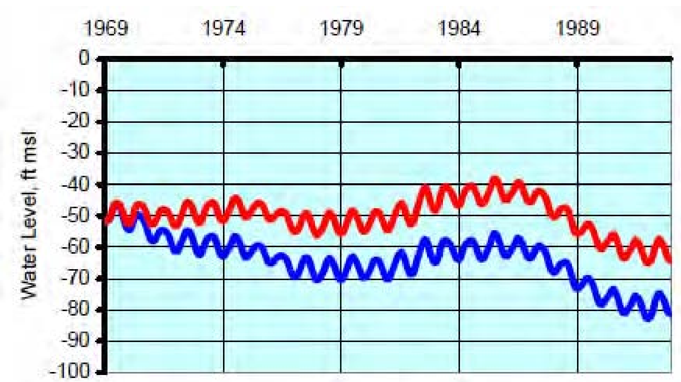

Figure 3. Sample Results from DSWP Simulation.

IWRMP, Integrated Conjunctive Use Program

More recently, the SJC DYNFLOW model was used in preparing the IRWMP. Again, similar to previous applications, the model was used to assess the relative changes to the groundwater basin resulting from proposed water management projects. The projects included in the IRWMP ranged from incorporation of new sources to conservation, groundwater banking, recharge ponds, and a saline injection barrier. Figure 4 shows a sample set of results from the IRWMP simulations with results for one of the management alternatives.

The model is also being used to support the EIR for one of the programs evaluated in the IRWMP. The ICU Program combines various groundwater and surface water management activities together into a set of Action Alternatives. These alternatives were simulated in the model. The potential impacts and/or benefits due to the alternatives are currently being evaluated.

Conclusions

To aid San Joaquin County in understanding and managing the water resources of the region, the SJC DYNFLOW model was developed, calibrated, and applied to a number of studies. This tool has provided, and continues to provide, San Joaquin County and

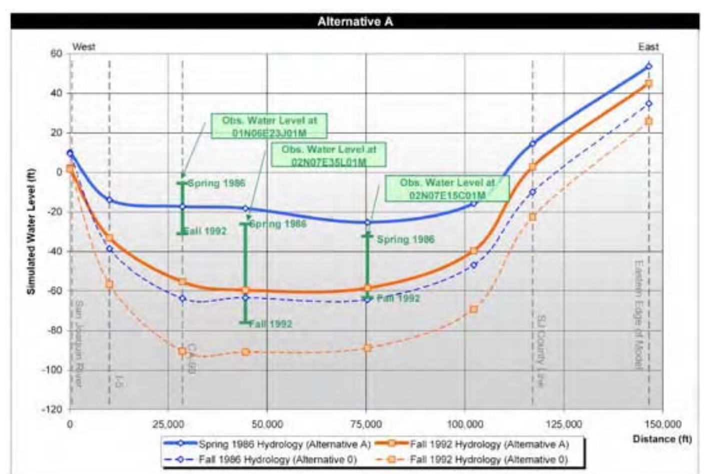

Figure 4. Sample Results from IRWMP Simulations.

surrounding groups with valuable quantitative information regarding the relative impacts to the groundwater basin due to various proposed water management projects.

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City-wide Groundwater Modeling for Remediation and Management – City of Lodi

Varinder S. Oberoi, PE, Michael D. Chendorain, and Patrick B. Hubbard, PG, CEG, Richard Prima, Wally Sandelin, Charles Swimley

As part of simulating the hydrogeologic regime underlying the City of Lodi (City), Treadwell & Rollo, Inc. (T&R) and the City developed a flexible, multipurpose, three-dimensional groundwater flow and contaminant transport model that is currently being applied to integrate the following groundwater remediation and management tasks: 1) demonstrate and support groundwater containment and compliance proposals to the RWQCB in accordance with California legislation AB303, SB1938, and AB3030; 2) evaluate remedial alternatives for the source areas, the Central Plume, and other chlorinated solvent plumes in the context of nearby City supply wells; 3) develop a City-wide groundwater monitoring program to effectively establish the behavior of the contaminant plumes; and, 4) evaluate modifications in the management of the City's groundwater supply system including new well design, wellhead protection, groundwater recharge basins, water recycling, aquifer storage and recovery, potential overdraft, and system optimization. The Groundwater Modeling System™ (GMS), a fully integrated pre- and post-processing modeling platform, was utilized for constructing the numerical groundwater model. The United States Geological Survey (USGS) Modular Three-Dimensional Finite Difference Groundwater Flow Model, MODFLOW2000, the particle tracking algorithm MODPATH, and the contaminant transport module MT3DMS were used for simulating groundwater flow and evaluating the effectiveness of the conceptual remedial alternatives. The model domain encompassed the Mokelumne River and existing City water supply wells, and extended southward to the East Stockton well field. The vertical extent of the model domain was simulated by eight model layers to provide additional resolution to the movement of groundwater and contaminants in the vertical direction. Data from a regional flow model, previous site investigations, and local and state agencies (such as DWR) were used to develop a conceptual site model and the model domain boundary conditions, and provide the hydrogeologic and contaminant transport parameters for the numerical model. Groundwater extraction within the model domain was simulated for 27 City supply wells and 700 irrigation and domestic wells that surround the City. In the future, the numerical model and other mathematical tools will be applied to evaluate groundwater sensitivity and vulnerability.

Introduction

Treadwell & Rollo, Inc. (T&R) and the City of Lodi (City) have developed a flexible, multipurpose, three-dimensional groundwater flow and contaminant transport model (Model) that is being applied to integrate groundwater remediation and management tasks. Currently these tasks include:

- Evaluation of remedial alternatives for several chlorinated solvent plumes located within the City limits, principally the chlorinated solvent plume known as the Central Plume;
- Development of a City-wide groundwater monitoring program to effectively establish the behavior of the contaminant plumes;
- Provide support documentation for groundwater containment and compliance proposals to the Regional Water Quality Control Board (RWQCB) in accordance with California legislation AB303, SB1938, and AB3030; and
- Evaluate modifications in the management of the City's groundwater supply system including new well design, wellhead protection, groundwater recharge basins, water recycling, aquifer storage and recovery, potential overdraft, and system optimization.

The City of Lodi overlies the Eastern San Joaquin Groundwater Basin (ESJGB), which is part of the Central Valley Groundwater Basin in California. As defined in Department of Water Resources (DWR) Bulletin 118-80, the ESJGB is bounded by the San Joaquin and Stanislaus rivers to the west and south, the Calaveras County line along the foothills to the east, and Dry River to the north. Camp Dresser McKee (CDM) developed a regional groundwater-surface water model for the ESJGB (San Joaquin County Department of Public Works [SJCDPW], 2004). The regional model provided a valuable context for the modeling of groundwater flow in the City.

The Model was developed to encompass the Mokelumne River and existing City water supply wells with detail focused primarily in tetrachloroethene (PCE)-contaminated groundwater plume area known as the Central Plume area. The model domain, defined as the area covered by the Model, is presented on Figure 1, which shows the model domain relative to groundwater elevation contours presented in the ESJGB regional model. The objectives of the Model development were as follows:

- Develop a flexible and calibrated City-wide three dimensional (3-D) numerical groundwater flow and contaminant transport model that represents groundwater flow and contaminant transport beneath the City; and
- Simulate the effects of pumping at several depths and locations to evaluate remedial alternatives to contain and treat the Central Plume and other plumes beneath the City.

Prior to constructing the Model, the existing hydrogeologic conceptual model was reviewed and supplemented to represent the major hydrostratigraphic units, aquifer properties, and boundary conditions that qualitatively describe groundwater flow and contaminant transport within the model domain. The review helped to identify data gaps and establish the framework for the Model. The conceptual model encompassed the Central Plume area and its immediate vicinity, the Mokelumne River, and areas that are hydraulically upgradient and downgradient of the Central Plume area (Figure 1).

Contaminants

The initial development of this Model was aimed at describing groundwater flow and contaminant transport within the Central Plume

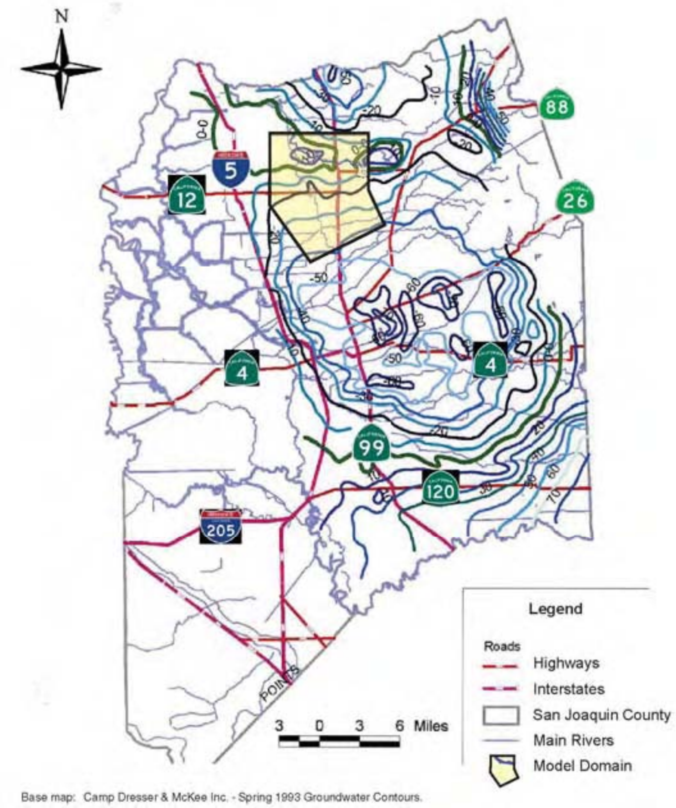


Figure 1. Model Domain Location Map

area. The Central Plume's sources likely include several businesses that historically utilized PCE in their operations. These businesses are located in a one-square-block area bounded by West Pine Street, West Oak Street, Pleasant Avenue, and Chestnut Street. An alleyway runs east-west through the approximate center of this block, and a variety of underground utilities are located along this alley, including a sanitary sewer. The site conceptual model assumes that PCE was released into individual sanitary sewer laterals and within or immediately outside oneor more of the buildings; the PCE traveled along the sewer lines; and the majority of the PCE was released into the subsurface as a pure-phase or dissolved-phase liquid within the one-block length of sewer between Pleasant Avenue and Chestnut Street. The highest PCE concentrations in the plume occur in the source area between Pine Street and Oak Street and have historically exceeded 50,000 micrograms per liter (µg/L) in groundwater. The limits of the Central Plume are defined by the EPA drinking water maximum contaminant level (MCL) for PCE of 5 µg/L. The Central Plume area extends approximately one mile south from the source area. The leading edge of the plume has reached City extraction well, Well-06R; however, concentrations at Well-06R have not exceeded the PCE MCL.

Although the Central Plume was the initial focus of Model development, several other chlorinated solvent plumes are known to exist within the City limits. The extent of PCE detected in the shallow groundwater zone (less than 75 feet below ground surface [ft bgs]) is on Figure 2. The additional plumes within the model domain that are planned for study include the Busybee Plume, Northern Plume, Southern Plume, and Central/Southwestern Plume. PCE has been the historic principal contaminant in the Busybee, Central, and Central/Southwestern Plumes. Both PCE and trichloroethene (TCE) are the principal contaminants in the Northern and Southern Plumes. Similar to the Central Plume, the other plume limits are defined by the areas exceeding MCLs for the principal contaminants of concern. Similar to PCE, the TCE MCL is 5 µg/L.

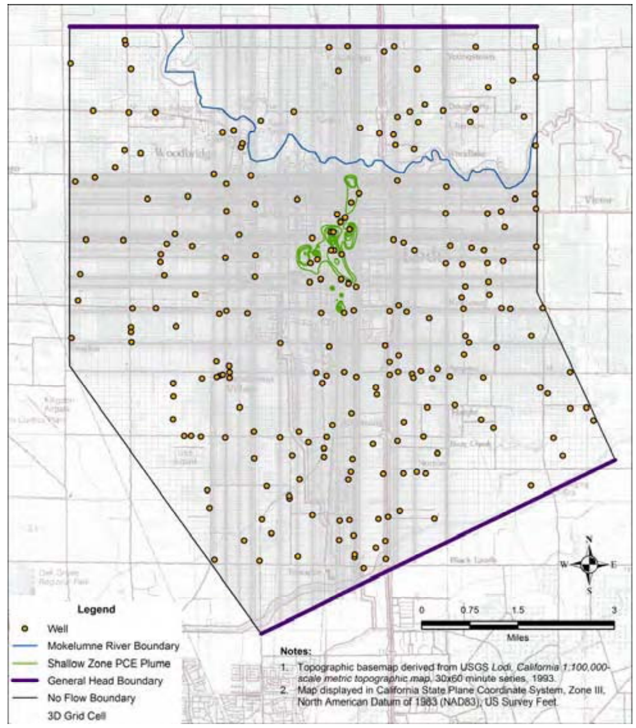


Figure 2. Model Domain and Boundary Conditions with City-wide Shallow Zone PCE Plumes.

Hydrostratigraphy

In the Central Plume area, the unsaturated zone is approximately 40 to 60 feet thick and consists of silty sand with interbedded sands, silts, and clays. The underlying saturated or water-bearing zones are composed of similar soil types and have been divided on the basis of more extensive and thicker sandy portions as follows:

- Shallow Zone which extends from the ground surface to a depth of 75 ft bgs;
- Intermediate Zone that extends from the bottom of the Shallow Zone to a depth of 125 ft bgs;
- Deep Zone that extends from 125 to 150 ft bgs; and
- Deeper Zone that extends below a depth of 150 ft bgs.

Overall, the hydrostratigraphic units are a heterogeneous, hydraulically interconnected system with areas of limited interconnectivity.

The deepest City of Lodi well (Well 23) extends to 545 ft bgs, and as a result, the vertical extent of the model domain was set at 600 ft bgs. The bottom of Well 23 does not extend into bedrock, and hence, soils likely extend below the bottom of the model domain.

Aquifer Properties

Hydrogeologic properties of the aquifer were estimated and used in the initial development of the model. Values for properties such as horizontal hydraulic conductivity K_h, leakance L, specific storage S_s, and storativity S, were obtained from pump tests performed by T&R (T&R, 2006a and 2007), specific capacity tests at the City of Lodi water supply wells (City of Lodi, 2004), and drawdown and specific capacity tests for some of the irrigation and domestic wells outside the City limits (DWR, 2007 and CDM, 2005). The retardation factor, R, for PCE was estimated to range from 1.07 to 1.50 (RAIS database, 2007, Levine Fricke Recon, 2004). Where limited data were available, generally outside of City limits, parameter values were extrapolated based on soil types and available nearby data such as water elevations. The soil types were obtained from boring logs from irrigation wells in these areas of limited data. Figure 3 presents the distribution of K_h and L values for Layer 1.

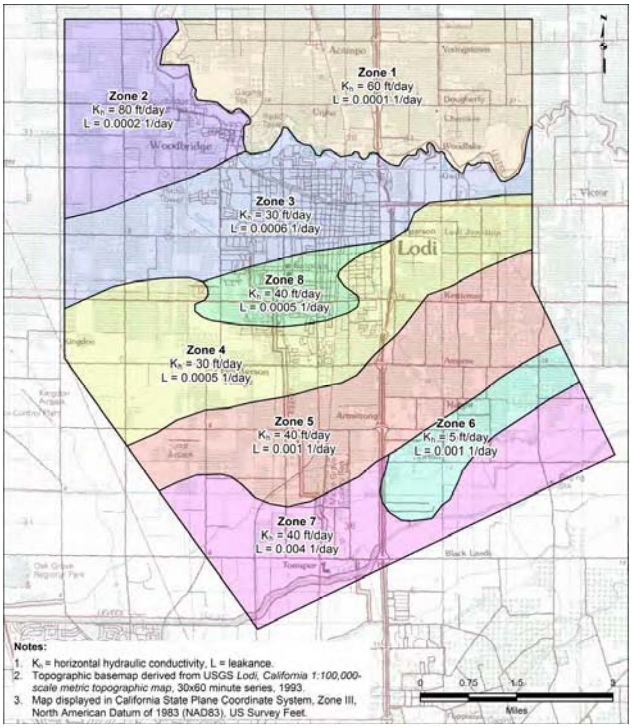


Figure 3. Aquifer Property Zones for Model Layer 1

Groundwater Flow System

Based on the hydrogeologic conceptual model, groundwater inflow into the model domain area was modeled as recharge from precipitation and irrigation, recharge from Mokelumne River seepage, and subsurface regional underflow. Groundwater flow out of the model domain was modeled as pumping from the City of Lodi water supply wells, domestic and irrigation wells, and from subsurface regional outflow along the southeastern perimeter of the model domain. It was assumed that all water not captured by the City of Lodi and irrigation wells within the model domain was transferred as lateral underflow towards the East Stockton well field.

Groundwater pumping east of the City of Stockton has caused regional groundwater levels to drop more than 60 feet below sea level in eastern San Joaquin County (Figure 1, [SJCDPW, 2004]). Another area of relatively low groundwater is present north of the Mokelumne River, where water levels have dropped to approximately 40 feet below sea level (Figure 1). Pumping in these areas has created relatively steep groundwater gradients and flow toward these areas of low groundwater elevations.

Within the Central Plume area, groundwater generally flows to the south-southeast with a relatively uniform gradient toward the area of regional low groundwater elevations. The groundwater elevations in the Shallow Zone decrease from just below river stage elevations near Mokelumne River to approximately 50 ft bgs at the Central Plume. A small vertical gradient is prevalent between shallow and deeper groundwater in the Central Plume area (T&R, 2006b).

Groundwater within the City limits is extracted from 27 City supply wells. Based on the results of a search of DWR well logs, groundwater within the Model domain, yet outside of the City limits, is extracted from approximately 700 domestic, irrigation, industrial, and commercial wells.

Methods

MODFLOW2000® and related computer codes were selected as the numerical codes to be used for the Model (USGS, 2000). MODPATH Version 4.0, a three-dimensional particle-tracking program, was used to simulate the groundwater flow paths and capture zones during the remedial simulations (USGS, 1994). MT3DMS® was selected to simulate the three-dimensional contaminant mass transport for the model domain (USACOE, 1999). The most current version of the graphical interface program Groundwater Modeling System (GMS) Version 6.1 was used to assemble and construct the input files for the Model (GMS, 2007).

Groundwater Flow Model

The extent of the model domain was located relatively far from the City limits (Figure 2) in order to minimize boundary effects and to reduce the effects of errors from input uncertainties on the model results. The surface water features of Mokelumne River were also incorporated into the model domain. The model's grid blocks were constructed with cell sizes ranging from 25 to 500 feet in plan view. The smaller cells were designed to provide greater resolution within the Central Plume area where more data were available. The vertical dimension of the model domain includes eight model layers of uniform thickness. The eight model layers include the following:

- Model Layer 1 represents the Shallow Zone. Model Layer 1 extends from ground surface to 75 ft bgs, incorporates the surface water features of Mokelumne River, and receives the simulated recharge from precipitation.
- Model Layers 2 and 3 represent the upper and lower portions of the Intermediate Zone beneath the City and each has a uniform thickness of 25 feet.
- Model Layer 4 represents the Deep Zone beneath the City and has a uniform thickness of 25 feet.
- Model layers 5, 6, 7, and 8 represent the Deeper Zone beneath the City and have a uniform thickness of 50, 100, 100, and 200 feet, respectively, throughout the model domain.

Surface and bottom elevations of each model layer were assigned using the model layer thickness. The ground surface elevations for the Model were manually entered based on a visual comparison of a USGS 1993 topographic map and ground surface elevation data from the wells within the model domain. The ground surface elevations were contoured using the inverse distance weighted method then adjusted and matched to the surface features of the topographic map. Bottom elevations of the model layers were obtained by subtracting the uniform thickness of each model layer from their respective top elevation for each nodal value within the model domain.

The model boundaries were generally selected to correspond to natural hydrogeologic features and to provide stability in the iterative solutions. These natural features include the regional groundwater flow directions and the effects of pumping from the well field east of Stockton and along the southeastern perimeter of the model domain (Figures 1 and 2). Figure 2 depicts the boundary conditions associated with the model layer.

No-flow boundaries were used along the eastern and western boundaries of the model domain where groundwater elevation contours are generally parallel to the groundwater flow directions. General head boundaries (GHB) were assigned to the northern and southern perimeter of the model domain (simulating inflow of groundwater to the model domain except in Model Layer 1) and the southern perimeter (simulating outflow from the model domain). The initial GHB node elevations were estimated by projecting the inferred groundwater elevations in the central portion of the model domain to the edges of the model boundaries. However, the GHBs were modified during the calibration process by varying the conductance term so that the total subsurface underflow into and out of the groundwater system was similar to values estimated in regional groundwater modeling (SJCDPW, 2004).

The river boundary condition was used to represent the Mokelumne River and its interaction with the aquifer under average flow conditions. The Mokelumne River was modeled as a losing stream (discharge of water from the river to aquifer) based on the results of the regional groundwater flow model and regional groundwater elevation contours (SJCDPW, 2004). The initial estimate of the leakance was modified during calibration of the Model. An initial conductance value of 1,000 ft2/day/ft was assigned to the river bed which was assumed to have similar properties as those of the underlying aquifer. The stage of Mokelumne River was based on the average of recorded stream stage data at the WBR station located at Woodbridge, California and operated by the East Bay Municipal Utilities District (DWR-CDEC). These data were further modified during calibration of the Model.

Initial values of aquifer properties were developed to correspond with the hydrogeologic conceptual model. During calibration and verification, the initial values of the aquifer parameters were modified in order to obtain an acceptable agreement between the observed and simulated calibration targets. The final calibrated aquifer properties are provided in Table 1. The distribution of Kh and L zones are shown on Figure 1 for Model Layer 1. Similar to Model Layer 1, Kh and L zones were developed and calibrated for the other model layers.

The initial groundwater recharge rate for the Model domain was estimated from the total recharge rate used in the San Joaquin County Groundwater Management Plan (SJCGMP) and is a function of net infiltration from precipitation, evapotranspiration (ET), canal leakage, and irrigation within the model domain area (SJCDPW, 2004). To reach calibration, the recharge rate within the City limits was set at a value which was 25% of the net recharge rate outside the City limits. This is likely attributed to the presence of paved areas and structures which impeded the recharge of groundwater. During calibration, recharge rates of 0.00138 ft/day and 0.00055 ft/day for areas outside and within the City limits, respectively, were found to be applicable (Table 1).

The extraction rates assigned to the City water supply wells were the average of the pumping rates during the months of January and February 2006. This period was selected because a relatively large dataset was available and because precipitation was high relative to other seasons within the last decade. Subsequently, the flow portion of the Model was calibrated to this period. The extraction rate assigned to each of the approximately 700 irrigation and domestic wells was 4,000 ft^3/day (20.75 gallons per minute [gpm]). This rate was estimated from the total groundwater pumping stated in the SJCGMP, the ratio of the current model domain to the area stated in the SJCGMP, and the total annual extraction of the City wells. However, due to the limitations of the grid cell sizes, the extraction of the 700 irrigation and domestic wells were condensed into 195 simulation wells. The extraction rates for each of the 195 simulation wells was weighted based on their proximity to actual wells and the actual wells' screen intervals. Therefore the extraction rate for each simulated well was increased according to the number of wells it represented within its vicinity or township-and-range section. Additionally, where the wells were screened across multiple model layers, GMS proportioned the extraction rate from each model layer based on the transmissivities of the model layers.

Contaminant Mass Transport Model

To develop the transport portion of the Model, transport parameters were iteratively adjusted to arrive at the calibrated three-dimensional mass transport solution for the Central Plume area. Table 1 provides a summary of calibrated transport parameters. The initial value used for longitudinal dispersivity, D_L, was obtained from empirical relationships between D_L and plume length (BIOCHLOR, 2000; Gelhar et al, 1992). Transverse dispersivity, D_T, values are typically an order of magnitude less than the longitudinal dispersivity values, while vertical dispersivity values, D_V, are typically two orders of magnitude lower than the longitudinal dispersivity values (BIOCHLOR, 2000; Gelhar et al, 1992). Therefore initial D_T and D_V values were based on the initial D_L value. The dispersivity values and ratios were modified during the initial calibration process.

To simulate the possible presence of residual PCE within the source area, a constant source term was used to simulate the Central Plume source area. It consisted of four constant source nodes which were incorporated into Model Layer 1 at a location near monitoring well MW-09. The residual PCE source concentration at these nodes was set at 50,000 µg/L and was based on the average of the maximum observed groundwater concentrations at MW-09 and nearby sampling points (T&R, 2006b). To simulate adsorption processes during contaminant

(a)

(b)

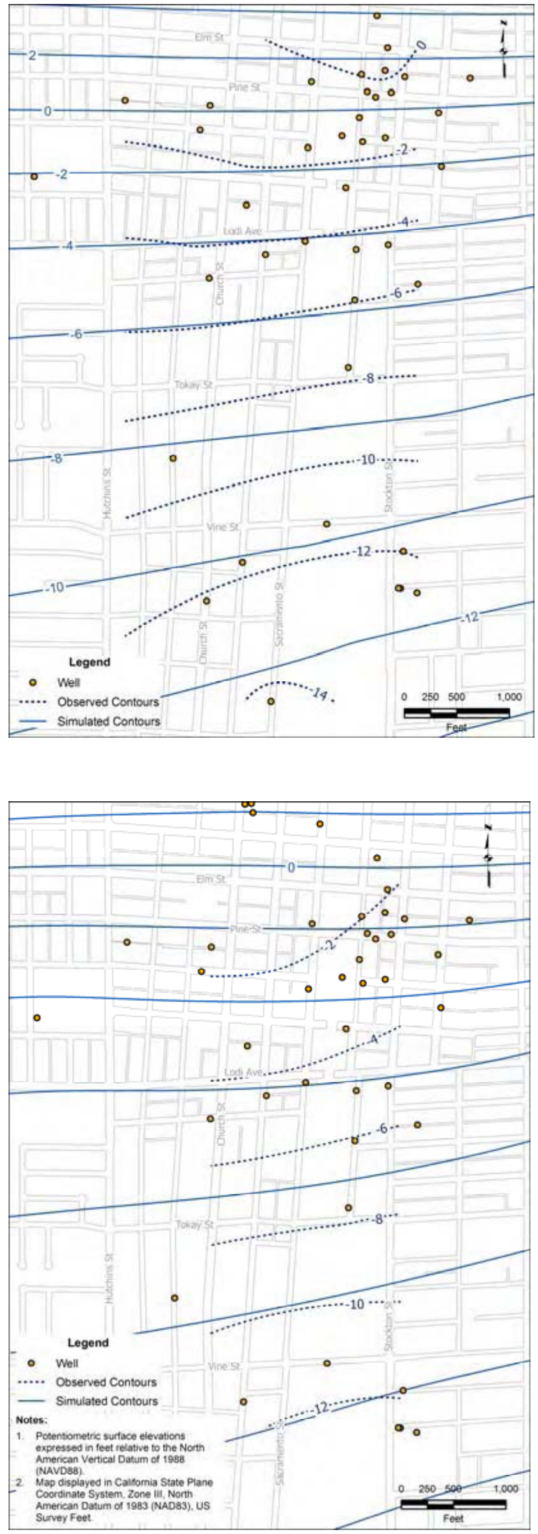


Figure 4. Observed vs. Simulated Potentiometric Surface, March 2006, Model Layer 1, A) Shallow Zone < 75 ft bgs, B) Intermediate Zone 75 – 100 ft bgs

transport, a retardation factor ranging between 1.07 to 1.25 was applied to all the cells of the model domain. Based on the groundwater sampling results for the Central Plume area, the breakdown of contaminants was considered to be negligible, and biodegradation was not simulated (T&R, 2006b).

Results

Groundwater Flow Model

The groundwater flow portion of the model was calibrated to groundwater elevation data collected in the Central Plume area duringMarch 2006. This time period was selected because it is a relatively large dataset of groundwater elevations and City supply well pumping rates, and it represents elevated water level conditions due to above average rainfall during 2006. The following model variables were adjusted during calibration: hydraulic conductivity, leakance, Mokelumne River bed conductance, conductance of the general head boundary cells, specific storage, and the hydraulic head assigned to the general head boundary cells. The final calibrated parameter ranges are presented in Table 1.

A qualitative evaluation of the calibration was made by comparing the shape and gradient of the simulated and interpreted potentiometric surface of the calibrated model layers. Figures 4A and B depict the comparison for the Shallow and Intermediate zones, respectively. As shown on these figures, the contours based on simulated elevations generally mimic the contours based on the observed elevations, and the elevation, shape, magnitude, gradient, and position of the contours based on the observed heads are accurately simulated by the calibrated model.

In addition, a statistical assessment of the calibration was performed on the available groundwater level data within the model domain (primarily within the Central Plume area). Both convergence and residual statistics were calculated for the calibrated groundwater model solution. The convergence statistics used to assess the quality of the iterative solution of the Model include the maximum groundwater elevation (i.e. head) change for all model cells between iterations (total head change) and the percent discrepancy between the total flow into and out of the Model (volumetric flow budget discrepancy). The calibrated groundwater flow model produced a total head change of 0.001 feet. The calibrated water budget indicated a discrepancy of 45.5 ft^3/d between the inflow and outflow values for the model domain. This translates to a discrepancy of less than 0.001%.

The residual statistics represent the groundwater head difference between the heads simulated by the Model versus the heads observed at the wells. These statistics were evaluated using traditional statistics, the spatial distribution of the residuals, and by a graphical presentation of the heads simulated by the Model versus the observed heads. Figure 5 illustrates the close fit between the simulated heads and the observed heads. The residuals for all the calibration targets are within a range of -4.03 feet to 2.93 feet for the calibrated groundwater flow simulation. The mean error was -0.466 and the root mean squared (RMS) residual error was 1.843. Although the overall fit by the model was good, discrepancies in residuals at individual wells could be attributed to localized variations such as surface control of recharge and spatial heterogeneities as well the inherent limitations of the model discretization.

Following model calibration, the Model was verified by simulating the constant-rate aquifer test performed at the City of Lodi Well-06R (T&R, 2006a). Simulated and observed pumping responses were compared to verify if the Model was capable of accurately simulating pumping stresses in the vicinity of the water supply wells. The Well-06R aquifer test was performed from August 30 through September 2, 2005. Groundwater was extracted at an average constant rate of 1,500 gpm for a period of 2.5 days. Simulated and observed drawdown curves at selected wells were compared. The results of the

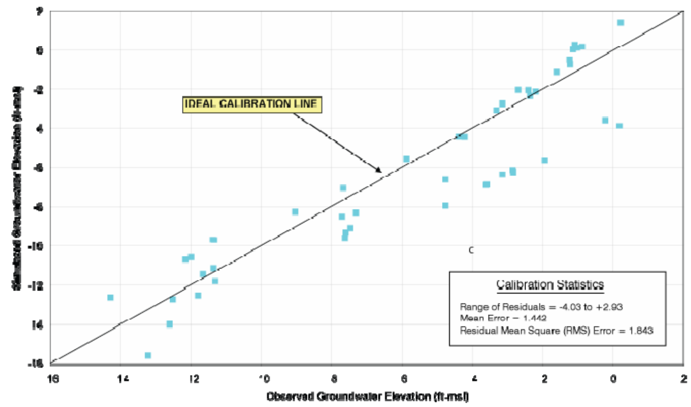


Figure 5. Comparison of Simulated vs. Observed Groundwater Elevations, March 2006

model verification generally indicated a good correlation between the simulated and observed drawdown values (Table 2). Discrepancies between the simulated and observed drawdowns can be attributed to the Modelrepresentation of the 8-inch diameter pumping well as a 25-foot by 25-foot cell and to local variations in aquifer characteristics. Following the model calibration, a sensitivity analysis was performed by systematically increasing or decreasing the values of the following model parameters: horizontal hydraulic conductivity (Kh),leakance (L), recharge (R), Mokelumne River conductance (C), and groundwater extraction rate. The results of the sensitivity analysis and the impact on groundwater elevations in the Central Plume wells are shown in Table 3. In general, the Model was sensitive to variations in Kh, L, R, and the pumping rate. However, changes in the values of the Mokelumne River bed conductance C had limited or no impact to groundwater levels in the Central Plume area wells.

Contaminant Mass Transport Model

The transport portion of the Model was calibrated by simulating PCE migration between 2001 to 2007. The model transport parameters were adjusted to achieve an acceptable match between the simulated and observed PCE concentrations for the Central Plume. Initially the retardation factor was modified to match the simulated and observed lateral plume extents. Then, the longitudinal dispersivity values and the dispersivity ratios were adjusted to reach an acceptable fit between the simulated and observed lateral and vertical extents of the Central Plume. The final calibration parameters are provided in Table 1.

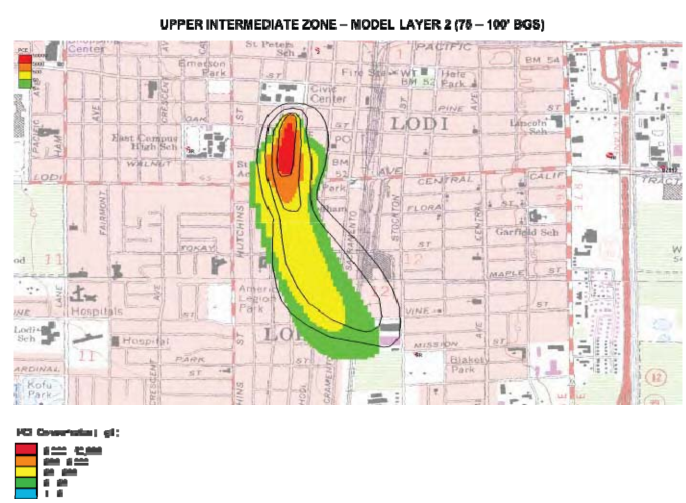


Figure 6. Interpreted vs Simulated PCE Concentration Contours, Model Layer 2, 75 - 100 ft bgs (March 2007)

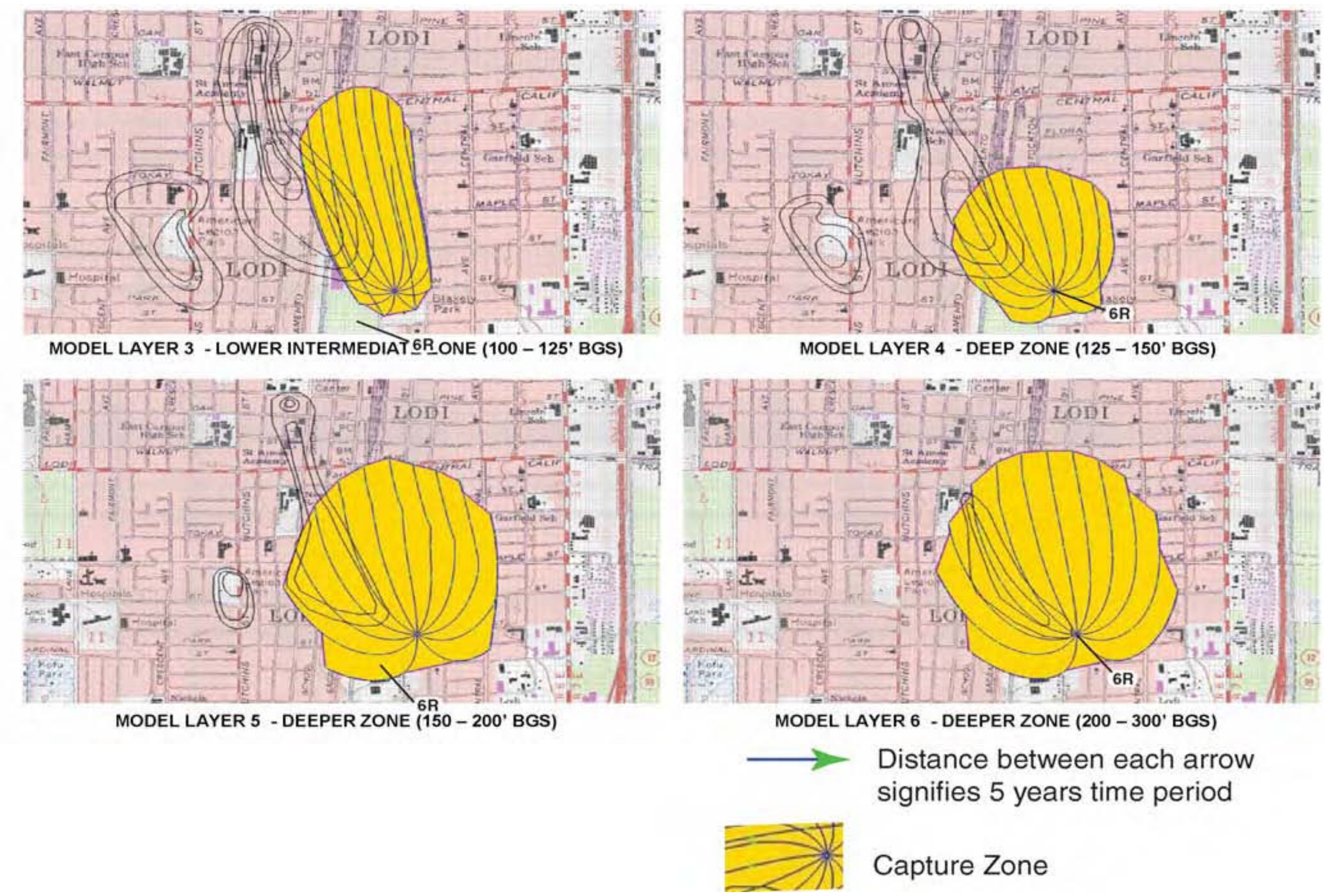


Figure 7. Remedial Alternative Simulation 1, 30 Year Capture Zones.

A qualitative analysis indicates a generally close correlation between the observed and simulated 2007 PCE contours (Figure 6). Discrepancies between simulated and observed concentrations occurred at some wells and can be attributed to local variations in the aquifer characteristics and variation in pumping rates during the simulated time period. In addition, the simulated concentrations are averages across the entire cell where the observed concentrations are derived from sample results. The sample results are subject to variability due to sampling technique, seasonal variation, and other external influences that cannot be adequately simulated using a numerical model such as MT3DMS®.

Remedial Alternative Simulations

One of the purposes of the calibrated Model was to evaluate remedial alternatives for containing and mitigating the Central Plume and other plumes within the City of Lodi. Two remedial alternatives for the Central Plume are presented here using simulations over a period of 30 years.

Remedial Alternative 1 – Central Plume Area, No Remedial Action

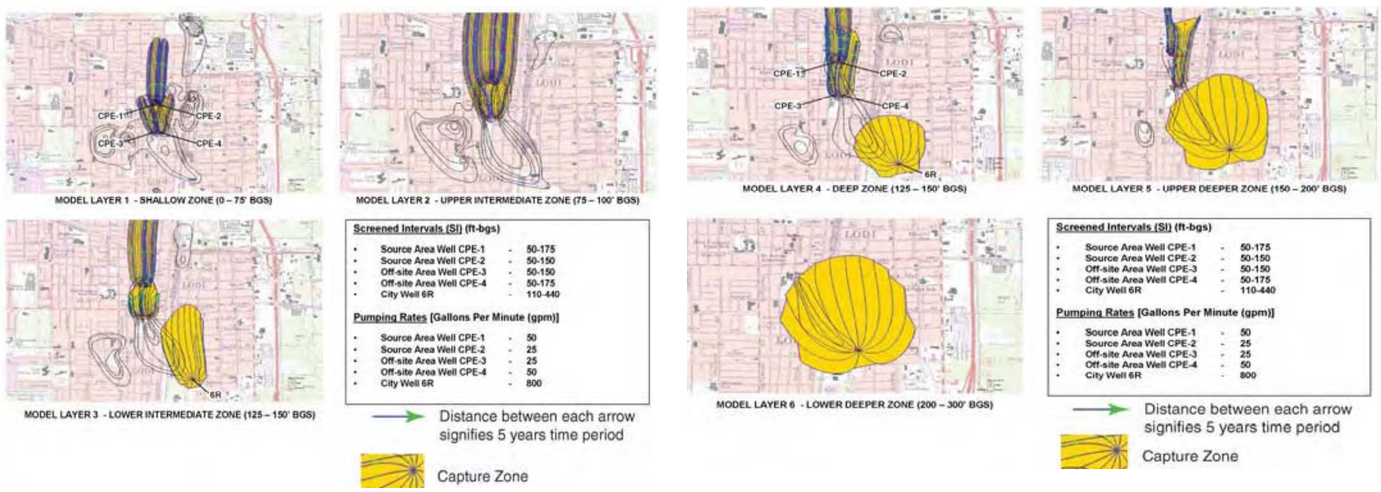
Remedial Alternative 1 simulates PCE migration without the addition of any remedial extraction wells. However, extraction from City water supply Well-06R was modeled to determine its effectiveness in containing and mitigating the leading edge of the Central Plume
within the different water bearing zones. Initial simulations of this rates alternative were performed with Well-06R pumping at varying flow to determine the rate at which optimal capture would be achieved. Well-06R is screened from a depth of 170 to 440 ft bgs and has a gravel pack from a depth of 109 to 439 ft bgs. Based on the length of the gravel pack and aquifer test results, pumping from City Well-06R was estimated to have minimal impact on the Shallow Zone (Model Layer 1) and the Upper Intermediate Zone (Model Layer 2). Hence, no capture zones for these two zones were estimated. Figure 7 provides the capture zones in the Lower Intermediate, Deep, and Deeper Zones with Well-06R pumping at a rate of 800 gpm.

As shown on Figure 7, extraction from Well-06R is not sufficient to contain the majority of the Central Plume in the Lower Intermediate and Deep Zones (Model Layers 3 and 4, respectively) even after 30 years. However, Well-06R provides adequate capture for remnants of the Central Plume prevalent in the Deeper Zones (Model Layers 5 and 6) over a 30-year period. Additional simulations with Well-06R pumping at higher rates did not improve the effectiveness of Well-06R in containing the remnants of the Central Plume in the Lower Intermediate and Deep Zones.

Remedial Alternative 2 – Central Plume Area and Source Containment

Remedial Alternative 2 simulates the effectiveness of source and mid-plume area remediation wells in containing the source and mid-plume portions of the Central Plume by limiting the downgradient migration of the Central Plume from the source area (i.e. where PCE concentrations are greater than 5,000 µg/L) and from the mid-plume area (i.e. where PCE concentrations are greater than 50 µg/L in the Shallow Zone [Model Layer 1]). Table 4 provides the number of wells used to contain the source and mid-plume areas, their recommended screen intervals, and their recommended pumping rates.

Figures 8A and B provide the capture zones of the remedial wells for the different aquifer zones defined for the Central Plume area. As shown on Figures 8A and B, this alternative was capable of sufficiently containing the majority of the source and mid-plume areas over a 30-year period. Figure 9 illustrates the performance of the



(A) (B)

Figure 8. Remedial Alternative Simulation 2, 30 Year Capture Zones: A) Model Layers 1 through 3, B) Model Layers 4 through 6.

Central Plume in Model Layer 1 after 1, 10, 20, and 30 years. Figure 9 also illustrates the transport of the other City area PCE plumes where no remedial extraction has occurred. Figure 10 provides a cross-sectional view of the migration of the Central Plume, along its longitudinal and vertical directions, after 1, 10, 20, and 30 years. As shown on Figures 9 and 10, the mid-plume wells (wells CPE-3 and CPE-4) provide a cutoff from further downgradient migration of the Central Plume, and are able to contain impacts within the source and mid-plume areas. Also, Figures 9 and 10 illustrate that PCE concentrations immediately downgradient of the mid-plume wells start to decrease. Figure 10 illustrates that remnants of the Central Plume in the Deeper Zones (Model Layers 5 and 6) are captured by City Well-06R.

Discussion

A three-dimensional, numerical groundwater flow and contaminant transport model has been developed to simulate several remedial alternatives for the Central Plume and eventually the entire City. Calibration, verification, and sensitivity analysis results of the model indicate good agreement with available data over the periods simulated. Sensitivity analysis has indicated that groundwater elevations within the Central Plume are not influenced by changes in the Moklumne River, but are influenced by changes in recharge (precipitation and irrigation), hydraulic conductivities (vertical and horizontal), and groundwater extraction rates in City supply wells. The final calibrated transport parameters indicate that the Central Plume is predominantly governed by advective flow in the longitudinal direction.Based on the results of the remedial alternative simulations, it appears that none of the recommended remedial alternatives are capable of mitigating or containing the leading edge of the Central Plume in the Shallow, Intermediate, and Deep Zones (Model Layers 1 through 4). Future remedial simulations will include two additional wells, screened across the Shallow through the Deep Zones (Model Layers 1 through 4), and pumping at a minimum of 25 gpm each, located in the vicinity of Vine Street to contain the leading edge of the Central Plume.

The current version of this Model is based on previously performed investigations, information and data provided by the City and other regulatory agencies, and available literature. The available information is limited for model parameters such as hydraulic conductivity, groundwater elevation data, extraction rate data for wells outside the City limits, and infiltration rates. Further hydrogeologic investigations may provide additional information, upon which to re-evaluate and update the model results. While the current version of the Model is believed to be accurate within the confines of the information available and the conceptual modeling approach, the results of groundwater flow and contaminant transport simulations are limited by the nature of the information available, especially in areas outside the City.

Ideally, any groundwater model should be calibrated using initial steady state conditions. Steady state conditions could mean either non-pumping (i.e. static) or even conditions where pumping at consistent rates has occurred for long enough to achieve steady state. Groundwater trends and production well data obtained from the City and irrigation wells suggest that the groundwater flow through the model domain is transient. In addition, it is unknown as to how close to steady state these transient conditions are. It is possible that the transient nature of this groundwater system is attributed to any one or a combination of the following: additional pumping by the City or the owners of wells surrounding the City, changes in groundwater recharge due to changes in annual precipitation, changes in pumping from the East Stockton well field, or changes in recharge from Mokelumne River. Because of the transient nature of the groundwater conditions beneath the model domain, simulations that extend into the future are influenced by any of the above ever changing conditions. Hence, the results of the 30-year remedial alternative simulations may be different from those projected by the model.

The next use of this model will be to expand the number of remedial extraction wells to contain a larger portion of the Central Plume area as well as portions of the Northern, Southern, and South Central/Western Plumes. Once a City-wide preferred remedial alternative has been developed, the Model will be used to aid in the design of the preferred remedial alternative. As more data is collected (such as drawdowns due to extraction wells and changes in contaminant concentrations), the Model will be revised as appropriate.

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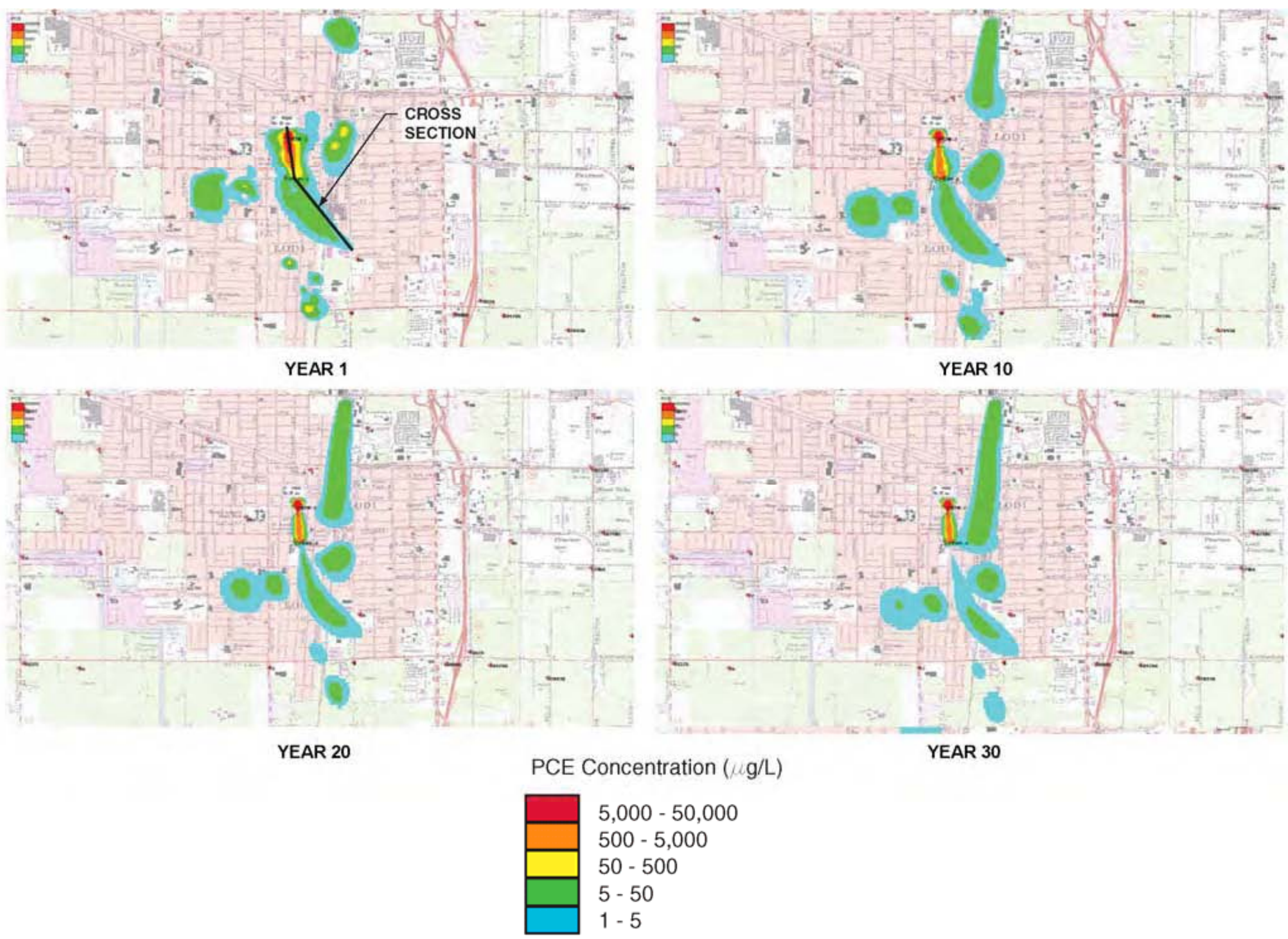

Figure 9. Remedial Alternative Simulation 2, Transport of PCE in Model Layer 1-after 1 year, 10 years, 20 years, and 30 years. Note that all plumes are shown, but only four remedial wells are simulated for the Central Plume source and mid-plume areas.

Table 1. Current Calibrated Model Parameters

Property	Symbol	Units	Range of Values
Horizontal Hydraulic Conductivity	K_h	ft/day	3 to 80
Leakance	L	1/day	0.0001 to 0.08
Recharge	R	ft/day	0.00055+, 0.00138*
Storage Coefficient	S_s	(unitless)	0.00005 to 0.02
River Conductance	C	ft^2/day/ft	1000
Retardation Factor	R	(unitless)	1.07 to 1.50
Longitudinal Dispersivity	D_L	Feet	20
Ratio of Transverse to Longitudinal Dispersivity	D_T/D_L	(unitless)	0.2
Ratio of Vertical to Longitudinal Dispersivity	D_V/D_L	(unitless)	0.001

+ Value for areas within City limits. * Value for areas outside of City limits.

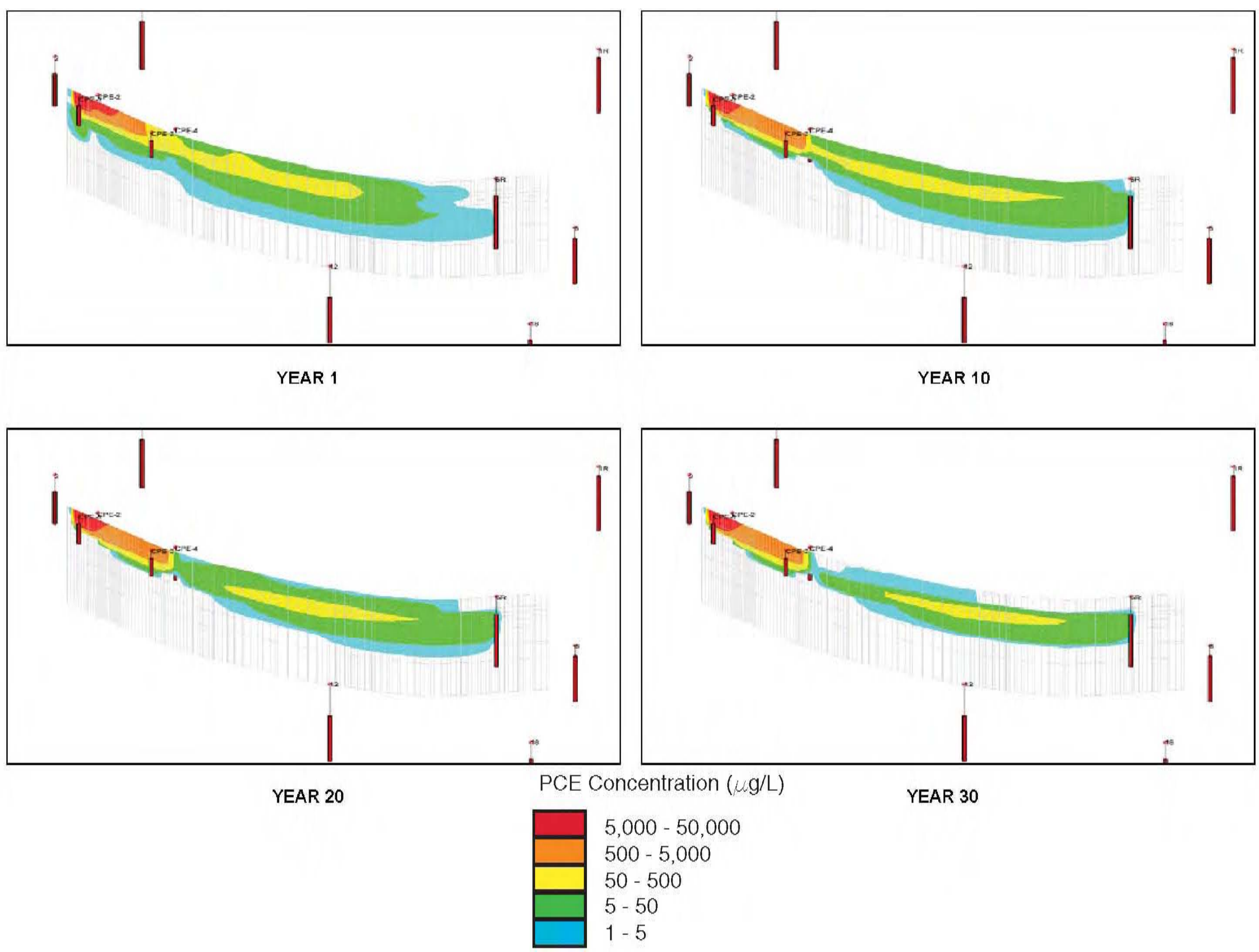

Figure 10. Remedial Alternative Simulation 2, Cross-Sectional View of PCE Transport after 1, 10, 20, and 30 years along the North to Southeast midpoint of the Central Plume.

Table 2. Results of Groundwater Model Verification, City of Lodi model.

Well	Model Layer	Maximum Drawdown (ft bgs)		Residuals
		Observed Head	Simulated Head	(ft)
MW-17	1	-0.97	-0.80	-0.17
MW-18	1	-0.46	-0.37	-0.09
MW-19	1	-0.35	-0.28	-0.07
MW-21A	1	-1.12	-0.98	-0.14
PCP-4	1	-1.19	-0.97	-0.22
MW-21B	2	-1.14	-1.00	-0.14
MW-22B	2	-0.73	-0.68	-0.05
MW-23B	2	-1.24	-1.00	-0.24
MW-21C	3	-1.19	-1.02	-0.17
MW-22C	4	-1.12	-1.69	0.57
MW-27D+	6	-10.45	-12.93	2.48
			Model Layers 1 - 6	Model Layers 1 - 4
Mean Error			0.16	-0.07
Mean Absolute Error			0.39	0.19
Root Mean Square Error			0.78	0.23

Table 3. Results of Sensitivity Analysis, City of Lodi model.

Parameter+	Change in Values*	RMS Error	% Difference	Comments
Calibrated Model		1.84	0	
K_h	+5x	13.14	610	Increased groundwater levels from 15 ft in Shallow Zone Central Plume wells to 7 ft in Deeper Zone wells
	-5x	--	--	Unstable solution as Model did not converge
L	+10x	12.63	590	Increased groundwater levels by 12 ft in Central Plume wells
	-10x	16.98	820	Increased groundwater levels by 18 ft in Shallow Zone Central Plume wells and decreased 7 to 13 ft in Deep and Deeper Zone wells
C	+4x	1.86	1.1	No significant impact on groundwater levels in the Central Plume wells
	-4x	1.84	0	
R	+5x	45.19	2300	Increased groundwater levels in Central Plume wells by >30 ft
	-5x	9.99	440	Decreased groundwater levels in Central Plume wells by >8 ft
Pumping Rate++	+2x	13.37	630	Decreased groundwater levels in Central Plume wells by >12 ft
	-2x	6.01	230	Increased groundwater levels in Central Plume wells by >6 ft

+ Kh – Horizontal Hydraulic Conductivity; L – Vertical Leakance between Model Layers; R – Recharge Rate;
C – River Bed Conductance, RMS – root mean squared, -- no result
* Change in values refers to the multiplier applied during the simulation (i.e. +5x is an increase by factor of 5)
++ Pumping Rate sensitivity analysis was performed by only changing City of Lodi supply well pumping rates

Table 4. Remedial Alternative Simulation 2 Information, City of Lodi model.

Remedial Alternative Wells	Screened Interval (ft-bgs)	Model Layers	Pumping Rates (gpm)	Comments
CPE-1	50 – 175	1 to 4	50	Source Area Containment
CPE-2	50 – 150	1 to 5	25	Source Area Containment
CPE-3	50 – 150	1 to 4	25	Mid-Plume Area Containment
CPE-4	50 – 200	1 to 5	50	Mid-Plume Area Containment
City Well 06-R	109 – 439	3 to 8	800	Leading Edge Containment

Impact of climate change on crop water requirements, groundwater and soil salinity in the San Joaquin Valley, CA

Gerrit Schoups, Jan W. Hopmans and Edwin P. Maurer

Recent analyses of climate change over California have provided projections of the range of warming and other changes that the region may face by the end of the 21st century. The projected reduction in surface water availability and potentially increased water requirements is expected to cause California's farmers to respond by supplementing available irrigation waters by increasing groundwater pumping. However, increased pumping will increase energy costs, and diminishing quality of groundwater applied as irrigation water will generally increase soil salinity. Our study applies a recently developed hydrosalinity model to project the impact of climate change on groundwater resources, crop water requirements, and soil salinity for a representative 1,400 km2 agricultural area in the San Joaquin Valley. The model couples projections of climate change through the 21st century with the MODHMS subsurface hydrology model, to evaluate the impact of climate change on irrigation water availability, crop water requirement and soil salinity. We contrast the variability in impacts due to different greenhouse gas emissions scenarios and different changes in availability of surface water deliveries on the impacts on both groundwater quantity and quality, and assess the sustainability of irrigated agriculture in this region under the different scenarios.

Introduction

We present the methodology and results of a quantitative analysis of the potential effects of climate change on the sustainability of irrigated agriculture in the western San Joaquin Valley, CA. The analysis is done at the regional scale (study area ~1400 km2), as shown in Figure 1, and for a time horizon extending to the year 2100.

An earlier study that focused on the modeling of historical changes in soil and groundwater salinity since the 1940's was published by Schoups et al. (2005), and concluded that irrigated agriculture has contributed significantly to deep groundwater salinity, and that gypsum dissolution was the principal salt source. A preliminary report of the presented modeling results with the focus on the future is available at Hopmans and Maurer (2007).

The analysis is based on projected global changes in greenhouse gas (GHG) emissions, and resulting changes in temperature and precipitation as simulated by global climate models (GCM). Uncertainty in climate change predictions is handled through the use of three GHGemission scenarios and two GCM's. These data serve as input for a downscaling procedure to determine changes in meteorological conditions (temperature, precipitation, and evapotranspiration) at the regional scale of this study. Resulting impacts on water supply and crop water demand are calculated for irrigated agriculture in the study area. Crop response includes changes in crop water demand due to changing atmospheric conditions. We considered future changes in potential crop ET rates caused by (i) increased atmospheric CO2 levels, (ii) increased reference ET, and (iii) increased air temperatures.

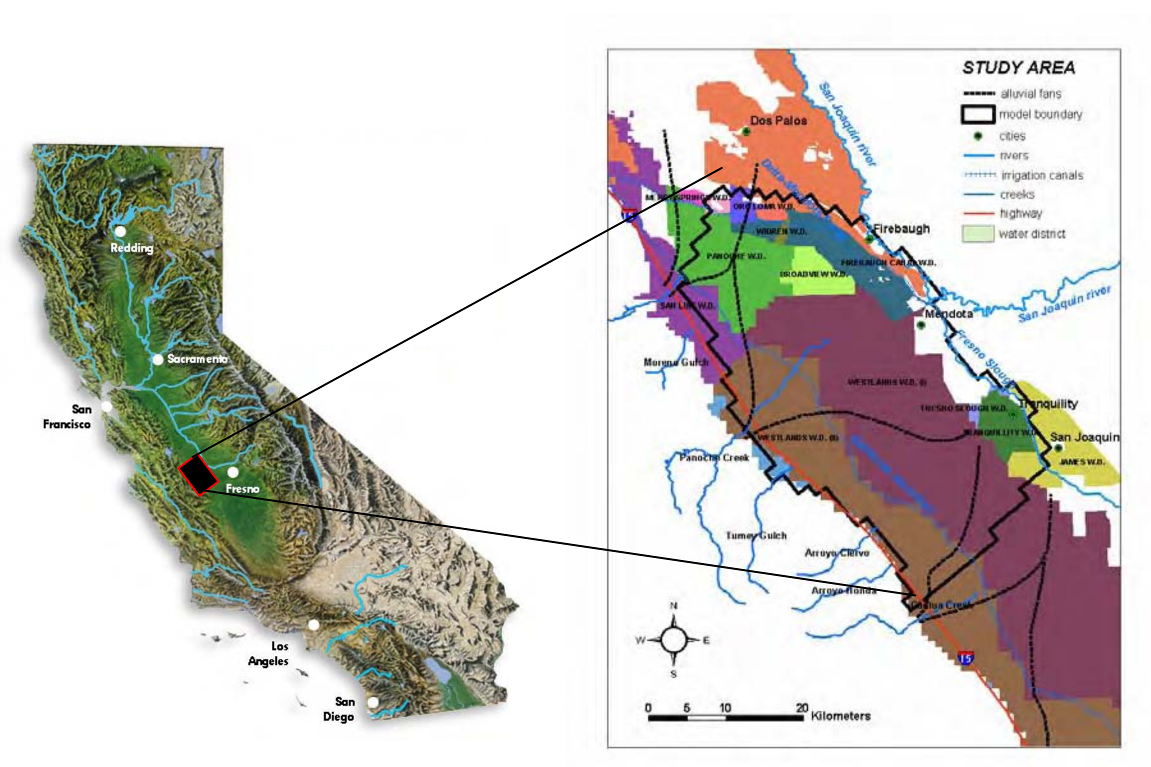

Figure 1. Location of the ~1400 km^2 study area in the western San Joaquin Valley, California.

We considered the following possible management responses to changes in surface water supplies and crop ET: (i) land fallowing and retirement, (ii) changes in cropping patterns, (iii) groundwater pumping, and (iv) technological adaptation. We predicted temporary land fallowing assuming it is inversely related to surface water supply, as indicated by historical fallowing during droughts in the study area. These results are used in turn to assess effects on agricultural water and crop management by quantifying potential changes in groundwater pumping, crop choices, and water use efficiency.

In the final step, the climate-change induced changes in crop ET, surface water supply, and groundwater pumping were used as input into a hydro-salinity model of the study area to assess resulting impacts on groundwater levels, land subsidence, soil salinity, and crop yields. This was done for 8 climate change scenarios, including a no-climate-change scenario and one that assumes a uniform irrigation efficiency of 90% by technological adaptations. Although scenarios differed significantly in the amount of groundwater applied, and the simulated extent of shallow water tables, soil salinity predictions do not vary greatly between scenarios. Wet scenarios resulted in less groundwater pumping, whereas the dry scenarios projected increased groundwater pumping, causing downward hydraulic gradients and lowering of shallow water tables. The recycling of groundwater by pumping exacerbates the groundwater salinity problem because of downward mobilization of dissolved gypsum.

Conclusions

The main conclusions on agricultural sustainability under climate change are as follows:

- Water demand: Irrigation water demand does not change much due to compensating effects of rising temperature on evaporative demand and crop growth rate. In other words, an increase in reference ET is compensated by shorter growing seasons. This conclusion is robust for the wide range of climate change scenarios considered here. One consequence of shorter growing seasons could be that it will be possible to produce two crops each year. At that point irrigation water demand will increase significantly, perhaps beyond what can be supplied.
- Water supply: There is large uncertainty in future water supply under climate change, due to large variation in projected precipitation among climate change scenarios. Water supply estimates range from an increase of 10% to a decrease of 30% in 2100, compared to current conditions.
- Soil salinity: The spatial extent of salt-affected soils is projected to remain fairly stable in the 21st century for all climate change scenarios (except the one considering technological adaptation in the form of an improvement in irrigation efficiency: this scenario shows a decrease in salt-affected area). High soil salinity is limited to the eastern half of the study area, in where topography is low and flat, and soils are poorly drained. The western half of the study area is characterized by steeper topographic gradients and coarser alluvial deposits, which is why salinization due to rising water tables is unlikely to occur in those areas.
- Crop productivity: All scenarios project an increase in soil salinity in downslope areas, to the point where tomato and even cotton yields are negatively affected. Part of this area has already been retired from agricultural production, although model simulations indicate additional upslope areas may be affected. If no artificial drainage is possible on these lands, then additional land retirement may be the only option. Model results show that this process of continued salinization will occur regardless of climate change. This is especially significant given an anticipated demand-driven switch from salt tolerant crops (such as cotton) to high-value, salt-sensitive crops (such as tomato and melons).
- Groundwater salinity: Leaching of salts to groundwater mostly occurs in the western half of the study area (upslope), where soils are well drained. Over the long term, this could negatively impact salinity of underlying production aquifers, although this salinization process will take hundreds of years. Downslope areas on the other hand are characterized by groundwater discharge, resulting in upward salt fluxes from deeper groundwater into the root-zone, causing excessive soil salinization. Differences between scenarios in salt loading to groundwater are related to the amount of groundwater pumping.
- Land subsidence: Land subsidence is projected to be very limited, with no subsidence for wet scenarios and for the no-climate-change scenario. Greatest total land subsidence is projected to occur in the driest (hadcm3-sresa1fi) scenario, although the maximum simulated value is only 1 ft.
- Technological adaptation: One scenario considered technological adaptation in the form of an improvement of irrigation efficiency to 90%. If indeed technologically possible, this adaptation could effectively mitigate many adverse effects projected in all other climate change scenarios. It would reduce groundwater pumping, irrigation water demand, groundwater recharge, soil salinity (both extent and level of salinity), and would decrease the need for land retirement due to excessive soil salinization.

In summary, the greatest threat to agricultural sustainability in the area appears to be the continued salinization of downslope areas, which may jeopardize crop production and require further land retirement. Technological adaptation, such as improvements in irrigation efficiency, may be a possible way to mitigate these effects. Future work should consider additional scenarios, and evaluate the vulnerability of the system to further increases in groundwater pumping. Also, more work is needed on quantifying uncertainties in projected impacts, caused by not only uncertain climate projections, but also by uncertainties in the hydrosalinity model.

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Sustainable root zone salinity in the context of shallow perched water table, and attenuation: Land retirement demonstration project in the west San Joaquin Valley*

Purnendu Singh and Wes Wallender

In the San Joaquin Valley of California, intensive irrigation in conjunction with a shallow underlying layer of heavy clay, and absence of a drainage system caused the root zone to become highly saline and a shallow water table to rise. Land retirement, which is proposed as one of the management tool to address the problem, would remove from production those farmlands contributing the poorest quality subsurface drain water. Based on numerical models results, it was expected that with land retirement of substantial irrigated lands with poor drainage characteristics, beneath which lies shallow groundwater with high salt load, the shallow water table beneath those lands should drop. On the other hand, a potential negative side of the land retirement option is that in certain enabling evapotranspiration, soil and water table conditions, water will be drawn upwards and evaporated, leaving a deposit of salts on the surface and in the root zone. The deposits of salt on the surface may then be wind blown to adjacent areas creating a potential environmental hazard.

Using field results from the Land Retirement Demonstration Project at the Tranquillity site located in western Fresno County by U.S. Department of the Interior, principles of mass balance in a control volume, the HYDRUS-1D Software Package for simulating one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, and PEST, a model-independent parameter optimizer, we have investigated the processes of soil water and salinity movement in root zone, the deep vadose zone and the groundwater. The simulation period covered was 5 years and we used measured perched water table depth and changes in the average root zone soil salinity as given by electrical conductivity measurements to optimize soil water retention properties, solute transport parameters and downward flux values at three locations of the Tranquillity site. The calibrated model is used to calculate the daily as well as the cumulative water and salt flux in the root zone for a sustainable water table elevation and root zone salinity. A new paradigm using a “bottom up” approach to site selection for land retirement as well as management of retired land has been developed. With this “bottom up approach”, we show that it is feasible to select a sustainable land use regimen for the retired lands.

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Introduction

In the San Joaquin valley of California, where a combination of lack of adequate out of basin drainage caused by topographic and environmental constraints, intensive irrigation practices, and the presence of a shallow underlying layer of clay has caused the root zone to become highly saline and the shallow water table to rise. To address theses issues, the Bureau of Reclamation (BR) has decided to implement a combination of drainage reduction measures, drainage water reuse, evaporation ponds and land retirement in what it calls the In-Valley/Water Needs Land Retirement Alternative (BR, 2007).

The link between the land retirement and shallow water table has been established in the hydrologic model studies (Purkey and Wallender 2001a, b and Fio, 1999). But it is also argued, based on a modeling study of water and salt transport in unsaturated soils in arid

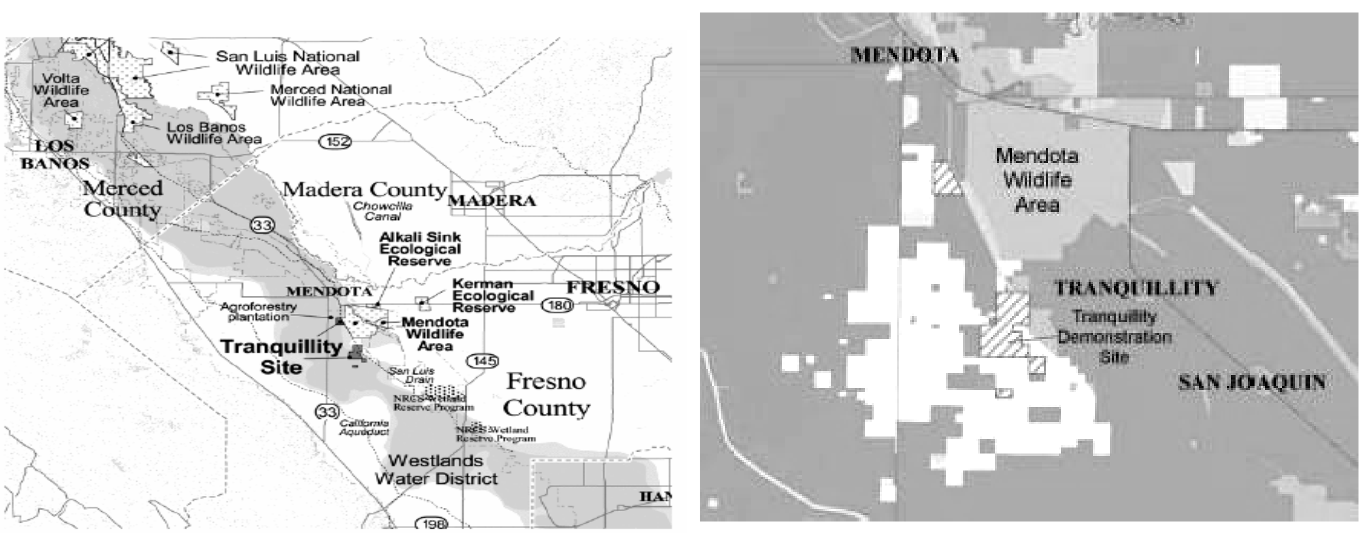

Figure 1. Location map for Tranquillity site

climates that the retired lands could become excessively salinized over time and would thus become unsuitable even for non-irrigated rangeland (Wallender et al., 2002). The lack of knowledge regarding the potential effects, positive and negative, of retirement of agricultural land on a large scale has long been identified as a cause of concern (USDI, 2000). Because of these concerns, the U.S. Department of Interior through the Interagency Land Retirement Team implemented the Land Retirement Demonstration Project (LRDP) located in western Fresno County of California to provide site specific scientific data (USDI, 2005). The objective of this study is to use the field data from the LRDP to set up a numerical modeling framework and then use inverse modeling to understand the dynamics of water and salt movement in vadose zone under land retirement.

Land Retirement Demonstration Project (LRDP)

In response to concerns about the lack of scientific data to identify potential benefits and impacts of retiring land from irrigated agriculture, the Land Retirement Program, an interagency Department of Interior initiative, completed a five-year, large scale Land Retirement Demonstration Project (LRDP) at two drainage–impaired sites on the west-side of the San-Joaquin Valley (USDI,2005). The full 5-year study, spanning the period 1999-2004, was completed at the Tranquillity site (Fig. 1).

Site Description

The site description and the methods utilized for monitoring soil and groundwater levels are described in the land retirement demonstration project five-year report (USDI, 2005).Three groundwater observation wells with adjacent soil sampling sites (15M1, 16A1 and 15P1) have been selected for the analysis in the present study. The site is characterized by the presence of perched water table conditions, with a downward water flux from the saturated zone to the regional water aquifer through a partially saturated layer.

The well 15M1 had the most saline groundwater with an EC of 52.2 dS/m, where as well 16A1 and 15P1 had a base EC of 35.5 and 26.0 dS/m, respectively.

Observed Changes In Perched Water Table Depth

Following land retirement, all the three wells showed a similar rate of decline in water table depth from the ground level with a total decline of 2.29 meters, 2.26 meters and 2.07 meters for 15M1, 16A1, and 15P1, respectively (Fig. 2).

Observed Changes In Root Zone Soil Salinity

The EC_{se} measurements represent the depth averaged value for three layers of the root zone, 0-30 cm (0-1 ft), 60-90 cm (2-3 ft) and 120-150 cm (4-5 ft) (Fig. 3).

Materials And Methods

With the principle of mass conservation, the change in water storage in the control volume over an annual time period can be expressed as,

$$\sum(P + i_s) - \sum ET - \sum BF = \Delta W_{vz} + \Delta W_{sz} \qquad (1)$$

where P = precipitation (L), i_s = irrigation if any (L), ET = evapotranspiration (L), BF = bottom flux out of the control volume (L), and ΔW_{vz}, ΔW_{vs} are the change in water storage (L) in vadose zone and the saturated zone, respectively. To achieve a fall in the shallow water depth and maintain a net downward flux of water out of the root zone to decrease the average root zone salinity levels, it is obvious that the following two relations must hold true:

$$(\sum DP - \sum UF) < \sum BF \qquad (2)$$

$$\sum DP > \sum UF \qquad (3)$$

For a completely closed system, if BF is zero, then it is not possible to decrease the depth to shallow water table and the root zone salinity simultaneously as it is not possible to meet both the constraints of Eqs. 2 and 3.

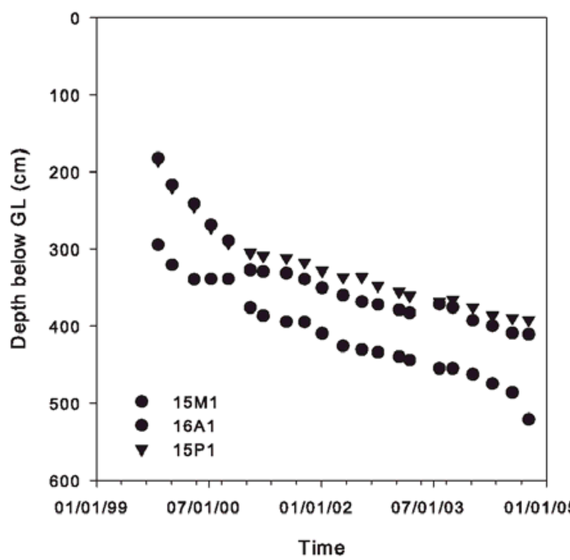

Figure 2. Decline in the perched water table following land retirement

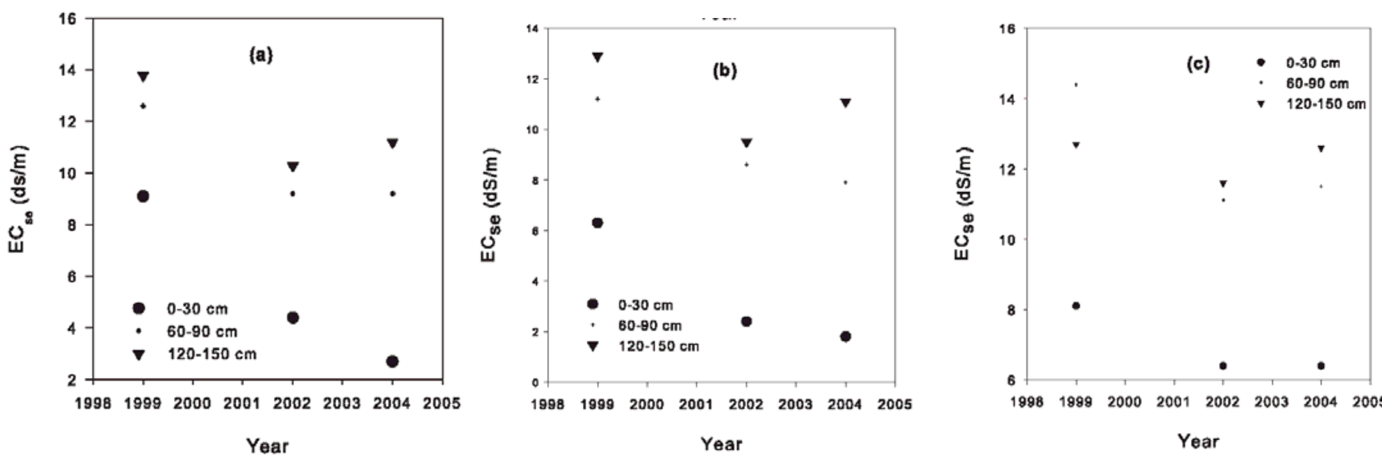

Figure 3. Changes in root zone salinity levels for sites for a) 15M1, b) 16A1, and c) 15P13.

HYDRUS-1D With UNSATCHEM Module

In the present study, HYDRUS 1D with the UNSATCHEM module (Šimůnek et al., 2005), a one-dimensional numerical soil water flow and transport model was used to simulate the responses of land retirement on vadose zone salinity and perched water table level.

Simulation Parameters And Input Data

The control volume used in the model is based on the site specific groundwater conditions at the Tranquillity site. The one dimensional vertical domain of the soil profile is fixed at 500 cm (15M1 and 15P1) or 600 cm (16A1), depending upon the depth to water table at the end of simulation period. The domain is discretized with 1 cm uniform nodal spacing to yield a total of 501 or 601 nodes nodes. The simulation period covered a time span of 5 years, and each year barley was grown as a cover crop to provide weed and dust control in the retired lands (USDI, 2005).

The upper (top) boundary conditions of rainfall, irrigation and potential evaporation and transpiration rates were specified on a daily basis. Daily meteorological data were taken from the California Irrigation Management System (CIMIS) weather station No. 105.

The lower boundary condition was specified as a variable flux. The top transport boundary condition was of the Cauchy type, with specified ion concentrations for rain (Schoups, 2004). The lower boundary was specified as a Neumann condition for the variable flux case with zero gradients, for which no diffusion or dispersion occurs across the lower boundary.

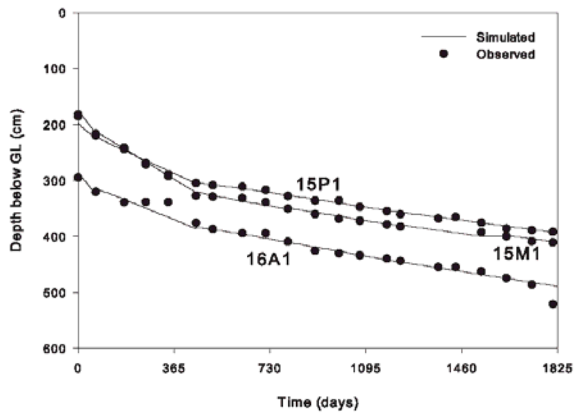

Figure 4. Observed and simulated perched water levels

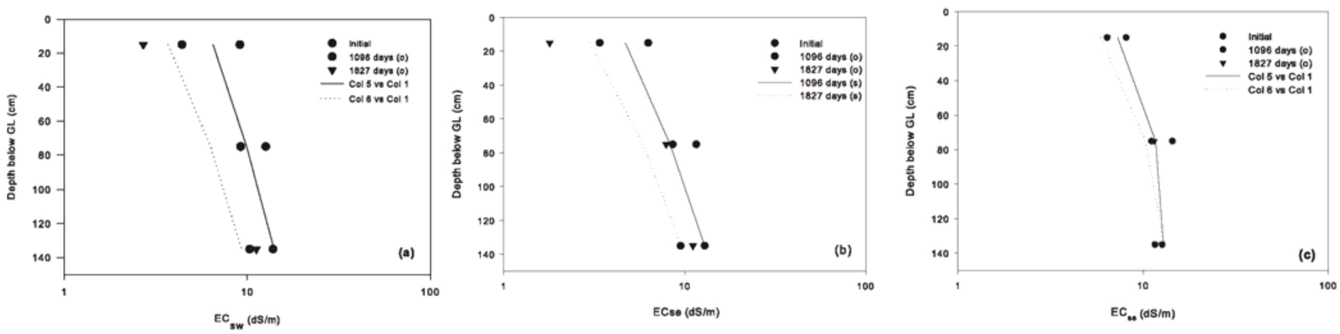

Figure 5. Observed (o) and simulated (s) EC_{se} (dS/m) for sites (a) 15M1, (b) 16A1, and (c) 15P1

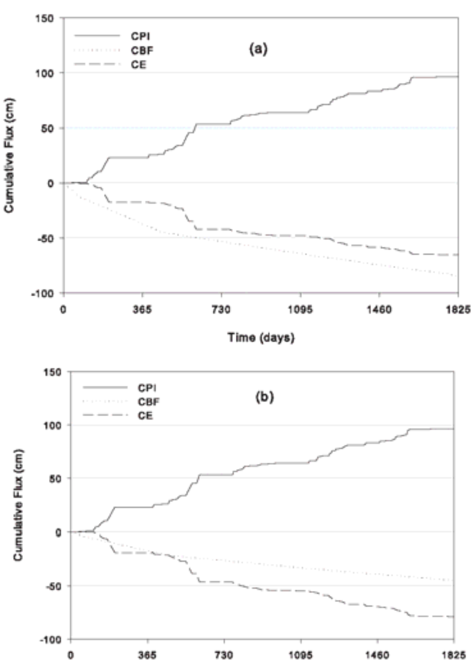

Figure 6. Cumulative fluxes at top and bottom boundaries for sites (a) 15M1 and (b) 15P1 starting in October 1999

Extract Chem software (Suarez and Taber, 2007) was used to convert the saturation extract (EC_{se}) salinity and ion chemistry to the soil solution ion chemistry for the assigned soil water contents.

PEST Optimization Model

PEST (Parameter Estimation) is a widely used calibration model, where parameter optimization is achieved using the Gauss-Marquardt-Levenberg method for which the discrepancies between model-generated numbers and corresponding field data is reduced to a minimum in the weighted least squares sense (Doherty et al., 2004).The comparison of observed to simulated perched water level with the optimized parameter values is presented in Fig. 4. Fig. 5 gives the observed and simulated value for the electrical conductivity of saturation extract soil water (EC_{se}) for all three sites.

Because annual salinity levels are decreasing in the root zone for both the sites, it is expected that the annual upward flux (UF) to the root zone should be less than the deep percolation (DP) from the root zone for both of the sites. This is confirmed in Fig. 7 in which the annual negative (UF-DP) shows a net downward flow of water from the root zone on an annual basis. As could be expected, the annual amount of net deep percolation varies from year to year, with highest net deep percolation corresponding to the largest rain fall year, net flux within the year depends upon the atmospheric demands, precipitation and irrigation, crop, and soil hydraulic properties. In summer and fall there is a net upward movement of water to the root zone, while during winter and spring (rainy period) there is a large net downward flux (Fig. 8). Since the downward flux during the winter is

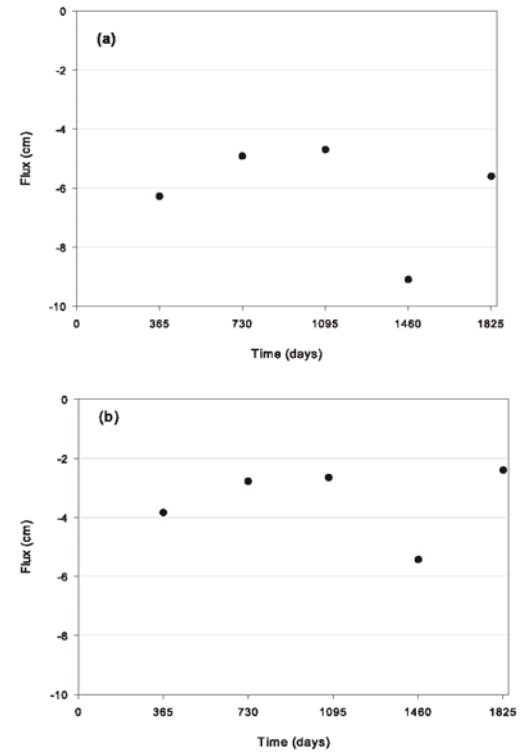

Figure 7. Annual net deep percolation flux for sites (a) 15M1, and (b) 15P1

larger than the upward flux during summer and winter, the net result is that on an annual basis there is always a net downward flux, explaining the declining trend in the annual root zone salinity.

Bottom Flux And Perched Water Table Depth

From a water budget perspective the reduction in the depth of the perched water table is caused by greater cumulative bottom flux compared to net deep percolation flux. The bottom fluxes for the three sites have been derived from the inverse modeling technique using PEST. Bottom flux is highly correlated with the head at 500 cm depth for sites 15M1 and 15P1 (Fig. 9).

The data and the simulation clearly show the pathways to the reduction in the salinity levels in the root zone and the reduction in the perched water table height. The pathway to reducing the salinity levels in the root zone is to maintain a condition where the annual downward flux from the root zone exceeds the annual upward flux from the root zone. If leaching is constrained to match the bottom flux, the danger of rising water table is avoided. Thus the critical component in the

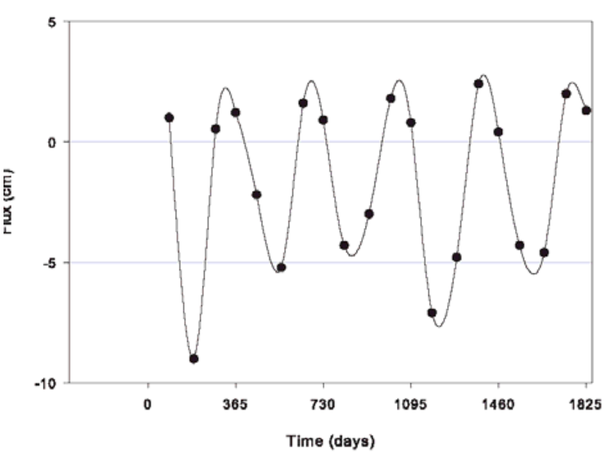

Figure 8. Quarterly net deep percolation flux at 15M1

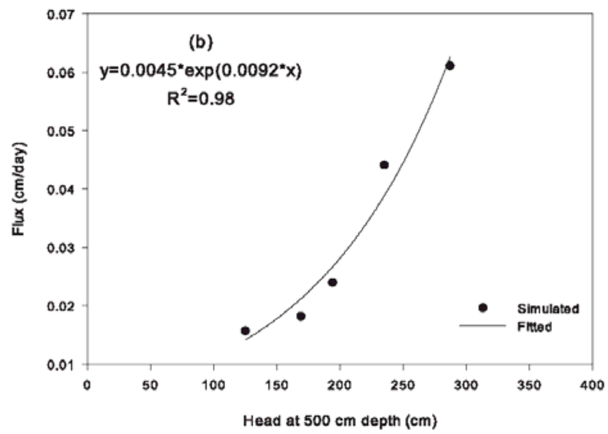

Figure 9. Bottom flux as a function of hydrostatic head at site 15P1

management of drainage impaired land selected for land retirement is the knowledge of the groundwater attenuation rate. A new 'bottom up approach' using the groundwater attenuation rate in designing a land and water use regimen for drainage impaired lands in general and retired lands in particular is presented here.

Bottom Up Approach

In the 'bottom up approach', the search for land use management starts from the determination of the natural attenuation rate of the groundwater (bottom flux) for a given site. Based on a proposed land use (root zone depth) and the soil type, a trial desired depth to groundwater table is then selected. The trial depth to groundwater table is then used to estimate the bottom flux for the given site. This estimated maximum possible amount of bottom flux is then used as a bottom boundary condition in a HUDRUS 1-D model to simulate the water table response for a given set of precipitation, irrigation, crop, and water management. The second output of concern from the simulation is the net downward flux which must always be negative to ensure that the root zone salinity is balanced.

Conclusions

Simulation quantified flow from the root zone control volume to perched water. Cumulative net downward flux of water from the root zone to the perched water zone was less than or equal to the cumulative bottom flux from the perched water zone (Eq. 2).

The second finding was that for salinity levels in the root zone to decline on an annual basis, there was cumulative net downward flux from the root zone (Eq. 3).

The bottom flux of the system constrains the capacity of the soil profile to accept water input. The formulation of land management options in drainage impaired areas without a priori taking into account the attenuation rate of the site leads to top down approach, and this may not always lead to a more efficient and sustainable solution.

The knowledge of attenuation rate of the site can be used to formulate a 'bottom up approach', where simulation using HYDRUS 1-D model can be used to arrive at a sustainable land use.

Acknowledgement

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Applications of the Sacramento County Integrated Groundwater and Surface water Model (SacIGSM)

Jim Blanke, P.G., C.Hg., Jon Traum and Ali Taghavi, Ph.D., P.E.

The Sacramento County Integrated Groundwater and Surface water Model (SacIGSM) was developed in the early 1990s and has widely been used over the past 15 years by the local and state agencies. The model has been maintained by various agencies responsible for the water resources planning and management in the Sacramento County area, and is a living model of the regional water resources conditions in the basin. The broad acceptance of the model across the community as the best available regional model for the area has allowed for the utilization of the model in numerous projects across the county. Refinements and updates are made to the model to meet the needs of each project, improving the model for future work. Projects include the Water Forum Agreement, American River Basin Cooperative Agencies studies, Zone 40 Water Supply Master Plan, assessment of impacts from development projects, assessment of project impacts to private wells, environmental impact studies, and river restoration projects. The model has been used by government, non-profits, and private parties and underwent a major refinement in 2007. This paper will briefly discuss the model features, and will mostly focus on the myriad of project applications for which the model has been used.

Introduction

Sacramento County is located mostly within the North American and South American Subbasins of the Sacramento Valley Basin and the Cosumnes Subbasin of the San Joaquin Valley Basin (Figure 1). In general, the county has urban areas in the north and west, agricultural areas in the south, and undeveloped land in the foothills in the east. The area utilizes both groundwater and surface water from the American River and Sacramento Rivers for its water supply. Rapid population growth and urbanization, environmental concerns, and uncertainties due to climate change have moved the area to the forefront of groundwater management. Activities such as the Water Forum Agreement, several groundwater management plans, an integrated regional water management plan, water supply plans, and other planning efforts have focused on proper management of the area's water resources.

The Sacramento County Integrated Groundwater and Surface water Model (SacIGSM) has played a key role in Sacramento County water management. SacIGSM was developed in the early 1990s and has widely been used over the past 15 years by the local and state agencies. The model has been maintained by various agencies responsible for the water resources planning and management in the Sacramento County area, and is a living model of the regional water resources conditions in the basin. The broad acceptance of the model across the community as the best available regional model for the area has allowed for the utilization of the model in numerous projects. Refinements and updates are made to the model to meet the needs of each project, improving the model for future work. Projects include the Water Forum Agreement, American River Basin Cooperative Agencies studies, Zone 40 Water Supply Master Plan, assessment of impacts from development projects, assessment of project impacts to private wells, environmental impact studies, and river restoration projects. The model has been used by government, non-profits, and private parties and underwent a major refinement in 2007. This report will briefly discuss the model features, and will mostly focus on the myriad of project applications for which the model has been used.

Applications

There have been numerous applications of the SacIGSM, as shown in Table 1. These applications meet a wide range of needs, including regional water resource planning, local water resource planning, development impacts, and environmental compliance. Projects involved basin management, stream/lake impact analysis, groundwater recharge, conjunctive use, groundwater availability, and water quality analysis. Of these projects, 6 are highlighted in the sections below.

The varied projects also allowed for the ongoing refinement of the model, as shown in Table 2. These refinements include refined

Figure 1. Location of Sacramento County, SacIGSM, and Groundwater Subbasins

grids, improved parameters, and extended hydrologic time periods. Each refinement is a benefit to that application as well as to all following model applications.

Sacramento Water Forum

The Water Forum, a broad-based stakeholder group in parts of Sacramento, Placer, and El Dorado counties, developed the Water Forum Proposal "for the effective long-term management of the region's water resources."

The Water Forum Proposal was formulated based on the two coequal objectives of the Water Forum:

1. Provide a reliable and safe water supply for the region's economic health and planned development through the year 2030; and
2. Preserve the fishery, wildlife, recreational, and aesthetic values of the Lower American River (Water Forum 1999).

Applications of the SacIGSM for this project included:

- Evaluation and quantification of basin yield,
- Evaluation of impacts of land and water use changes, and
- Evaluation of impacts of various county-wide and localized projects on the groundwater and surface water resources in the basin.

Alternatives analysis was used in the evaluation of different alternatives in the EIR process. Results of model applications to Water Forum studies were used in discussions leading to sustainable yield of each subbasin (Water Forum 1999, 2000).

Zone 40 Water Supply Master Plan

SacIGSM was used to provide an impact analysis to support Sacramento County Water Agency's (SCWA) preparation of the Zone 40 Water Supply Master Plan (Master Plan; SCWA 2005). The Master Plan was designed to provide a flexible program of water management alternatives that can be implemented and revised as availability and feasibility of water supply sources change in the future. Zone 40 provides drinking water for expanding urbanizing areas in the Laguna, Elk Grove, and Vineyard communities in central Sacramento County.

The Master Plan also reflects changes in the pattern of water demand growth, treatment for water quality, expansion of original service area, and in the availability of potential sources of surface water. SacIGSM was refined for:

1. Daily hydrologic time step,
2. Better definition of jurisdictional boundaries in the Central Basin for water accounting purposes, and
3. Improved calibration in the Central Basin for both groundwater levels and streamflow.

SacIGSM was implemented to analyze the impacts of different pumping distribution and water supply scenarios. Impacts were shown for groundwater levels and surface water impacts in the Cosumnes and American Rivers. This analysis supported plan development and the development of the project Environmental Impact Report (EIR).

Aerojet Surface Water Discharge Permitting

SacIGSM was used to support the 404-permit application by Aerojet for their groundwater remediation activities. Pumping for remediation purposes removes a significant quantity of groundwater from the Rancho Cordova site. The 404-application sought to discharge the water into Alder and Buffalo Creeks. Concerns were raised as to the net amount of water that would be removed from the groundwater system, taking into account the amount of remediation pumping and the amount of additional recharge after discharge into the creek system. SacIGSM was used to model these impacts. The model results properly addressed the concerns of the Regional Water Quality Control Board and Sacramento County with regards to the impacts of remediated water extraction and discharge on groundwater yield and streamflow.

Cosumnes River Flow Enhancement

SacIGSM was used in a study of stream-aquifer interaction for the Cosumnes River (**Figure 2**). Research and monitoring by University of California, Davis researchers (Fleckenstein 2004) indicated that the Cosumnes River has significant interaction with the local groundwater system; therefore, there was a desire to analyze the effects of this interaction at a much more detailed level. As part of his research work, Fleckenstein developed a MODFLOW model simulating the groundwater and streamflow conditions in the Cosumnes River corridor. Although a powerful tool for evaluation of the detailed localized effects of the soil and shallow groundwater system, the MODFLOW model relied on the regional IGSM for boundary conditions. Technical representatives of the stakeholder group concluded that there was a need to refine the regional IGSM model to provide more detailed simulation capabilities at the local level, while preserving the regional perspective. The refinement to the SacIGSM was, therefore, conceived as a method for analysis of effects of regional projects on the groundwater and surface water, including streamflows, at a local level, allowing for the MODFLOW model to act as a research tool to evaluate the effects of localized hydrogeologic conditions on the riparian and wetland habitat.

Figure 2, Location of Cosumnes River and Refined Model Grid

This study included the refinement of SacIGSM for:

1. Grid resolution along the Cosumnes River,
2. Streamflow data refinement for the Cosumnes River, and
3. Channel geometry and stream-aquifer interaction along the Cosumnes River.

Table 1. Applications of SacIGSM

Sacramento County IGSM Application	Year	Study Name	Study Area	Basin Management	Stream/Lake Impact Analysis	Groundwater Recharge	Conjunctive Use	Groundwater Availability	Water Quality Analysis
1	1992	City of Sacramento IGSM	City of Sacramento POU	X	X		X	X	
2	1993	Sacramento County IGSM	Sacramento County	X	X		X	X	
3	1996	American River Water Resources Investigation	Western Placer County, Sutter County, Sacramento County, San Joaquin County	X	X		X	X	X
4	1996	Northridge WD Conjunctive Use Study	North American River Basin		X		X		
5	1996	Rio Linda Water Supply Analysis	North American River Basin				X	X	
6	1997	Sacramento Water Forum	Sacramento County	X	X	X	X	X	
7	1998	Sunrise Douglas Water Supply Analysis	Sacramento County Central Basin		X			X	X
8	1999	Sunrise Douglas Water Supply Analysis	Sacramento County Central Basin		X			X	X
9	1999	Zone 40 (North Vineyard Well Field)	Sacramento County Central Basin		X		X	X	
10	2000	American River Basin Cooperating Agencies (ARBCA)	North American River Basin	X	X		X		
11	2002	Zone 40 Water Supply Master Plan	Sacramento County Central Basin		X	X	X		
12	2005	Aerojet Surface Water Discharge Permitting	Aerojet area		X	X		X	
13	2005	Cosumnes River Flow Enhancement	Cosumnes River Area		X	X	X		
14	2007	Well Protection Program	Sacramento County Central Basin	X				X	
15	2007	North Area Model Refinement	North American River Basin	X	X	X	X	X	
16	2008	Sutter Pointe	Natomas		X	X	X	X	
17	In Progress	South/Central Area Model Refinement	South American and Cosumnes Basins	X	X	X	X	X	

* Bold projects are presented in more detail in this document.

The refined model was applied for:

- Evaluation of environmental conditions in the Cosumnes River preserve area, as related to the surface water and groundwater operations,
- Evaluation of the localized effects of regional groundwater operations on the Cosumnes River flow system,
- Evaluation of the effects of the Cosumnes River flow enhancement options on the localized and regional groundwater conditions, and
- Confirmation of the conclusions from the Hydrologic Analysis Study (WRIME 2004) on project impacts, as documented in the Draft EIR for the Zone 40 Water Supply Master Plan.

Well Protection Program

A Well Protection Program is being developed by the Sacramento Central Groundwater Authority (SCGA) to provide a funding mechanism for mitigating potential impacts to private wells as a result of ongoing groundwater management activities

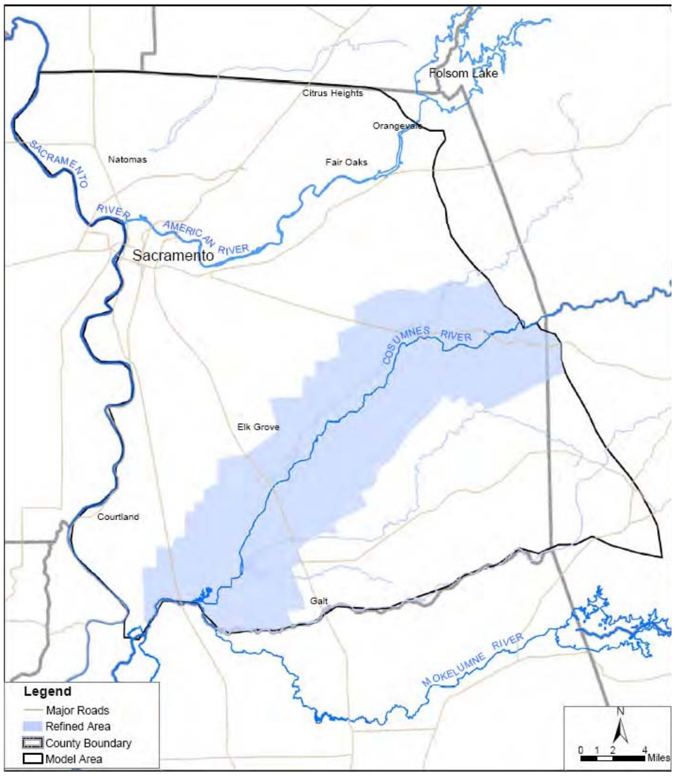

Figure 2 Location of Cosumnes River and Refined Model Grid

guided by the Zone 40 Water Supply Master Plan and the area's groundwater management plan. SacIGSM was used to estimate the number of wells that would be affected under the proposed project, as represented in the Zone 40 Water Supply Master Plan, and under an alternative water supply scenario reflecting reduced surface water availability. The analysis assisted in the understanding of the potential costs of the program, and assisted in focusing outreach and field verification activities to areas most likely to be impacted by the project. These are critical components as the basin includes over 6,000 domestic and agricultural wells.

Sutter Pointe

SacIGSM has been utilized to analyze the impacts of several proposed developments. One such project involved Sutter Pointe, a proposed development just north of the Sacramento County line in Sutter County. The project covers 7,528 acres of the Natomas Basin within the Natomas Central Mutual Water Company. Groundwater and surface water are both anticipated water supplies. SacIGSM was used in an integrated form with the North American River IGSM (NARIGSM) to simulate groundwater conditions on both sides of the Sacramento-Sutter county line. Simulations compared with- and without- project conditions at two phases of development and under multiple water supply scenarios to estimate project impact. Refinements were made to the models to account for additional data analyzed and developed for the project particularly with regards to aquifer parameters, stream-aquifer interaction, and deep percolation from agriculture.

Conclusions

The SacIGSM is a living model that has provided and continues to provide benefits to the community. As a result of the broad-based acceptance of the model, it has been implemented in a wide variety of applications, including regional water resource planning, local water resource planning, development impacts, and environmental compliance. The model has the flexibility to meet the varied needs of these projects, including impacts and benefits of each project individually and/or on a cumulative basis. The model has been and continues to be a strong tool for support of regional and local project impact and benefit evaluation

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Table 2 Refinements and Enhancements to SacIGSM

Features	Version 1	Version 1.1	Version 2	Version 3
Average Grid Size (acres)	343	343	230*	116
Total Model Area (acres)	562,000	562,000	562,000	686,000
No. of Subregions	31	35	35	54
No. of Stream Nodes	360	360	470*	978
No. of Calibration Wells	67	67	87*	138
Simulation Period (Water Year)	1970 - 1990	1970 - 1995	1970 - 1995	1970 – 2004
Time Step	Monthly	Monthly	Daily **	Daily
Model Code	IGSM 3.1	IGSM 5.0	IGSM 6.0	IGSM 6.4

* These updates were specific to the Cosumnes River area.

** The daily hydrologic data was developed only for the central county area.

Butte Basin IWFM Model

Brian J. Heywood, P.E., Karilyn J. Heisen, and Kristen H. McKillop

The Butte County Department of Water and Resource Conservation's mission is "to manage and conserve water and other resources for the citizens of Butte County." To support this mission, Butte County developed a fully functional integrated groundwater/surface water model using the California Department of Water Resources' (DWR) Integrated Water Flow Model (IWFM). This model is capable of assessing flow directions, water levels, hydraulic gradients, and water budgets in portions of the Butte Basin, located in areas of Butte, Colusa, Glenn, Sutter, Tehama, and Yuba counties. A previous model that used the U.S. Geological Survey's (USGS) FEMFLOW3D code was updated significantly to create the current model.

The geologic layering included in the model was updated to be consistent with the latest interpretation available from DWR's Northern District. The updated geologic interpretation includes eight separate units, including the Tuscan and Tehama formations. Updated land and water use information from DWR was also incorporated into the model.

Common in areas utilizing groundwater for agricultural irrigation, information quantifying groundwater pumping for agriculture was scarce. Therefore, the Butte County model was built to utilize IWFM's irrigation supply requirement calculation capabilities. Based on the specified land use acreage and crop evapotranspiration patterns, IWFM calculated the amount of water required for irrigation. Any irrigation demand that is not met by applied surface water or natural precipitation is assumed to be satisfied by groundwater pumping in areas where groundwater pumping provides at least part of the agricultural supply.

The calibration simulation period covers water years 1971 through 1999. Historical groundwater level and stream flow measurements were used to calibrate the model. A "base case" simulation was developed using the calibrated model. Groundwater levels from the base case and potential water management scenarios are compared to assess impacts to the groundwater aquifer. To date, a single water management scenario has been simulated, which quantified the maximum drawdown and recovery rates due to potential cutbacks in California State Water Project surface water deliveries. In the water management scenario, the cutbacks were assumed to result in both fallowing of land and increased groundwater pumping. In regions with cutbacks in surface water deliveries, the groundwater table dropped an average of 4 to 7 feet, as compared to groundwater levels without a cutback. Maximum drawdown of the groundwater table was from 11 to 15 feet. After 1 year, the average recovery in the impacted region was approximately 50 percent. Seventy percent of recovery was achieved approximately 2 years after maximum drawdown. Groundwater levels had recovered to approximately 95 percent of the pre-cutback values after 6 years.

Introduction

Following the drought period of the late 1980s and early 1990s, the Butte Basin Water Users Association (BBWUA) funded the initial development of the BBWUA groundwater model to support water management activities. BBWUA subsequently entered into an agreement with Butte County determining that model maintenance and updates would be completed by Butte County.

The BBWUA groundwater model was originally developed to assess the groundwater resources of the Butte Basin, develop a quantitative hydrologic understanding of groundwater resources, and provide a tool for evaluating regional hydrologic impacts to groundwater of alternative water policy decisions. These overall goals of the modeling have not changed. Under the direction of the Butte County Department of Water and Resource Conservation (DWRC), CDM provided a complete review and update of the BBWUA model.

Butte County DWRC identified the following objectives of the model review and update process:

- Improve the understanding and characterization of the hydrogeology and groundwater hydrology of the Butte Basin.
- Support the periodic updates of the water inventory and analysis and annual groundwater status reports through the development of water budgets, based on inventory units or other identified "zones."
- Conduct project feasibility evaluations on water management alternatives identified during the IWRP.
- Assist in the screening of water transfer applications under Chapter 33 of the Butte County Code.
- Evaluate the potential regional impacts of droughts, or changes in surface water availability.
- Evaluate the benefits and effects of recharge projects, and potential county-wide conjunctive use programs.
- Provide the means, through geographical and graphical interfaces, to inform and educate stakeholders about the hydrogeology and hydrology of the basin.

Model Development

Development of the updated model began with a review of the previous BBWUA model. The review involved assessing the BBWUA model input datasets and the numerical code used to develop the model— FEMFLOW3D code (Durbin and Bond 1998). Based on the review process, it was recommended that the BBWUA model be converted to the Integrated Water Flow Model (IWFM) code, maintained by the California Department of Water Resources (DWR).

IWFM is a quasi-3D finite-element model that simulates, among other processes: groundwater flow, stream flow, reservoir operations, rainfall runoff processes, land use processes (crop consumptive use and evapotranspiration), unsaturated zone flow, and land subsidence.

During the update process much of the historical input data from the BBWUA model was converted for to the IWFM format for use in the county's updated Butte Basin groundwater model.

Basic Model Characteristics

A few of the basic components of the updated Butte Basin groundwater model are presented here. A more complete description of the model can be found in Butte Basin Groundwater Model Update Phase I and Phase II Reports (CDM 2004, 2008).

Model Domain And Grid

Figure 1 shows the domain of the previous BBWUA groundwater model along with the domain of the updated Butte Basin groundwater model. The extent of the updated model is similar to that used in the groundwater model, in most areas. The model covers portions of Butte County and extends north into Tehama County, west into Colusa and Glenn Counties, and south into Yuba and Sutter Counties. The western boundary of the model follows the Sacramento River. In the northeast, the updated model domain was extended to incorporate areas hypothesized by DWR as the outcrop of the Tuscan Formation in the foothills. This area was included in the updated model to potentially assess the impacts of groundwater recharge to the Tuscan Formation through these outcrops. Additionally, the model was extended north to Deer Creek. The updated model domain encompasses 1,265 square miles.

The finite-element grid used in the updated Butte Basin groundwater model is shown in Figure 2. The node spacing in this grid is approximately 5,000 feet over much of the model. The typical node spacing in the previous BBWUA Groundwater Model was approximately 8,000 feet. Finer node spacing, approximately 2,500 feet, was used in the vicinity of Chico and other areas where greater hydraulic gradients are expected in the groundwater flow field.

Subsurface Representation

IWFM simulates flow in both the saturated and unsaturated portions of the soil column. In the updated Butte Basin groundwater model, the unsaturated zone is represented by two layers. The saturated zone is composed of eight layers based on the geologic representation developed by DWR. The geologic units represented in the model are:

- Basin Deposits - layer 1
- Alluvium (Riverbank and Modesto Formations) - layer 2
- Sutter Formation - layer 3
- Laguna Formation - layer 3
- Tehama Formation - layer 4
- Tuscan Formation (Tuscan A, B, and C) - layers 5, 6, and 7
- Neroly, Upper Princeton Gorge and Ione Formations – layer 8

Figure 3 shows an east-west cross-section through the central portion of the model. Horizontal hydraulic conductivities in the model range from 5 feet per day in the Basin Deposits to 100 to 200 feet per day in the Tehama and Tuscan formations

Land Use

Agriculture is the predominant land use within the valley portion of the updated Butte Basin groundwater model. Rice and deciduous fruit and nut trees comprise the largest acreages within the model domain. Land use/crop assignments in the model for recent conditions are based on the most recent surveys completed by DWR at the time of the model

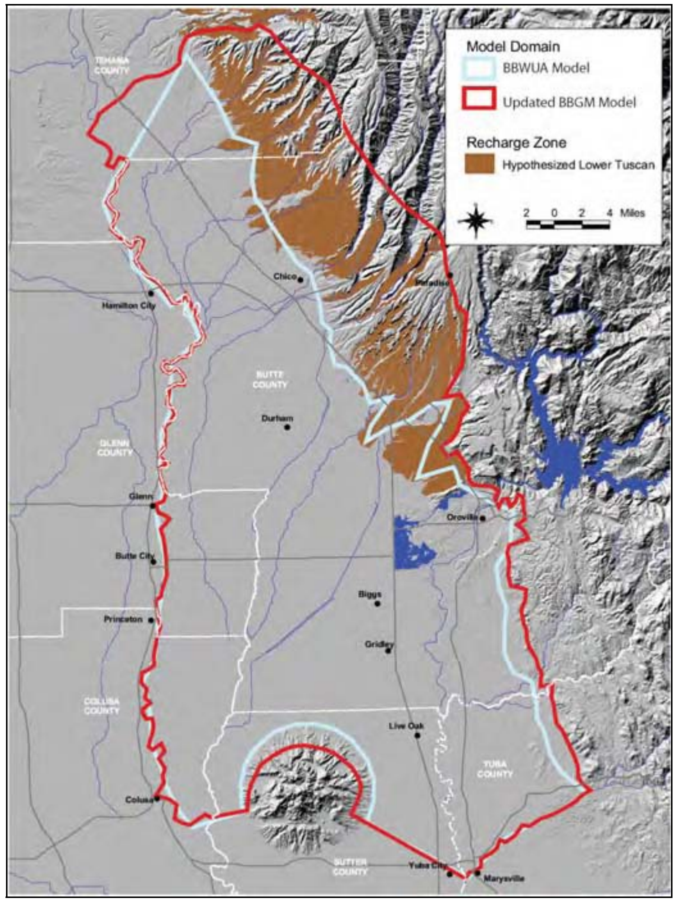

Figure 1. Domains of BBWUA and Updated Butte Basin Groundwater Models

construction. These land use surveys occurred between 1995 and 1999, depending on the county. The most recent DWR land use survey for Butte County occurred in 1999. To represent historic land use practices, land use for 1970 to 1994 were assigned based on data in the previous BBWUA groundwater model.

Monthly potential evapotranspiration (ET) rates are assigned in the model for each modeled crop/land use. To account for the flooding of rice fields, the timing of ET/consumptive use assigned to rice in the model was adjusted to more closely match the timing of water application. In the process of shifting the ET pattern in time, the total amount of annual ET remained unchanged. IWFM does not explicitly represent storage of excess irrigation water in rice paddies; therefore, this adjustment was made to prevent IWFM from erroneously computing too much runoff early in the growing season when irrigation water application exceeds crop needs. Most of the runoff should be computed near the end of the growing season to the degree that total application exceeds total rice ET and deep percolation.

Applied Hydraulic Stresses

Groundwater recharge and discharge and surface water interaction were simulated in the updated model. Historic pumping representing municipal groundwater pumping was incorporated into the model based on data from the BBWUA model.

Agricultural pumping, which is mostly unrecorded, was calculated by IWFM based on the data assigned at the ground surface. The amount of agricultural pumping calculated by IWFM was based on crop evapotranspiration patterns, irrigation efficiency, soil runoff characteristics, and surface water irrigation rates and locations.

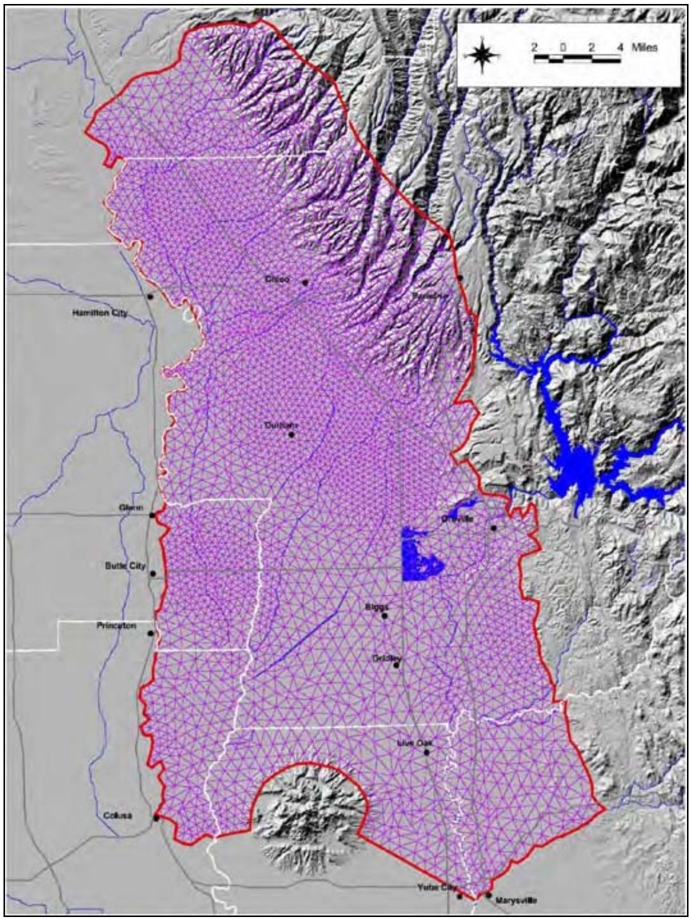

Figure 2. Finite-element Grid for the Updated Butte Basin Groundwater Model

Surface Water

Surface water features (e.g. streams and rivers) throughout the study area interact with the underlying groundwater. Depending on the relative elevations of the stream stage and the groundwater table, watermay pass from the stream to the groundwater or may enter the stream from groundwater. The study area includes hundreds of small irrigation ditches and canals. However, only the larger, major streams and rivers are explicitly modeled. The waterways explicitly incorporated into the model are the Sacramento River, Feather River, Yuba River, Singer Creek, Rock Creek, Pine Creek, Mud Creek, Big Chico Creek, Little Chico Creek, Little Dry Creek, Dry Creek, Butte Creek, North Honcut Creek, South Honcut Creek, and Deer Creek.

Model Calibration

The updated model was constructed to simulate hydrologic conditions for a 29 year period from water year 1971 through water year 1999 (October 1, 1970 to September 30, 1999) using a 1-day time step. Groundwater elevation targets were obtained for 197 groundwater wells located spatially across the model domain and screened in each of the modeled geologic formations. Figure 4 shows sample calibration results.

The simulated transient history of groundwater water levels at groundwater wells across Butte County was compared to observed readings available during the transient calibration period. Validation of the level of calibration was limited in some areas and depths due to an absence of existing monitoring locations.

The measured and simulated groundwater levels show virtually no seasonal or long-term variation in the Basin Deposits. Wells screened in the alluvial deposits exhibit a moderate long-term variation. Some wells show significant seasonal variation. Wells screened in the Sutter and Laguna formations show small to moderate long-term and seasonal variations. The model is able to adequately reproduce the observed long-term and seasonal groundwater level behavior for wells screened in the Basin Deposits, and the Alluvium, Sutter, and Laguna formations.

. Some wells show little seasonal and long-term variations while others show large variations. The simulated long-term trend and seasonal variations are adequately reproduced by the model for the Tuscan Formation.

For the total of 7,406 observations available in all wells for the entire 29-year calibration period, the mean difference between the simulated and observed heads is 2.4 feet and the standard deviation is 13.9 feet.

River stage and flow information, as available from DWR and U.S. Geological Survey (USGS) gages, was also used during the calibration process. In addition to these measured data items, estimated water budgets for Butte County sub-regions developed by the DWR Northern District were used to evaluate the specified diversions and groundwater pumping calculations performed by IWFM.

The results of the calibration indicate that the overall structure of the model and model parameter assignments are appropriate, and that there are no significant errors or flaws in the input data. Overall, the model is able to reasonably reproduce observed groundwater gradients and flow directions. The simulated horizontal and vertical distribution of groundwater heads is consistent with the observed data, and simulated flows and depths in the major surface water features are consistent with measured data. The simulated transient or dynamic response of the groundwater levels reflects the measured short-term seasonal variation in groundwater levels, and trends driven by long-term hydrology are also simulated.

Base Case Simulation

Following the calibration of the updated model, base case and water management simulations were developed and run. A base case was developed to serve as the basis of comparison to evaluate a proposed water management scenario. The base case simulation replaces all water demand and supply inputs in the calibrated model to represent a constant level of projected future development and a historical sequence of hydrologic conditions. Aquifer parameters that define the physical nature of the system (stratigraphy, aquifer properties, streambed properties, etc.) remain unchanged.

Specifically, the base case is a 29-year simulation using the calibrated updated model with alternate datasets for land use, urban pumping, and surface water diversions. Land use and groundwater pumping were updated to estimated 2030 conditions. Surface water diversions were approximated based on the historical surface water diversions and adjusted based on the hydrology (i.e. water year index). Precipitation data from October 1970 to October 1999 was used for the 29-year simulation.

In the base case, agricultural land use was updated based on forecasts made in Butte County's Agricultural Water Demand Forecast (CDM 2003). The crop acreage specified in the base case was calculated using the forecast changes for the year 2030. Based on the reported information, total irrigated agricultural acreage is forecast to decrease approximately 10 percent by 2030 as compared the agricultural acreage in 1998/1999. Irrigation efficiency was also adjusted as reported in the demand forecast report.

In addition to changes in agricultural land use, an increase in urban water use and acreage is expected by the year 2030. Butte County's Urban Water Demand Forecast Technical Memorandum (CDM 2003) provides estimates of changes in urban water use. These values were used to adjust both urban water use and urban land use for the base case simulation.

Averages of the historical diversions for the last 5 years of the calibration simulation were used to assign the diversions for the base case simulation. The base case diversions were adjusted annually based on historical surface water diversions and correlation to DWR's

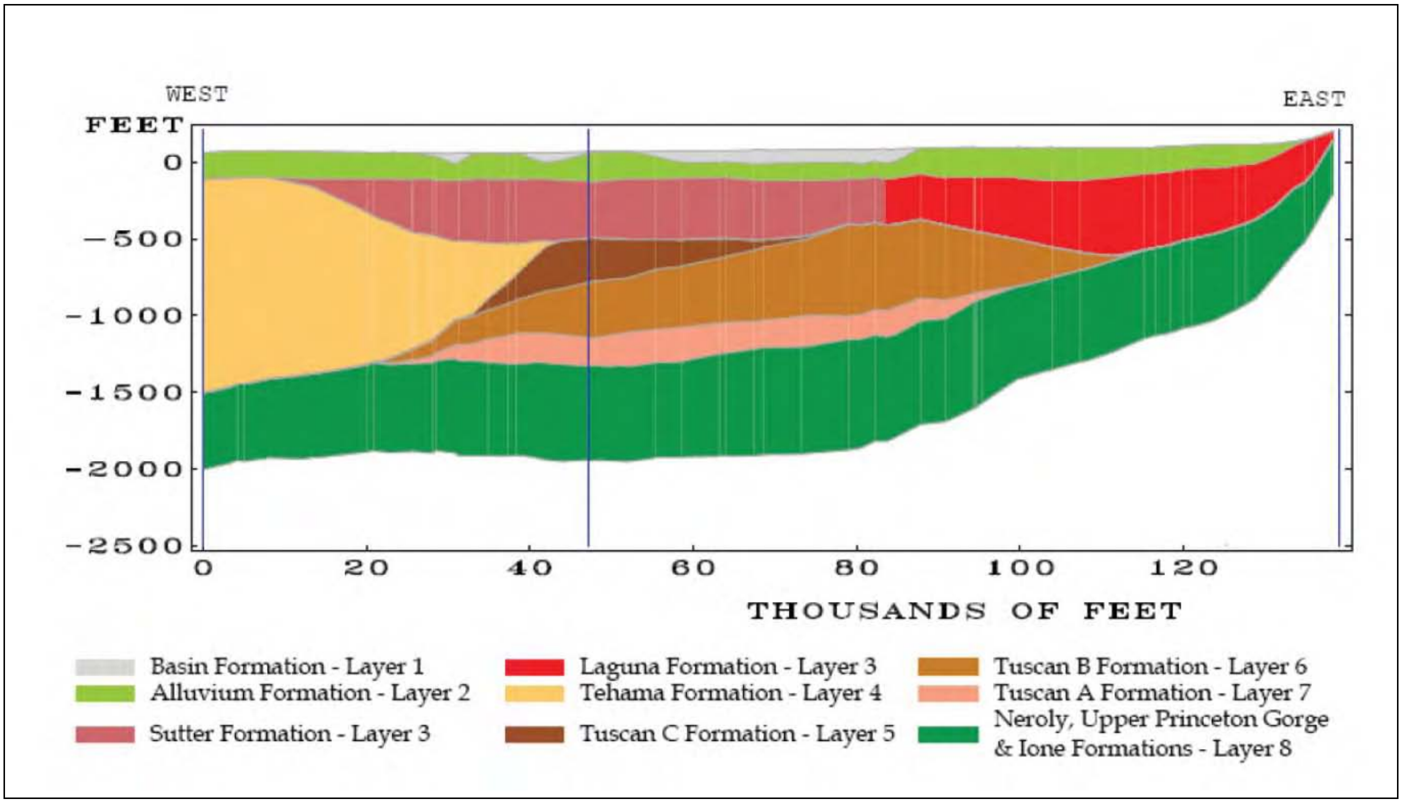

Figure 3. East-west Cross-section through the Updated Butte Basin Groundwater Model

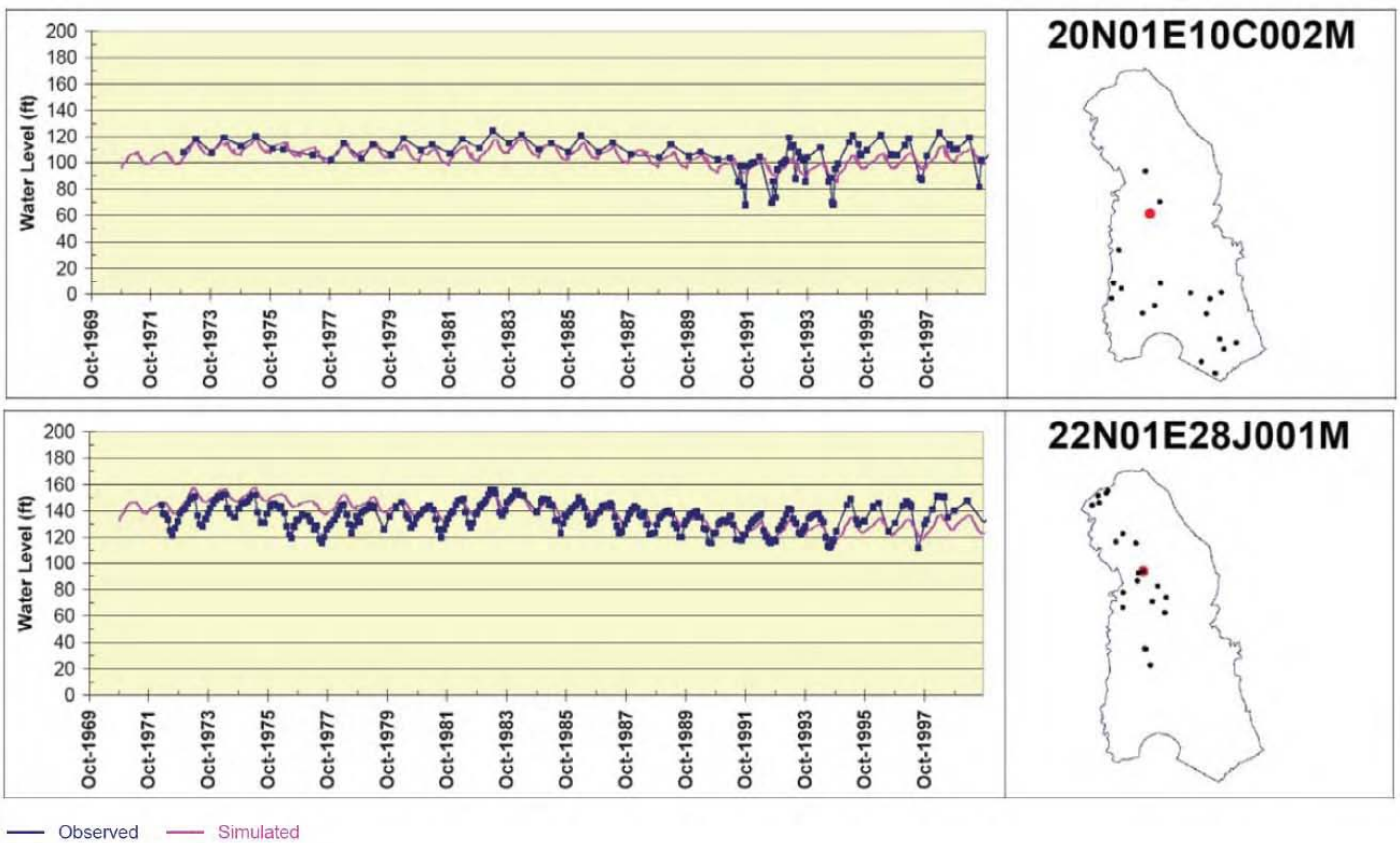

Figure 4. Sample Calibration Results from the Updated Butte Basin Groundwater Model

Water Year Hydrologic Classification Index. The adjustment factors were developed using the 29-year diversion record from the calibration simulation. Diversions were also adjusted in proportion to the expected decrease in agricultural land discussed above.

The historical hydrology (e.g. precipitation pattern, stream inflows) from October 1970 through October 1999 is used in the base case simulation without any modification. Using historical hydrology allows for the assessment of water resources conditions based on a known range of hydrology, from wet to critically dry.

Water Management Scenario Simulation

A water management scenario is a modification of the base case simulation that can be used to assess the impacts due to a specific change in water management activities. Butte County's DWRC determined that the impacts—due to a cutback in State Water Project (SWP) surface water deliveries to Western Canal Water District (WCWD) and the Joint Water Districts (JWD) during select dry years—would be simulated as the first water management scenario. As part of the scenario, the cutbacks in surface water deliveries are made-up through a combination of fallowing of agricultural land and increased groundwater pumping. The specific year(s) when cutbacks occur and percent changes in surface water supply, fallowed acreage, and groundwater pumping were specified as part of the water management scenario definition.

Surface water diversions from the base case were reduced to the WCWD and JWD regions for simulation water years 7, 21 and 22 in the water management scenario. These water years represent critical hydrologic conditions which followed years of dry and critical conditions according to the DWR water year index. The settlement contracts between WCWD/JWD and DWR specify that cutbacks cannot exceed 50 percent of the settlement delivery in any given year and not more than a total of 100 percent over a 7-year period. The settlement delivery is a subset of the total surface water delivery to these districts. Surface water deliveries to these districts have been cut three times during the settlement agreement period in water years 1977, 1991, and

Table 1. Simulated Surface Water Deliveries, Groundwater Pumping, and Fallowing for Scenario

	Western Canal Water District	Joint Water Districts
Base Case Surface Water Delivery	258 TAF	385 TAF
Settlement Delivery	131 TAF	382 TAF
Cutback (50% of Settlement Delivery)	65 TAF	191 TAF
Scenario Surface Water Delivery (Base Case Delivery minus Cutback)	192 TAF	194 TAF
Allocation of Cutback Quantity		
Additional Groundwater Pumping (60% of Cutback)	39 TAF	115 TAF
Fallowed Land in lieu of Water Supply (40% of Cutback)	26 TAF	76 TAF

1992. For each cutback year, DWR exercised the maximum cutback of 50 percent per year.

Therefore, the county decided to simulate the impacts using the historical cutback pattern of 50 percent per year, during the years with simulated hydrology equivalent to 1977, 1991, and 1992. Table 1 shows the base case surface water deliveries, the settlement delivery used to calculate the cutback, and the model simulated surface water deliveries used for the scenario.

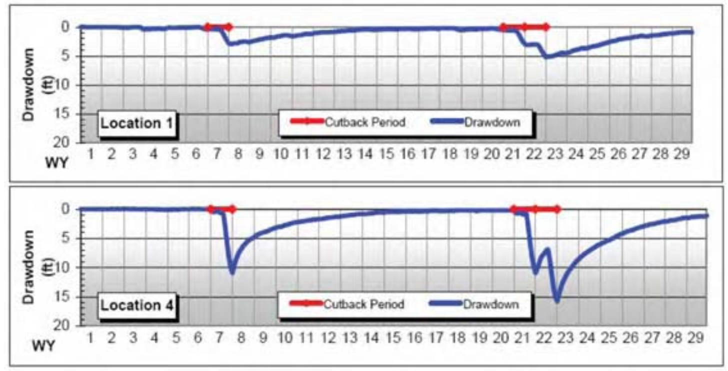

Figure 5. Sample Water Level Drawdown Resulting from Increased Groundwater Pumping

For the scenario simulation, the reduction in surface water supply to these districts is specified to be a combination of fallowing of agricultural land and increased groundwater pumping. The county specified that 40 percent of the cutback quantity should be accounted for through land fallowing. Groundwater pumping would make up the remaining 60 percent of the cutback quantity. This quantity of groundwater is the amount which the districts indicated could be pumped, based on existing or planned infrastructure. The quantities pertaining to additional groundwater pumping and agricultural land fallowing are shown in Table 1. The crop acreage reduction needed to result in a 40 percent reduction in water use, based on the average acre-feet of water used in the region divided by the acres of agricultural land. Each crop type was reduced by the percentage of total acres to be fallowed.

To assess the groundwater level impacts of the water management scenario, the results of the water management scenario simulation were compared to the results of the base case simulation. Differences between the base case and scenario simulations are due to the changes in surface water supply, agricultural land acreage, and groundwater pumping imposed during the water management scenario.

Impacts to groundwater levels were evaluated by comparing base case and scenario groundwater levels at selected locations and within the impacted subregions at times of maximum drawdown. Figure 5 shows a sampling of water level drawdown resulting from the increased groundwater pumping.

Groundwater levels dropped in the water management scenario as expected as a result of the increased groundwater pumping and reduced recharge associated with fallowing of agricultural land. Table 2 shows the average and maximum simulated drawdown in each of the cutback years. Groundwater levels rebounded over the years following the cutback. The magnitude of the increase in drawdown for each cutback year is similar. During simulation water year 22 the water

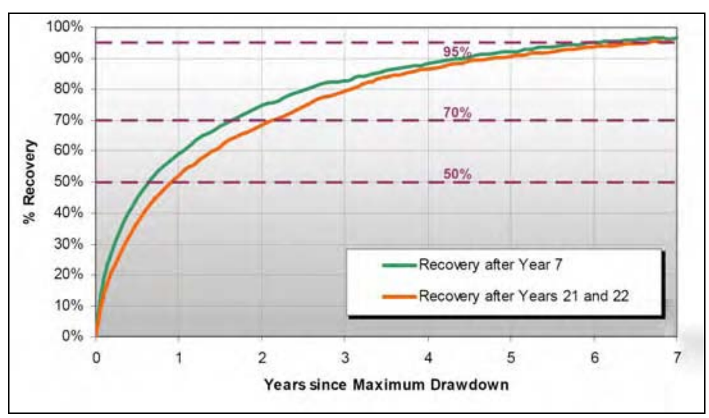

Figure 6. Recovery Times after Cessation of Groundwater Pumping

Table 2. Average and Maximum Drawdown in WCWD and the JWD

Cutback year	Average Drawdown (feet)	Maximum Drawdown (feet)
WY 7	4.1	11.2
WY 21	4.2	11.2
WY 22	7.0	15.5

levels recovered an average of 37 percent at the hydrograph locations during the winter months just prior to the beginning of a second year of cutbacks.

Recovery times for water levels after cessation of groundwater pumping are shown in Figure 6. The rate of recovery depends on both the magnitude of the drawdown and the precipitation in the subsequent years. Recovery time is based on the average percentage recovery of water levels at the 12 hydrograph locations. After 1 year, the average recovery was approximately 50 percent. Seventy percent of recovery was achieved at around 2 years after maximum drawdown. Groundwater levels had recovered to approximately 95 percent of the pre-cutback values after 6 years.

Conclusions

The updated Butte Basin groundwater model provides Butte County with a valuable tool to aid in the DWRC's mission. The IWFM allows simulation of impacts to groundwater from changes in surface water hydrology, pumping, and recharge from urban, agricultural, and undeveloped land. The base case simulation provides a bench mark for assessing water management scenarios. This tool will enable Butte County to make informed decisions regarding potential changes to water management practices.

Acknowledgements

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SACFEM: A Land Use Based Transient Finite-Element Groundwater Flow Model of the Sacramento Valley

Peter Lawson, P.G., C.HG., Heather Perry, Lee G. Bergfeld, P.E., and Walter Bourez, P.E.

A finite-element groundwater flow model of the Sacramento Valley has been developed, linking a relatively high resolution groundwater flow model (89,000 surface nodes, 7 layers) with an external surface water budgeting tool to provide transient surface water budget terms. Monthly estimates of the deep percolation of applied water and precipitation were computed according to current land use, crop type, location, and water year type. Agricultural pumping quantities were computed as the difference between applied water demand and available surface water for irrigation. The linked models can be used to compute well-field-scale impacts on groundwater levels and surface water flows due to groundwater substitution and conjunctive water management type projects.

Introduction

Implementation of conjunctive water management within the Sacramento Valley is one strategy being used to enhance the reliability of the existing water supply, as well as potentially improve water quality, within the San Francisco Bay Delta. However, the operation of conjunctive water management, or groundwater substitution projects, can result in adverse impacts on water resources within the valley. The two most critical potential impacts of additional groundwater production are depression of local groundwater levels, with associated impacts on well yields from nearby water supply wells, and changes in the hydraulic relationship between the surface water and groundwater systems in the area. To support the evaluation of these potential impacts, a high-resolution, numerical groundwater modeling tool was developed to estimate the impacts of potential future conjunctive water management projects on surface water and groundwater resources within the Sacramento Valley. Specific objectives of the modeling effort included the following:

Development of a regional-scale, water-budget-based numerical model covering the Sacramento Valley Groundwater Basin. This model will utilize a transient surface water budget based on land use, water district operations, cropping patterns, surface water availability, and required supplementary groundwater pumping to meet agricultural demands.

Quantification of the transient impacts to streams resulting from the implementation of various alternative conjunctive water management projects within the northern Sacramento Valley.

Calculation of transient valley-wide and project-specific drawdown in groundwater levels resulting from the implementation of various water management projects.

Consideration of the effects of operating conjunctive water management projects in both wet and dry hydrologic periods, and the effects of operating projects only in certain selected years within a longer hydrologic period.

Model Code Description

MicroFEM© (Hemker, 1997), an integrated groundwater modeling package developed in The Netherlands, was chosen to simulate the groundwater flow systems in the Sacramento Valley Groundwater Basin. The current version of the program (3.60) has the ability to simulate up to 25 layers and 250,000 surface nodes. MicroFEM© is capable of modeling saturated, single-density groundwater flow in layered systems. Horizontal flow is assumed in each layer, as is vertical flow between adjacent layers.

MicroFEM© was the chosen modeling platform for both basins for the following reasons:

- The finite-element scheme allowed the construction of model grids covering large geographic areas (over 5,955 square miles in the Sacramento Valley Groundwater Basin) with coarse node spacings outside of the simulated project areas and finer node spacings in areas of interest (e.g., near potential project areas). The finer node spacing near simulated production wells provides greater resolution of simulated groundwater levels and stream impacts.
- The graphical interface allows rapid assignment of aquifer parameters and allows proofing of these values by graphical means.
- The flexible post-processing tools allow rapid evaluation of transient water budgets for model simulations and identification of changes to stream discharges and other water fluxes across the model domain.

SACFEM Model Development

Spatial Grid

The Sacramento Valley Groundwater Model grid consists of 88,922 nodes and 177,095 elements. Nodal spacing varies from as large as 5,800 feet (1,750 meters) near the model boundary to as small as 500 feet (150 meters) in areas where groundwater production is simulated (Figure 1). The finer spacing in these areas of interest allow for more refined estimates of the groundwater levels and the magnitude of groundwater/surface water interaction that would occur due to project pumping. The model boundary represents the extent of the fresh water aquifer in the Sacramento Valley.

Vertical Layering

The total model thickness represents the thickness of the fresh water aquifer (less than 3,000 micromhos) as defined by Berkstresser (1973) and subsequently refined in the northern portion of the valley by the California Department of Water Resources (DWR) (DWR, 2002). For the southern portion of the model area, defined by Berkstresser data, elevation contour lines of the base of fresh water, along with information from boring locations (point measurements of the elevation of the base of fresh water), were used to define the elevation of the base of fresh water. For the northern portion of the model area, the depth to fresh water defined on DWR geologic cross-sections was utilized. These data sets were then merged to yield a single interpretation of the structural contour map of the base of fresh water across the Sacramento Valley.

Total Aquifer Thickness

To develop a total aquifer thickness distribution, and therefore a total model thickness distribution, it was necessary to develop a groundwater elevation contour map and then subtract the depth to the base of fresh water from the groundwater elevation contour map. As will be discussed in more detail below, the water level calibration targets for this groundwater modeling tool are the steady-state groundwater heads measured in calendar year 2000. Therefore, to develop a target groundwater elevation contour map, all available groundwater elevation measurements in the DWR Water Data Library were obtained from DWR central and northern district staff. These measurements were primarily collected bi-annually, during the spring and fall periods, and these values were averaged at each well location to compute an average water level at each well point. These values were then contoured, in conjunction with the streambed elevations for the 37 major streams included in the model, to develop a target groundwater elevation contour map for the year 2000. As described above, the distribution of the elevation of the base of fresh water was subtracted from this groundwater elevation contour map to yield an estimate of the distribution of the total aquifer thickness across the model domain.

Model Layer Thickness

Layers 1 through 5 represent shallower producing zones within the valley. The thicknesses of these layers were assigned based on a specified percentage of the available aquifer thickness at a given location, to provide multiple depth zones within which to assign regional pumping. The assumed layer thicknesses for Layers 1 through 5 were also selected to reflect typical screened intervals of production wells in the Sacramento Valley. Layer 1 represents approximately 6 percent of the total aquifer thickness, except along certain portions of the model perimeter where the total aquifer thickness becomes very small. In these areas, Layer 1 thickness was increased to up to 24 percent of the total aquifer thickness to improve numerical stability of the flow calculation. The thicknesses of Layers 2 through 4 each represent approximately 10 percent of the total aquifer thickness, and the thickness of Layer 5 represents approximately 15 percent of the total aquifer thickness. Layers 6 and 7 represent the Lower Tuscan aquifer, where present, or the lower Tehama Formation. These two layers represent the remaining thickness of the fresh water aquifer in the model.

Boundary Conditions

A combination of head-dependent, specified flux, and no-flow boundary conditions were used to simulate the groundwater flow system within the Sacramento Valley. Each of these boundary conditions will be discussed in more detail below.

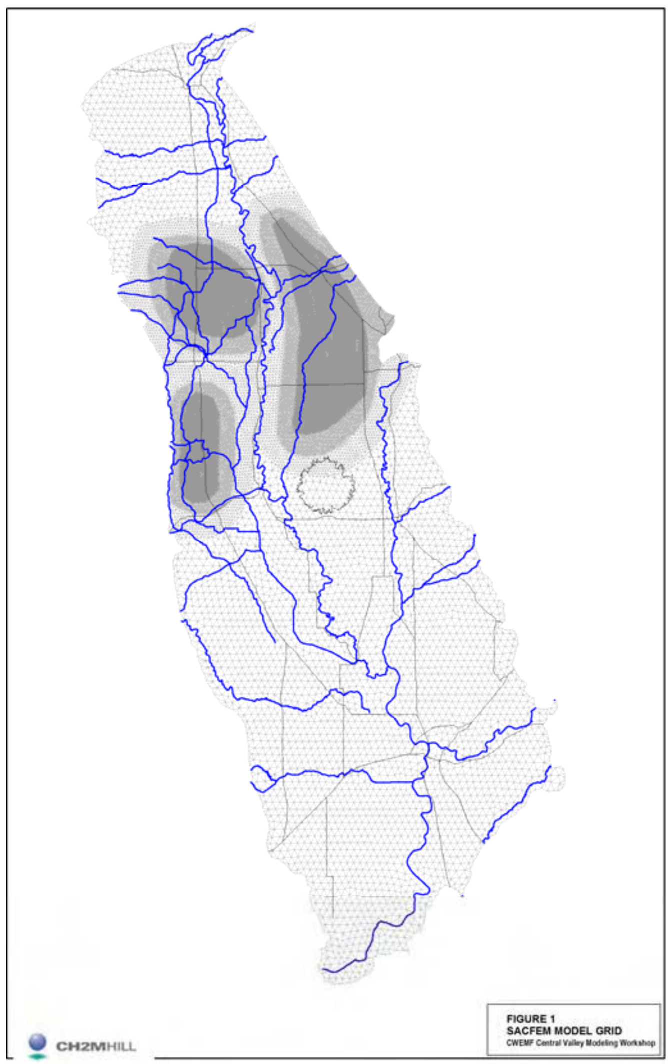

Figure 1. SACFEM model grid.

Head-Dependent Boundaries

A head-dependent boundary condition was chosen to simulate the streams within the Sacramento Valley. The MicroFEM© wadi system was used to implement streams within the model domain. MicroFEM©'s wadi package calculates the magnitude and direction of nodal fluxes based on the relative values of the user specified stream stage and the calculated head in the upper aquifer, but is limited by a critical depth. When calculated groundwater elevations fall below this critical depth, it is assumed that the water table de-couples from the river system, and the leakage rate from the river to the aquifer becomes constant.

Most major streams in the Sacramento Valley were included in the groundwater flow model. A total of 37 streams are represented. Stream locations and elevations were digitized from existing base maps and U.S. Geologic Survey (USGS) topographic quad sheets and imported into the model domain. Stream length within a given node is a grid-dependent variable calculated by MicroFEM© at each river node.

Specified Flux Boundaries

There are two sets of specified flux boundaries used in the SACFEM model. The first set reflects aerially distributed stresses applied to every node within the model domain. These include: deep percolation of precipitation, deep percolation of applied water, agricultural groundwater pumping, and urban groundwater pumping. The deep percolation flux values were applied to surface nodes located in Layer 1. The pumping stresses due to agricultural and urban groundwater production are applied to nodes within Layers 2 through 4 of the SCAFEM model, with pumping quantity apportioned between the layers based on relative layer transmissivity. Layers 2 through 4 were chosen for agricultural pumping because these layers represent a depth interval of between 200 and 500 feet below ground surface, which is the depth at which a significant quantity of the regional agricultural pumping across the valley occurs. The spatial distribution and magnitudes of these specified flux boundaries were derived from the surface water budget calculations described in the Surface Water Budget section below.

The second set of specified flux boundaries represent aerially distributed stresses applied to surface nodes located along the SACFEM model boundary. The subsurface inflow of precipitation falling within the Sacramento River watershed but outside the extent of the model domain, mountain front recharge, was estimated for streams not explicitly simulated in the SACFEM model. To estimate these flux values, the USGS 10-meter Digital Elevation Model (DEM), along with existing hydrography Geographic Information System coverages for the Sacramento Valley, were used to delineate the drainage areas for these tributary streams. It is these watershed areas that can contribute water to the model domain but are not accounted for in the wadi boundary conditions defined in the model. Once the extent of these watershed areas were defined, they were intersected with PRISM (Daly et al, 2008) rainfall data using Geographic Information System tools, and the volume of precipitation falling on the watershed computed. Based on the computed total volume of precipitation, the deep percolation to the groundwater system was calculated using the empirical relationship developed by Turner (1991). The computed annual deep percolation volume (converted to a flux) was then imposed at the model boundary coincident with the drainage area of interest.

No-Flow Boundaries

A no-flow boundary was specified across the bottom boundary of the model, representing the fresh water/brackish water interface.

Surface Water Budget

One of the most critical components to the successful operation of the SACFEM model is the computation of the transient surface water budget components. These water budget components were estimated based on a variety of spatial information including land use, cropping patterns, source of irrigation water, surface water availability in different year types and locations, and the spatial and temporal distribution of precipitation.

A root zone model is used to track soil moisture accounting and calculate monthly requirements for applied irrigation water and quantities of deep percolation that recharge the underlying aquifer. DWR extracted the root zone component of their Integrated Water Flow Model (IWFM) to simulate the physical processes of the root zone in a stand-alone model. The IWFM Demand Calculator (IDC) combines data on precipitation, land use, crop evapotranspiration, irrigation efficiencies, and soil parameters to simulate the root zone and calculate a time-series of applied water requirements and deep percolation. These calculations were performed for each node in SACFEM based on the land use mix within the individual nodes. The quantity of deep percolation estimated by the IDC model was modified during the calibration process to improve agreement between simulated and measured groundwater levels across the valley. These calibration adjustments are described more completely in the Model Calibration section of this document. These refined monthly estimates of deep percolation of applied water and precipitation at each model node were used as specified flux boundary conditions for the SACFEM model.

Applied water demands for each node are evaluated based on the location of the element, computing whether the element falls within a water district with known water rights and availability for a given water year type, or outside of a district in areas known to be irrigated from groundwater. The availability of surface water in a given month of a given year type is then determined for each element. In areas where the source of irrigation water is groundwater only, or mixed source, the crop demand is compared to the availability of surface water for irrigation. Any deficit in available surface water to meet crop requirements is assumed to be provided by agricultural pumping. The spatial and temporal distribution of this agricultural groundwater production, estimated on a nodal basis by this methodology, was implemented in the SACFEM model as a specified flux boundary, as described above.

The final component of the water budget that required estimation was the quantity of urban pumping. The population data from the year 2000 census were used to estimate urban groundwater pumping quantities for all cities within the model domain that rely on groundwater as a drinking water source and have populations greater than 5,000. It was assumed that urban pumping in communities with a population of less than 5,000 was insignificant compared to the agricultural pumping that occurs in those areas. A per capita water use estimate of 200 gallons per capita per day was applied to the census population data to estimate pumping quantities for each city. The total estimated urban groundwater demand for each city was apportioned to all nodes falling within the city municipal boundaries based on relative nodal area. During the calibration process, it was necessary to increase the per capita water use factor for both the Chico and Sacramento urban areas. These higher per capita use rates resulted in significant improvement in the match between simulated and observed groundwater levels in these areas.

Aquifer Properties

The distribution of aquifer properties across the Sacramento Valley is poorly understood. In certain areas with significant levels of groundwater production, the collection of aquifer test data, and the measurement of historic groundwater level trends in response to known groundwater production rates has provided valuable information on aquifer properties. However in the majority of the valley, these data are not available.

To estimate the spatial distribution of aquifer properties across the model domain for this numerical modeling effort, a database of well productivity information was used. In consultation with DWR staff, a database was obtained that included all of the pump efficiency testing data collected by Pacific Gas and Electric over the last several decades. When pump efficiency tests are conducted, the static groundwater elevation in the well along with the dynamic groundwater level at a known pumping rate is measured; typically while the well is operating at a rate that reflects normal operating conditions. These data were compiled along with well construction information for each production well to yield a representative data set of well productivity across the valley. Wells that did not have available construction data were omitted from further consideration.

The intent of the modeling analysis described herein is to simulate the operation of high productivity irrigation wells screened within the major producing zones in the valley to support conjunctive water management projects. Therefore, the aquifer properties that are of primary interest are those of the major aquifer zones tapped by large diameter irrigation wells. The well database described about was filtered to remove data obtained from tests on low yield or shallow domestic type wells. All test data from wells that reported a well yield below 100 gallons per minute (gpm) were eliminated from consideration as was the test data from wells with a total depth of less than 100 feet. The only exception to this second consideration was for wells located along the basin margins, where aquifers are thin, that reported what appeared to be valid test results. Data from these wells was considered as they were often the only data available in the basin margin areas. The total number of wells that remained in the database for consideration was approximately 1,000 wells.

Once the data set for consideration was finalized, the reported specific capacity data for each well was used to estimate an aquifer transmissivity for that location. The relationship used to estimate aquifer transmissivity was the following form of a simplified version of the Jacob non-equilibrium equation:

$$Sc = T/2000 \tag{1}$$

Where:

Sc = specific capacity of an operating production well (gpm per foot of drawdown)

T = aquifer transmissivity (gallons per day per foot)

Once a transmissivity estimate was computed for each location, the transmissivity value was then divided by the screen length of the production well to yield an estimate of the aquifer hydraulic conductivity. The final step in the process was to smooth the hydraulic conductivity field to provide regional scale information. Individual well tests produce aquifer productivity estimates that are local in nature, and may reflect small scale aquifer heterogeneity that is not necessarily representative of the basin as a whole. To average these smaller scale variations in the data set, a FORTRAN program was developed that evaluated each independent hydraulic conductivity estimate in terms of the available surrounding estimates. When this program is executed, each hydraulic conductivity value was considered in conjunction with all other values present within a user-specified critical radius, and the geometric mean of the available hydraulic conductivity values calculated. This geometric mean value is then assigned as the representative regional hydraulic conductivity value for that location. The critical radius used in this analysis was 10,000 meters, or approximately 6 miles. The point values obtained by this process were then kriged to develop a hydraulic conductivity distribution across the model domain.

Model Calibration

The calibration approach used to develop this modeling tool was significantly influenced by the resources available to fund the project. While a fully transient calibration approach, in which the model is used to replicate groundwater levels and flow conditions throughout some period of record, would be the more desirable approach, the resources were not available to fund such an effort. Instead, a more limited steady-state calibration approach was implemented. In a steady-state calibration process, the monthly water budget components for a selected period are averaged, and the model is calibrated to both average groundwater levels and stream discharges that occur during the calibration period. The calibration selected for this effort was calendar year 2000, the most recent year for which water budget information is available that was characterized by average hydrologic conditions. A calendar year instead of a water year was used to facilitate the development of average groundwater elevation calibration targets. The available water level data was obtained from DWR, and much of that data is collected in the spring and the fall. If a water year was used, the cut-off between water years is the end of September, which coincides with the mid-point of the fall sampling event. The result would be that when average groundwater elevation values were calculated, some of the measurements would be from October of the previous year and some would be from September of the subsequent year, which would introduce error in the data set, especially if the year types were different. The use of a calendar year eliminates this potential for error.

Calibration Targets

Several quantitative and qualitative calibration targets were used in the calibration process. These calibration targets are:

- Average year 2000 groundwater elevations (257 wells used as calibration targets)
- Areas of gaining and losing streams (approximate)
- Approximate water budget quantities (order of magnitude comparison as no precise estimates are available)

Water Budget Modification

During the calibration process, it was anticipated that some adjustment to the water budget components computed using the methodology described above would be necessary to obtain an acceptable degree of calibration. A water budget analysis performed on the raw input data provided by the IDC root zone model, combined with simulated groundwater heads from model runs using that deep percolation data, suggested that the prescribed percolation rates in the north (Red Bluff area) and south (Davis/Woodland area) were too

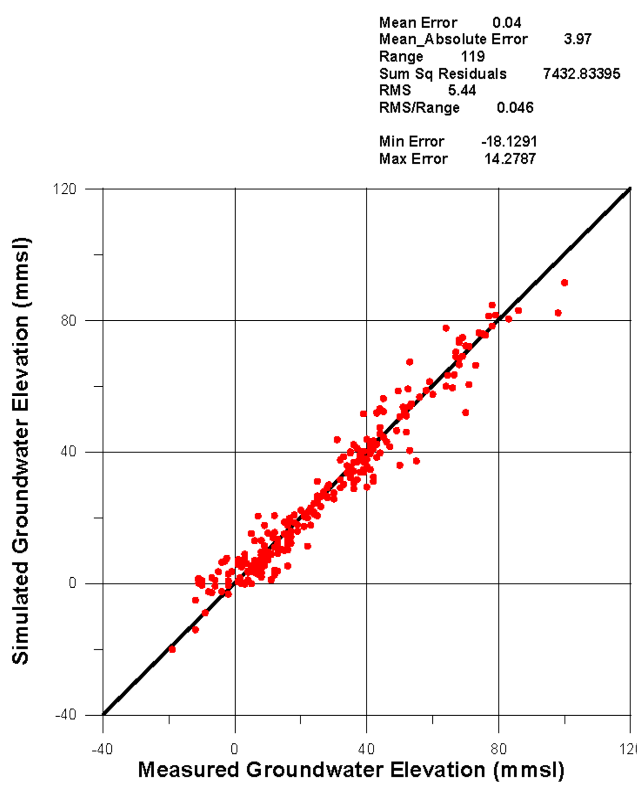

Figure 2. SACFEM calibration scattergram.

high. Percolation rates were reduced in these areas resulting in a significant improvement in calibration residuals.

Calibration To Groundwater Elevations

A scattergram, which plots the simulated versus the measured groundwater elevation at each target calibration well, is a graphical measure of the state of calibration. A plot of this type is shown on Figure 2. A perfect fit between simulated and observed groundwater elevations would plot as a 45 degree line (slope = +1.0, Y-intercept = 0). As can be seen in Figure 2, the model shows good agreement between simulated and observed groundwater levels. Another quantitative measure of calibration that is commonly used is to calculate the root mean square error (RMS) divided by the range of observations. As a rule of thumb, a well calibrated regional model will have an RMS/Range of less than 10 percent, and a well calibrated local scale mode will have an RMS/Range of less than 5 percent. The RMS/Range of the steady state calibration presented here is 4.6 percent, well below the 10 percent criteria.

Calibrations To Gaining And Losing Stream Segments

In the Sacramento Valley, a further qualitative calibration target is the identification of stream segments that are gaining flow through groundwater discharge versus losing flow to groundwater recharge. While the exact stream reaches that gain or lose flow due to surface water/groundwater interaction are not fully delineated, and this relationship changes seasonally with fluctuating groundwater levels and stream stages, the general pattern observed in the valley is that the major trunk streams such as the Sacramento, Feather, and American rivers tend to gain flow, while the smaller upper tributaries near the basin margin tend to lose flow to the groundwater system. The pattern predicted by the calibrated groundwater flow model is reasonably consistent with the generally accepted pattern described above. The calibrated model indicates the upper reaches of the Sacramento River gain flow from groundwater discharge, but further south in the Yolo-Zamora and Sacramento areas, the depressed groundwater levels result in theSacramento River losing flow to the aquifer system. The model further suggests that the smaller tributaries to the Sacramento River lose flow in their upper reaches, and in many cases transition to gaining flow nearer their confluence with the Sacramento River, especially in the northern portion of the valley.

Calibration To Steady-State Water Budget

The magnitude of the water budget components derived from the steady-state calibration run are summarized in Table 1. While exact comparative estimates are not available for most of these components, rough estimates are. For example the 2002 calibration simulation estimates a combined 2.9 million acre-feet of groundwater pumping within the model domain, which agrees reasonable well with the generally accepted value of between 2.5 and 3.0 million acre-feet of groundwater withdrawal in an average year. Similarly, while no independent estimates of the quantity of groundwater that discharges to the Sacramento River are available, given the average flows that are observed in the Sacramento River, an average value of 975 cubic feet per second of groundwater discharge seems reasonable.

Conclusions

The SACFEM model represents a new high resolution groundwater modeling tool to support the evaluation of various groundwater related projects within the Sacramento Valley. The surface water budgeting tool was constructed using detailed spatial information regarding water source, crop type, district water rights holdings, and soil moisture accounting to develop a node-specific (89,000 surface nodes) representation of deep percolation and agricultural pumping throughout the Sacramento Valley. The model grid has sufficient resolution (150 meters) to accurately depict well field scale effects due to the implementation of conjunctive water management projects, while the seven layer construction allows assignment of groundwater stresses to appropriate aquifer zones within the valley. Overall, the SACFEM model represents a significant contribution to the suite of modeling tools available for the Sacramento Valley offering coverage of the entire valley at higher resolution than is available with existing models of this scale.

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Table 1. Model Simulated Water Budget Components

	Acre-Feet	CFS
Recharge		
Deep Percolation of Precipitation	1,398,461	1,932
Deep Percolation of Applied Water	865,131	1,195
Mountain Front Recharge	495,507	684
Seepage from Streams to Groundwater	816,848	1,128
Total Recharge	**3,575,947**	**4,939**
Discharge		
Agricultural Pumping	2,417,506	3,339
Urban Pumping	451,507	624
Groundwater Discharge to Streams	705,999	975
Total Discharge	**3,575,012**	**4,938**

Integrated Hydrologic Models in the Central Valley, CA

Ali Taghavi, Ph.D., P.E.

Central Valley of California has been the breeding grounds for many groundwater models throughout the past several decades. Much of these models were localized to evaluate and simulate the groundwater flow conditions in specific areas, while there were others which provided more regional perspectives to the groundwater flow conditions in the Central Valley. Starting in late 1980s, there was a strong consensus that the groundwater conditions in the Central Valley, at both regional and/or localized scale, can not be evaluated without considering the interaction with the surface water system, thus an integrated system. Possibly, the first generation of linked surface water and groundwater models developed for a portion of Central Valley was in 1989, focusing on the San Joaquin and Tulare basin. Since then, number of integrated hydrologic models have been developed that cover parts or all of Central Valley.

In 2007, the Department of Water Resources was interested in developing a modeling approach to support the hydrologic impacts evaluation of Sacramento Valley Water Management Program. As part of this effort, a study of existing models in Sacramento Valley was conducted. Scope of this study was to identify, collect information, analyze, and synthesize information with regards to the existing groundwater and hydrologic models that cover the Sacramento Valley, California, and propose an approach to develop an integrated hydrologic model for the Sacramento Valley in support of the regional and local water planning programs.

In preparation for the CWEMF conference, additional work has been performed to inventory other models in the San Joaquin and Tulare Valley, as well. Figure 1 shows the pool of integrated hydrologic models that have been identified as part of the DWR study and the updated work. It should be noted that although this work has attempted to identify most of the integrated hydrologic models in the Central Valley, there are potentially other models that have not been identified.

There is significant amount of data and information that has been collected, analyzed, synthesized, and used in development of each of these models, some of which include electronic data; much of which, though, includes data entry from hard copy maps, documents, and tables. The importance of efforts that have gone into development of each of these models will be amplified significantly once the opportunities to use, link, or integrate these models together are explored. As part of their 2007 study, DWR explored possible integration options for the models in Sacramento Valley, which may be used as part of the modeling protocols for the Sacramento Valley Water Management Program EIR.

What is an Integrated Hydrologic Model?

An integrated hydrologic model simulates the various components of the hydrologic cycle, including the surface processes of rainfall runoff, infiltration, soil moisture accounting and deep percolation of infiltrated water, flow in the unsaturated zone, groundwater flow, stream-aquifer interaction, and river/reservoir operations (Figure 1). Some integrated hydrologic models may be comprehensive enough to simulate such refine processes, such as snowmelt runoff. Various methodologies are used in modeling.

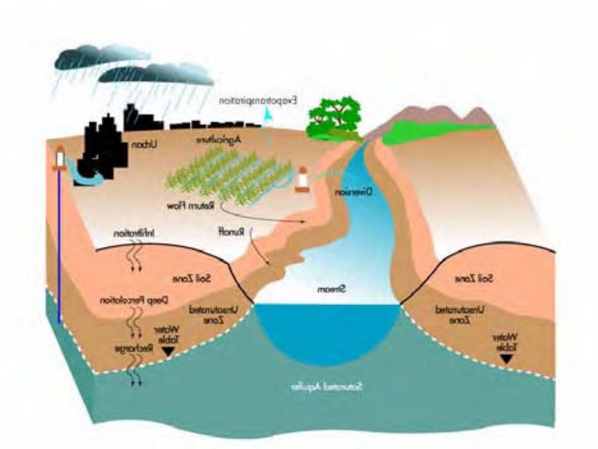

Figure 1. Typical Components of Hydrologic Cycle included in an Integrated Hydrologic Model

platforms to integrate the hydrologic components, including sequential, coupled, and modular formulation. Typical examples of Integrated Hydrologic modeling codes are IGSM, IWFM, MIKESHE, and Hydrogeosphere.

The integrated approach to modeling can potentially have three dimensions (Figure 2):

Resources: The model can integrate various resources, such as water flow and/or quality, fisheries, biological resources, etc.

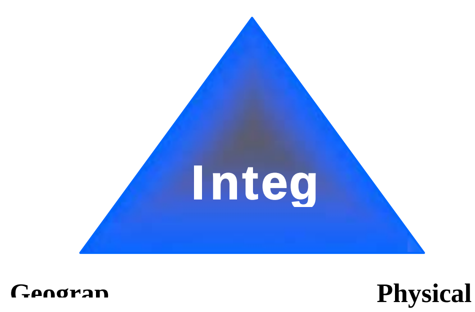

Figure 2. Dimensions of an Integrated Model

Physical Processes: The model can integrate various physical processes that govern the system, including the groundwater, surface water, rainfall runoff, soil infiltration, etc.

Geographic Boundaries: The model can integrate processes and/or resources across various geographic boundaries, including hydrologic, political, institutional, etc.

An integrated model can be developed using any combination of the three dimensions most comprehensive integrated model would use all three dimensions. Integrated hydrologic models generally focus on the water-related resources, but provide integration across multiple physical processes and various geographic boundaries.

Scope of Hydrologic Models

The scope of application of a model is a major criterion in determining the scale of data and information processing and simulation. Model scopes can be considered at (i) Regional, (ii) Local, and (iii) Site-Specific levels. Table 1 presents the main scope issues for hydrologic models. In order to meet the objectives of this study, the focus of the study was to identify and inventory models that are considered regional or local in design and application. The scope is considered either according to the model report and documentation available to us, or by evaluation of the available data and application types of the model. There were several models that were identified as site specific and not regional in design and/or application. These models are excluded from the analysis in this study.

Figure 3 shows the location of the integrated hydrologic models that were identified and data was available to this study. Table 2 presents some brief information about the models, with references to the model source documentation.

Following are brief descriptions of models that we had information available for.

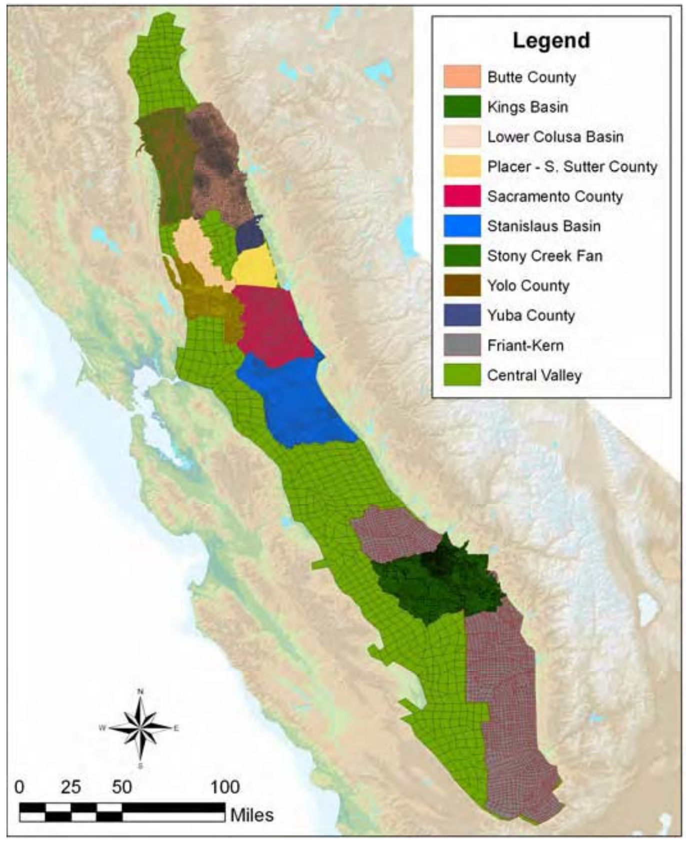

Figure 3. Map of Integrated Hydrologic Models in the Central Valley, CA, available to this study.

Central Valley Groundwater & Surface Water Model (CVGSM)

This model was first developed in 1990 as the Central Valley Groundwater and Surface water Model (CVGSM). The model was developed by the Department of Water Resources, the State Water Resources Control Board, and the Contra Costa Water District, as part of the analytical tools to evaluate the effects of CVP and SWP operations on the groundwater resources in the Central Valley. The model was developed based on the IGSM computer code. From 1990 to 2002, the model has undergone numerous updates and refinements, including major update as part of the analytical tools development and enhancement for the Central Valley Project Improvement Act. These updates and refinements included improvements and modifications to the IGSM code to include new features and address comments on the code as part of peer review processes. The CVGSM currently runs on IGSM v. 6.0, with hydrologic period of 1922 through 1995 and monthly time step.

California Central Valley Simulation Model (C2VSIM)

In 2003, the DWR initiated a review and update of the data files and conversion of the CVGSM from the IGSM code to the IWFM code. Although the model grid network and subregions were remained intact, the geologic stratification was modified based on the CVRASA1 model, the surface water delivery and groundwater pumping was revised based on additional data and information available and the agricultural demand and pumping estimation methodologies in the IWFM code. Corrections were also made following a review of the original source data also, and the time series data (and simulation extended to 2003). The model was subsequently renamed as C2VSIM. The primary purpose of the C2VSIM development is to provide a Central Valley wide integrated hydrologic model for development of hydrology and as part of CALSIM III operations model. The C2VSIM currently runs on IWFM v. 3.0, with hydrologic period of 1922 through 2003 and monthly time step. The model is currently calibrated for regional groundwater levels and stream flows, with additional work required to complete and enhance the calibration for specific areas. The model will serve as an analytical tool for evaluation of Central Valley wide project impacts and for developing boundary conditions for smaller and local models.

Central Valley RASA Model

The Central Valley Regional Aquifer System Analysis (CVRASA) is a model developed by the USGS to simulate the groundwater flow conditions in the Central Valley. The original model was developedbased on the MODFLOW program in 1988, and included the hydrologic period 1961 through 1977. The model finite difference grid spacing was 6 x 6 miles. The geologic stratification data was developed based on a previous report prepared by USGS on the Central Valley geologic conditions. The agricultural groundwater pumping estimates in the model was based on the power consumption records acquired from Pacific Gas & Electricity. In 2004, USGS embarked on a major update to the CVRASA model. This revision includes a finer grid cell (1 x 1 mile); incorporation of a newly developed MODFLOW module, the Farm Package, which uses soil moisture accounting methodology to calculate recharge from rain and applied water in an agricultural area; a more refined geologic representation of the Central Valley, and extension of the hydrologic time period to 2003. The model hydrologic time step is monthly. The revised model is called CVRASA2. This model is currently undergoing final stages of calibration and internal review by the USGS, and is reported to be available in late 2008. Once available, the model will be a good analytical tool for evaluation of Central Valley wide project impacts and can serve well for developing boundary conditions for smaller and local models. In addition, results of the Texture modeling will be of significant use in development of the hydrogeologic conditions of the valley.

USBR Model

The USBR has been in the process of developing an integrated hydrologic modeling platform with fully coupled hydrologic processes. The model is capable of optimizing the solution of the groundwater flow equation by using subgridding and sub-timing methodologies. This model is called the Hydrogeosphere. The model code is under development in various phases. The current phase of the code is being applied to the Klamath basin. In addition, an application to the Sacramento Valley with very fine grid network is currently being developed. The model code is proprietary and not available for public review. Information on the completion date of this model is not available; however, once completed, this model will have significant details on the hydrologic processes simulated, and will require significant data for calibration and/or project evaluations.

SVWMP EIS/EIR Superposition Model

The groundwater flow model developed as part of the EIS/EIR for the Short-Term Program impacts superimposes projected impacts of the proposed projects over current and future conditions; therefore the name “Superposition Model”. The model is based on the MicroFEM code, a proprietary model code retained by C.J. Hemker (1997). The Superposition model superimposes the projected impacts of the proposed projects over current and future conditions. In other words, average annual pumping rates from 1995 are simulated at monthly time steps for one year followed by a similar simulation where the system improvement "pumping" and project pumping are added to the 1995 average annual pumping rates. Results from both sets of transient simulations (with and without system improvements and project pumping) are then subtracted to estimate monthly impacts resulting from implementation of system improvements and project pumping. Therefore, the Superposition model does not explicitly simulate the hydrologic conditions in the groundwater basin, but it estimates the relative changes in the system. In addition, the model does not include long-term hydrologic variabilities, such as dry and wet and/or drought cycles. This model was not intended for evaluation of the details of regional and/or local project operations and impacts at various levels of development.

Stony Creek Fan Model

This model is developed to evaluate the state of the surface water and groundwater system in the Stony Creek Fan area, Glenn County. The model is based on the IGSM v. 6.1 computer code, and simulates the daily hydrologic conditions for the period 1970 to 2000. The historical model data includes several land use and water use surveys, as well as the historical surface water supplies and groundwater pumping in the basin. In addition, the model represents the hydrogeologic conditions in a 4-layer aquifer system underlain in the Glenn County area. This model includes a reservoir operations module to evaluate the operations of the Black Butte reservoir, regulating the flows in the Stony Creek. This module allows for evaluation of the changes to the streamflows and resulting effects on the groundwater conditions due to potential changes to the operations of the Black Butte reservoir. The model is calibrated for the hydrologic period 1970 to 2000, and has been applied to the regional aquifer studies to evaluate the yield of the basin, effects of artificial recharge projects on the water resources in the area, and effects of the changes in the streamflow conditions on the groundwater levels in the basin. The model boundary to the east is Sacramento River, and as such the surface water and groundwater conditions and use to the east may not properly be represented during the historical conditions as well as for analysis of future conditions.

Butte County Model

This model is developed to evaluate the surface water and groundwater conditions in the Butte basin. This model is based on the IWFM v. 3.0 code has preserved much of the data sets from its predecessor the FEMFLOW3D model developed for the BBWUA. A number of the data sets have, however, been updated and refined to ensure proper representation of the latest land and water use conditions in the basin. The model hydrologic period is from 1970 to 1999, with daily rainfall and streamflow data. The model geology has been refined to reflect the 9-layer aquifer system underlain the Butte County area, based on the latest data available from the DWR. The model boundary to the west is Sacramento River, and as such the surface water and groundwater conditions and use to the west may not properly be represented during the historical conditions as well as for analysis of future conditions.

Yuba County Model

This model has been developed by the DWR in coordination with the Yuba County Water Agency to evaluate the surface water and groundwater conditions in the Yuba basin. The model is based on IGSM, and includes the monthly hydrologic period from 1970-1995. The model includes a 3-layer aquifer system based on the Central Valley model. Since its original development, the model has been used for a number of limited applications, including basin yield studies.

Lower Colusa Basin Model

This model has been developed by the DWR in coordination with the Colusa County and other local stakeholders to evaluate the surface water and groundwater conditions in the lower Colusa basin. The model is based in IGSM, and includes the monthly hydrologic period from 1981-2000. The model includes a 3-layer aquifer system, which is primarily based on shallow and deep pumping zones, and a non-pumping aquifer zone. Since its original development, the model has been used for a number of applications, including basin yield studies, and Yolo-Zamora conjunctive use feasibility study.

Yolo County Model

This model is developed to evaluate the surface water and groundwater conditions in the Yolo groundwater basin area. The model is based on the IGSM v. 6.2 computer code, and simulates the daily hydrologic conditions for the period 1970 to 2004. The historical model data includes several land use and water use surveys, as well as the historical surface water supplies and estimated groundwater pumping in the agricultural lands and recorded groundwater pumping in the municipal areas of Davis, Woodland and Winters. In addition, the model represents the hydrogeologic conditions in a 3-layer aquifer system underlain in the Yolo County area. The model is calibrated for the hydrologic period 1970 to 2004. The model boundary to the east is Sacramento River, to the north is the Yolo-Colusa County line, and to the south is Yolo-Solano County line. In the Putah Creek area, the model boundary is set to approximately a mile south of Putah Creek to minimize boundary effects at the Putah Creek. The Yolo County IGSM has been applied to evaluate the feasibility of the Cache Creek Recharge and Recovery project, one of the many projects under consideration by the stakeholder group involved in the development of the Integrated Regional Water Management Plan (IRWMP).

North American River Model

This model was developed to evaluate the surface water and groundwater conditions in the western Placer and south Sutter county portions of the Northern American River groundwater basin. The model is based on the IGSM v. 6.2 computer code. The model was originally developed for the DWR, as part of the American River Watershed Investigation Study. The model has subsequently gone through several revisions, the latest being a code update for linkage to the updated Sacramento County IGSM. The model has been used for evaluation of various project level hydrologic impacts for proposed development sites in Placer and Sutter counties.

Sacramento County Model

This model is developed to evaluate the surface water and groundwater conditions in the groundwater basins within the Sacramento County area. This IGSM based model was originally developed in 1993 to support the development of the Water Forum Agreement, and evaluate the yield of the groundwater basins within the county. The model was subsequently used in more than a dozen applications to evaluate water supply conditions for various land use planning efforts, and specific plan development permits. The model was lately used in the evaluation of the Zone 40 Water Supply Master Plan, as part of which the model code was upgraded to the IGSM 6.1, model grid was refined along the Cosumnes River, and the hydrologic database in the Central groundwater basin was refined. The model has recently undergoing a major overhaul for spatial and temporal refinements, hydrologic period updates to 2004, additional code updates, and recalibration to groundwater level measurements at new locations (WRIME, 2007). The model represents the hydrogeologic conditions in a 3-layer aquifer system underlain in the Sacramento County area. The model boundary to the west is Sacramento River, to the north is the Sacramento County line, and to the South is Mokelumne River. The model boundary to the east is typically the boundaries of the groundwater basin and/or the County line.

Redding Basin Model

The Redding Groundwater Basin Model (RGBM) is based on MicroFEM (Hemker, 1997) model, and similar to the application to the Sacramento Valley, uses the superposition principle to evaluate the relative impacts of the projects in the Redding Basin. The model has a very fine finite element mesh with nodal spacing of about 500 to 3,200 feet. The 4-layer aquifer system in the model represents the freshwater above the Chico Formation as defined by the DWR Bulletin 74-8. The simulation of relative impacts to the stream system is simulated by the MicroFEM wadi package. Recharge from precipitation as well as applied water is estimated by a separate study for the RAWC. Similar to the Sacramento Valley Superposition model, the RGBM does not include a long-term hydrologic condition, and as such simulates the impacts one year at a time, which limits its use for long-term impacts assessment. In addition, all the impacts are estimated as relative, which causes an abstract analysis of actual groundwater and surface water conditions.

Summary

This study included identification and evaluation of regional integrated hydrologic models in Central Valley. Eighteen models have been identified, basic data was collected on much of these models, and summary information on the history of development, calibration, documentation, and application of these models were compiled for this study.

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Table 1. Scope and Scale Factors in Hydrologic Modeling

Scale of Data	Scope of Models		
	Regional	**Local**	**Site-Specific**
Geographic Coverage	Large basins and/or watersheds, covering several groundwater basins.	Small basins and/or limited to one watershed or groundwater basin.	Area is specifically limited to the project site.
Spatial Scale	Data scale is at county or watershed level; often times at a Depletion Study Area (DSA) level.	Data scale is at units smaller than a county; e.g., irrigation or water district, city/municipality, or Detailed Analysis Unit (DAU) level.	Data scale is limited to the site, and at very small scale.
Temporal Scale	Annual, seasonal, or at the smallest scale monthly.	Monthly or daily.	Often times daily, hourly, or minute time interval.
Processes	Course simulation of processes, often aggregated processes. For example, saturated groundwater flow in multi-aquifer system.	Refined processes simulated individually and/or coupled. For example, saturated groundwater flow in multi-aquifer system, with simulation of unsaturated zone flow, and rainfall-runoff processes, and linear relationship for stream-aquifer interaction.	Detailed processes that would reflect the level of detail needed in the simulation results. For example, saturated groundwater flow in multi-aquifer system, with simulation of unsaturated zone flow, and rainfall-runoff processes, and non-linear relationship for stream-aquifer interaction and non-linear simulation of unconfined groundwater flow.

Table 2. Models Identified in Sacramento Valley and the Available Information

Model	Model Code Platform	Model Code Available	Model Data Available	Documents/ Reports	Reference
1. CVGSM	IGSM 6.0	Yes	Yes	Yes	JMM, 1990
2. C2VSIM	IWFM 3.0	Yes	No	Yes	DWR, 2006
3a. CVRASA 1	MODFLOW	Yes	Yes	Yes	Williamson et.al., 1989
3b. CVRASA2*	MODFLOW	Yes	N/A	N/A	Faunt, C. et.al., 2007
4. USBR Model	Hydrogeosphere	No	No	No	Matanga, 2007a & 2007b
5. Sacramento Valley Superposition Model	MicroFEM	Yes	Yes	Yes	CH2M Hill, 2005
6. Stony Creek Fan Model	IGSM 6.1	Yes	Yes	Yes	WRIME, 2003a
7. Butte County Model	IWFM 3.0	Yes	Yes	Yes	CDM, 2006
8. Yuba County Model	IGSM 6.0	Yes	Yes	Yes	N/A
9. Lower Colusa Basin Model	IGSM 6.0	Yes	Yes	Yes	WRIME, 2003b
10. Yolo County Model	IGSM 6.13	Yes	Yes	Yes	WRIME, 2006a
11. North American River Model	IGSM 6.13	Yes	Yes	Yes	MW, 1995
12. Sacramento County Model	IGSM 6.41	Yes	Yes	Yes	WRIME, 2006b
13. Redding Basin Model	MicroFEM	Yes	No	Yes	CH2M Hill, 2007
14. San Joaquin County IGSM	IGSM 5.0	Yes	Yes	Yes	MW, 1995
15. Kings Basin IGSM	IGSM 6.4	Yes	Yes	Yes	WRIME, 2007
16. Friant-Kern IGSM	IGSM 3.2	Yes	Yes	Yes	MWH, 1995
17. WESTSIM*	IWFM	Yes	N/A	N/A	N/A
18. SANTUCM	FEGW	Yes	Yes	Yes	BEC, 1990

* Information regarding the details of these models were not available at the time of preparation of this article.

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Applying MODFLOW's Farm Process to California's Central Valley

Claudia C. Faunt, Randall T. Hanson, Wolfgang Schmid and Kenneth Belitz

California's Central Valley has been one of the most productive agricultural regions in the world for more than 50 years. The Central Valley also is rapidly becoming an important area for California's expanding urban population. During 1980–2007 the population nearly doubled, increasing the competition for water within the Central Valley and statewide. Because of the importance of ground water in the Central Valley, the U.S. Geological Survey's (USGS) Ground-Water Resources Program is evaluating ground-water conditions in the valley based on historical and anticipated future water use. This study is updating the USGS's Central Valley Regional Aquifer System and Analysis (CV-RASA) model and supporting information previously developed by the USGS to quantitatively address ground-water issues in the valley. The Central Valley aquifer system was characterized using a detailed textural analysis of more than 8,500 driller's logs. The updated model utilizes the Farm Process (FMP) for MODFLOW that provides coupled simulation of the ground-water and surface-water components of the hydrologic cycle mainly in irrigated but also in non-irrigated areas. The FMP provides a dynamic allocation of ground-water recharge and ground-water pumping based on crop-water demand after surface-water deliveries and root uptake from shallow ground water. The FMP links with the Streamflow Routing Package (SFR1) to facilitate the simulated conveyance of surface-water deliveries. The FMP also simulates ground-water pumpage through both single-aquifer and multi-node wells, irrigation return flow, and variable irrigation efficiencies. The Subsidence (SUB) package was used to simulate land subsidence, a consequence of overdraft. The simulated deliveries and ground-water pumpage reflect climatic differences, differences among the water-balance regions, and changes in the water-delivery system during the 1961–2003 simulation period. The model is designed to be coupled with forecasts from Global Climate Models (GCMs) to simulate the potential variabilities of surface-water delivery, ground-water pumpage, and ground-water storage in response to climate change. The model provides a detailed transient analysis of changes in ground-water availability in relation to climatic variability, urbanization, and changes in irrigated agriculture.

Introduction

California's Central Valley covers about 20,000 mi^2 and is one of the most productive agricultural regions in the world (fig. 1). More than 250 different crops are grown in the valley with an estimated value of $17 billion/yr. This irrigated agriculture relies heavily on surface-water diversions and ground-water pumping. Approximately one-sixth of the Nation's irrigated land is in the Central Valley, and about one-fifth of the Nation's pumping is from its aquifers (Great Valley Center, 2005). The Central Valley also is rapidly becoming an important area for California's expanding urban population. Since 1980, the population of the valley has nearly doubled from 2 to 3.8 million people (California Department of Finance, 2007), and the U.S. Census Bureau projects that the valley's population will increase to 6 million people by 2020. This increase in population has increased the competition for water within the Central Valley and statewide. Competition for water is likely to be exacerbated by reduced deliveries of Colorado River water to southern California and reduced deliveries through the Sacramento-San Joaquin Delta owing to environmental flow requirements. As a result, a number of issues have gained prominence: conservation of agricultural land, conjunctive use, aquifer storage and recovery, hydrologic implications of land-use change, and effects of climate variability. To help address these issues, the U.S. Geological Survey (USGS) Ground-Water Resources Program initiated a study in 2005 to assess ground-water availability of the Central Valley, including: 1) quantifying the present status of ground-water resources; 2) evaluating how the availability and allocation of these resources have changed over time, and; 3) developing a tool to assess aquifer-system responses to stresses from future human uses and climate variability and change. This effort builds on previous investigations, such as the USGS CV-RASA (Williamson and others, 1989) and several other studies conducted in the valley by federal, State and local organizations at various scales. This newly developed tool, the Central Valley hydrologic model (CVHM), incorporates a dynamically integrated water supply-and-demand accounting within agricultural areas to simulate surface-water and ground-water flow across the entire Central Valley watershed.

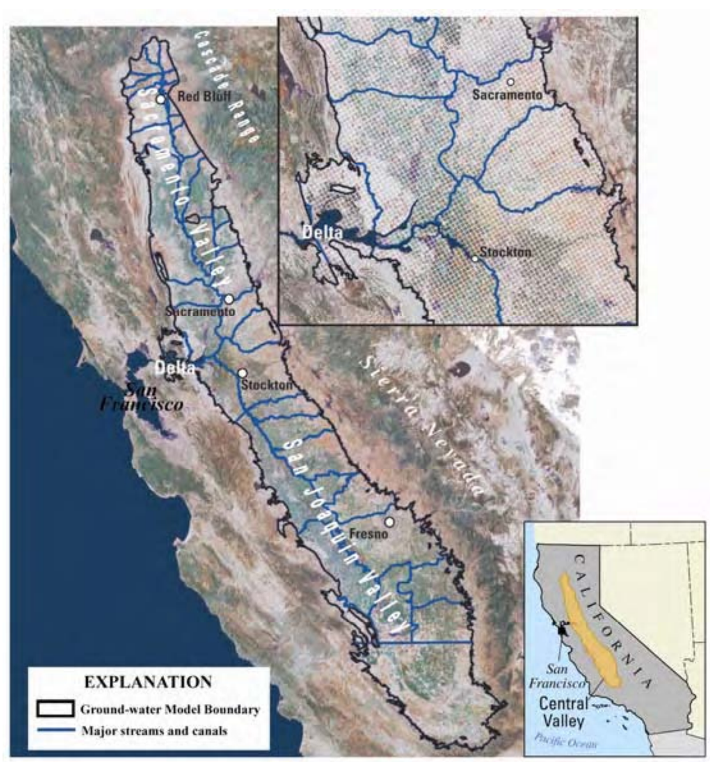

Figure 1. Location and extent of regional-scale ground-water model of Central Valley and one-square mile model cells.

The approach taken to characterize and assess ground-water availability for the Central Valley consists of three major tasks: (1) develop a texture model to characterize the aquifer system in the valley; (2) estimate the water-budget components in irrigated areas of the valley with the aid of the FMP; and (3) develop, calibrate, and utilize the CVHM to assess and quantify current and future ground-water conditions in the valley. When developing a three-dimensional (3D) ground-water flow model of a heterogeneous aquifer system with complex surface-water management processes, such as the Central Valley, it is extremely difficult to recognize and understand spatial relations within or between data sets without the aid of a Geographic Information System (GIS). As a result, a GIS was developed for the Central Valley to store, analyze, link, and visualize both the spatial and temporal model input and output data.

Texture Modeling

The Central Valley is a large structural trough filled with sediments of Jurassic to Holocene age, up to 3 mi deep in the San Joaquin Valley, which constitutes the southern two-thirds of the Central Valley, and up to 6 mi deep in the Sacramento Valley, constituting the northern one third of the valley. Most of the fresh water, however, is contained in post-Eocene continental rocks and deposits (Berkstresser, 1973; Williamson and others, 1989) 1,000–3,000 ft thick. Aquifer-system sediments comprise heterogeneous mixtures of unconsolidated to semi-consolidated gravel, sand, silt, and clay. In the southwestern portion of the area, the lower aquifer system is confined by the extensive Corcoran Clay.

In order to better characterize the aquifer deposits, a 3D texture model was developed by compiling and analyzing lithologic data from approximately 8,500 drillers' logs ranging from 12 to 3,000 ft below land surface. The lithologic descriptions on the logs were simplified into a binary classification of coarse- or fine-grained. The percentage of coarse-grained sediment, or texture, was then computed from this classification for each 50-ft depth interval of the driller's logs. A 3D texture model was developed for the aquifer-system sediments of the valley by kriging the texture data onto a 1-mi spatial grid at 50-ft depth intervals from land surface to a depth of 2,800 ft.

The kriged estimates of percentage coarse-grained texture show significant heterogeneity in the texture of the sediments. The texture model results correlate well with depositional source areas, independently mapped geomorphic provinces, and factors affecting the development of fluvial fans. In general, the Sacramento Valley is predominantly fine-grained and reflects the more fine-grained volcanic-derived sediments. However, some relatively coarse-grained isolated deposits do occur along the river channels and the distal parts of alluvial fans of the Cascade Range and the northern Sierra Nevada.

In the San Joaquin Valley, especially on the eastern side, the areas of coarse-grained texture are more widespread than the areas of fine-grained texture, and occur along the major rivers and alluvial fans. In the southern portion of the San Joaquin Valley, the alluvial fans of the glaciated portions of the Sierra Nevada are much coarser grained than the alluvial fans to the north. In contrast to the eastern San Joaquin Valley, the western San Joaquin Valley is generally finer-grained and includes the major confining unit, the Corcoran Clay. The marine deposits of the Coast Ranges generally yield finer grained sediments than the granitic parent rocks that make up the alluvial fans on the eastern side of the valley. In addition, this finer-grained texture may be related to the fact that the area is internally drained with no outlet for exporting the finer-grained deposits. This fine-grained area of the western San Joaquin Valley is where the largest amount of subsidence has been recorded in the Central Valley, yet the majority of the subsidence is largely occurring in fine-grained interbeds and not in the Corcoran Clay.

Farm-Process Modeling

The original CV-RASA model utilized a water budget based on net recharge to the flow system, which makes it difficult to relate management decisions related to water deliveries and cropping patterns to corresponding changes in the water budget input for the model. The updated CVHM utilizes the FMP for MODFLOW-2000 (Schmid and others, 2006) to simulate the ground-water and surface-water components of the hydrologic cycle in irrigated areas, as well as areas of natural vegetation. The FMP provides a dynamic allocation of ground-water recharge and ground-water pumping based on crop water demand, surface-water deliveries, and depth to the water table. This is particularly useful in the Central Valley where ground-water pumping typically is not metered.

The farm delivery requirement (irrigation requirement) of the FMP is based on crop consumptive use, effective precipitation, ground-water uptake by plants, and on-farm efficiency. The FMP balances the farm requirement against surface-water deliveries and ground-water pumpage. The FMP links with the SFR1 of MODFLOW-2000 to facilitate the simulated conveyance of surface-water deliveries. The FMP also simulates ground-water pumpage through both single aquifer wells and multi-aquifer, or multi-node wells (MNW Package) (Halford and Hanson, 2002), irrigation-return flow, and allocates irrigation efficiencies. Although the FMP also is capable of incorporating economic and other management criteria, these options have not yet been included in this model. The FMP is used to estimate metered and un-metered historical pumpage and to simulate the delivery of surface water for 21 water-balance regions within the Central Valley on a monthly basis during the historical simulation period, 1961–2003. The FMP also simulates net ground-water recharge for irrigated and natural vegetation areas.

Ground-Water Flow Modeling

The CVHM is designed to simulate spatial and time scales relevant to water management decisions for the entire Central Valley. The model area includes the entire Central Valley aquifer system, which is subdivided laterally using a 1 mi2 grid and vertically into 10 layers. The texture model is used to estimate hydraulic conductivity for every cell in the model. The FMP is used to simulate irrigated agriculture, including routed diversions from streams and canals. Land subsidence, an important side-effect of intense ground-water pumpage, especially in the San Joaquin Valley, is simulated with the Subsidence (SUB) package. Intra-borehole flow, an important contribution to vertical flow is simulated with the MNW package.

The simulated deliveries and ground-water pumpage reflect climatic differences, differences among the water-balance regions, and changes in the water-delivery system. In general, the Sacramento Valley receives more precipitation than the drier, more heavily pumped, San Joaquin Valley. The surface-water delivery system in the Central Valley redistributes this water from the Sacramento to the San Joaquin Valley. Through the FMP the CHVM incorporates the deliveries and diversions on a monthly basis and the calculation of agricultural pumpage. Results from the CVHM monthly budgets indicate that precipitation and surface-water deliveries supply most of the consumption in the initial part of the growing season, whereas, increased ground-water pumpage augments these supplies later in the season. Additionally, the model shows that during wet years, water generally goes into ground-water storage and during dry years water is pulled out of storage. Even during dry years, recharge occurs during the heavy spring precipitation. In the 1960s, the surface-water delivery system began to deliver water from the Sacramento Valley to San Joaquin Valley. Both the original CV-RASA model and the CVHM show that at this time, ground-water pumping exceeded surface-water deliveries, causing water levels to decline to historic lows on the west side of the San Joaquin Valley resulting in large amounts of subsidence. By the early 1970s, the surface-water system was in place and both models simulate water-level recovery and little subsidence because surface-water deliveries exceeded ground-water pumping. However, the CVHM simulates the effect of climatic variability on the system during this time. For example, during the droughts of 1976–77 and 1987–92 observed and simulated water levels declined rapidly and subsidence resumed. Since the mid-1990s, the simulation shows that although surface-water deliveries exceed ground-water pumpage, water is being removed from storage in most years; however, during years in the top twenty-fifth percentile of precipitation large amounts of water are going into storage and replenishing the ground-water system. In summary, the CVHM improves our understanding of the Central Valley aquifer system by providing a detailed transient analysis of changes in ground-water availability and flow paths in relation to climatic variability, urbanization, stream flow, and changes in irrigated agricultural practices and crops.

The CVHM also is designed to be coupled with forecasts from GCMs to provide a tool for stakeholders to forecast the potential supply of surface-water deliveries, demand for ground-water pumpage, and ultimately the change in ground-water storage and land subsidence in response to predicted changes in the future climate. Implementation of the FMP with GIS facilitates the use of remotely-sensed evapotranspiration data, and therefore allows for the spatial and temporal input data for the model to be updated more efficiently. This capability, in turn, facilitates using the climate forecasts from the GCMs as input data to the crop-based water budget of the CVHM.

In the future, the CVHM could be used 1) as the platform to connect the simulation of ground-water/surface-water flow with the water allocation/optimization model called CALSIM (California Department of Water Resources, 2008); 2) for evaluation of subregional proposals such as the exportation of water from the Sacramento Valley to Southern California; or 3) to assess the forthcoming restoration of the salmon habitat of the San Joaquin River. These types of regional and subregional water-management issues could be incorporated into local-scale models that are dynamically linked to the regional CVHM through the embedded model technology of the Local Grid Refinement (LGR) package (Mehl and Hill, 2005).

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Estimating hydrologic flow components of the Central Valley hydrologic flow system with the California Central Valley Groundwater-Surface Water Model

Charles F. Brush, Emin C. Dogrul, Michael R. Moncrief, Jeff Galef, Steve Shultz, Matt Tonkin, Daniel Wendell, Tariq N. Kadir, and Francis I. Chung

The California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) is an integrated hydrologic model developed using the Integrated Water Flow Model (IWFM) program. C2VSIM simulates land-surface, groundwater and surface-water flow in the alluvial portion of California's Central Valley, an area of approximately 20,000 mi2, with a monthly time step from October 1921 through September 2003. The Central Valley's hydrologic system experienced significant changes during this period as a result of steady agricultural expansion, extensive groundwater pumping, the development of surface water storage and conveyance systems, and recent urban expansion. Simulating the aquifer system over this period provides an understanding of unmeasured historical water budget components, especially rates and distribution of groundwater pumping and recharge. The model also serves as a useful planning tool to assess regional impacts of water management programs such as conjunctive use of groundwater and surface water, climatically induced changes in surface water inflows to the valley, or significant changes in land use.

Introduction

The California Department of Water Resources (DWR) has developed numerous modeling tools to aid in the planning and management of the State Water Project. Development of the Integrated Water Flow Model (IWFM) application and the California Central Valley Groundwater and Surface Water Simulation Model (C2VSIM) were initiated to improve the groundwater representation within CALSIM, a water resources planning model for simulating operation of the California State Water Project and Federal Central Valley Project. Flows between rivers and adjacent aquifers can significantly affect flow rates in many reaches of Central Valley rivers, and river flows can be significantly affected by for example groundwater pumping from aquifers that have historically discharged water to rivers. CALSIM-III, currently under development, directly incorporates the groundwater flow process from IWFM and the hydraulic parameters of C2VSIM to dynamically simulate stream-groundwater flows and aquifer response to groundwater pumping. The current integrated groundwater-surface water model of the Central Valley is also being used to provide estimates of historical flows in support of other DWR programs, and to assess potential changes to the Central Valley hydrologic system that could result from changes in surface water availability as a result of climate change, to assess the impacts of proposed water resources projects on in-stream flows, and to establish basin-wide groundwater flow components to serve as boundary conditions for smaller-scale models.

California's Central Valley is a northwest-trending asymmetric trough approximately 400 mi long and varying from approximately 20 mi to 70 mi wide (Page, 1986). The valley is surrounded on all sides by mountains, with a narrow opening in the western side that leads through the Carquinez Straits to San Francisco Bay and the Pacific Ocean; this opening is the only natural drainage outlet for the valley. The eastern boundary is formed by the Sierra Nevada Mountains, the northern boundary by the Klamath Mountains, the western boundary by the Coast Ranges, and the southern boundary by the Tehachapi Mountains. The interior of the valley contains the Sutter Buttes, a volcanic plug approximately 10 mi in diameter that rises to an altitude of approximately 2,000 ft; and the Kettleman Hills, Dunnigan Hills, and Corning Domes. The Coast Ranges and Sierra Nevada generally extend beneath the surficial sediments toward the center of the valley, forming the basement of the alluvial basin; these basement rocks do not yield significant amounts of water. The topography of the alluvial portion of the Central Valley ranges from below sea level in portions of the Sacramento-San Joaquin Delta to as high as 1,800 ft (550 m) on some alluvial fans in both the south and northwest.

The Central Valley alluvium that comprises the main aquifers is composed of continental and marine sediments derived from the surrounding mountains. Surface sediments are generally composed of alluvial fans, stream channel deposits and flood plain deposits. The Sacramento Valley contains up to 10 vertical miles of sediment, with no extensive confining layers, but some locally confined and semi-confined aquifers. Much of the fresh groundwater pumped in the Sacramento Valley has historically been derived from the unconfined aquifer. The San Joaquin Valley contains up to 6 vertical miles of sediment, with several areally extensive confining layers present, most notably the Corcoran Clay Member of the Tulare Formation. Fresh groundwater has historically been derived from both the unconfined and confined aquifers. Geologic features such as faults and folds play an important role in local hydrogeology. Several faults are known to significantly affect ground water movement in the Central Valley, including the Red Bluff Arch, White Wolf Fault, Edison Fault and Springs Fault. Anticlinal folds restricting groundwater movement have been inferred in the Kettleman Hills (Page, 1986).

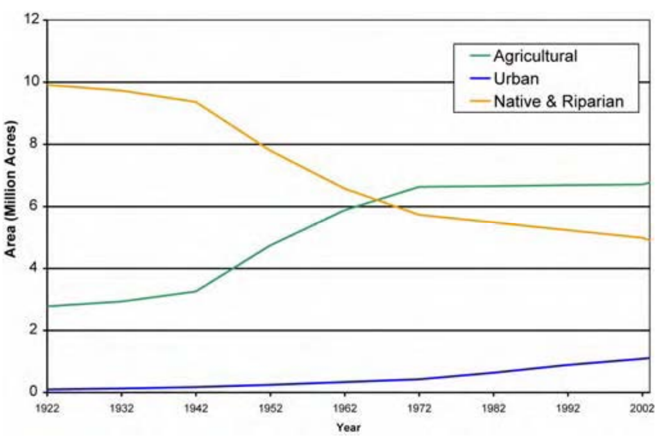


Figure 1. Historical land use changes in California's Central Valley as represented in the C2VSIM model.

The population in California's Central Valley has increased from less than 700,000 people in 1922 to an estimated six million people in 2003 (Bureau of the Census, 1921; California Department of Finance, accessed June 2008). The cultivated land area expanded from approximately 4,300 mi^2 in 1920 to 10,600 mi^2 in 2003 (figure 1). Urban land use has increased steadily, but began growing at a faster rate in the 1970s. The area covered by native and riparian vegetation decreased from approximately 15,400 mi^2 in 1922 to 7,500 mi^2 in 2003.The majority of the surface water available to the Central Valley derives from streams draining mountain watersheds to the north and east, and a significant portion of the water demand occurs south of the Sacramento-San Joaquin Delta. Development of Central Valley water resources can be generalized as occurring in three phases: (a) capture surface water for local use and then for export westward to the San Francisco Bay area; (b) expansion of groundwater pumping; and (c) development of large canals and infrastructure to capture surface water in the north and east and deliver it to the west side of the Sacramento Valley, the San Joaquin Basin, the Tulare Basin and over the Tehachapi Mountains and Coast Range to population centers along the south coast.

Large-scale groundwater and surface water development significantly altered the natural groundwater flow pattern, creating areas of high water table in areas of high irrigation water application and cones of depression centered on areas of high groundwater pumping. Excessive groundwater pumping has also caused subsidence of more than 1 ft between 1900 and 1980 over an area of 5,200 mi^2 in the San Joaquin Valley, mostly in the Tulare Basin and on the west side of the San Joaquin Basin, with a maximum of 30 ft (9 m) near Los Banos (Ireland, 1986). Partly to counter subsidence and to also to utilize and store available surface waters during extremely wet years, programs to directly recharge groundwater have been implemented in the San Joaquin and Tulare basins since at least 1921 (Davis et al. 1963; California Department of Water Resources, 1977). Artificial recharge programs implemented in the Tulare Basin portion of Kern County since the 1970's have been credited with significantly reducing groundwater overdraft in that area (Kern County Water Agency, 1973-2005).

Model History and Development

The C2VSIM model is based on the model framework and input data sets of the Central Valley Ground-Surface Water Model (CVGSM), which incorporated information from several earlier models. Williamson et al. (1985, 1989) developed a finite differences groundwater flow model of the Central Valley for the period 1961-1976. Boyle Engineering used the model of Williamson et al. (1985) as the basis for a finite element model called the Central Valley Groundwater Simulation Model which incorporated both the surface water and groundwater flow systems (Boyle Engineering, 1987). The model of Boyle Engineering (1987) served as the basis for the CVGSM model, which was developed by James M. Montgomery Consulting Engineers and Boyle Engineering using the finite element Integrated Groundwater and Surface Water Model (IGSM) application (James M. Montgomery Consulting Engineers, 1990a and 1990b). A key innovation of the IGSM application was the coupled simulation of land surface, surface water and groundwater flow processes, and the dynamic calculation of water budget components (such as recharge), and inter-process flows (such as groundwater-surface water flows). Development of the CVGSM model was funded by the U.S. Bureau of Reclamation (USBR), California Department of Water Resources (DWR), California State Water Resources Control Board (SWRCB) and Contra Costa Water District (CCWD).

California's Central Valley can be divided into five hydrologic regions: the Sacramento Valley, San Joaquin Basin, Tulare Basin, Eastside Streams and Sacramento-San Joaquin Delta. For the purpose of developing the CVGSM model, the Central Valley was further divided into 21 subregions, roughly corresponding to Depletion Study Areas (DSAs) developed by DWR in the 1970s to facilitate data collection and analysis. The Sacramento Valley hydrologic region (subregions 1-7) covers the northern part of the Central Valley, drained by the Sacramento River, and includes the Redding Basin and Sacramento Basin. The San Joaquin Basin (subregions 10-13) is in the center of the Central Valley and is drained by the San Joaquin River. The Tulare Basin (subregions 14-21) is in the southern part of the Central Valley and is normally a closed hydrologic basin with interior drainage; rivers generally lose most of their flow to infiltration before reaching terminal lakes on the valley floor, with some discharge to the San Joaquin River during extreme flood events. The Eastside Streams (subregion 8) includes the lower Cosumnes and Mokelumne Rivers. The Sacramento-San Joaquin Delta (subregion 9) is a low-lying area where the Sacramento River, San Joaquin River and the lesser Cosumnes and Mokelumne Rivers meet before discharging westward through the Carquinez Straits to San Francisco Bay and the Pacific Ocean.

The original CVGSM project had numerous goals, most notably development of a comprehensive hydrologic database for the Central Valley for the 59-year period from October 1921 to September 1980; development of a model grid that would support regional, sub-regional and site-specific analyses; incorporating variable land uses and crops through time; and estimating rates and distribution of groundwater pumpage (James M. Montgomery Consulting Engineers, 1990b). At the time, the CVGSM input data set was considered to be perhaps the most comprehensive set of water-resources data ever compiled for the Central Valley. The original model contained data sets to operate on a monthly time step from October 1921 to September 1980. The CVGSM model was extended and updated several times, for October 1981 through September 1993 by CH2M Hill (CH2M Hill, 1996), October 1993 through September 1998 by DWR (unpublished report), and then for October 1998 through 2003 by DWR.

In 2001, DWR began a lengthy review of the IGSM application and CVGSM model. A peer review of IGSM, conducted the California Water and Environmental Forum (CWEMF) with assistance from researchers at U.C. Davis (LaBolle et al., 2002) identified several issues regarding both theoretical foundations and implementation of the application. These included improper implementation of head-dependent boundaries, lack of a methodology to simultaneously solve coupled models (such as surface water and groundwater flow processes), non-standard formulation of boundary conditions and head-dependent transmissivity, incorrectly reported water budgets, lack of a methodology to assure convergence to non-linear boundary conditions, and inadequate documentation of some portions of the computer code. DWR responded to the review by thoroughly reviewing the existing IGSM code and documentation, refining the theoretical foundation, rewriting significant portions of the code, and producing complete documentation and examples. The updated finite element groundwater-surface water application was renamed the Integrated Water Flow Model (IWFM). IWFM development has continued, and the application is currently at version 3.0 (California Department of Water Resources, 2008a, 2008b; Dogrul and Kadir, 2006). IWFM incorporates a three-dimensional finite element groundwater flow process dynamically coupled with one-dimensional land surface, river, lake and unsaturated zone processes and a simplified land-surface process to simulate surface and subsurface flows from ungaged small-stream watersheds adjacent to the model boundary. CVGSM data sets were updated to simulate the period from September 1921 through October 2003 and modified to conform to the IWFM application, and the resulting model was named C2VSIM.

The IWFM land-surface process partitions precipitation to infiltration and runoff, calculates aggregate water demands, routes runoff to rivers and deep percolation to the unsaturated zone, allocates available surface water to meet agricultural and urban demands, and calculates the amount of groundwater pumping required to meet the remaining demands (especially useful in California where groundwater pumping is not recorded), and the IWFM surface water process routes river flows and calculates stream-groundwater interactions. In the C2VSIM model, the groundwater flow system is represented with three layers of 1392 elements, the surface-water network is simulated using 449 river nodes representing 75 river reaches, with a single outflow point at the Carquinez Straits, and the small-stream watershed process calculates surface and subsurface flows from 210 ungaged watersheds (figure 2).

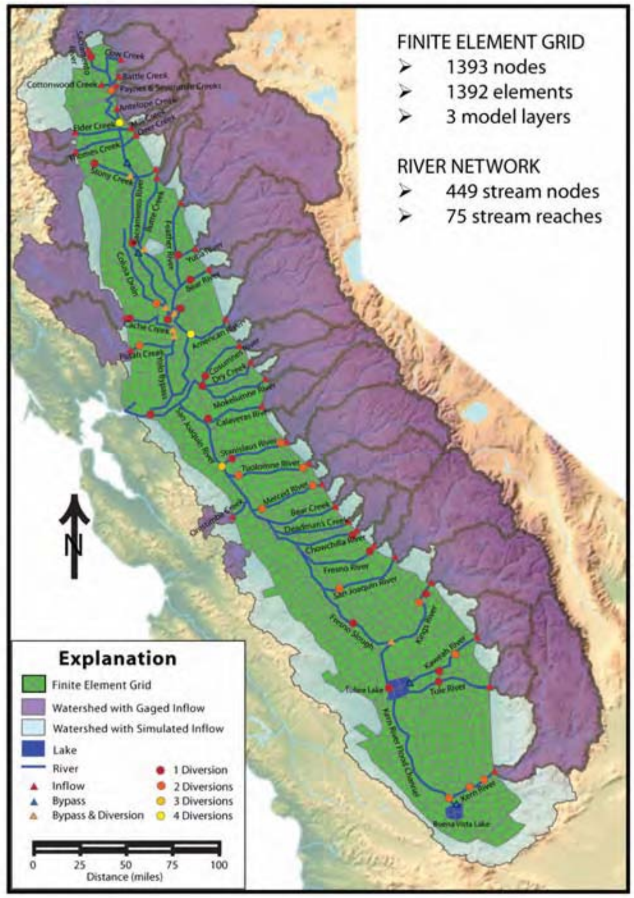


Figure 2. Model framework of the California Central Valley Groundwater-Surface Water Flow Model.

The updated model also incorporates numerous improvements and expanded data sets, notably including areally distributed precipitation, removal of constant-head nodes in the Sacramento-San Joaquin Delta, re-configured hydrology for the rivers and lakes in the Tulare Basin,

new small stream watershed delineation, re-configured tile drains in the western San Joaquin Valley, and distributing groundwater pumping based on well construction information in the DWR well completion database.

C2VSIM incorporates a detailed historical hydrologic database currently covering the period from October 1921 through September 2003 (water years 1922-2003). Monthly environmental data include precipitation by model element, evapotranspiration by land use type and agricultural crop for each subregion, and surface water inflow on major river reaches. Land use data include the proportion of each land use type in each model element by water year, and agricultural crop acreages for each model subregion by water year. Monthly boundary surface-water inflows are specified for 40 gaged river locations. Surface water diversion data are aggregated to thesubregion level for each water source (river reach, irrigation district or major canal) resulting in 107 specified surface-water diversions from 97 diversion locations.

Model Calibration

A preliminary calibration of C2VSIM with the parameter estimation program PEST (Doherty, 2004) was conducted in 2005-2006 to develop regional-scale hydraulic parameter values and to identify areas in which the model framework should be improved (CH_2M Hill, Inc., and S. S. Papadopulos and Associates, 2006). PEST runs a model many times, and evaluates the difference between observed values (such as groundwater head and river flow) and simulated equivalents after each run, adjusting model parameters to achieve the best match between simulated and observed values. The C2VSIM model was calibrated to match observations for a 25-year recent period (water years 1975-1999) starting from an initial condition of October 1972, and was then verified against the same \set of observations with a simulation for water years 1921-2003. The 25-year calibration period had the advantages of significant data availability and a reduced simulation time, facilitating calibration with PEST.

IWFM incorporates time-stamped data sets for model inputs, which allow C2VSIM simulations to be conducted with a monthly or daily time step for the period from October 1921 through September 2003 or from any starting date after October 1921 for which initial conditions are available. Initial conditions for October 1921, developed for the CVGSM model, were modified to conform to the C2VSIM model framework. Initial groundwater heads for October 1921 were developed by James M. Montgomery Consulting Engineers (1990b) for the CVGSM model, based on a 1912 water-table map for the Sacramento Valley (California Department of Public Works, 1918) and a 1921 water-table map for the San Joaquin Valley (California Department of Public Works, undated). Initial pre-consolidation heads for all groundwater nodes for October 1921 were assumed to be equal to the initial groundwater heads. Initial conditions for October 1971 were developed for the preliminary model calibration using available groundwater observations (CH_2M Hill, Inc., and S. S. Papadopulos and Associates, 2006). Initial pre-consolidation heads for October 1971 were assumed to be equal to the initial groundwater heads. Initial lake elevations for Buena Vista Lake and Tulare Lake were assumed to be equal to the minimum land surface elevation for each lake for all simulations.

The calibration data set for the initial calibration of regional parameters consisted of groundwater head observations at 221 wells, paired groundwater head observations for calculating vertical head gradients at 9 locations, monthly river flow observations at 7 locations, and stream-aquifer flow along 33 river reaches. Selected groundwater head observation wells for both groundwater head observations and vertical groundwater head gradients have at least semi-annual observations, with observations starting before October 1974 and ending after September 1999. Surface-water flow observations were selected for nine locations, four on the Sacramento River and five on the San Joaquin River and its tributaries. Monthly flow observations for water years 1975-1999 were available for eight locations and for water years 1975-1995 for one location, the Merced River near Stevinson. The calibration data set did not include any surface water flow observations in the Eastside Steams, Delta or Tulare Basin hydrologic regions. Stream-aquifer flow values along selected river reaches were compiled from Mullen and Nady (1985). Mullen and Nady (1985) reported monthly water budgets for water years 1961-1977, which does not match the calibration time period; average monthly stream-aquifer flow values for each reach were therefore used as the calibration targets.

The PEST program (Doherty, 2004) and associated utility programs were written for use with the MODFLOW groundwater flow simulation application. To facilitate model calibration with the PEST program, the PEST utility programs were modified for use with IWFM, and IWFM was modified to read parameter values from a separate file generated by a new PEST utility program (CH_2M Hill, Inc., and S. S. Papadopulos and Associates, 2005). This involved changing sections of individual utility programs to read information from IWFM input files, to read simulation results from IWFM output files, and to generate the C2VSIM input file CVOverwrite.dat to transfer PEST-generated aquifer parameter values to IWFM.

The PEST pilot-point framework (Doherty, 2003) was used to estimate distributed values for seven groundwater flow system parameters – horizontal hydraulic conductivity, vertical hydraulic conductivity, vertical hydraulic conductivity of the Corcoran Clay confining unit (where present), specific yield, and specific storage. With this framework, PEST calculates optimum parameter values at a reduced set of points called pilot points, and uses kriging to allocate the resulting parameter values to the more densely spaced model nodes. This method allows the rapid estimation of regional parameter values. Three sets of pilot points were developed to calibrate the C2VSIM model, a concentrated set with 139 pilot points, a more diffuse set with 39 pilot points, and a set with 19 pilot points for calculating the vertical conductance of the Corcoran Clay. 81 riverbed conductance parameters were calibrated, one for each river reach, with a second parameter for the portions of some river reaches that extend into the Delta. The hydraulic conductivities of two faults that serve as hydraulic flow barriers were included: the White Wolf Fault in Kern County and the Red Bluff Arch in Shasta County.

In addition, many unit conversion factors were included as calibration parameters in the PEST input file to test for model sensitivities to various parameters and processes. Three unsaturated zone factors were included: the conversion factor for unsaturated zone thickness, the weighting factor for unsaturated zone porosity, and the conversion factor for unsaturated zone hydraulic conductivity. Four root-zone hydraulic conductivity parameters were included, one for each hydrologic soil group (A, B, C and D) for each subregion, a total of 84 root-zone hydraulic conductivity parameters. Three small stream watershed factors were included as parameters to estimate model sensitivity to the small watershed process parameters: the root-zone depth factor, root-zone hydraulic conductivity factor, and recession coefficient factor. Two factors were included as parameters to estimate model sensitivity to the lake parameters: the lake bed hydraulic conductivity factor and the lake bed thickness factor. The root-zone depth factor was also included as a parameter to estimate model sensitivity to the root zone depths in the land and water use process.

Calibration Results

The preliminary model calibration produced hydraulic parameter values that reflect the geologic composition of the Central Valley alluvium, with higher hydraulic conductivities in sediments derived from the Sierra Nevada, and lower hydraulic conductivities in the sediments derived from the Coast Ranges and where anticlinal folds may restrict lateral flow along the west side of the valley. The calibrated horizontal hydraulic conductivities of model layers 1 and 2, vertical hydraulic conductivity of the Corcoran Clay, and specific yield of model layer 1, along with the pilot points used for each parameter are shown in figure 3. The calibrated riverbed conductances are shown in figure 4.

The average residual values and the root-mean square error for groundwater heads at each observation well used to calibrate the model are shown in figure 5. These maps show that simulated heads at many wells are within a reasonable range, and there are several areas where simulated and observed heads differ significantly. These differences may arise from one or more of the following: local deviation from the model-calculated subregional recharge and pumping rates, siting of the observation well near a pumping well, or observations taken at times when the groundwater head is not representative of the local average groundwater head. These issues will be addressed in subsequent model calibration.

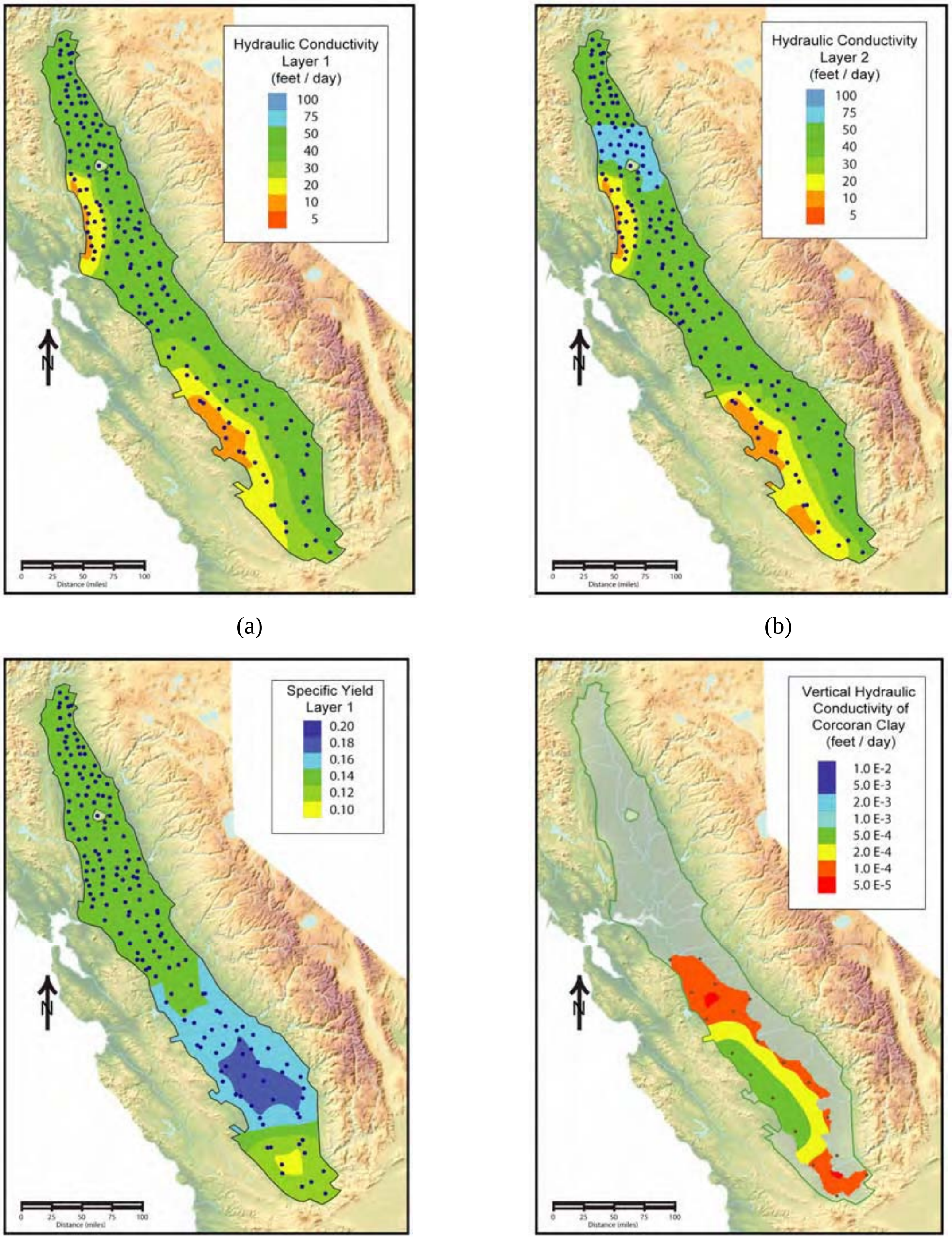


Figure 3. Hydraulic parameter values and pilot point locations from the initial calibration of the California Central Valley Groundwater Surface Water Simulation Model, (a) horizontal hydraulic conductivity of model layer 1, (b) horizontal hydraulic conductivity of model layer 2, (c) specific yield of model layer 1, and (d) vertical hydraulic conductivity of the Corcoran Clay between model layers 1 and 2.

The model was verified by simulating water years 1922-2003 and comparing simulated heads and flows with the calibration data set. The average difference between simulated and observed groundwater heads for water years 1975 to 1999 was 13.5 ft, and the root mean square error was 73.4 ft (Table 1). These are reasonable values for the preliminary calibration, considering the large distance between model nodes and the averaging of land surface processes such as recharge and groundwater pumping across subregions, with the large root mean square error reflecting large head differences at a small number of wells. The average difference between simulated and observed surface water flows for the Sacramento Valley and San Joaquin Basin for water years 1975 to 1999 was 35.7 TAF/mo, and the root mean square error was 139.0 TAF/mo (Table 2). These are very reasonable values, considering an average flow 2.1 MAF/mo passes through these basins. The model provides a fairly accurate simulation during times of low to moderate flows, and less accurate during periods of high flows. This is a reasonable result, as the river network in C2VSIM does not accurately represent the flow system configuration during high flow events.

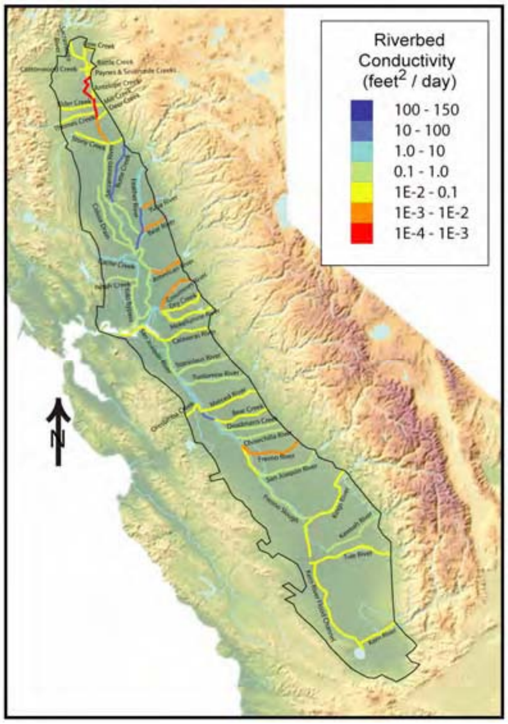


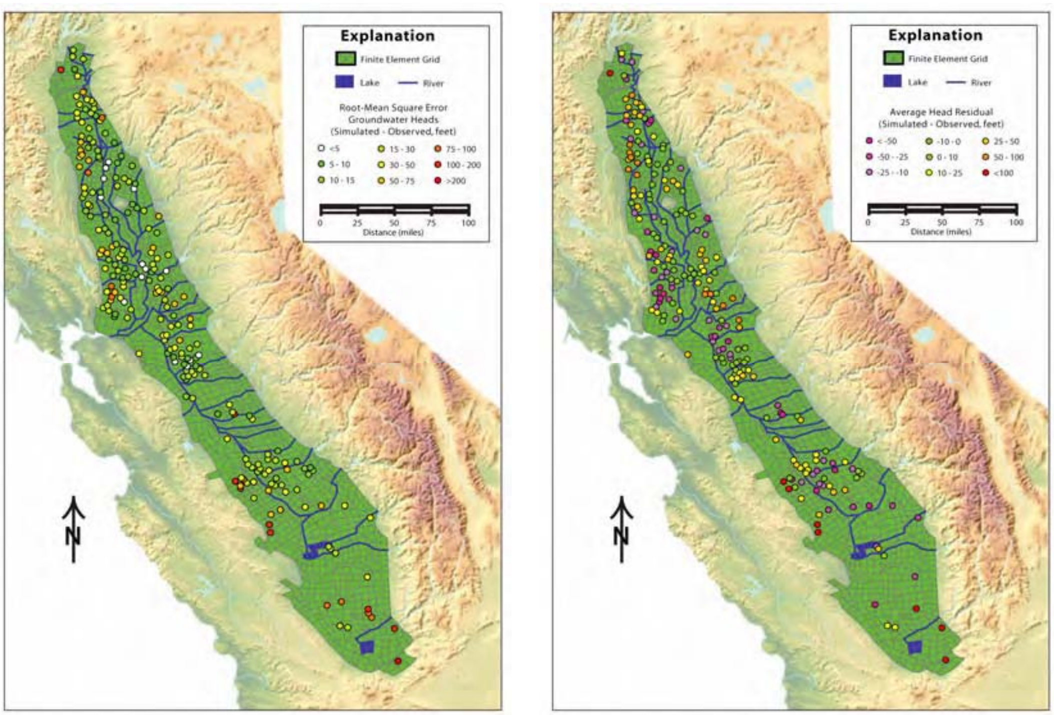
Figure 4. Riverbed conductance parameter values from the initial calibration of the California Central Valley Groundwater Surface Water Simulation Model.

Simulation Results

Annual precipitation, inflows, pumping, diversions, groundwater-surface water and withdrawals from storage for water years 1922-2003 are displayed graphically in figure 6. Precipitation in the Central Valley has fluctuated significantly; this is not representative of the precipitation in the surrounding mountains. The precipitation trend line shows the cumulative deviation from the period average precipitation. The trend line shows two periods of precipitation below the period average, from 1922 to the early 1930s and 1945 to 1960, with the other periods showing precipitation rates above the period average. Simulated surface water inflow includes natural and regulated flows. Significant annual variations in surface water inflows have occurred recently, with higher values representing years with high winter flows.

IWFM dynamically calculates groundwater pumping as the difference between total water demands and surface water deliveries. Figure 6 shows that simulated groundwater pumping increased significantly from the early 1920s through approximately 1960, and surface water deliveries increased fairly steadily through 1980 with some interruptions during periods of drought. After 1960, groundwater pumping generally increased in years of low surface water deliveries and decreased in years of high surface water deliveries. Groundwater discharges to surface water were fairly constant in the 1920s, and then declined consistently through 1960 as groundwater pumping increased. Between 1960 and 2003, groundwater discharges to surface water show considerable fluctuations, with two years of net surface water flows to groundwater in the 1990s. Flows to and from groundwater storage vary significantly from year to year, with several periods of consistent withdrawals from storage followed by one or more years of low withdrawals or recovery. The general trend has been consistent withdrawals from groundwater with no significant periods of groundwater recovery.

Average annual simulated flows into and out of the Central Valley hydrologic system for water years 1975 to 2003 are listed in table 3. Evapotranspiration is significantly greater than precipitation within the Central Valley. The difference is made up with surface water (surface water imports and inflows from rivers and small watersheds) and withdrawals from groundwater storage. Internal flows



(a) (b)

Figure 5. (a) Root-mean squared error and for simulated and observed groundwater heads, and (b) difference between average simulated and observed groundwater head observations, for water years 1975-2003, for the California Central Valley Groundwater Surface Water Simulation Model.

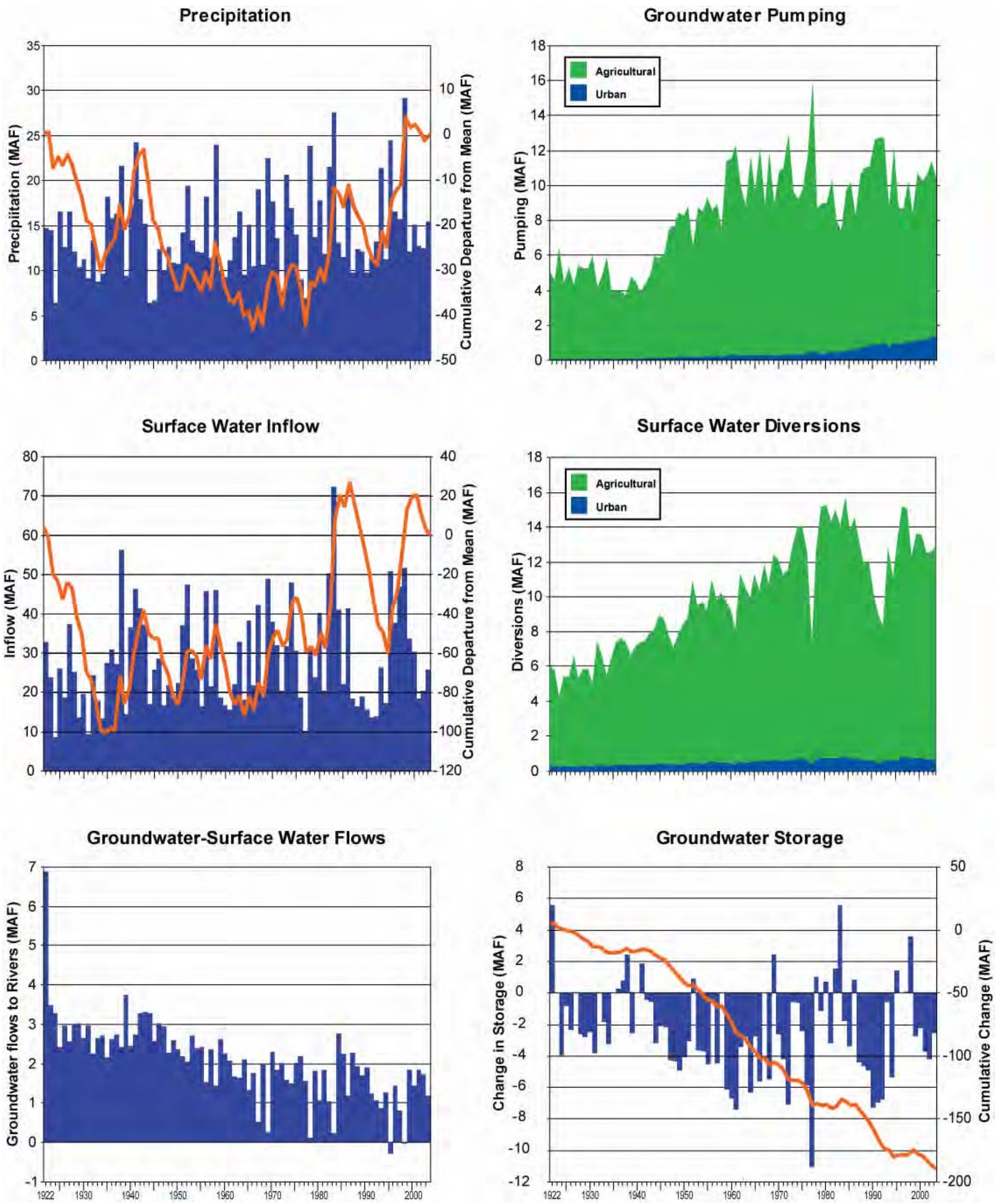


Figure 6. **Annual precipitation, groundwater pumping, surface water inflow, surface water diversions, groundwater-surface water flows and groundwater storage for California's Central Valley for water years 1922 to 2003 for C2VSIM.**

between processes for the entire model area for water years 1975 to 2003 are shown in figure 7. This information can be displayed for each hydrologic region or subregion and for any time period from one month to many years. This figure, which includes flow values for 30 separate flow paths, provides a powerful synthesis of model results that is easy to understand.

Water balances for each hydrologic region are listed in table 4. Precipitation and surface water inflows are significantly greater in the Sacramento Valley than in the San Joaquin Basin and Tulare Basin. Evapotranspiration rates are significantly higher in the San Joaquin Basin and Tulare Basin than in the Sacramento Valley. Water balances for the groundwater process for each hydrologic region are displayed in table 5. Approximately half of the groundwater pumping occurred in the Tulare Basin, along with a significant portion of the total subsidence and withdrawals from groundwater storage. Significant discharges from groundwater to rivers occurred in the Sacramento Valley region.

Conclusions

Significant progress has been made toward developing a comprehensive model that simulates the groundwater and surface water flow system of the Central Valley. DWR has developed the IWFM application which is currently serving as the platform for the C2VSIM model and for incorporating a groundwater flow simulation into CALSIM-III. Recent improvements to the C2VSIM model include incorporating monthly precipitation for each model element and reconfiguring the hydrology of the Tulare Basin to incorporate changes in the water management system implemented between 1980 and the present. The model has also been used to study the affects of conjunctive use programs on surface water flows, and the impacts on the groundwater flow system of increased groundwater pumping in response to reduced precipitation and river flows.

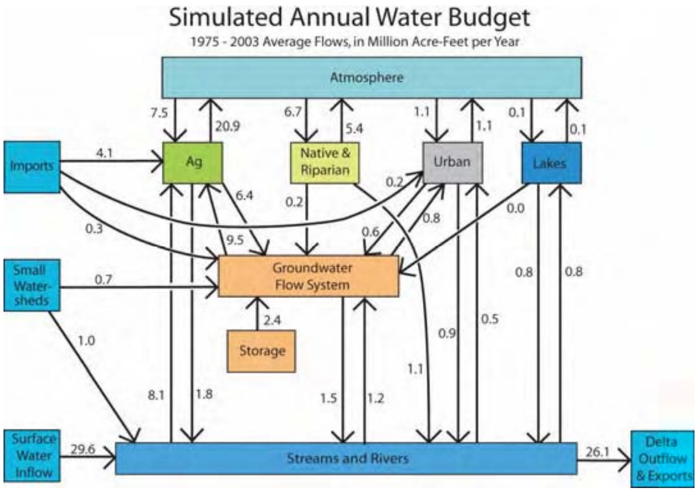


Figure 7. Average water balance components for water years 1975-2003, for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM R323). [All values in million acre-feet per year.]

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Table 1. Performance of the calibrated model with respect to groundwater head observations, water years 1975-2003, starting from October 1921 initial condition. [All values in feet.]

Hydrologic Region	No. of Wells	No. of Obs.	Root Mean Square Error	Average Difference
Sacramento Valley	118	6,361	53.9	-24.5
Delta	24	1,216	36.5	-25.5
Eastside Streams	8	420	36.2	-22.9
San Joaquin Basin	41	2,130	53.0	-3.9
Tulare Basin	44	2,352	130.1	17.8
Model Area	235	12,479	73.4	13.5

Table 2. Performance of the calibrated model with respect to surface water flow observations, water years 1975-2003, starting from October 1921 initial condition. (C2VSIM R323). [All values in thousand acre-feet.]

Hydrologic Region	No. of Sites	No. of Obs.	Root Mean Square Error	Average Difference
Sacramento Valley	4	3,936	204.4	58.2
San Joaquin Basin	5	4,117	127.8	48.3
Model Area	9	8,053	139.0	35.7

Table 3. Average annual total inflows to and outflows from the Central Valley, water years 1975-2003, from the Central Valley Groundwater-Surface Water Simulation Model (C2VSIM R323). [All values in million acre-feet per year.]

Flow Component	Inflows	Outflows
Precipitation	15.3	
Evaportanspiration		27.4
Rivers	29.6	26.1
Small Watersheds	1.7	
Groundwater Storage	2.9	0.5
Surface Water Imports	4.6	
TOTAL	54.1	54.1

Table 4. Average boundary flow components by hydrologic region, water years 1975-2003, for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM R323). [Areas in million acres and flow volumes in million acre-feet per year.]

Hydrologic Region	Area	Surface Water Inflows*	Surface Water Outflows*	Small Watersheds to Groundwater	Precipitation	Actual Evapo-transpiration
Sacramento Valley	3.7	20.0	17.8	0.4	6.8	7.6
Delta	0.7	31.0	25.6	0.0	0.9	1.5
Eastside Streams	0.9	1.3	1.4	0.0	1.4	1.6
San Joaquin Basin	2.5	5.8	4.5	0.0	2.5	5.5
Tulare Basin	4.9	3.2	1.2	0.2	3.5	10.8
Model Area	12.7	30.6	26.1	0.7	15.1	27.0

* Surface water inflows and outflows are not additive across hydrologic regions

Table 5. Average internal groundwater flow components by hydrologic region, water years 1975-2003, for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM R323). [All values in acre-feet per year.]

Hydrologic Region	Storage	Stream Leakage	Subsidence	Pumpage	Recharge	Interbasin Flows
Sacramento Valley	256,785	-1,219,814	261	-1,907,125	2,873,325	-3,431
Delta	-38,310	-204,586	-39	-259,195	581,336	-79,206
Eastside Streams	139,548	108,200	143	-782,394	382,789	151,714
San Joaquin Basin	258,617	-665,573	790	-1,766,905	2,298,641	-125,579
Tulare Basin	1,806,148	491,023	8,258	-5,599,745	3,237,710	56,502
Model Area	2,422,788	-1,490,749	9,413	-10,315,364	9,373,801	0

Analysis of Droughts in the California Central Valley Surface-Groundwater-Conveyance System

Norman L. Miller, Charles F. Brush, Larry L. Dale, Sebastian D. Vicuna, Tariq N. Kadir, Emin C. Dogrul, and Francis I. Chung

Introduction

During the last 150 years, California has been in a slightly above average wet regime, with at least 11 short-duration drought periods (Cook et al. 2004). At the same time, California Central Valley agriculture has expanded over most of the Valley floor, and includes a system of managed irrigation and water conveyance that assumes climatically stationary conditions for conveyance system development and planning. The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. However, the California Department of Water Resources (DWR) and other water agencies have begun to evaluate new approaches for managing water resources in response to the changing climate (DWR 2006).

In this study we quantify the impacts of long-term droughts - an analogue for climate change related snowpack reduction - on water storage, and to illustrate the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply. This includes understanding how groundwater pumping compensates for reductions in surface inflow, the extent to the water table is reduced, and how, when, and if this system recovers or reaches a new equilibrium.

Approach

Analysis of California Central Valley impacts of sustained droughts are based on a series of specified reductions in net surface flows corresponding to historical 30% (below average), 50% (dry), and 70% (critically dry) effective reduction, for periods ranging from 10 to 60 years, and applied to the CDWR's California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM). This simplified methodology represents a means to evaluate the impacts of reductions in net surface flow from reservoirs and Central Valley precipitation. The DWR is addressing global climate change in the California Water Plan, Bulletin 160 (DWR 2005). Rather than focus on causes of global climate change, which are being addressed by other agencies and research institutions, the DWR Water Plan looks at potential impacts of climate change on water resources in California and strategies for adaptation.

Model Descriptions

The DWR water allocation and flow models, the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and the California Simulation model (CALSIM) were used for this study.

California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM)

The C2VSIM model was developed as an application of the DWR's Integrated Water Flow Model (IWFM: DWR 2006), and simulates land-surface processes, surface water flow and groundwater flow. The land-surface module computes infiltration and runoff from net precipitation; consumptive use by native vegetation, irrigated crops and urban areas; surface water diversion and application; groundwater pumping and application; infiltration and return flow from irrigation; and recharge. Surface water flow is simulated as a function of flow from upstream reaches, tributaries and lakes; surface runoff; agricultural and urban return flows; diversions and bypasses; and exchanges with the groundwater flow system. The C2VSIM model simulates land surface processes, groundwater flow and surface water flow in the alluvial portion of the Central Valley (Fig. 1) using a monthly time step. C2VSIM covers an area of approximately 20,000 mi^2, and incorporates 1392 nodes forming 1393 elements and 3 layers, 431 stream nodes delineating 74 stream reaches with 97 surface water diversion points,two lakes, and 8 bypass canals (Fig. 1a). Surface water inflows are specified for 35 gauged streams and simulated for ungauged small watersheds. The model area is divided into 21 sub-regions (Fig. 1b), where each sub-region is treated as a virtual farm for allocating groundwater and surface water to meet water demands in the land-surface process.

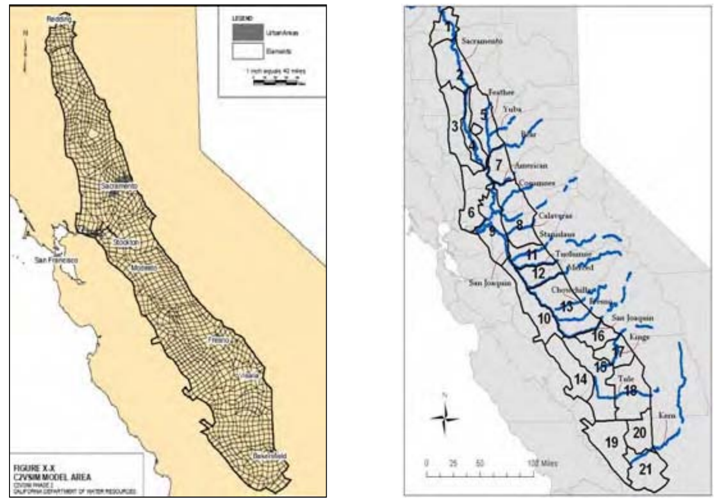

Figure 1. C2VSIM finite element grid and sub-basins for the California Central Valley.

California Simulation Model Version II (CALSIM II)

The CALSIM model (Draper et al. 2004) is a general-purpose, network flow, reservoir and river basin water resources allocation model, and is used for evaluating operational alternatives of large, complex river basins. CALSIM integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. CALSIM was originally designed, and has been successfully implemented as a planning model of the State Water Project (SWP) and Central Valley Project (CVP) system to examine the range of options to improve supply reliability. The second-generation version used here (CALSIM II) calculates the reservoir operations and time dependent rimflow into the Central Valley on monthly timesteps, providing the needed boundary conditions to C2VSIM.

Drought Scenarios

Drought scenarios are defined here as constructed surface flow reductions representing scenarios with effective reductions from 30% to 70%, for periods ranging from 10 years to 60 years, with a 10-year spin-up and a 30-year recovery. The C2VSIM boundary forcing was generated using the CALSIM II model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each scenario. The methodology used to create drought scenarios consists of selecting anomalously hydrologic dry years (in terms of reservoir inflow) from the historic record and appending them to create the specified droughts. It wasn't assured through this method that the exact specified amount in reduction in deliveries would occur, because there is not a perfect correlation between inflows to reservoirs and deliveries, and also because the reductions were assumed to be homogeneous throughout the different regions included in the model. An analysis of the input data that went into the model shows that the derived scenarios were underestimations of the expected reductions and the distribution of reductions were not homogeneous.

Results

Stream to groundwater flow, water table height, and groundwater volumetric storage response to drought scenarios are dynamically interrelated, along with the change in pumping under the fixed 1973-2003 set of demands, land use, and population. Here we discuss the drought responses for four major hydrologic regions: Sacramento, Eastside, San Joaquin, and Tulare, and for the entire Central Valley.

Surface Diversions

The defined droughts all begin with a ten year base period, during which surface diversions across the Central Valley average 10.65 million acre feet (maf) per year, followed by surface diversions in the Central Valley falling 36% for the severe drought scenario, 22% for the moderate drought scenario, and 10% for the light drought case. Drought impacts are modeled separately for the above four Central Valley sub-regions. The Central Valley region includes 12.8 million total acres and 6.8 million crop acres. Drought scenario impacts are concentrated in the San Joaquin and Tulare Basins, where the severe 60-year drought scenario results in 0.41 ft and 0.42 ft per year declines in surface deliveries, compared to the base period for the Tulare and San Joaquin Basins, respectively. The moderate 30-year and light 60-year drought scenarios, result in declines of about 0.20 ft and 0.13 ft per year from base year levels for the Tulare and San Joaquin Basins. Deliveries to the Tulare basin decline 0.36 ft and 0.14 ft per year respectively, during the moderate and light drought scenarios, while the Sacramento Basin and Eastside regions experience comparatively small changes in surface diversions during such droughts. Sacramento Basin diversions decline 0.22 ft per year in the severe drought, but only change by a slight amount (0.04 to 0.07 ft/y for the other two drought scenarios. Eastside diversions are virtually the same during all drought scenarios.

Groundwater Pumping

Farmers in the Central Valley increase groundwater pumping during drought periods to make up for the decline in surface water deliveries. To maintain irrigation levels in the entire Central Valley, groundwater pumping is increased by 74% in the severe drought, 51% in the moderate drought, and 27% in the light drought scenario. Groundwater pumping during droughts more than offsets declines in surface diversions. In most regions, groundwater pumping increases by 0.05 and 0.15 af/a/y more than irrigation diversions go down.

Stream-To-Aquifer Flows

In normal years, the San Joaquin and Sacramento rivers are gaining rivers, and this groundwater source decreases during droughts, reducing recharge and increasing withdrawals. During the severe drought scenario, groundwater flows to the San Joaquin River are reversed with the aquifer drawing water from the river, while for moderate and light droughts, diminished water flows from the aquifer (Table 1). For normal years the Eastside and Tulare streams are "losing streams, but in drought years stream-to-aquifer flows diminish due to loss of stream-to-aquifer connectivity. Sacramento and San Joaquin stream-to-aquifer flows are larger than Eastside and Tulare flows, and tend to dominate the Central Valley averages helping maintain drought groundwater levels as a source of natural recharge.

Aquifer Recharge

In a normal year recharge to the Central Valley aquifers are recharged with excess from surface irrigation deliveries and rainwater percolation exceeds groundwater withdrawals. In the base period for example, the Central Valley groundwater recharge is 0.76 af/a/y compared to groundwater pumping of 0.49 af/a/y. Excess groundwater storage derived from recharge in normal years helps to maintain

Table 1. Impact of drought on stream to aquifer flows

	Base Period af/a/y	Severe drought Impact af/a/y	Moderate drought Impact af/a/y	Light drought impact af/a/y
Sacramento	-0.44	0.14	0.01	-0.07
Eastside	0.13	-0.06	-0.06	-0.05
San Joaquin	-0.17	0.21	0.06	0.02
Tulare	0.08	-0.02	0.03	0.01
Central Valley	-0.18	0.07	0.02	-0.02
Change (%)		-38%	-10%	13%

groundwater storage levels during droughts when there is a dramatic decline in recharge. Average recharge across the Central Valley drops 12%, during the light drought scenario, to as much as 41%, during thesevere drought scenario. Across regions, recharge varies inproportion to changes in surface deliveries and rainfall. In the severe drought scenario for example, the Sacramento, San Joaquin and Tulare regions register large declines in aquifer recharge and experience large declines in surface deliveries and register large declines in aquifer recharge. The Sacramento and Eastside regions also experience the largest decline in rainfall totals during droughts. This variation in rainfall helps to explain the regional variation in recharge not explained by regional differences in surface deliveries.

Changes In Aquifer Storage

Change in aquifer storage over time is the sum of aquifer withdrawals, including groundwater pumping, minus the aquifer inflows, including stream inflows and irrigation recharge. Changes in boundary flows have an additional, but very minor, impact on storage levels. During the base period (a mix of normal and above normal rainfall years), Central Valley storage increases by 0.16 af/a/y. During the drought scenarios, Central Valley aquifer storage declines by 0.28 af/a/y in the light drought scenario to 0.60 af/a/y in the severe drought scenario.

Groundwater Levels

Central Valley groundwater levels adjust to changes in storage, rising during the base period and falling during the drought scenarios. During the base period, Central Valley groundwater levels rise 0.98 af/a/y, with the Sacramento and San Joaquin Basins increasing by 1.52 af/a/y and 1.07 af/a/y, respectively, and the Tulare Basin increasing by only 0.11 af/a/y. The Central Valley groundwater levels decline 1.81 af/a/y and 3.79 af/a/y, respectively, during the light and severe drought scenarios, with substantial variation by region. The changes in groundwater levels closely match changes in storage levels. Groundwater levels at the end of the severe drought drop 169 ft and levels at the end of the moderate drought fall 143 ft. Levels at the end of the light drought decline 50 ft. During the base period, groundwater levels rise 6.25 ft for every additional 1 ft of storage added to the groundwater. During the drought periods, groundwater levels decline slightly more than 6.25 ft per storage ft on average.

Groundwater Decline And Recovery

At the end the drought scenarios, groundwater levels across the Central Valley generally decline by less than 200 ft (Table 1). At the end of the severe 60-year drought scenario, Central Valley groundwater levels drop an average of 169 ft, groundwater levels fall 144 ft at the end of the moderate drought, and 50 ft at the end of the light drought. Groundwater levels in the San Joaquin and Tulare Basins drop more than the other basins due primarily to the compensating increase in pumping for these regions. The Tulare basin experiences the largest decline, ranging from 92 ft in the light drought scenario to 289 ft in the severe drought scenario (Table 2).

The model runs include a 30-year recovery period indicating how aquifers in the Central Valley respond to a return to normal rainfall and irrigation conditions. The average Central Valley groundwater

Table 2. Groundwater drought decline and recovery.

	End Severe 60 year drought (feet)	Recovery (feet)	Recovery (%)	Moderate 30 year drought (feet)	Recovery (feet)	Recovery (%)	Light 60 year drought (feet)	Recovery (feet)	Recovery (%)
Sacramento	-34	25	74%	-27	13	48%	-7	9	129%
Eastside	-76	27	35%	-69	15	22%	-44	17	39%
San Joaquin	-209	78	37%	-157	61	38%	-46	39	85%
Tulare	-289	25	9%	-256	32	12%	-92	14	15%
All	-169	35	20%	-144	29	20%	-50	17	34%

level recovers 20% of the pre-drought levels after the severe and moderate droughts, and 34% of pre-drought levels after the light drought during this recovery period (Fig. 2). In general, groundwater levels recover most rapidly in the San Joaquin Basin, and less rapidly in the Tulare Basin and Eastside region. The recovery rates suggest that the TulareBasin would not achieve pre-drought groundwater levels for a very long period of time, if ever. Other regions experience more rapid rates of groundwater recovery. These regions would likely achieve pre-drought groundwater levels relatively rapidly after a drought.

Stream to groundwater flow, water table height, and groundwater volumetric storage change in response to drought scenarios are dynamically interrelated, along with the change in pumping under the fixed 1973-2003 set of demands, land use, and population. Here we discuss the drought responses for four major hydrologic regions: Sacramento, Eastside, San Joaquin, and Tulare, and for the entire Central Valley, with a detailed focus on three drought scenarios, the 30-year moderate drought, the 60-year light drought, and the 60-year severe drought.

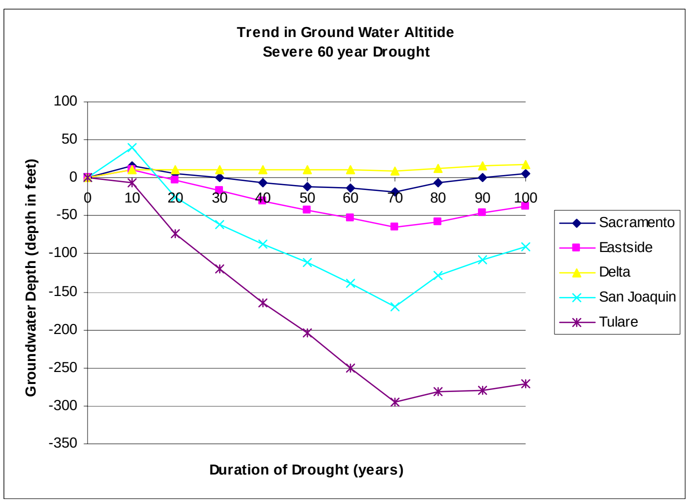

Figure 2. Groundwater trends during spin-up (10 years), drought (60 years), and recovery (30 years) for a prescribed 60-year severe drought.

Conclusions

Global warming and long-term drought is likely to deplete aquifers, increase electricity demand (cooling and pumping) and decrease hydropower generation. This study is intended to illustrate the impacts of climatic events on water storage and suggest water management techniques to counter some of these adverse impacts. C2VSIM and all water allocation models are only partially verified, and many empirical parameters are included. Total groundwater pumping is not known and groundwater processes lack sufficient physical descriptions. Pumping is based on a limited available demand record. Demand is fixed and agriculture does not shift with change in supply.

Acknowledgements

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