MODFLOW Simulation of Transient Surface Water/Groundwater Interactions in a Shallow Riparian Zone Using HEC-2-Based Water Surface Profiles

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ABSTRACT

Interest in habitat restoration along riparian corridors has heightened the need to quantify the relationship between surface and groundwater conditions. Particularly in lower flow conditions, understanding the transient nature of river seepage losses and groundwater accretions/depletions is critical to assessing the surface and subsurface riparian environment. This paper describes an application of MODFLOW for simulating the effects of changes in surface water flow on groundwater elevations along the San Joaquin River from the Friant Dam to the Merced River. Transient river boundary conditions in this application are developed from HEC-2 model generated water surface profiles. River boundary conditions are identified corresponding to a wide range of river discharge profiles. Calibration is initiated using available data; however, a rigorous calibration requires additional flow and water-level data focused on dynamic exchange processes occurring in the near-river zone. The model is used to illustrate the sensitivity of river seepage rates and groundwater elevations to present and antecedent river discharge profiles and to regional groundwater conditions. Sensitivity results illustrate the dynamic and transient nature of surface water/groundwater interactions.

INTRODUCTION

Storage and diversion of supplies for various uses in the San Joaquin River basin have decreased the flows of the San Joaquin River over the past century. Entities pursuing river and habitat restoration desired a tool for assessing the mechanism of river losses/gains and groundwater conditions under various flow regimes. Groundwater flow models were developed to simulate the impacts of changes in river operations on the shallow groundwater environment along the San Joaquin River, from Friant Dam to the confluence with the Merced River (Figure 1).

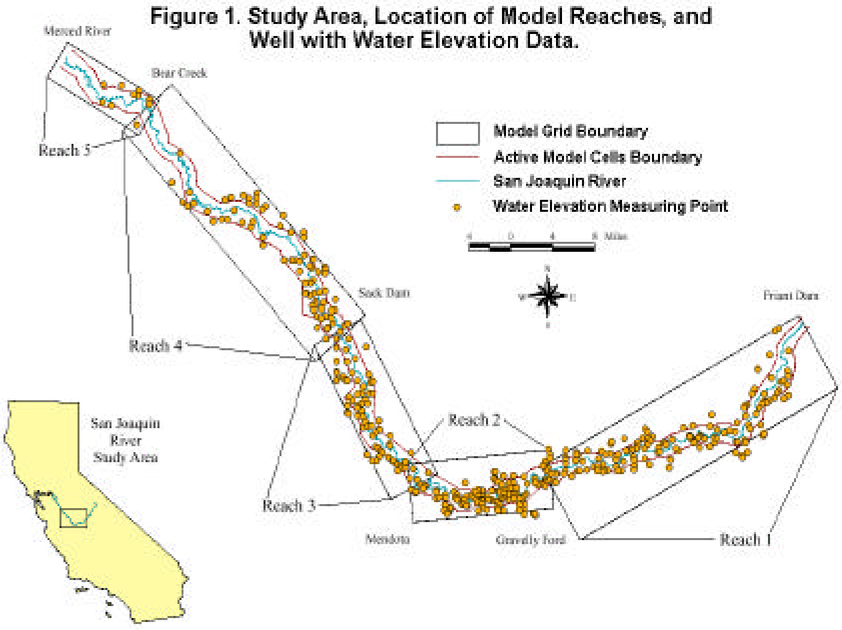


Figure 1. Study Area, Location of Model Reaches, and Well with Water Elevation Data.

The riparian groundwater models incorporate river conditions using existing HEC-2 surface-water models (COE, 1990). 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.

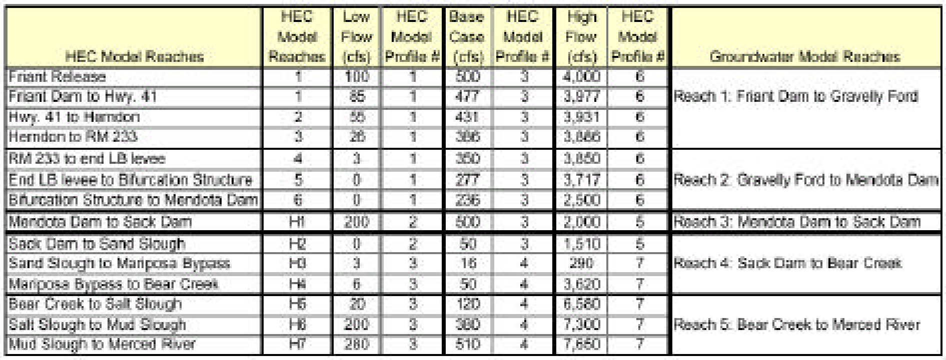
MODEL DEVELOPMENT

Model development involved the characterization of river conditions, soil texture, water table elevations, evapotranspiration; and, assembly into a model grid with fine resolution.

River Conditions

Output from existing HEC-2 surface-water models (1-D step backwater model for open channel flow) of the 150-mile stretch of the San Joaquin River (Mussetter Eng., Inc., 2000a, 2000b) were used to develop MODFLOW river conditions. The output of these models that are used to develop input to the groundwater model are 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 selected to represent low, mid-range and high flow conditions for initial model development and sensitivity analysis purposes. For each of these flow profiles, an input file for the MODFLOW River Package identifying inundated cells and the corresponding stage was prepared. Flow profiles for the low, mid-range and high condition are shown in Table 1 (S. S. Papadopulos & Associates, Inc, 2000).

Table 1. River Flow Conditions for Alternate MODFLOW River Package Specifications.



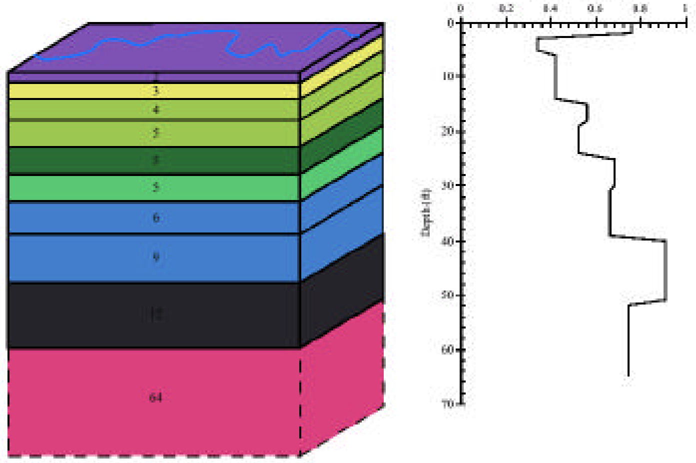
HEC Model Reaches	HEC Model Reaches	Low Flow (cfs)	HEC Model Profile #	Base Case (cfs)	HEC Model Profile #	High Flow (cfs)	HEC Model Profile #	Groundwater Model Reaches
Friant Release	1	100	1	500	3	4,000	6	Reach 1: Friant Dam to Gravelly Ford
Friant Dam to Hwy. 41	1	85	1	477	3	3,977	6	
Hwy. 41 to Herndon	2	55	1	431	3	3,931	6	
Herndon to RM 233	3	26	1	396	3	3,866	6	
RM 233 to end LB levee	4	3	1	350	3	3,850	6	Reach 2: Gravelly Ford to Mendota Dam
End LB levee to Bifurcation Structure	5	0	1	277	3	3,717	6	
Bifurcation Structure to Mendota Dam	6	0	1	236	3	2,500	6	
Mendota Dam to Sack Dam	H1	200	2	500	3	2,000	5	Reach 3: Mendota Dam to Sack Dam
Sack Dam to Sand Slough	H2	0	2	50	3	1,510	5	Reach 4: Sack Dam to Bear Creek
Sand Slough to Mariposa Bypass	H3	3	3	16	4	290	7	
Mariposa Bypass to Bear Creek	H4	6	3	50	4	3,620	7	
Bear Creek to Salt Slough	H5	20	3	120	4	6,580	7	Reach 5: Bear Creek to Merced River
Salt Slough to Mud Slough	H6	200	3	380	4	7,300	7	
Mud Slough to Merced River	H7	280	3	510	4	7,650	7	

All measurements indicated are mid-reach, with the exception of the Friant Release, which was measured from the start of Reach 1.

Soil Texture

Geologic logs from over 300 wells drilled in the upper 100 feet of the aquifer have been evaluated to obtain an idealized representation of the nature of the floodplain deposits (Figure 1). A soil texture analysis was conducted for multiple spatial units to develop representative conditions. This process involved labeling texture as coarse or fine, and assigning a numeric indicator to these divisions to develop composite soil texture indices for a vertical profile. Figure 2 is the soil texture profile for reach 2 based on 50 well logs (Johnson, Nicholas M., 2000, personal communication). Initial assignment of hydraulic conductivity values to the idealized soil texture representation was conducted following a review of the literature with regard to aquifer parameters within the aquifer of the San Joaquin Valley and studies relating soil texture to hydraulic conductivity. Parameters were adjusted during calibration for reaches where suitable data were available (discussed below). The resulting parameters identified for the Reach 2 model are shown on Table 2. Vertical hydraulic conductivity was based on an assumed vertical to horizontal anisotropy ratio of 1:10. This assumed value can be evaluated for reasonableness following collection of water level data from nested piezometers during pilot or other transient flow events. Groundwater storage was assigned to the model water table layers within the range of 0.1 to 0.3, for fine

Figure 2. Soil texture profile of reach 2.

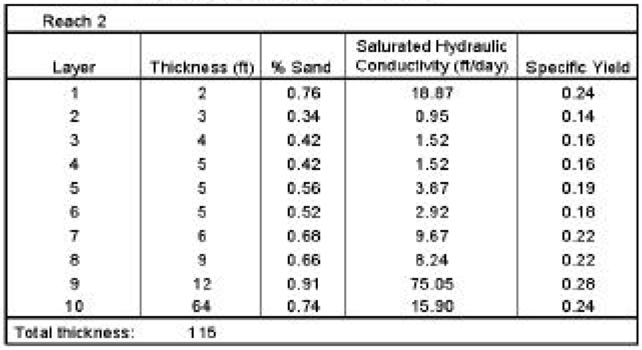


to coarse-grained sediments, respectively. Soil moisture accounting is incorporated as an option into the MODFLOW analysis to represent soil moisture storage and depletion above the active water table. Parameters required for the vadose zone option were developed using the soil texture analysis of lithologic logs (Blum, Israel, and Larson, 2001).

Groundwater Elevation

Groundwater elevation data were obtained from the California Department of Water Resources, the City of Fresno, the U.S. Bureau of Reclamation and several irrigation districts. Groundwater conditions vary greatly along the 150-mile stretch of the San Joaquin River. In the upper part of the reach, the river loses flow to the groundwater system as regional groundwater flow is generally away from the river and the riparian zone toward regional pumping centers. In the lower part of the reach, groundwater discharges into the river in part because the regional water table on the west side of the river has increased as the result of irrigated agriculture.

Table 2. Model Layer Thickness and Initial Hydraulic Parameters for Reach 2 Model.



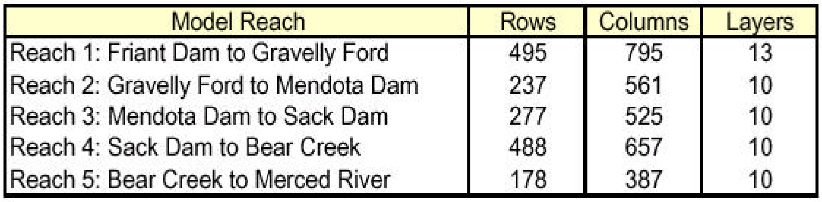
Reach 2				
Layer	Thickness (ft)	% Sand	Saturated Hydraulic Conductivity (ft/day)	Specific Yield
1	2	0.76	18.87	0.24
2	3	0.34	0.95	0.14
3	4	0.42	1.52	0.16
4	5	0.42	1.52	0.16
5	5	0.56	3.67	0.19
6	5	0.52	2.92	0.18
7	6	0.68	9.67	0.22
8	9	0.66	8.24	0.22
9	12	0.91	75.05	0.28
10	64	0.74	15.90	0.24
Total thickness:	115			

A *Base Case* characterization of regional groundwater conditions was developed and translated to boundary conditions for the riparian zone model using groundwater level data from the spring of 1996. Examination of groundwater hydrographs in all model reaches indicates that this period adequately represents near-average groundwater conditions, for the present state of development, water demand, and land use. These conditions may be contrasted with conditions in 1993, which represent low groundwater conditions, or 1997, which represent high groundwater conditions. Hypothetical high and low water level boundary conditions have been identified for purposes of demonstrating model sensitivity to alternate water level conditions, by adjustment of the Base Case conditions by amounts approximating the changes observed in these years. The hypothetical high and low boundary conditions are set 20 feet above and below the base case boundary condition, respectively, in reaches 1 and 2; and, at 10 feet above and below the base case condition, respectively, for reaches 3, 4 and 5.

Model Structure

MODFLOW (Harbaugh and McDonald, 1996) is 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. Five submodels are defined in this study. The finite difference grid for each submodel contains up to a maximum of 495 rows, 795 columns and 13 layers, as shown on Table 3.

Table 3. Number of Model Rows, Columns, and Layers for Modeled Reaches.

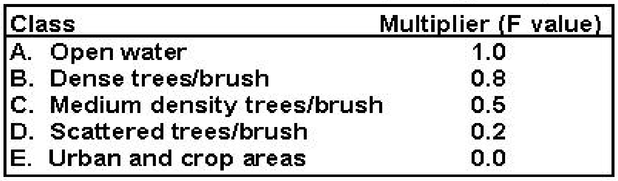


Model Reach	Rows	Columns	Layers
Reach 1: Friant Dam to Gravelly Ford	495	795	13
Reach 2: Gravelly Ford to Mendota Dam	237	561	10
Reach 3: Mendota Dam to Sack Dam	277	525	10
Reach 4: Sack Dam to Bear Creek	488	657	10
Reach 5: Bear Creek to Merced River	178	387	10

Within this framework, active cells are designated within about ½ mile on either side of the river. Grid spacing along the river averages about 300 feet; grid spacing perpendicular to the river is set at 50 feet. Layer thickness ranges between 2 and 65 feet. Typically, beyond the extent of the river under high flow conditions, there is little opportunity for model cells in upper layers to be saturated. In these areas, the lower model layers represent groundwater conditions. The fine-mesh spacing allows accurate representation of the stream geometry, changes in stream geometry with river stage, and the lateral position of the stream within the riparian zone.

Evapotranspiration

Table 4. ET Classes and the Corresponding Multiplier.



Class	Multiplier (F value)
A. Open water	1.0
B. Dense trees/brush	0.8
C. Medium density trees/brush	0.5
D. Scattered trees/brush	0.2
E. Urban and crop areas	0.0

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 (Groeneveld, David. P. 2000, personal communication). Evaporation classes and the corresponding class multiplier are listed in Table 4. A seasonal model reflecting maximum evapotranspiration, to which the multipliers listed above 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, with a seasonal high of 8.75 feet. The MODFLOW ET package is employed using an array of evapotranspiration potential rates, as described above, and an extinction depth of ten feet. An alternate approach for ET handling is included in the vadose option (Blum, Israel , and Larson, 2001).

MODEL CALIBRATION

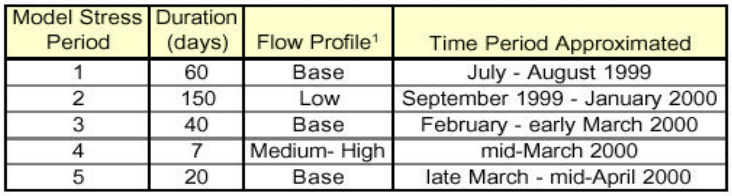
Ideally, all sub-models would be calibrated to steady-state and transient conditions. For calibration purposes, data needs would include detailed groundwater elevation data spanning a multiple year period, and associated flow and pumping records for the surrounding region. For most sub-models, sufficient data in the near-river zone were unavailable to conduct a rigorous calibration. For Reach 2, some data were available and calibration efforts were conducted as described below. For the remaining reaches, steady-state groundwater elevations, assuming Base Case conditions, were simulated and compared to existing conditions. While not serving calibration purposes, these simulations showed that the model representations were not unreasonable.

Steady-State Calibration – Reach 2

The steady-state calibration for this reach employed Base Case conditions, including: 1) river flow at 20 – 30% exceedence frequency; 2) regional boundary conditions set at "mid-range" levels, based on present development condition; 3) hydraulic parameters as described above; and, 4) ET rates set at a constant value for each class, representing the average annual potential rate for the class. Groundwater elevations resulting from this simulation compared reasonably well to those represented in the record. However, simulated reach losses were unreasonably low for this reach. A transient calibration was then employed (described below) to provide improvement in parameter estimation, resulting in multiplying the initial hydraulic conductivity distribution by a factor of 4. Using this distribution, the steady-state simulation was repeated. Water level elevations remained reasonably consistent with observed conditions, and reach losses increased to a more realistic range.

Transient Calibration – Reach 2

Table 5. Reach 2 Transient Model Flow Profiles Approximating Summer 1999 to Spring 2000 Flow Conditions.



Model Stress Period	Duration (days)	Flow Profile[1]	Time Period Approximated
1	60	Base	July - August 1999
2	150	Low	September 1999 - January 2000
3	40	Base	February - early March 2000
4	7	Medium- High	mid-March 2000
5	20	Base	late March - mid-April 2000

[1] Low and Base flow profiles were derived as described on Table 3. The Medium-High profile represents an average flow of about 1700 cfs, and is based on MEI Profile # 5.

Water level and flow data recorded during a pilot release program conducted during the summer of 1999 and subsequent data collected in 2000 were used to evaluate the initial model parameters for Reach 2. During and subsequent to the pilot release program, water level data were collected from piezometers located along several river cross sections under varying flow regimes (cooperative program conducted by the U.S. Bureau of Reclamation and the Friant Water Users Association). These data were used in the transient calibration for the Reach 2 sub-model. Table 5 identifies the time periods and flow profiles selected to approximate the flow events from July 1999 to April 2000. Regional groundwater boundary conditions were specified at Base Case elevations.

Figure 3. Comparison of Simulated to Observed Water Levels Near MP220 in Model Reach 2 Under Transient River Flow Conditions, July 1999 to April 2000.

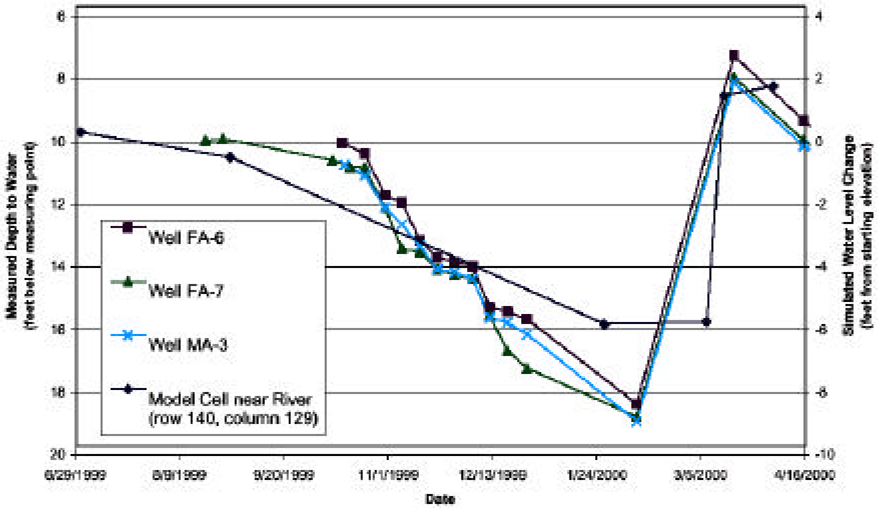


Figure 3 provides a comparison of the water-level changes observed in alluvial wells at one of the monitored river sections and the model simulated water-level changes. Results indicate that the model reasonably simulates the transient water-level changes observed near the river in the area of these wells. Similar data from nested piezometers is needed to address the hydraulic communication through the vertical profile and should be obtained prior to fine-tuning the hydraulic conductivity distribution. Additionally, flow monitoring under a range of flow conditions is recommended, to provide control on the model-calculated river losses. Finally, a transect of wells spanning a greater width across the model area would be helpful in constraining the calibration process.

SENSITIVITY OF RIPARIAN ZONE CONDITIONS TO REGIONAL GROUNDWATER LEVELS AND RIVER OPERATIONS

A series of model simulations was conducted to evaluate the sensitivity of riparian zone conditions to regional groundwater levels and to river operations. For these simulations, three conditions were defined for the regional boundary condition and for the river condition, each representing a low, mid, 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.

Sensitivity to River Flow Conditions

Steady-state simulation of riparian groundwater conditions resulting from different river operations was conducted for flows at the 5%, 20 – 30% and 60% exceedence levels, while holding groundwater boundary conditions at the Base Case level. For all reaches, the 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.

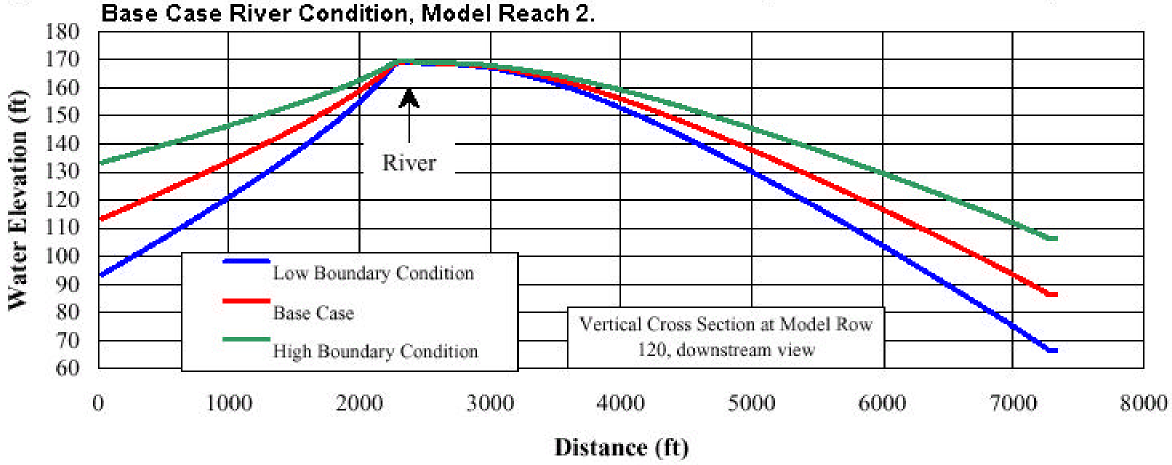
Sensitivity to Antecedent River Conditions

Hypothetical transient runs similar to the calibration run were structured to evaluate the effect of antecedent river flow conditions on simulated seepage rates in Reach 2. For these runs, the nine-month 1999-2000 flow sequence (Table 5) was preceded by a year of “low” flow in one case, and by a year of “mid-range” flows in a second case. At the end of the simulation (both simulations had identical transient flow conditions for the last nine months), the seepage rate for the case with low flow antecedent conditions was higher, by a factor of ten, than the case preceded by a year at mid-range flow conditions. The sensitivity of seepage to antecedent conditions is expected to be variable, depending on the reach lithology and other conditions. This example is provided only to illustrate that antecedent conditions should not be discounted, as they may exert significant influence on surface water/groundwater interactions.

Sensitivity to Regional Groundwater Conditions

Steady-state simulation of riparian groundwater conditions was conducted for low, mid or high regional groundwater boundary conditions, as identified from hydrographs of groups of wells in each sub-model region. The difference in head assumed for the boundary condition ranged from 10 to 20 feet plus or minus the base case, depending on the reach. Examination of steady-state water levels under base case river flow conditions indicates that riparian zone water levels are impacted by the regional boundary condition, although not dramatically near the river. Seepage rates are influenced typically by less than a factor of two over this range of fluctuation for these simulated conditions. Figure 4 is the water-level profile across vertical section at model grid row 120. In some model reaches, similar profiles indicate that a change in the regional boundary 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.

Figure 4. Effect of Change in Regional Groundwater Condition on Riparian Zone Water Levels, with Base Case River Condition, Model Reach 2.



APPLICATION OF MODEL FOR RIPARIAN WATER MANAGEMENT

The groundwater models developed in this study 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 this model to evaluate alternatives are to identify the hydrologic conditions associated with the alternative (regional water level boundary conditions and river flows) and land use conditions (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, in order to achieve reasonable convergence of assumed surface-water model losses to calculated groundwater losses. The results obtained from this process can be used by decision-makers to understand how changes in river operations or regional groundwater conditions affect groundwater conditions in the riparian zone; and, to evaluate groundwater conditions associated with proposed riparian or habitat restoration options.

At present, additional model calibration is needed in several model reaches for which suitable data were unavailable. However, the range of conditions that may result under proposed restoration scenarios can be identified with these models "as-is", using a range of multipliers for initial parameter arrays, as in a sensitivity analysis. Alternatively, uncertainty in the models can be significantly reduced through collection of additional data to support the calibration effort, including:

- Lithologic characterization of the upper 50 feet of aquifer in the near-river zone, to assess presence of fine-grained units that could function as perching beds or maintain soil moisture following managed release events;
- Hydraulic characterization of water table gradients to or from the river, to support refinement of surface-water/aquifer relationships;
- Vertical and horizontal conductivity assessment, to support characterization of the aquifer response to managed release events;
- Seepage runs, to quantify river losses or gains under constant flow conditions and known hydrologic regimes;
- Assessment of hydrologic-riparian plant associations, to support additional inference and calibration between instrumented cross-sections; and to support assignment of evaporative functions to the predictive model;
- Installation of nested piezometers at several locations close to the river. Particularly in sub-reaches critical to specific alternatives analyses, to provide additional information concerning the river-aquifer connection and vertical hydraulic conductivity.

Regardless of the need for additional calibration, several "take-home" lessons emerge from the analysis with relevance for decision-makers:

- River gains and losses are transient processes – seepage rates will vary depending on groundwater conditions, flow rates and antecedent conditions;
- Pumping in surrounding areas impacts the boundary condition to the riparian zone – and consequently, has the potential to impact river seepage rates and riparian groundwater conditions;
- Hydrologic conditions in the riparian zone occur at the interface between the surface water, groundwater, atmospheric, and biological domains – accurate assessment of conditions in the riparian zone requires consideration of dynamic exchanges between these four domains.

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