Managing Surface Water-Groundwater to Restore Fall Flows in the Cosumnes River

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Abstract: Declining fall flows are limiting the ability of the Cosumnes River to support large fall runs of Chinook salmon. Management scenarios linking surface water and groundwater alternatives to provide sufficient fall flows are examined using groundwater flow and channel routing models. Results show that groundwater overdraft in the basin has converted the river to a predominantly losing stream, practically eliminating base flows. Management alternatives to increase net recharge (for example, pumping reductions) were examined along with surface water augmentation options. Using a minimum depth standard for fish passage, average surface water flow deficits were computed for the migration period of Chinook salmon. Groundwater deficits were evaluated by comparing simulated current groundwater conditions with conditions under various scenarios. Increases in net recharge on the order of 200 to 300 million m^3/year would be required to reconnect the regional aquifer with the channel and in turn reestablish perennial base flows. Options that combine surface water augmentation with groundwater management are most likely to ensure sufficient river flows in the short term and to support long-term restoration of regional groundwater levels.

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Introduction

The Cosumnes River in Sacramento County, California, has historically supported a large fall run of Chinook salmon (the word ‘‘Cosumnes’’ derives from the Miwok word for salmon). An early study by the California Department of Fish and Game (CDFG) [1957, cited in USFWS (1995)], estimated that the river could support up to 17,000 returning salmon under suitable flow conditions. Over the past 40 years fall runs ranged from 0 to 5,000 fish according to fish counts by the CDFG (USFWS 1995). In recent years, estimated fall runs have consistently been below 600 fish (Keith Whitener, researcher, Nature Conservancy of California, personal communication). Declines in fall flows have been identified as a major inhibitor of successful Chinook salmon spawning in the Cosumnes (TNC 1997) and in other California rivers (Drake et al. 2000). Fall flows in the Cosumnes have been so low in recent years that the entire lower river has frequently been completely dry throughout most of the salmon migration period (October to December). Previous investigations of stream-aquifer interactions along the lower Cosumnes River (river-km 0–58) suggest that loss of base flow support as a result of groundwater overdraft is at least partly responsible for the decline in fall flows (Fleckenstein et al. 2001). Increased groundwater withdrawals in the Sacramento basin since the 1950s have substantially lowered groundwater levels throughout the county. Major cones of depression in the water table have formed north and south of the Cosumnes River with groundwater levels as low as 24 m below mean sea level at their center. Management strategies that address existing groundwater and surface water deficits are needed to promote Chinook salmon fall runs. This study quantifies these deficits by means of numerical simulations of groundwater and surface water flow, investigates potential remedies for extended low flow conditions in the Cosumnes River, and identifies, additional analysis needs.

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Related Work on Groundwater–Surface-Water Interactions

Although early work in hydrology emphasized the linkages between surface water and groundwater (Theis 1941; Rorabaugh 1964), water managers have long looked at groundwater and surface water as two separate entities. With increasing development of land and water resources, however, the understanding that development of either of these resources will affect the quantity and quality of the other has gained importance (Winter et al. 1999). This understanding has resulted in a large body of literature on groundwater-surface water interactions and their ecological, economic, and legal implications. Comprehensive reviews of that literature are given by Winter (1995), Woessner (2000), and Sophocleous (2002), Bouwer and Maddock (1997) outline some of the legal ramifications of groundwater-surface water interactions; Glennon (2002) describes a series of case studies where groundwater use has negatively affected surface water; and theoretical considerations of river-aquifer interactions and their mathematical formulation are discussed in Kaleris (1998) and Rushton and Tomlinson (1979).

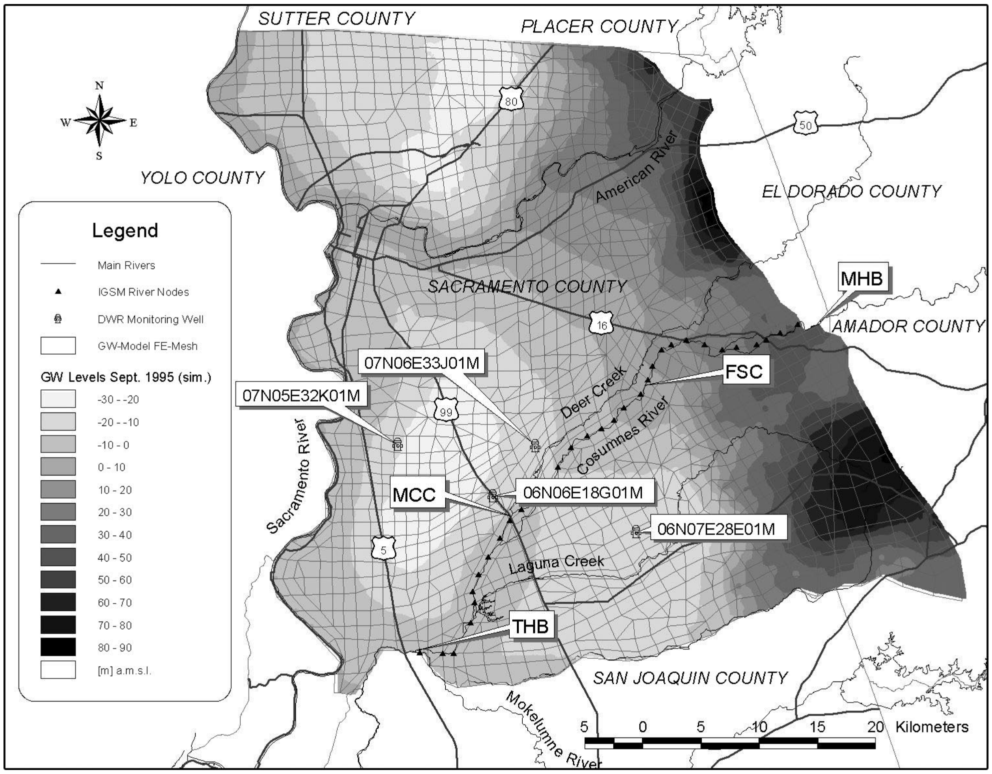

Fig. 1. Location map and groundwater model mesh (THB=Thornton Bridge, MCC=McConnell, FSC=Folsom South Canal, MHB=Michigan Bar)

Groundwater discharge to streams, or base flow, often constitutes the major source of stream flow during dry periods. During these periods groundwater use is usually highest and minimum flow requirements can be violated if base flows are reduced. Kondolf et al. (1987) described the impacts of groundwater pumping on stream flows in a case study of the Carmel River in California. Groundwater withdrawal locally decreased or even eliminated base flows and inhibited steelhead migration. Quantity and timing of base flows were identified as very important for fish migration. Along the Mojave River in California, increasing groundwater pumping has caused seasonal and long-term stream flow depletion (Lines 1996). Chen and Soulsby (1997) used a numerical model to assess impacts of proposed groundwater development on stream flow in a nearby stream that was important for salmonids. In their study changes in stream stage caused by the proposed development were small and were found to have only minimal impacts on fish habitat. Ramireddygari et al. (2000) used a numerical groundwater and surface water model to investigate the effects of irrigation practices and stream diversions on river flows and water levels in an environmentally important wetland in Kansas. They found that stream flows were most sensitive to changes in groundwater pumping for irrigation. Under increasing pressure to meet water demands and yet comply with environmental standards, numerical models that include stream-aquifer interactions have become indispensable tools for water management in many parts of the world (Pelka and Horst 1989; Pucci and Pope 1995; Nobi and Das Gupta 1997; Perkins and Sophocleous 1999; Sophocleous and Perkins 2000).

Cosumnes River Watershed

The Cosumnes River is located on the western side of the Sierra Nevada in Amador, El Dorado, and Sacramento counties, California (Fig. 1). The basin covers an area of approximately 3,300 km^2 and ranges in elevation from 2,400 m at the headwaters to near sea level at its outlet in the Sacramento/San Joaquin Delta. In the upper basin the Cosumnes River consists of three forks, which join near Michigan Bar (MHB). From MHB the river extends another 58 km before it flows into the Mokelumne River (Fig. 1). The only reservoir on the Cosumnes River is a small irrigation reservoir (Sly Park) in the upper basin. Weather conditions are characterized by a mediterranean-type climate with strong seasonality in rainfall. About 75% of the annual precipitation occurs between November and March (PWA 1997). Flows in the Cosumnes River range from no flow in late summer and fall during dry to moderate years to a peak flow of 2,650 m^3/s passing MHB during the 1997 flood.

In the alluvial lower basin (downstream of MHB) the river flows through the groundwater-bearing sedimentary deposits of the Central Valley of California. Current groundwater conditions in this part of the basin are characterized by two major cones of depression in the water table to the north and south of the river (Fig. 1). These cones have formed over the last six decades as a result of intensive pumping of groundwater for agricultural and municipal use (MW 1993a). Isotopic composition of groundwater and surface water in southern Sacramento County indicates that the Cosumnes River recharges groundwater (Criss and Davisson 1996).

The annual fall run of Chinook salmon on the Cosumnes River occurs from early October through late December, with a peak in November. A moderate historical run ranges from 0 to 5,000 fish, while the basin has been estimated to have a capacity to handle runs of up to 17,000 fish (USFWS 1995; TNC 1997). During 1997–2001 Chinook salmon runs of 100 to 580 fish have been estimated based on carcass counts (Keith Whitener, personal communication). Field analyses indicate the need for a minimum river stage of 18 cm to allow fish migration to the spawning habitat around and just downstream of MHB (Keith Whitener, personal communication). Based on rating tables from the McConnell gauge (MCC), this water depth corresponds to a flow of approximately 0.57 m^3/s at MCC. This threshold flow will subsequently be referred to as the minimum flow requirement at MCC.

Methods

Two methods were used to investigate declines in fall flows on the Cosumnes River. First, river flows and groundwater levels in the basin from historical records and recent groundwater monitoring were analyzed to quantify linkages between groundwater conditions and river flows. In a second step, numerical models of groundwater and surface water flow were used to describe the hydrologic conditions in the lower Cosumnes basin and to simulate stream-aquifer interactions and channel flows under current and scenario conditions. Scenario simulations explored management strategies to sustain fall river flows and promote Chinook salmon fall runs. Two numerical models were used: a one-dimensional (1D) channel routing model that incorporates vertical seepage and a quasi three-dimensional (3D) finite-element regional groundwater flow code that also simulates stream-aquifer interactions and mean monthly river flows. The 1D routing model was used to estimate a target flow at MHB that would be required to maintain the minimum flow requirement at MCC under current conditions. The 3D regional groundwater model was employed to quantify annual amounts of groundwater required to establish base flows to the river and meet minimum flow requirements for salmon migration. Various management options for restoration of fall flows were evaluated by means of scenario simulations.

Analysis of Stream Flows and Groundwater Levels

Mean daily flow data from a gauge at MHB, where the river enters its alluvial lower basin, and from the MCC gauge about 40 km downstream of MHB were used. At MCC flows were only recorded between 1941 and 1981; the MHB record extends from 1908 to the present. These data constitute the only flow record for the lower basin. Changes in fall flows in the alluvial lower basin were assessed by determining the frequency of days at MCC with flows below the minimum flow requirement during October and November over the 1941–1981 record. Changes in the relative frequency of these days between MCC and MHB were quantified by calculating the difference in the number of days for which flows were below the threshold. Seasonal groundwater-level readings from a set of monitoring wells in Sacramento County and weekly to monthly readings from a network of 33 municipal and agricultural wells in the vicinity of the river were analyzed for trends in groundwater levels.

Channel Routing Model

To calculate the target flow rate at MHB corresponding to the 18 cm depth requirement at MCC, the routine DIFWAVE (Anderson 1993) was employed, which solves the diffusion wave approximation to the momentum equation. Based on measured groundwater levels in the vicinity of the river it was inferred that the river is seepage dominated and does not receive significant groundwater discharge between MHB and MCC from October to December. To simulate seepage losses through the riverbed, a Green and Ampt infiltration routine was added to DIFWAVE. For a detailed description of the model, see Anderson et al. (2004). The channel flow model was calibrated to observed flows in the channel at MCC. Peak stage at the downstream node (MCC) and total volume were matched. Peak stage was matched to within 3 mm or 2%, and total volume was matched to within 2.5%. The Nash–Sutcliffe coefficient R^2 for the calibration run was 0.974 (Nash and Sutcliffe 1970). For the verification run, the total volume was overestimated by 5%. Peak stage was matched within 1%, although the timing of the peak flow in the numerical simulation was early by 5 h. The Nash Sutcliffe coefficient for the verification run was 0.777. Once the model was calibrated and verified, a target flow at MHB was estimated with DIFWAVE such that the downstream stage at MCC was greater than or equal to the 18 cm target depth. Comparing the target flow with historical flows at MHB, surface water deficits could be determined with respect to the minimum flow requirement at MCC in wet, dry, and average years for the fall months October to December.

Simulations of Regional Groundwater Flow

Numerical Groundwater Model

A groundwater model for Sacramento County (SCM), which had previously been calibrated to 1969–1990 groundwater levels and mean monthly stream flows (MW 1993a), was obtained from the Sacramento County Water Agency. The model is based on the numerical finite-element code IGSM (Integrated Groundwater Surface Water Model), Version 3.1 (MW 1993b). IGSM simulates quasi-3D groundwater flow in multiple aquifers that can be separated by aquitards. The SCM represents a system of three aquifers, which consist of the sedimentary deposits of the late Tertiary Mehrten and Quaternary Laguna and Riverbank formations. River flows in the model are calculated based on a monthly water balance over individual river reaches, including direct runoff and stream-aquifer interactions. Exchange between surface water and the upper aquifer per unit area of a river reach is calculated as the product of the hydraulic gradient and a conductance term, representing hydraulic connection between the river and the subsurface below the streambed. Recharge to the aquifer is calculated in the model as deep percolation based on a two-compartment model of the unsaturated zone representing a water balance in the root zone and deep vadose zone (MW 1993b). Flows below the root zone depend on land use and cropping patterns.

The geometry of the finite element mesh of the SCM was slightly modified to better represent the course of the Cosumnes River. Riverbed elevations in the Cosumnes River, as represented in the SCM, were found to be inaccurate and were adjusted based on a recent detailed survey of the river channel (Guay et al. 1998). The modified model was run for the 1969–1990 calibration period and another 5 years for corraboration (1990–1995). Simulated groundwater levels in the upper two aquifers over the entire 26-year simulation period were compared to observed groundwater levels at 43 wells throughout Sacramento County. Simulated groundwater levels were found to be in reasonable agreement with observed values (Fig. 2). Comparison of simulated mean monthly river flows at MCC with observed flows yielded a Nash-Sutcliffe R^2 of 0.984 (0.983 in the unmodified model). (Nash and Sutcliffe 1970).

During the course of this investigation an independent review of the IGSM source code (LaBolle et al. 2003) revealed limitations of the code in handling nonlinear groundwater surface water interactions. Errors in simulated heads and stream flows can occur in the case of direct hydraulic contact between the stream and aquifer in time steps over which stream flows or groundwater

Table 1. Groundwater Scenarios

Parameter/variable	Scenario 1 (baseline)	Scenario 2 (no pumping)	Scenario 3 (flow augmentation)	Scenario 4 (pumping reductions upstream)	Scenario 5 (pumping reductions downstream)	Scenario 6 (S3 combined with S4)
General						
Simulation period	15 years	15 years	15 years	15 years	15 years	15 years
Initial conditions	1995 September GW levels	1995 September GW levels	1995 September GW levels	1995 September GW levels	1995 September GW levels	1995 September GW levels
Static over years						
Land-use	1993 land-use survey	1993 land-use survey	1993 land-use survey	1993 land-use survey	1993 land-use survey	1993 land-use survey
GW pumpage (time variant within year)	1994 pump rates	No pumping in all 35 subregions of model	1994 pump rates	Pumping reduced by 205 million m^3 with emphasis on upstream reaches	Pumping reduced by 308 million m^3 with emphasis on downstream reaches	Pumping reduced by 205 million m^3 with emphasis on upstream reaches
SW diversions and Imports (time variant within year)	1994 diversions and imports	1994 diversions and imports	1994 diversions and imports plus 1.42 m^3/s flow augmentation from FSC from September to December	1994 diversions and imports	1994 diversions and imports	1994 diversions and imports plus 1.42 m^3/s flow augmentation from FSC from September to December
Water requirement (per year)	None	~703 million m^3	~15 million m^3	~205 million m^3	~308 million m^3	~220 million m^3
Time variant						
Stream/river inflows	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record
Precipitation input	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record	1980–1995 record
Boundary conditions	Provided by simultaneous model runs from bordering groundwater models (North American River and San Joaquin County models)	Provided by simultaneous modelruns from bordering groundwater models (North American River and San Joaquin County models)	Provided by simultaneous model runs from bordering groundwater models (North American River and San Joaquin County models)	Provided by simultaneous model runs from bordering groundwater models (North American River and San Joaquin County models)	Provided by simultaneous model runs from bordering groundwater models (North American River and San Joaquin County models)	Provided by simultaneous model runs from bordering groundwater models (North American River and San Joaquin County models)

Note: GW=ground water; SW=surface water; FSC=Folsom South Canal.

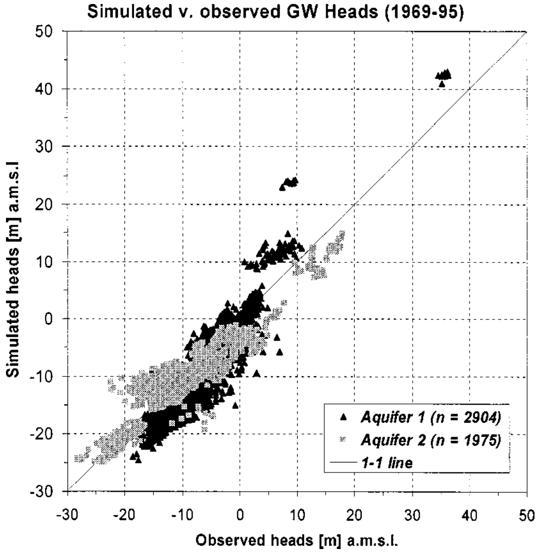

Fig. 2. Simulated versus observed head for aquifers 1 and 2 over calibration/validation period

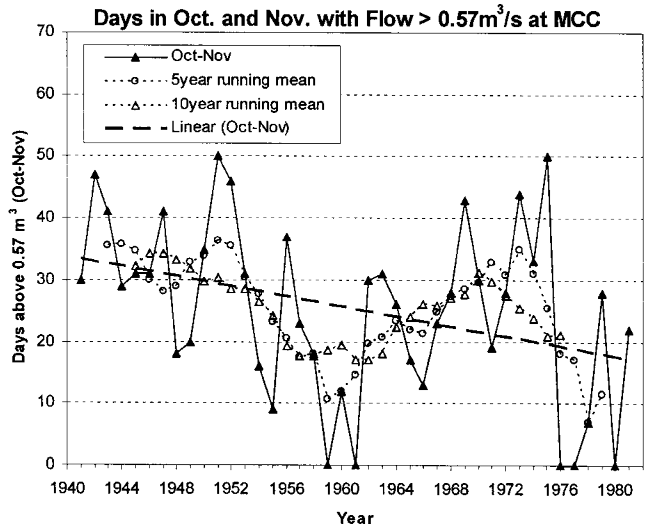

Fig. 3. Number of days in October and November with flows above 0.57 m^3/s at the McConnell gauge (MCC)

heads change significantly. In our simulations with the SCM such errors were only notable as small oscillations of groundwater heads at certain nodes below the river only during winter months in very wet years. During most years, and in the summer and fall months in particular, such errors were not encountered. This is due to the coarse spatial discretization and the monthly time step used in the regional model. Simulated heads and river flows represent monthly averaged values that do not account for short-term transients in groundwater levels and river flows. Therefore changes in groundwater heads between time steps are gradual, minimizing potential errors. Also, extended reaches of the river remain hydraulically disconnected from the aquifer throughout most simulations under which conditions seepage becomes a linear function of the river stage. Therefore it is believed that the limitations of IGSM do not significantly affect the results presented here.

Scenario Simulations

Six scenario simulations (S1 to S6) were run with the regional groundwater model (Table 1). To evaluate the level of disturbance of the current groundwater system relative to natural, undisturbed conditions, a baseline scenario (S1), in which recent land and water use conditions are held constant, and a ‘‘no-pumping’’ scenario (S2) representing natural, predevelopment groundwater conditions, were simulated. In scenarios S3 to S6 different management options were evaluated. The considered options fall into one of three categories: (1) flow augmentation with available surface water (S3); (2) increase of net recharge (represented as pumping reductions) to restore base flows (S4 and S5); and (3) a combination of (1) and (2) (S6). All simulations were run over a 15-year period with simulated September 1995 heads as initial conditions. Land use, groundwater pumping and surface water diversions were kept static from year to year to assess long-term impacts of fixed land and water use patterns. Rainfall and river inflows into the model domain for all simulations were taken from the 1980–1995 hydrologic record.

Baseline conditions (S1) were represented by the most recent available data for the SCM. Monthly data sets representing 1994 levels of surface water diversions and groundwater pumping and the 1993 land use survey were used. The no-pumping simulation (S2) is identical to the baseline simulation except that all groundwater pumping in the model domain was set to zero. In S3 river flows were augmented from September through December with a constant flow of 1.42 m^3/s from Folsom South Canal (FSC), a water delivery canal that crosses the Cosumnes River at river-km 37. In S4 and S5 groundwater pumping was reduced in the vicinity of the river downstream and upstream of MCC, respectively, to estimate how much the groundwater budget would have to change (increase in net recharge) to achieve greater connection between river and aquifer, thereby generating additional base flow. In S6, upstream pumping reductions from S4 and flow augmentation from S3 were combined.

Results and Discussion

Analysis of Historical Trends in River Flows and Groundwater Levels

From 1941 to 1981 the number of days in October and November with mean daily flows above the minimum flow requirement of 0.57 m^3/s at MCC steadily decreased from more than 30 days on average in the early 1940s to less than 20 in 1980 (Fig. 3). A comparison of daily flows at MCC with flows at the upstream gauge at MHB for the same time period shows that the frequency of occurrence of days with flows below the threshold have increased more rapidly at MCC than at MHB (Fig. 4). These results indicate that flow losses between MHB and MCC increased between 1941 and 1981. This trend coincides with a drastic decline in regional groundwater levels in the alluvial lower basin since the early 1940s (Fig. 5), suggesting that loss of base flow support in the lower basin is in fact a major reason for declining fall flows.

Recent groundwater level monitoring from wells within 1,000 m from the river channel indicate that the regional water table lies below most of the lower Cosumnes channel. In 2000 and 2001, depth to the regional water table from the river channel elevation ranged from 2 m in the Dillard Road area (river-km 44.2) to 16.7 m around Wilton Road (river-km 27.8). Data from downstream of Twin Cities Road suggest at least a seasonal connection between river and aquifer in the lowest reaches. Under these conditions

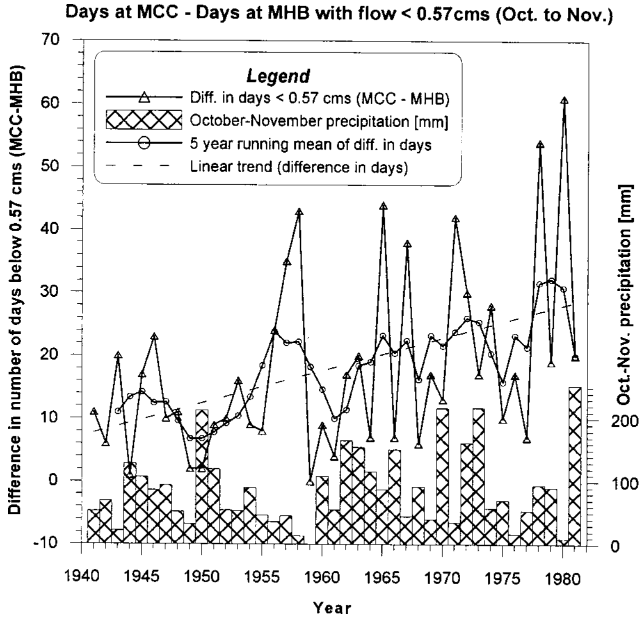

Fig. 4. Difference in number of days with flow below 0.57 m^3/s between McConnell gauge (MCC) and Michigan Bar (MHB) (October to November)

most of the lower river does not receive base flow contributions from the regional aquifer. To restore and sustain base flows or reduce seepage losses along the entire lower river, water tables would have to be raised by up to 17 m.

Current Surface Water Deficits (One-Dimensional Routing Model)

A target flow of 1.55 m^3/s at MHB was estimated as the amount needed to maintain the minimum flow requirement at MCC. Using this value, estimates of surface water deficits were obtained for the October through December period by comparing the target flow to historical flows at MHB. Historical flows at MHB were grouped according to water-year type (dry, average, and wet) and averaged to obtain a mean historical flow for each water-year type. The flows associated with these mean values are shown in Fig. 6 for (A) October, (B) November, and (C) December, along with the target flow of 1.55 m^3, which is shown as a bold dashed line. Fig. 6 shows that flow deficits exist in October for all water-year types and in the first part of November for all but wet years. By December, the mean historical conditions are above the 1.55 m^3/s threshold. Volumes associated with the monthly mean deficits for each water-year type are shown in Table 2, which also shows the observed maximum deficits for each month.

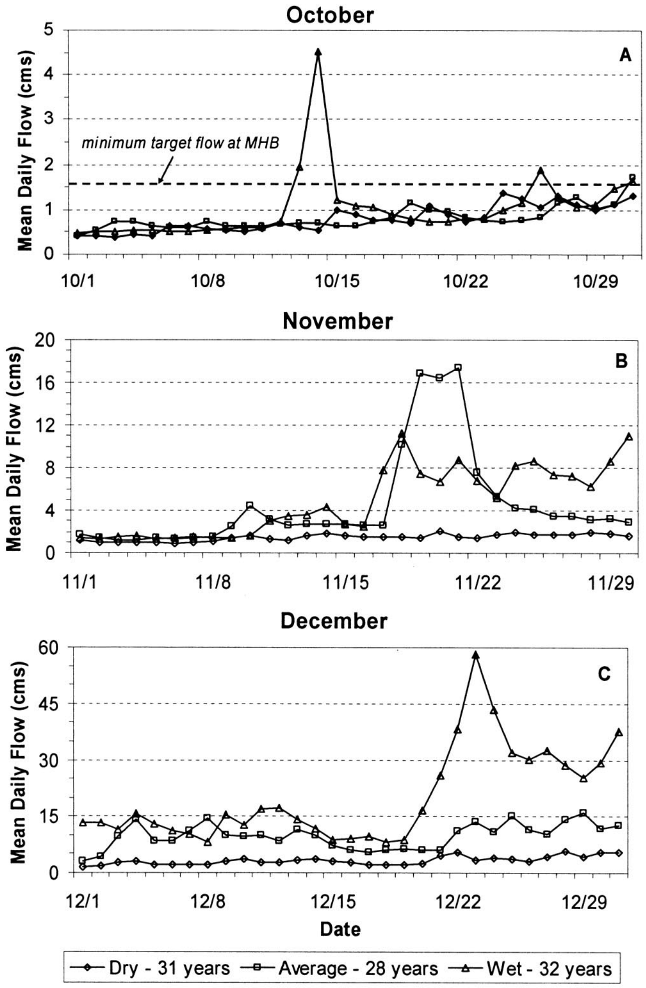

Fig. 6. Mean flow at Michigan Bar by water-year type for (A) October, (B) November, and (C) December

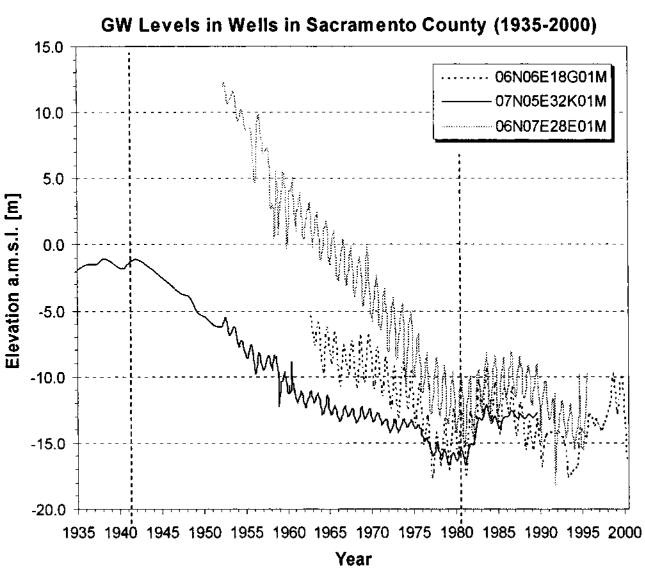

Fig. 5. Groundwater levels in three monitoring wells in Sacramento County (1935–2000)

Table 2. Mean Fall Flow Deficit Volumes ($m^3 \times 10^6$)

Water year classification	Dry	Average	Wet	Maximum observed deficit
October	2.5	2.0	1.7	4.55
November	0.56	0.12	0.10	3.82
December	0	0	0	3.16
Total Fall	3.06	2.12	1.80	11.53

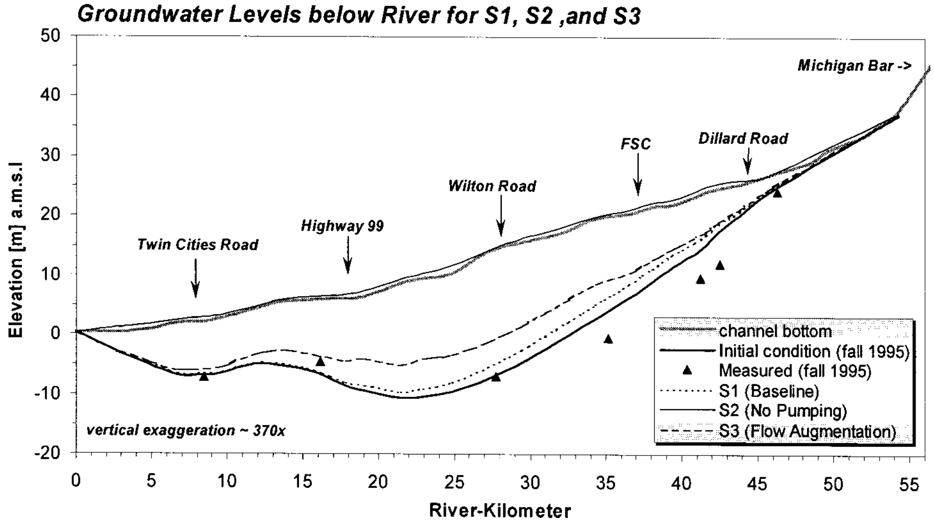

Fig. 7. September groundwater levels below river channel (aquifer 1) at end of 15-year simulation period for scenarios S1, S2, and S3

Scenarios 1 and 2 (Baseline and No-Pumping)

Fig. 7 shows a longitudinal profile of the river channel between MHB and Thornton Bridge (THB) and simulated groundwater levels below the channel at the end of the simulation period (September of year 15) under baseline and no-pumping conditions. Under baseline conditions, the river channel is largely hydraulically disconnected from the regional aquifer. Annual groundwater pumping in the model domain amounted to 703 million m^3, a significant groundwater deficit with respect to predevelopment conditions. In the no-pumping scenario groundwater levels rose above the channel elevation over the entire length between MHB and MCC within 4 years of the imposed changes. These results suggest that before substantial groundwater development occurred in the county in the 1950s and 60s the entire lower Cosumnes River probably received base flows from the regional aquifer and was able to sustain perennial flows.

Simulated seepage from the river channel between MHB and MCC under baseline conditions fluctuated between 48 and 105 million m^3 per year. [Fig. 8(A)]. Seepage rates in the model fall within the range of annual seepage volumes estimated by an independent study for the 1962 to 1969 period, which ranged from 35 million to 152 million m^3 with an average of 89 million m^3 (DWR 1974). Simulated annual seepage between MCC and the confluence of the Cosumnes with the Mokelumne River at THB under baseline conditions ranged from 27.1 to 77.7 million m^3, [Fig. 8(B)]. Under no-pumping conditions, seepage between MHB and MCC rapidly declined over the first 7 years of the simulation, and after year 12 this stretch of river became a net gaining reach, with base flow contributions of up to 14.8 million m^3/year [Fig. 8(A)]. In the reach between MCC and the river mouth (THB), net gaining conditions were already established after the 6th year of the simulation with base flow contributions of up to 13 million m^3/year [Fig. 8(B)].

Scenario 3 (Flow Augmentation)

Flow augmentation with available surface water was considered as a management option that could open the river channel for fish without the immediate need to recover regional groundwater levels and reinitiate base flows. In the long term such measures could also be beneficial for groundwater recovery from increased channel seepage. Releases from FSC to sustain sufficient fall flows in the lower river reaches, which are most susceptible to drying in the late summer and fall, were evaluated with the groundwater model. A 1.42 m^3/s augmentation from September through December during the 15-year simulation period significantly raised groundwater levels below the river downstream from the augmentation point due to increased channel seepage from additional augmented river flow (Fig. 7). Compared to the baseline simulation, annual seepage amounts increased slightly, mainly upstream of MCC [Fig. 8(A)]. Additional recharge from increased river seepage also raised groundwater levels further away from the river, as Fig. 9 shows for a well (07N06E33J01M) three km

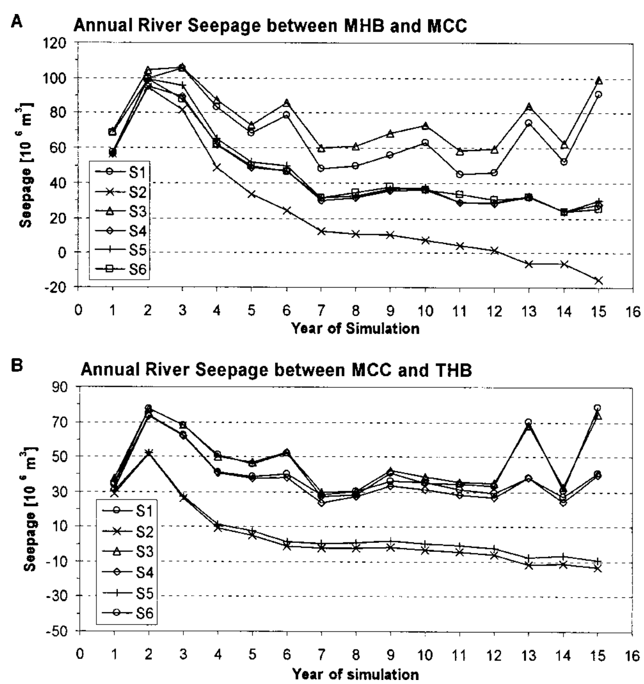

Fig. 8. Net annual seepage from lower Cosumnes River channel between Michigan Bar (MHB) and McConnell gauge (MCC) and MCC and Thornton Bridge (THB) for the 15-year simulation period (positive values signify seepage from river into aquifer)

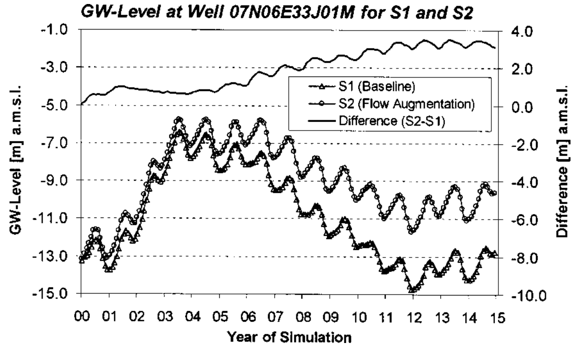

Fig. 9. Groundwater hydrographs at well 07N06E33J01M for scenarios S1 and S2

northwest of the river. Hydrographs for scenarios 1 and 2 and the head differences between both scenarios are plotted for the 15-year simulation period. After 4 years groundwater levels for S2 start to increase significantly in comparison to S1 (baseline), indicating additional groundwater-level recovery from flow augmentation. After 11 years this trend levels off, suggesting that the system reaches a new equilibrium.

Scenarios 4 and 5 (Pumping Reduction)

The pumping reduction scenarios aimed at determining necessary increases in net recharge to locally raise the water table to the channel elevation and to restore base flows. In the model increases in net recharge were implemented as pumping reductions. Pumping was reduced in the vicinity of the river so that local reconnections could be established. Scenario 4 focused on regions around the upper river reaches in the study area (MHB to MCC) and scenario 5 on the lower reaches (THB to MCC). Annual pumping reductions on the order of 205 million m^3 were necessary to hydraulically reconnect the aquifer with the channel upstream of FSC (Fig. 10). Even larger reductions of approximately 308 million m^3 were needed to establish a similar hydraulic reconnection downstream of MCC. Annual seepage amounts between MHB and MCC decreased to about 30 million m^3 after year 6 of the simulation period [Fig. 8(A)]. Seepage volumes between MCC and the basin outlet fluctuated around 30 million m^3 after the 6th year of the simulation for scenario 4 and reversed to net gaining conditions in year 6 for scenario 5 [Fig. 8(B)].

Scenario 6 (Pumping Reduction and Flow Augmentation)

In scenario 6 upstream pumping reductions (same as in S4) were combined with flow augmentation from FSC (same as in S3). Groundwater levels downstream of MCC increased due to increasing seepage from augmented river water whereas groundwater levels between FSC and MCC were practically unchanged compared to S4 (Fig. 10). This indicates that the latter river reach was no longer seepage dominated under the implemented upstream pumping reductions. Due to raised groundwater levels as a result of pumping reductions, seepage losses from the channel were greatly reduced. Significantly more of the augmented surface water could be maintained in the channel. Downstream of MCC, where the effects of the implemented pumping reductions diminish, seepage losses increased again.

Effects on Fall Flows

Impacts of changes in groundwater levels on fall flows were evaluated by comparing mean fall flows from October to December at different locations along the channel. Flows were averaged over the last 10 years of the 15-year simulation period for all scenarios. The first 5 years of the simulations were not included because they are characterized by the transition from the initial conditions of the simulations to the new quasi-steady-state scenario conditions and were therefore not representative for the specific scenarios. Fig. 11 shows mean fall flows at different channel locations expressed in percent of upstream inflows from MHB. In this figure FSC refers to the river just before the augmentation point at Folsom South Canal, and MCC1 and MCC2 signify the river at MCC before and after the confluence with Deer Creek, respectively. Under baseline conditions (S1), less than 10% of the inflow from MHB reached MCC. The simulations also suggest that even under no-pumping conditions (S2) the river reach between MHB and MCC would be a net losing reach in the fall. Downstream of MCC base flow contributions exceeded seepage losses in the fall and the river was gaining. Flow augmentation (S3) could maintain average fall flows at MCC above the mini-

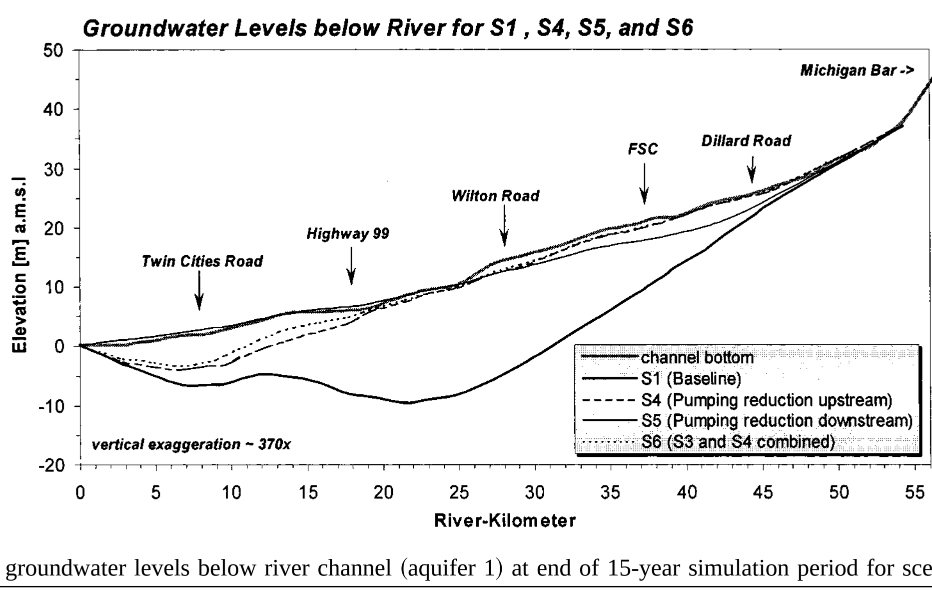

Fig. 10. September groundwater levels below river channel (aquifer 1) at end of 15-year simulation period for scenarios S4, S5, and S6

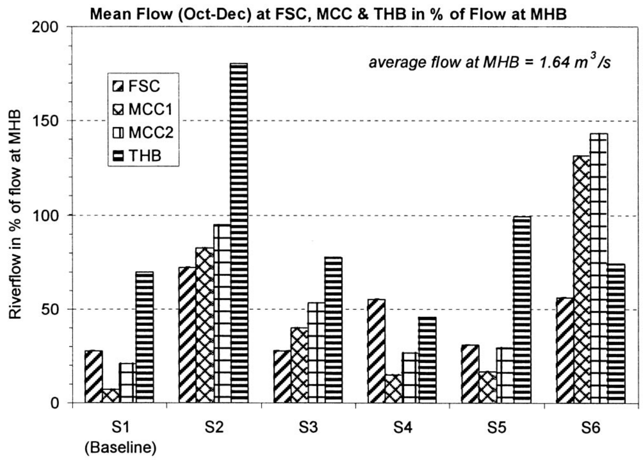

Fig. 11. Mean fall flows along river in percent of flow at Michigan Bar (MHB)

mum flow requirement despite increasing seepage losses. Upstream pumping reductions (S4) maintained significantly higher fall flows at FSC but only marginally increased flows at MCC (Fig. 11). Downstream pumping reductions (S5) mainly benefited fall flows at THB. The highest average fall flows at MCC could be sustained with the combination of upstream pumping reductions and flow augmentation (S6).

Management Options

Results from the scenario simulations support the findings from the analyses of river flow and groundwater level data. The Cosumnes River downstream of MHB is seepage dominated. Estimated average seepage losses per river kilometer calculated from the simulation results were on the order of 0.024 m^3/s. These rates fall within the range of flow losses estimated from stream gauging of individual river reaches. Based on the channel routing simulations, a flow of approximately 1.55 m^3/s is needed at MHB to maintain the minimum flow requirement of 0.57 m^3/s at MCC (corresponding to the 18 cm stage requirement). Management strategies that aim at promoting Chinook salmon fall runs have to either sustain the 1.55 m^3/s target flow at MHB or substantially reduce seepage losses from the channel downstream of MHB. Flow deficits in October and November could be covered with releases from Sly Park reservoir (in the upper watershed) and FSC.

Recovery of fall flows by means of groundwater management can only be a long-term strategy in light of increasing water demands in Sacramento County (MH 1997). Annual amounts of several hundred million cubic meters of water would be needed to partially or fully reconnect the Cosumnes River with the regional aquifer and reinitiate base flows between MHB and the basin outlet. To ensure fall flows that promote Chinook salmon fall runs in the short and intermediate term, flow augmentation with surface water will be necessary. Besides the no-pumping scenario (S2), only scenarios 3 and 6, which both involved augmentation of flows with surface water, could ensure average fall flows above the minimum flow requirement for all locations along the channel (Fig. 11). These results clearly demonstrate the severity of existing regional groundwater deficits with respect to natural flow conditions on the Cosumnes. Based on these results, management strategies that combine flow augmentation at times of fall flow deficits with long-term efforts to recover regional groundwater levels seem most viable to promote Chinook salmon fall runs.

Model Limitations and Future Work

The spatial and temporal resolution of the regional groundwater model used in this analyis is coarse. Average node spacing in the finite-element mesh is larger than 1,000 m and simulations were performed with a monthly time step. Hence local geologic heterogeneity in the aquifer and river bed cannot be resolved in the model, and river flows are only represented as monthly averages. Field measurements of seepage fluxes in the river channel have indicated that seepage fluxes can be highly variable over small spatial scales and that geologic heterogeneity can exert important controls on seepage. It was also observed that seasonal perched aquifers develop locally between the river channel and the regional aquifer, which can temporarily reduce or even reverse seepage fluxes. These phenomena are not included in the coarse regional model but could be important for the implementation of certain management strategies.

For the purpose of this study model results were acceptable. Simulated average annual seepage volumes were found to be within the range of previous studies (DWR 1974) and estimates based on our field measurements. General directions for management of groundwater and surface water along the Cosumnes River can be inferred from the findings. To develop a detailed management strategy to restore fall flows, further work remains to assess the effects of geologic heterogeneity and perched aquifers on seepage rates and water table recovery. A spatially and temporally more resolved model will be needed for such a purpose.

Conclusions

Overdraft of groundwater in Sacramento County over the last 6 decades has significantly impacted the magnitude and duration of fall flows on the Cosumnes River. The decline in fall flows is a primary stressor of spawning success of fall-run Chinook salmon. Management of linkages between surface water and groundwater were evaluated in order to guide restoration efforts. Under current conditions most of the lower river is seepage dominated. Restoration of fall base flows to the lower Cosumnes through groundwater management alone would require significant increases in net recharge through extensive pumping reductions or artificial recharge to reconnect the river with the regional aquifer. Annual groundwater deficits are on the order of several hundred million cubic meters. Benefits from pumping reductions could only be realized after several years. In contrast, surface water management that augments flows during the critical salmon migration period could be used to enhance spawning success and have immediate impact.

The combined efforts of reduced pumping or artificial recharge and surface water augmentation provide immediate benefits as well as changes that could improve long-term river conditions. An improved hydraulic connection between the regional aquifer and the river provides the opportunity to decrease the quantity of surface water augmentation required for fish passage. An optimized combination of releases from a small reservoir in the upper watershed and a water supply canal in the lower basin could be used to sustain flows throughout the fall, providing greater access to spawning habitat for fall-run Chinook salmon. Future work remains to quantify the effects of geologic heterogeneity and perching on seepage and river flows, so that optimal surface and groundwater management strategies can be developed to minimize impacts on existing demands for water in the region while providing sufficient flows for fish migration. Artificial recharge, if technically and politically feasible on a large scale, could provide a viable alternative to groundwater pumping reductions in an area with growing water demands and environmental resources under stress.

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