

3 LINKS BETWEEN RIVER FLOWS AND GROUNDWATER CONDITIONS

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, 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-mile 0-36) 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 Sacramento County since the 1950s have substantially lowered groundwater levels in the area. Major cones of depression in ground water levels have formed north and south of the Cosumnes River with levels as low as 80 ft. below mean sea level. Management strategies that address existing groundwater and surface water deficits are needed to promote Chinook salmon fall runs. As part of a CALFED-funded project links between river flows and groundwater conditions in the lower Cosumnes basin (below Michigan Bar) were investigated between January 2000 and 2003. Aim of these investigations was to analyze river and aquifer interactions along the alluvial reaches of the river between Michigan Bar and the basin outlet and to assess management alternatives for enhancing fall flows to promote Chinook salmon spawning on the Cosumnes. A combination of historical data analyses, field investigations and numerical modeling was used to address the problem. Results from those investigations and recommendations for management are presented here.

Background

River and groundwater interactions

Rivers and underlying groundwater interact by water being exchanged through the river bed and banks. The magnitude and direction of exchange depends on the hydraulic properties of the material making up the river bed and banks and the gradient between the river stage and nearby groundwater levels (hydraulic gradient). The hydraulic gradient is the major driving force in that exchange process and determines the direction of the exchange. Figure 3.1 conceptualizes the three different hydraulic situations that govern river groundwater interactions. In case A groundwater levels adjacent to the river are higher than the river stage

and groundwater flows into the river (influent conditions). In case B the groundwater levels are lower than the river stage and the hydraulic gradient is directed away from the river. River water flows into the aquifer (effluent conditions). Relative changes in the elevation of the water table and the river stage determine the magnitude of river groundwater exchange in cases A and B. If groundwater levels are lower than the elevation of the river bed (case C) the direct hydraulic connection between the river and aquifer is lost. The area separating the river bed from the water table becomes partially unsaturated. River water seeps through the river bed and vertically percolates to the water table. In that case seepage rates are independent of water table fluctuations and unsaturated flow governs recharge to the water table. All three cases can occur simultaneously along different reaches of a river.

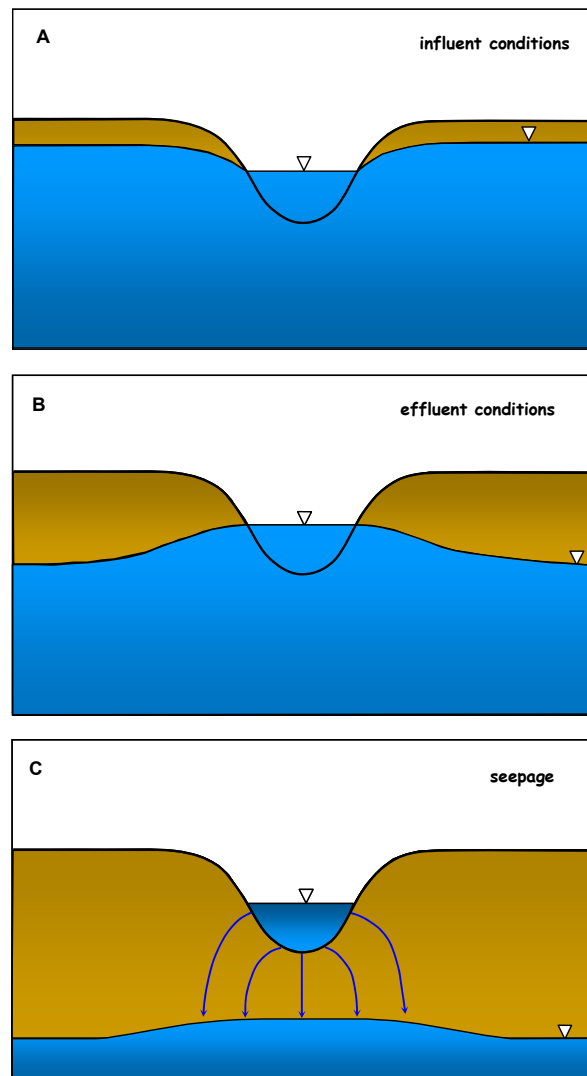


Figure 3.1. *Different types of river aquifer interactions.*

Related work on groundwater and surface water interactions

Although early work in hydrology has 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 and surface water interactions and their ecological, economic, and legal implications. Comprehensive reviews of that literature are given by Sophocleous (2002), Woessner (2000), and Winter (1995). 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 waters. Theoretical considerations of river aquifer interactions and their mathematical formulation are discussed in Kaleris (1998) and Rhuston and Tomlinson (1979).

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 & 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. Ramireddygaru 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 (Nobi and Das Gupta 1995, Perkins and Sophocleous 1999, Pelka and Horst 1989, Pucci and Pope 1995, Sophocleous and Perkins 2000).

The 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. 3.2). The basin covers an area of approximately 1300-square miles and ranges in elevation from 7,900 ft at the headwaters to near sea level at its outlet in the Sacramento/San Joaquin Delta. In the upper basin the Cosumnes River is comprised of 3 forks, which join near Michigan Bar (MHB). From Michigan Bar the river extends another 36 miles before it flows into the Mokelumne River (Fig. 3.2). 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 93,580 cfs at Michigan Bar during the 1997 flood.

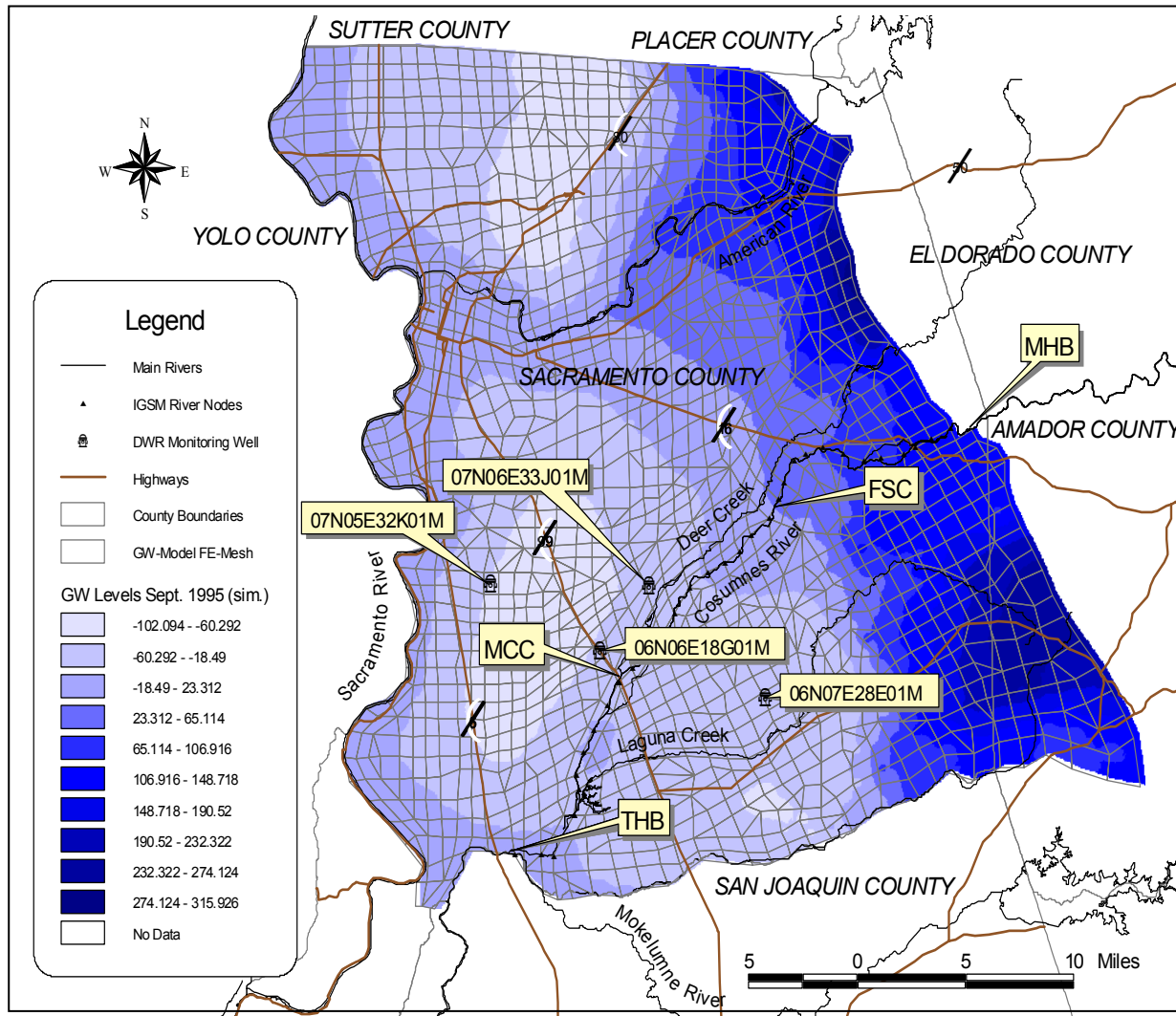


Figure 3.2. Location map and groundwater model mesh.

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 groundwater levels to the north and south of the river (Fig. 3.1). These cones have formed over the last six decades as a result of intensive pumping of groundwater for agricultural and municipal use (Montgomery Watson, 1993b).

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 historic 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 0.6 ft to allow fish migration to the spawning habitat around and just downstream of Michigan Bar (Keith Whitener, personal communication). Based on rating tables from the McConnell gage, this water depth corresponds to a flow of approximately 20 cfs at McConnell. This threshold flow will subsequently be referred to as the minimum flow requirement at McConnell.

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 monitoring were analyzed to evaluate historic changes in river flows and groundwater conditions. In a second step, numerical models of groundwater and surface water flow were used to describe the current hydrologic conditions in the lower basin and to simulate stream-aquifer interactions and channel flows under current and scenario conditions. Scenario simulations explored management strategies to enhance river flows and promote Chinook salmon fall runs. Two numerical models were used: a one-dimensional (1-D) channel routing model that incorporates vertical seepage and a quasi three-dimensional (3-D) finite element regional groundwater flow code (Montgomery Watson, 1993a) that also simulates stream-aquifer interactions and mean monthly river flows. The 1-D routing model was used to estimate a target flow at Michigan Bar that would be needed to maintain the minimum flow requirement at McConnell under current conditions. The 3-D 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 Michigan Bar (MHB), where the river enters its alluvial lower basin, and from the McConnell gauge (MCC) about 25 miles downstream of MHB were used. At McConnell flows were only recorded between 1941 and 1981. The Michigan Bar record extends from 1908 to present. These data constitute the only flow record for the lower basin. Frequency and trends of low flows in the lower basin were evaluated based on that record. Changes in fall flows 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 McConnell and Michigan Bar were quantified by calculating the difference in the number of days for which flows were below the thresholds. 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. Water levels were monitored in 2 to 4 week intervals from April 2000 to September 2002. At two locations on the river quasi-continuous monitoring sites of groundwater levels and river stage were established. At the first site a pressure transducer was installed in a piezometer below the river channel close to McConnell in September 2001. Water levels were recorded at

hourly intervals. Fifteen minute river stage data were obtained from the McConnell gauge. The second site was established at Folsom South Canal (FSC) in January 2002 with transducers in an abandoned well and the river. Figure 3.3 shows the locations of the monitoring wells and transducer sites.

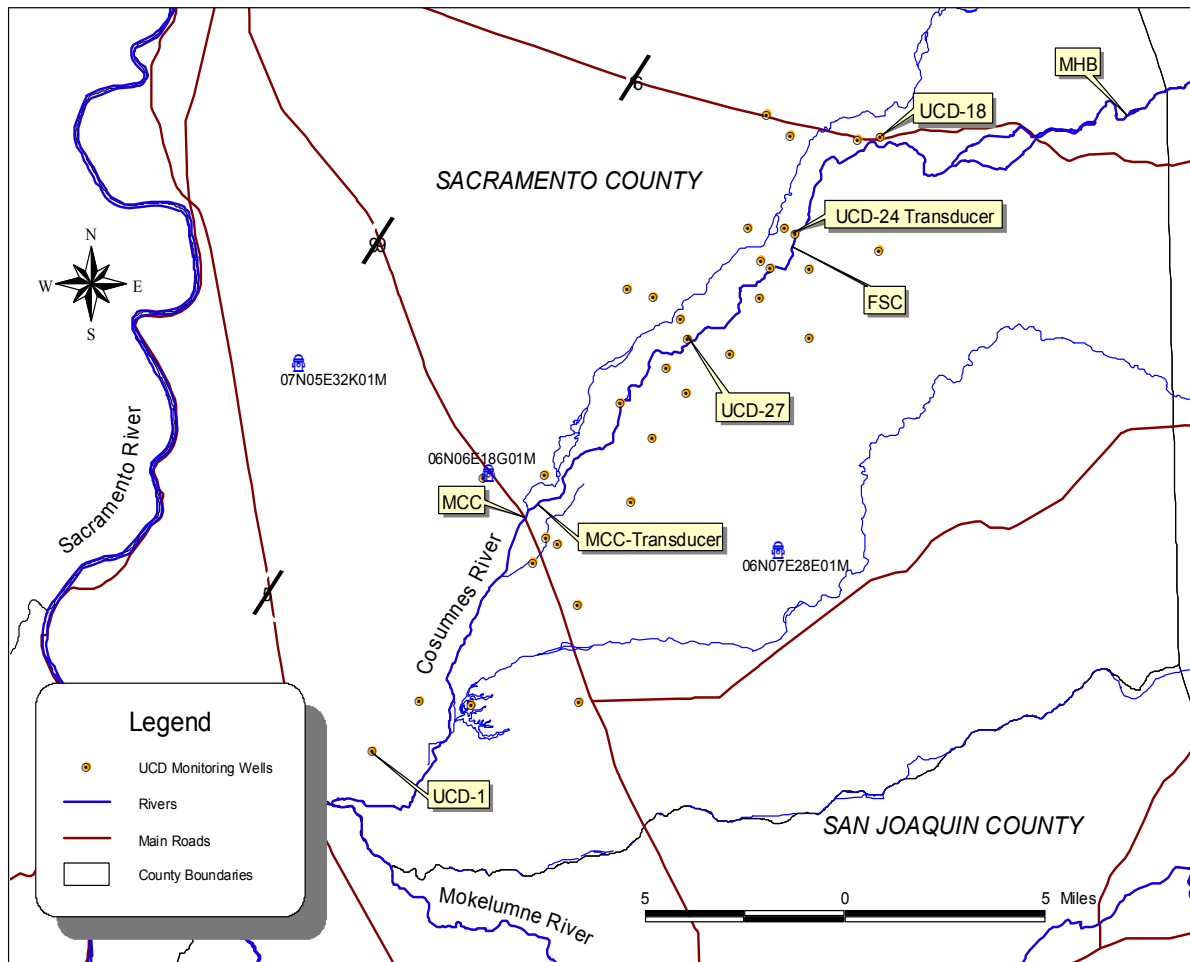


Figure 3.3. Locations of monitoring sites.

The Channel Routing Model

To calculate the target flow rate at Michigan Bar corresponding to the 0.6 ft depth requirement at McConnell the routine, DIFWAVE (Anderson, 1993), which solves the diffusion wave approximation to the momentum equation was employed. It was assumed that the river is seepage dominated and does not receive significant groundwater discharge between Michigan Bar and McConnell 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. (2002). After the channel flow model was calibrated to observed flows in the channel, a target flow at Michigan Bar was estimated with DIFWAVE such that the downstream stage at McConnell was greater than or equal to the 0.6 ft target depth. Comparing the target flow with historical flows at Michigan Bar, surface water deficits with respect to the

minimum flow requirement at McConnell in wet, dry and average years for the fall months October to December could be determined.

Simulations of Regional Groundwater Flow

The 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 (Montgomery Watson 1993b), was obtained from the Sacramento County Water Agency (SCWA). The model is based on the numerical finite element code IGSM (Integrated Groundwater Surface Water Model) Version 3.1 (Montgomery Watson, 1993a). IGSM simulates quasi-3-D 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 simulated with Darcy's equation (i.e., 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 (Montgomery Watson 1993a). The amount of water that seeps 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 validation (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 and mean monthly river flows at McConnell were found to be in reasonable agreement with observed values (Fig. 3.4).

During the course of this investigation an independent review of the IGSM source code (Eric M. LaBolle, personal communication 2001) revealed limitations of the code in handling non-linear 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 heads change significantly. These errors do not appear to be large in our implementations of ths SCM, mainly because the depressed groundwater levels have resulted in a lack of tight coupling between the river and groundwater. Nevertheless, a corrected and updated model will be essential for future investigations involving more complex scenarios of groundwater and surface water interaction.

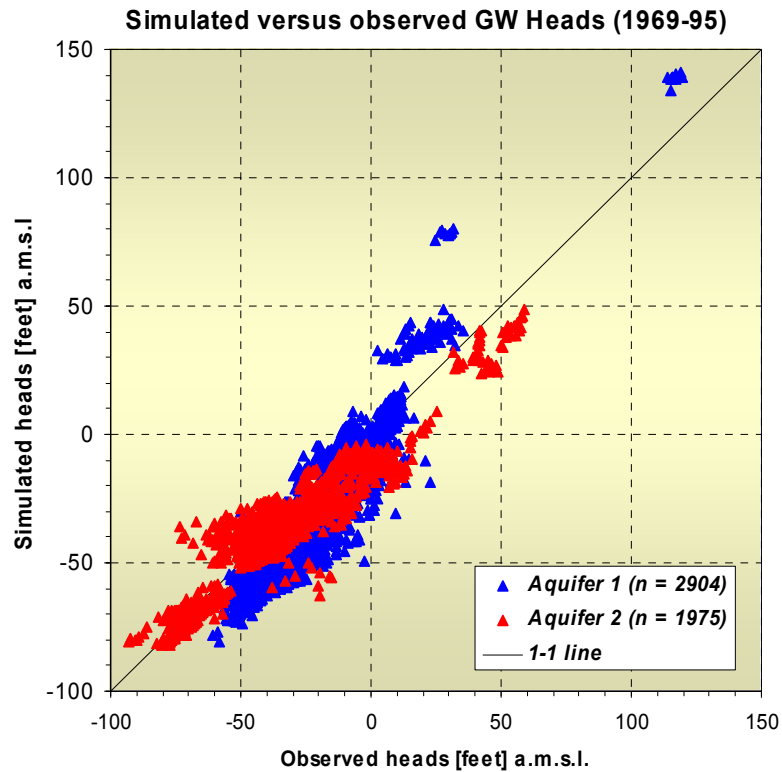


Figure 3.4. Simulated versus observed head for aquifers 1 and 2 over calibration/validation period.

Scenario Simulations

Six scenario simulations (S1 to S6) were run with the regional groundwater model (Table 3.1). 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, pre-development 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.

Table 3.1. Groundwater Scenarios.

general	Parameter / variable	Scenario (baseline)	Scenario 2 (no pumping)	Scenario 3 (flow augmentation)
	Simulation period	15 years	15 years	15 years
	Initial conditions	1995 fall GW levels	1995 fall GW levels	1995 fall GW levels
Static in time	Landuse	1993 land use survey	1993 land use survey	1993 land use survey
	GW pumpage (time variant within year)	1994 pump rates	No pumping in entire model domain	1994 pump rates
	SW-diversions & imports (time variant within year)	1994 diversions & imports	1994 diversions & imports	1994 diversions & imports plus 50 cfs flow augmentation from FSC from Sept. to Dec.
	Additional water needed (per year)	None	~ 570,000 ac-ft	~ 12,000 ac-ft
time variant	Stream/River inflows	1980-95 record	1980-95 record	1980-95 record
	Precipitation input	1980-95 record	1980-95 record	1980-95 record
	Boundary Conditions	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)

general	Parameter / variable	Scenario 4 (pumping reductions upstream)	Scenario 5 (pumping reductions downstream)	Scenario 6 (S3 combined with S4)
	Simulation period	15 years	15 years	15 years
	Initial conditions	1995 fall GW levels	1995 fall GW levels	1995 fall GW levels
Static in time	Landuse	1993 land use survey	1993 land use survey	1993 land use survey
	GW pumpage (time variant within year)	Pumping reduced by 166,000 ac-ft with emphasis on upstream reaches	Pumping reduced by 250,000 ac-ft with emphasis on downstream reaches	Pumping reduced by 166,000 ac-ft with emphasis on upstream reaches
	SW-diversions & imports (time variant within year)	1994 diversions & imports	1994 diversions & imports	1994 diversions & imports plus 50 cfs flow augmentation from FSC from Sept. to Dec.
	Additional water needed (per year)	~ 166,000 ac-ft	~ 250,000 ac-ft	~ 178,000 ac-ft
time variant	Stream/River inflows	1980-95 record	1980-95 record	1980-95 record
	Precipitation input	1980-95 record	1980-95 record	1980-95 record
	Boundary Conditions	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)

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 50 cfs from Folsom South Canal (FSC), a water delivery canal that crosses the Cosumnes River at river-mile 23. In S4 and S5 groundwater pumping was reduced in the vicinity of the river downstream and upstream of McConnell, 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

Analysis of the historical flow record at Michigan Bar (MHB) shows that the Cosumnes has sporadically experienced intermittent flows in its alluvial reaches since the early 1900s. In very dry years flow at MHB completely ceased typically during the late summer and fall (Fig. 3.5). In moderate to wet years, however, the river could sustain perennial flows at Michigan Bar.

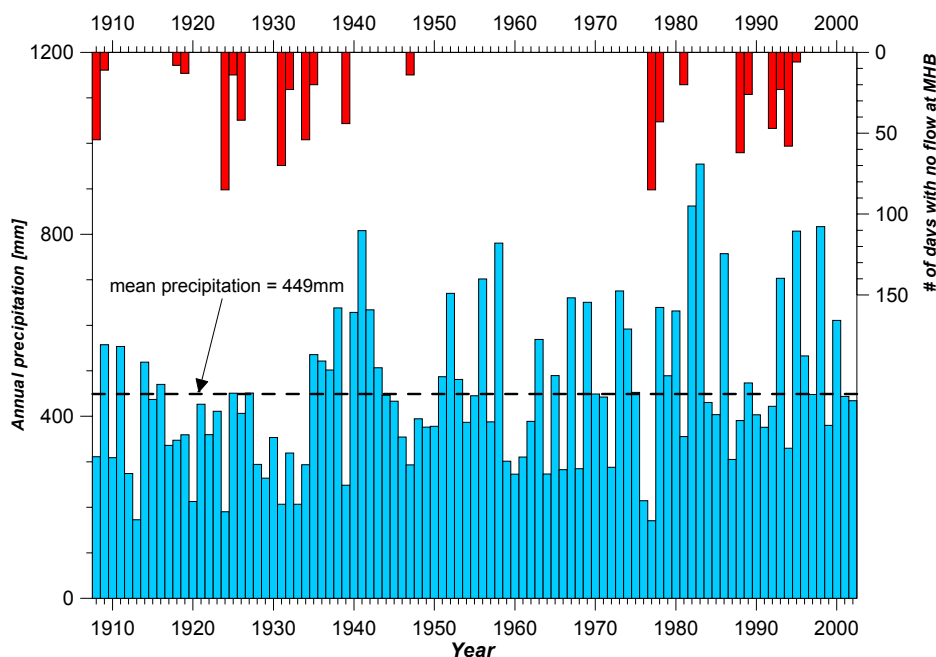


Figure 3.5. *Total annual precipitation and number of days with no flow at Michigan Bar (MHB).*

The same data for the historical flow record at McConnell (MCC) are depicted in Figure 3.6. Over the 1941-82 record the occurrence of days without flow is much more frequent than at Michigan Bar. These data indicates that at least since the early 1940s the Cosumnes River has been experiencing substantial flow losses

between Michigan Bar and McConnell. Interestingly, however, in the 1940s and early 1950s the river could sustain perennial flows even at MCC during very wet years whereas between 1955 and 1982 during similarly wet years flow was intermittent. This suggests an increase in flow losses between Michigan Bar and McConnell over the 1941-82 time period.

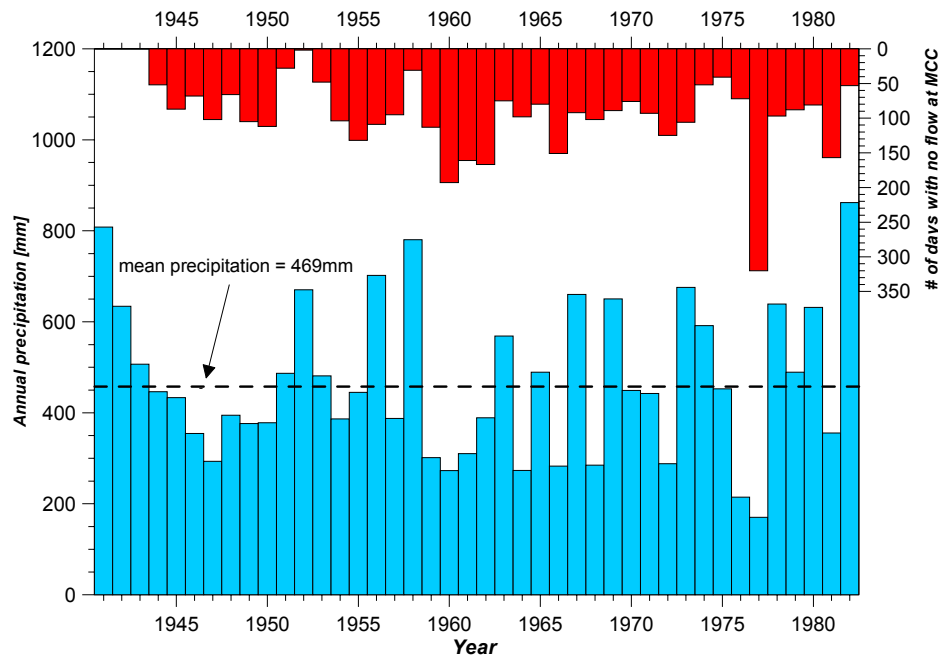


Figure 3.6. Total annual precipitation and number of days with no flow at McConnell (MCC).

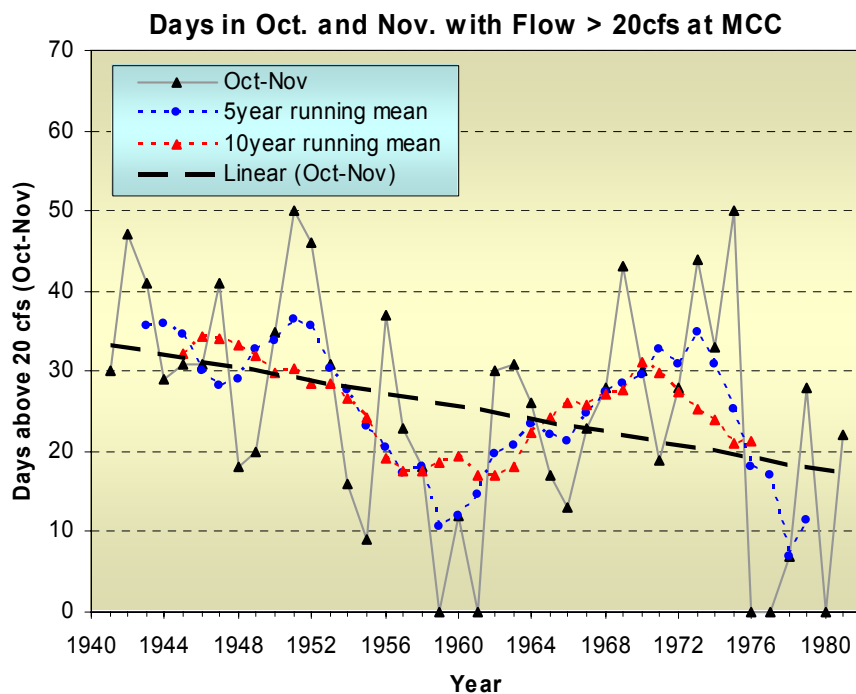


Figure 3.7. Number of days in October and November with flows above 20 cfs at McConnell.

Between 1941 and 1981 the number of days in October and November with mean daily flows above the minimum flow requirement of 20 cfs at McConnell has steadily decreased from, on average, more than 30 days in the early 1940s to less than 20 in 1980 (Fig. 3.7). Based on gauge data and simulations with the 1-D channel model it can be inferred that currently a minimum flow of approximately 55 cfs is needed at Michigan Bar to meet the minimum flow requirement of 20 cfs at McConnell. A comparison of daily flows at McConnell and Michigan Bar for the 1941-82 time period reveals a relative shift in the frequency of occurrences of flows below those thresholds between the two gauges. In Figure 3.8 the difference in the number of days in October and November during which flows were below the 55 and 20 cfs thresholds at Michigan Bar and McConnell respectively are plotted over the 1941 to 1982 period. At the beginning of the data record days with flows below the respective thresholds were more frequent at Michigan Bar than at McConnell. Over the 40 year period that difference has declined to values around zero. This indicates a shift in those thresholds and a corresponding increase in the flow losses experienced between the two gauges. In the 1940s and 50s less than 55 cfs were necessary at Michigan Bar to sustain flows above 20 cfs at McConnell. Over the 40 year period the threshold flow at Michigan Bar to maintain the 20 cfs flow requirement at McConnell increased to about 55 cfs consistent with increasing flow losses between Michigan Bar and McConnell. This increase in flow losses coincides with a drastic decline in groundwater levels over the same time period (Fig. 3.9) suggesting that flow losses are linked to loss of base flow support and increasing seepage from the river.

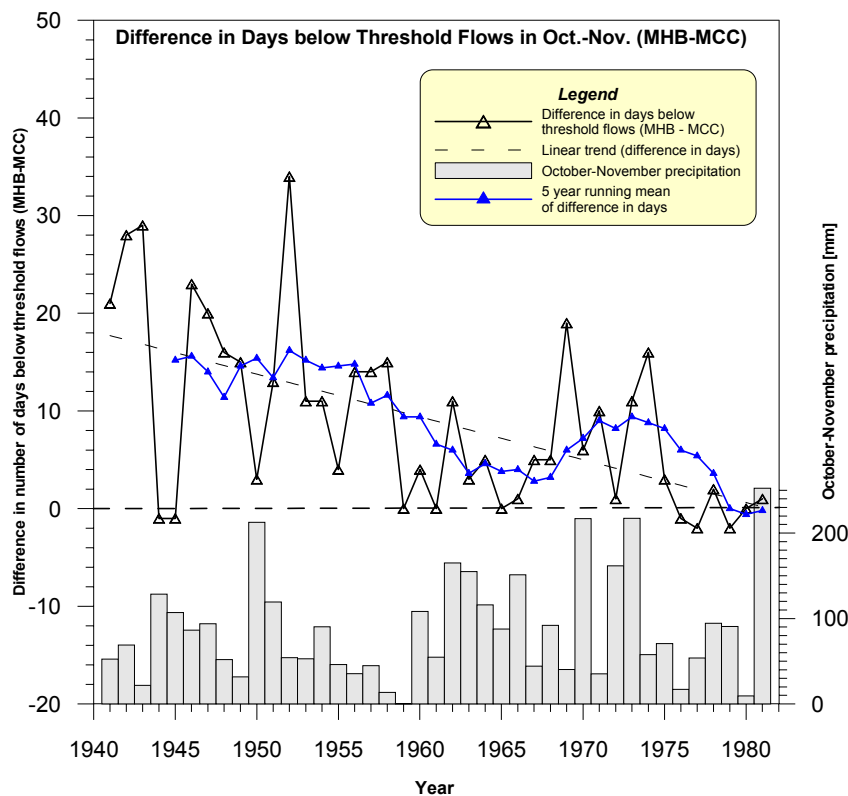


Figure 3.8. Difference in the # of days with flows below thresholds at MHB and MCC (Oct.-Nov.).

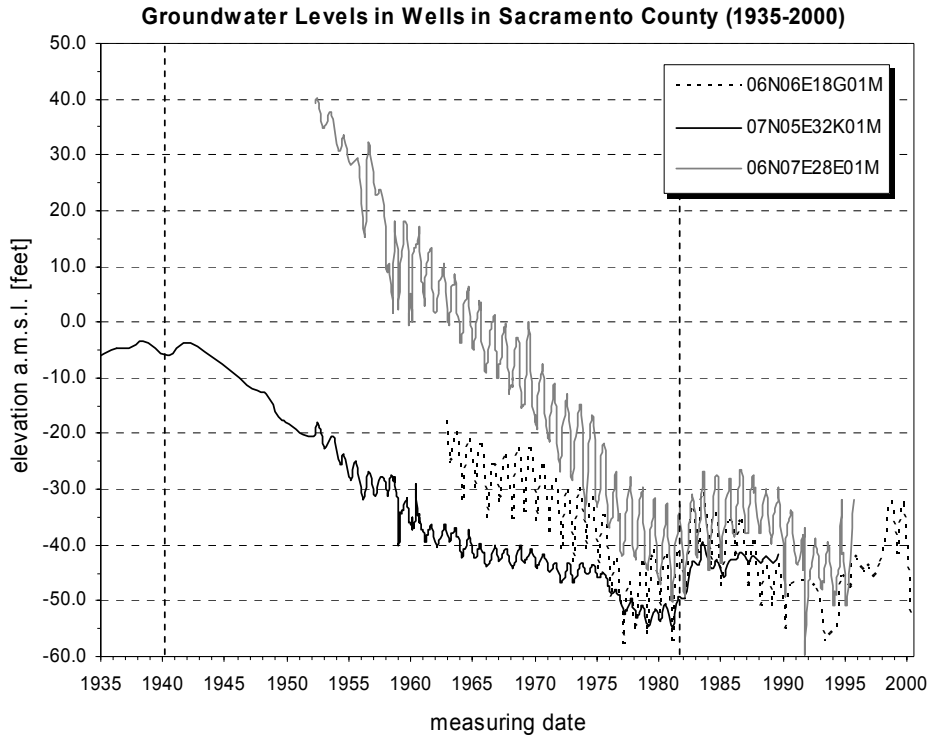


Figure 3.9. Groundwater levels in three monitoring wells in Sacramento County (1935-2000).

Current groundwater conditions

Groundwater level data from wells within 1000 m of the river channel indicate that the regional water table lies below most of the lower Cosumnes channel. In 2000 and 2001, depth to the potentiometric surface (based on water levels measured primarily in wells tapping the semi-confined aquifers) from the river channel elevation ranged from 6.5 ft in the Dillard Road area (river-mile 27.5) to 54.8 ft around Wilton Road (river-mile 17.3). Data from downstream of Twin Cities Road suggests that at least a seasonal connection exists between the river and the aquifer in its lowest reaches. Under these conditions 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, groundwater levels would have to be raised by up to 55 ft.

Groundwater level contours at the end of the wet season (March 22, 2001) and towards the end of the dry seasons (August 27, 2001) are shown in Figure 3.10. Both maps show very similar groundwater level configurations, with the influence of the groundwater cones of depression to the north (Elk Grove) and south (Galt) being clearly visible. In the north-east portions of the river groundwater flows in a south-westerly direction from the Sierra foothills towards the center of the Central Valley. The curvature of groundwater contours in the vicinity of the river in that area indicates seepage from the river. In the middle portions of the river the cones of depression dominate the groundwater flow field. Flow is directed north-west and south-east towards their centers. In the lowest reaches of the river, slightly west of the cones of depression, groundwater flow is also directed toward the cones in northerly and easterly directions.

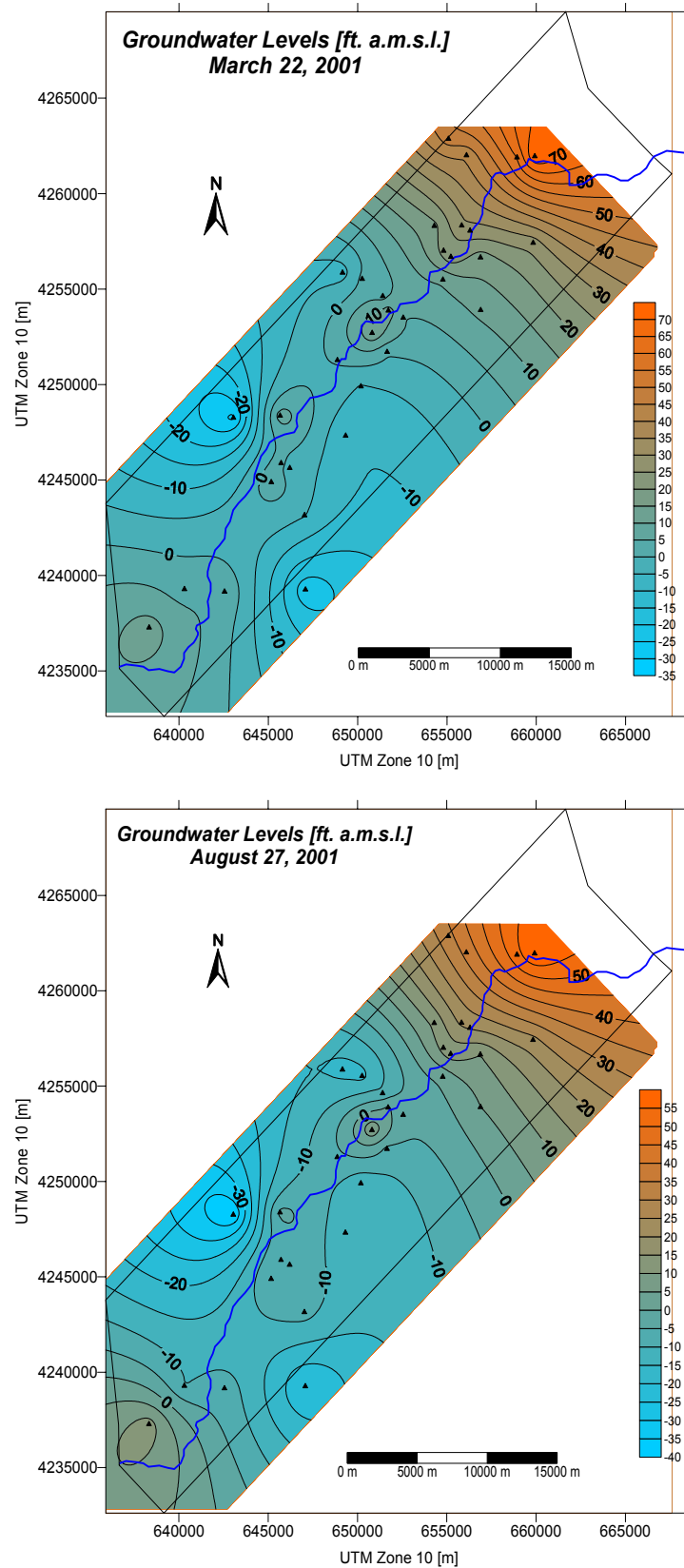


Figure 3.10. Groundwater Contours Spring and Fall 2001.

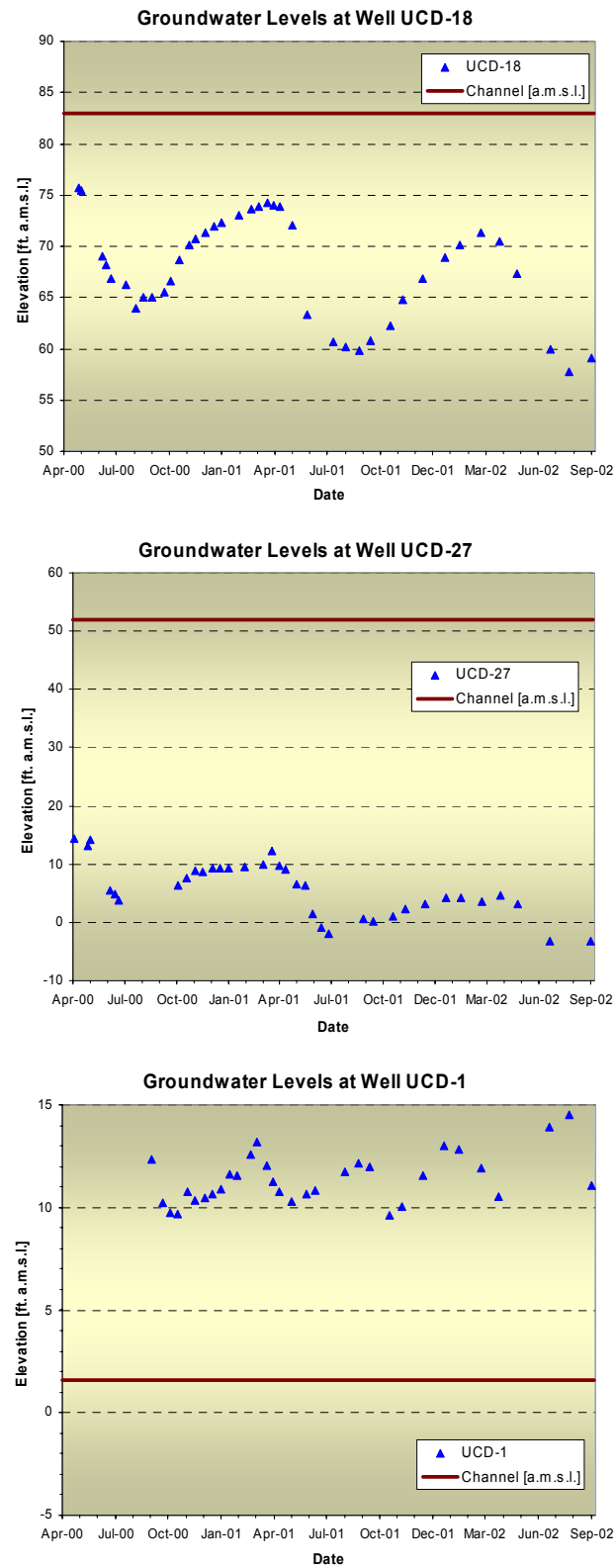


Figure 3.11. Groundwater levels in selected monitoring wells.

All monitored wells display seasonal oscillations in their hydrographs, which in some wells are superposed by short term transients caused by individual pumping events. Seasonal fluctuations ranged from 3.5 to 20 ft. Most wells show a general decline in groundwater levels between 3 and 9 ft over the 2.5 year monitoring period. Figure 3.11 shows groundwater hydrographs from three wells close to the channel in the upper, middle and lower parts of the river. The solid line in the graphs indicates the elevation of the river bed at or close to the well. Depth to the regional water table from the river bed increases downstream of Highway 16 and starts decreasing close to Highway 99. Downstream of Twin Cities Road groundwater levels rise above the elevation of the river channel. At the end of the wet season groundwater levels at the river around Dillard Road (UCD-18) rose to within 8 feet of the elevation of the river channel. This is consistent with results from the regional groundwater modeling that suggest that the regional aquifer seasonally reconnects with the river channel upstream of Dillard Road. Well UCD-27 indicates significant separation between the river channel and the regional aquifer in the middle reaches of the river. Groundwater levels are more than 40 ft below the river channel. At well UCD-1, which is about 1.4 miles away from the river and the only well in the vicinity of the lowest river reaches, groundwater levels were above the elevation of the river channel for the entire monitoring period. That suggests that the regional aquifer is in contact with the river channel in those reaches.

Figure 3.12 depicts river stage and groundwater levels below the river channel at the two sites with quasi-continuous monitoring devices. Groundwater levels were recorded at hourly intervals and river stages at 15 minute intervals. At both sites the regional water table lies several tens of feet below the river channel. At well UCD-24 the separation ranges from 52 to 62 ft and at McConnell from 30 to 40 ft. Groundwater levels at UCD-24 show much larger short term fluctuations than at McConnell suggesting that the groundwater system at UCD-24 is more confined so that pumping transients from distant wells significantly affect the piezometric surface at this site. Seasonal water table recovery at McConnell shows an increase in the slope of the hydrograph about six weeks after the onset of flow in the river. This change of slope may be interpreted as a response of the water table to recharge from the river. The response is delayed in time due to slow flow of water through the extensive unsaturated zone (vadose zone) separating the two systems. No similar response was observed at UCD-24 probably due to the existence of a significant confining layer.

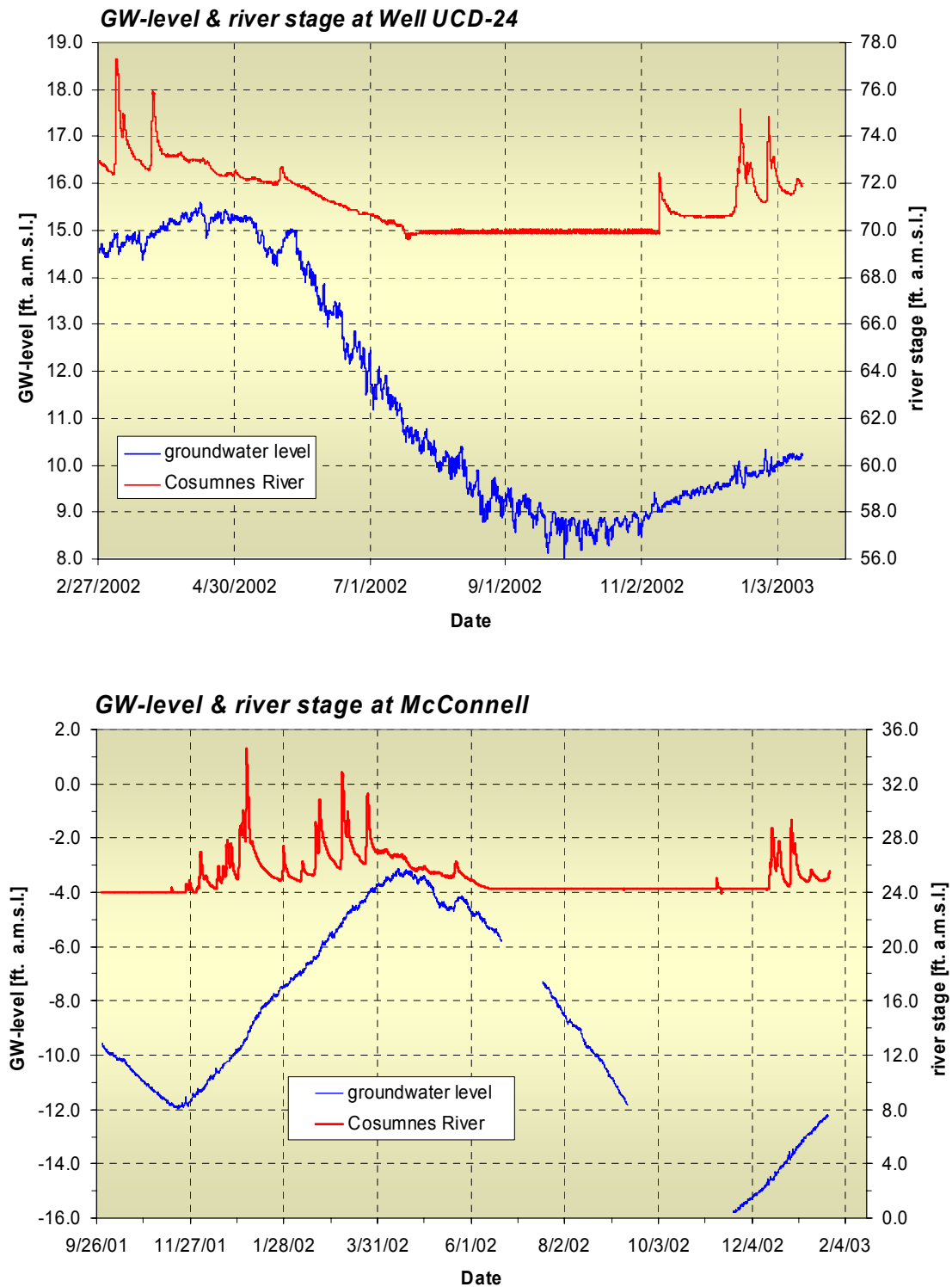


Figure 3.12. Groundwater levels and river stage at sites with pressure transducers.

Current Surface Water Deficits (1-D routing model)

With the 1-D routing model a target flow of approximately 55 cfs at Michigan Bar was estimated as the amount needed to maintain the minimum flow requirement at McConnell. 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 Michigan Bar. Historical flows at Michigan Bar 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 Figure 3.13 for (A) October, (B) November, and (C) December along with the target flow of 55 cfs, which is shown as a bold dashed line in (A).

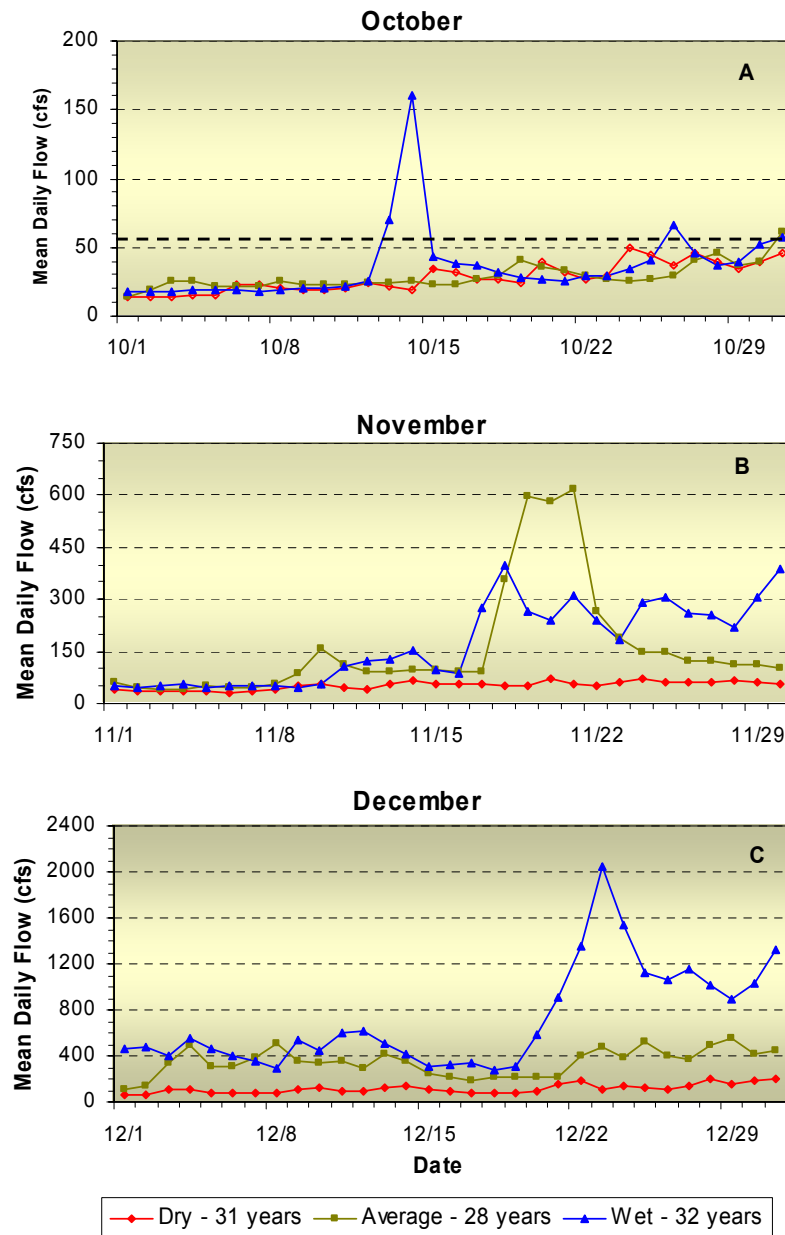


Figure 3.13. Mean flow at Michigan Bar by water year type for (a) October, (b) November, (c) December.

Figure 3.13 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 55 cfs threshold. Volumes associated with the monthly mean deficits for each water year type are shown in Table 3.2. Also shown in Table 3.2 are the observed maximum deficits for each month.

Table 3.2. Mean fall flow deficit volumes [ac-ft.]

Water Year Classification	Dry	Average	Wet	Maximum Observed Deficit
October	20,267	16,214	13,782	36,887
November	4,540	973	811	30,969
December	0	0	0	25,619
Total Fall	24,808	17,187	14,593	93,475

Groundwater Scenarios

Scenarios 1 and 2 (Baseline and No-Pumping)

Figure 3.14 shows a longitudinal profile of the river channel between Michigan Bar 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.

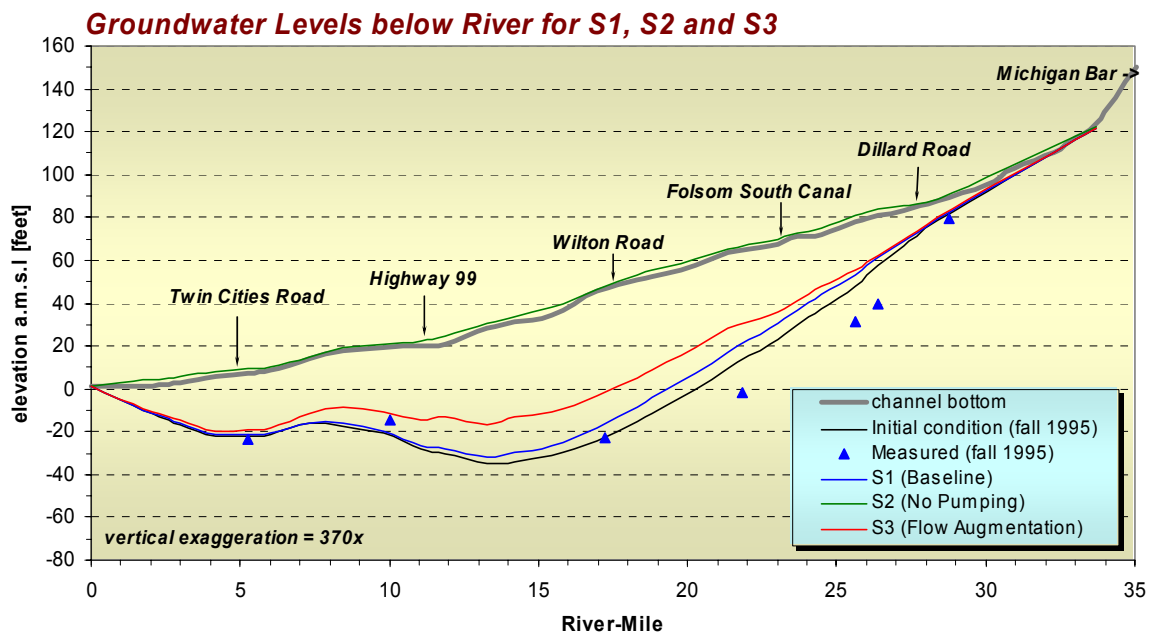


Figure 3.14. September groundwater levels below the river channel (aquifer 1) at the end of the 15 year simulation period for scenarios S1, S2, and S3.

Under baseline conditions, the river channel is largely hydraulically disconnected from the regional aquifer; that is, the water table no longer intersects most of the river channel, thereby significantly lessening the influence of water table fluctuation on streamflow. Annual groundwater pumping in the model domain amounted to 570,000 ac-ft, creating a significant groundwater deficit relative to pre-development conditions. In the no-pumping scenario groundwater levels rose above the channel elevation over the entire length between Michigan Bar and McConnell 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 received baseflows from the regional aquifer and was probably able to sustain perennial flows in most years.

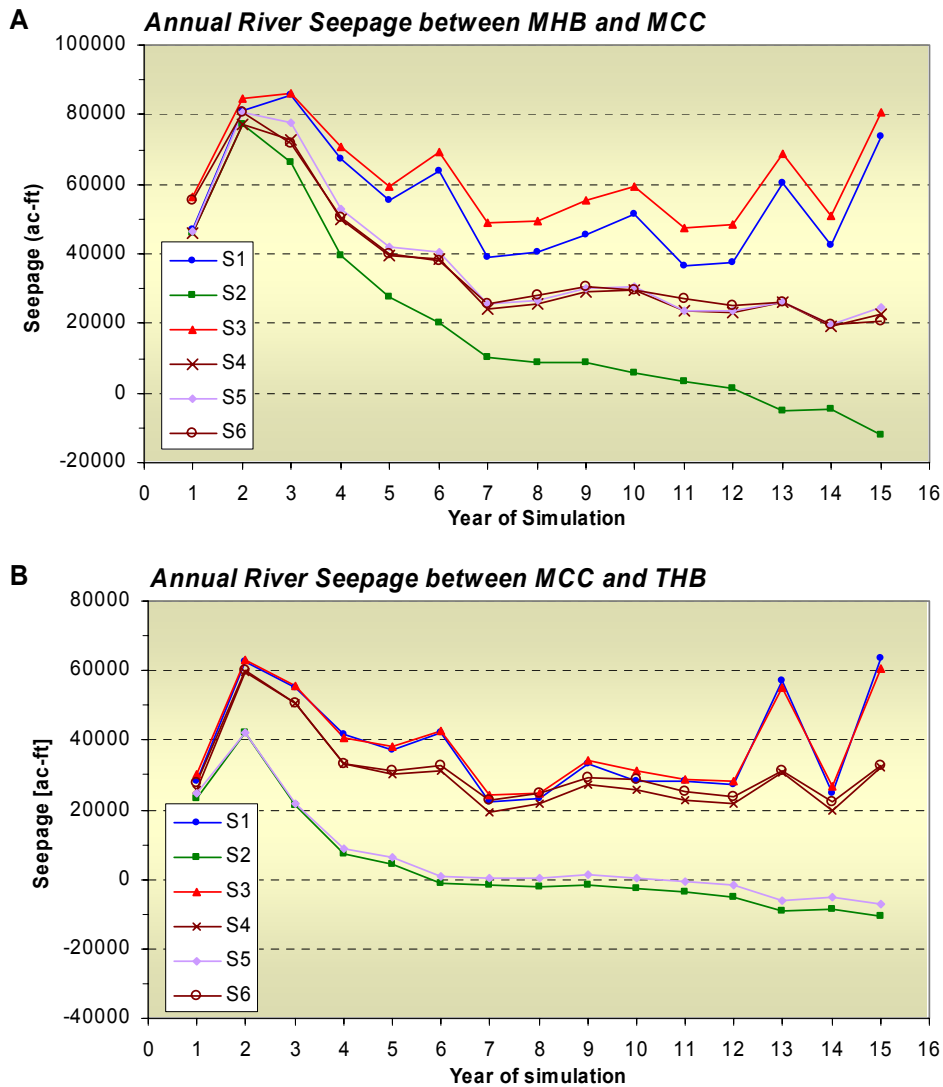


Figure 3.15. Net annual seepage from the lower Cosumnes River channel between MHB and MCC and MCC and THB for the 15 year simulation period (positive values signify seepage from the river into the aquifer).

Simulated seepage from the river channel between Michigan Bar and McConnell under baseline conditions fluctuated between 36,000 and 86,000 ac-ft/yr (Fig. 3.15A). 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 28,000 to 132,000 ac-ft/yr, with an average of 72,000 ac-ft/yr (DWR, 1974). Simulated annual seepage between McConnell and the confluence of the Cosumnes with the Mokelumne River at Thornton Bridge (THB) under baseline conditions ranged from 22,000 to 63,000 ac-ft/yr (Fig. 3.15B). Under no-pumping conditions seepage between Michigan Bar and McConnell 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 12,000 ac-ft/yr (Fig. 3.15A). In the reach between McConnell 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 10,000 ac-ft/yr (Fig. 3.15B).

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 Folsom South Canal 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 50 cfs 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. 3.16).

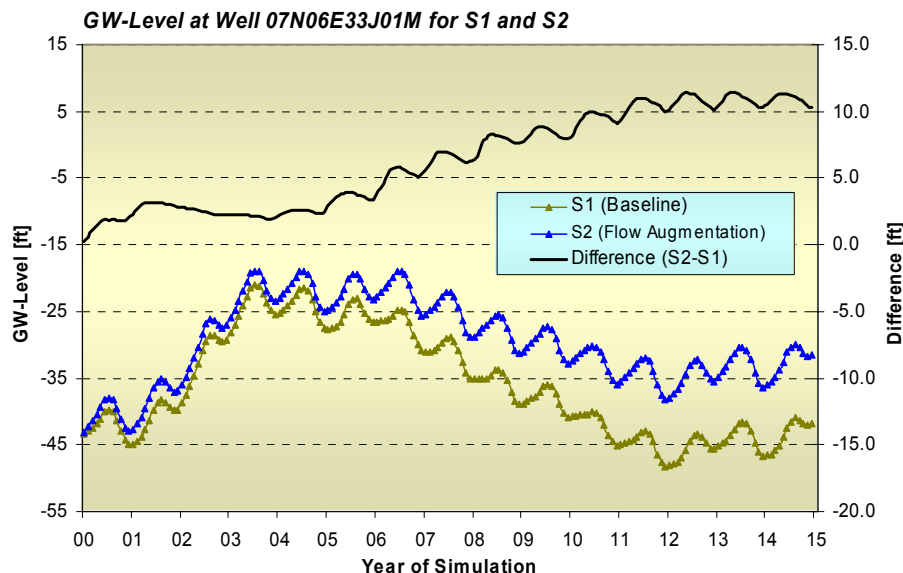


Figure 3.16 Groundwater hydrographs at Well 07N06E33J01M for scenarios S1 and S2.

Compared to the baseline simulation (Fig. 3.15A), annual seepage amounts increased slightly mainly up-stream of McConnell. Additional recharge from increased river seepage also raised groundwater levels

further away from the river, as Figure 3.16 shows for a well (07N06E33J01M) 1.8 miles north-west of the river. Hydrographs for scenarios 1 and 2 and the head difference 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 were aimed at estimating increases in net recharge necessary 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-MCC). Annual pumping reductions on the order of 166,000 ac-ft were necessary to hydraulically reconnect the aquifer with the channel upstream of Folsom South Canal (Fig. 3.17). Even larger reductions of approximately 250,000 ac-ft were needed to establish a similar hydraulic reconnection downstream of McConnell. Annual seepage amounts between Michigan Bar and McConnell decreased to about 25,000 ac-ft after year 6 of the simulation period (Fig. 3.15A). Between McConnell and the basin outlet seepage fluctuated around 25,000 ac-ft after the 6th year of the simulation for scenario 4 and reversed to net gaining conditions in year 6 for scenario 5 (Fig. 3.15B).

Scenario 6 (Pumping Reduction and Flow Augmentation)

In scenario 6 upstream pumping reductions (same as in S4) were combined with flow augmentation from Folsom South Canal (same as in S3).

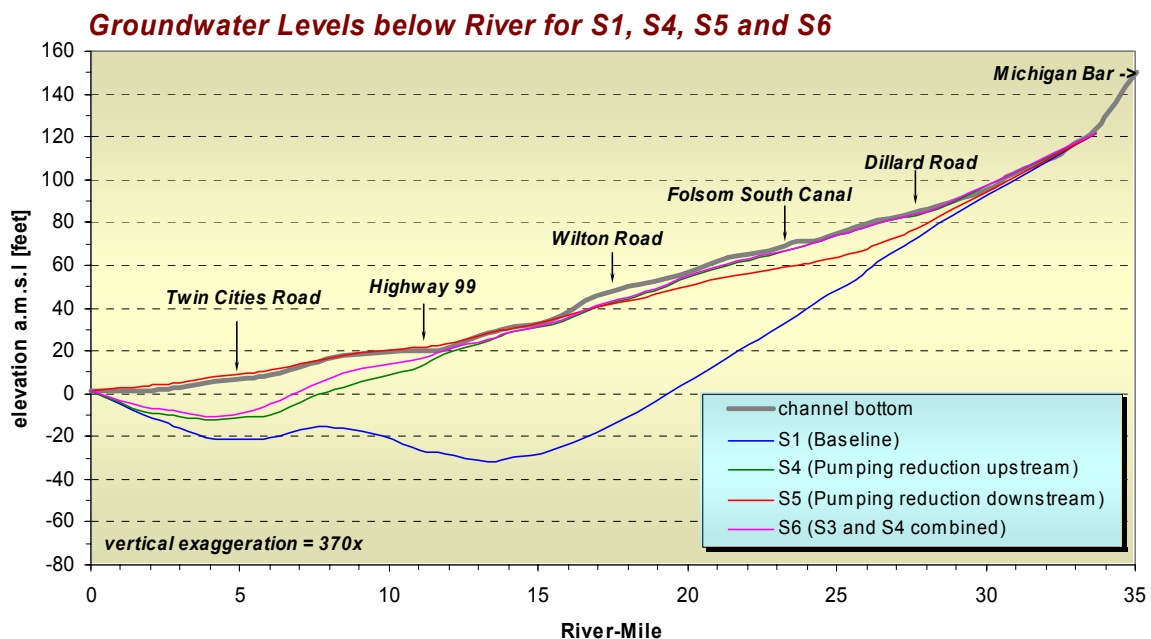


Figure 3.17. September groundwater levels below the river channel (aquifer 1) at the end of the 15 year simulation period for scenarios S4, S5, and S6.

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.3.17). That 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 McConnell, 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. Figure 3.18 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 McConnell before and after the confluence with Deer Creek respectively.

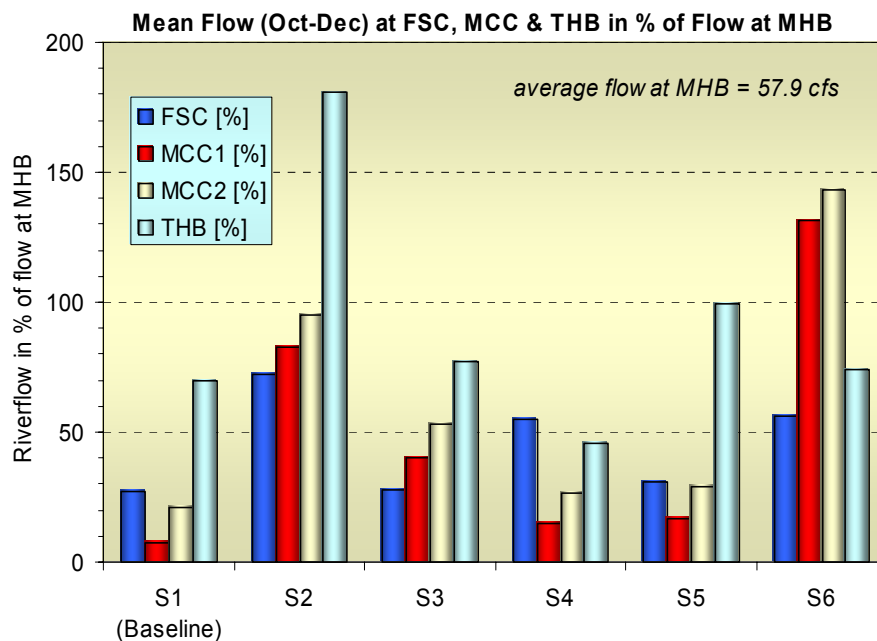


Figure 3.18. Mean fall flows along the river in percent of flow at MHB.

Under baseline conditions (S1) less than 10% of the inflow from Michigan Bar reached McConnell. The simulations also suggest that even under no pumping conditions (S2) the river reach between Michigan Bar and McConnell would be a net losing reach in the fall. Downstream of McConnell base flow contributions exceeded seepage losses in the fall and the river was gaining. Flow augmentation (S3) could maintain

average fall flows at McConnell above the minimum flow requirement despite increasing seepage losses. Upstream pumping reductions (S4) maintained significantly higher fall flows at Folsom South Canal but only marginally increased flows at McConnell (Fig. 3.18). Downstream pumping reductions (S5) mainly benefited fall flows at Thornton Bridge. The highest average fall flows at McConnell could be sustained with the combination of upstream pumping reductions and flow augmentation (S6).

Model Limitations

The spatial and temporal resolution of the regional groundwater model used in this analysis is coarse. Average node spacing in the finite element mesh is larger than 3,000 ft and simulations were performed with a monthly time step. Hence local geologic heterogeneity in the aquifer and river bed can not 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 are likely very important for the implementation of certain management strategies. Furthermore, as pointed out previously in this report, the present implementation of the Sacramento County groundwater model with the computer code IGSM is flawed because IGSM introduces errors where there is full coupling between streams and the aquifer, and streamflow and groundwater levels are fluctuating significantly. These errors, however, were not great enough in the simulations of this study to affect or weaken our conclusions.

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 drawn 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.

Management Implications

Analyses of historical data, field monitoring and the conducted numerical simulations all show that extended reaches of the lower Cosumnes River are ‘disconnected’ from the regional aquifer system, meaning that further declines in groundwater levels will not cause greater streamflow losses in those particular reaches. Nevertheless, further declines in groundwater levels will likely increase streamflow losses in those reaches that presently intersect the water table and will likely impact riparian vegetation. Between Dillard and Twin Cities Roads the unsaturated zone separating the river channel from the regional water table ranges in thickness from a few feet to more than 50 ft. The river is largely seepage dominated (case C in Figure 3.1). Based on field evidence the river upstream of Dillard Road appears to seasonally transition between losing and gaining conditions (case A and B in Figure 3.1) and might be predominantly gaining upstream of Highway 16. Similar data suggest that downstream of Twin Cities Road a transition zone exists and that the

lowest river reaches are in gaining reaches. These findings have significant implications for management of fall flows. Minimum flow requirements at Michigan Bar to sustain sufficient flows for fish migration at McConnell are dependant on the magnitude of flow losses occurring between Michigan Bar and McConnell. In turn, flow losses hinge on the level of connection between the river and the regional aquifer. Further decline of water tables in the areas where temporal or constant connection between the river and the aquifer currently exists could raise the minimum flow requirement at Michigan Bar. Already under current conditions the minimum flow requirement at Michigan Bar is often not met in October and early November, making flow augmentation necessary if sufficient flow should be maintained throughout the fall. Volumes of water needed for flow augmentation could increase. Attempts to reconnect the river with the regional groundwater system over larger portions of the river would require significant recovery of regional groundwater levels. Large annual increases of net recharge to the groundwater system would be needed to accomplish such a recovery. Given projected increases in water demands in Sacramento County (Montgomery and Watson, 1997) it is unlikely that these amounts of water will be available for such an effort in the near future. 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. 3.18). Additional efforts should focus on stabilizing groundwater levels in the sensitive transition areas upstream of Dillard Road and downstream of Twin Cities Road as well as on long term efforts to recharge the regional groundwater system.

Conclusions

Overdraft of groundwater in Sacramento County over the last 5 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 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 thousand acre-feet. Benefits from pumping reductions would be realized after several years. Benefits from increases in recharge to the basin on the order of the simulated pumping reductions could be just as large, but would take much longer to develop. 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 both immediate benefits as well as changes which 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.

Management Recommendations

In the light of the results presented in this report it is evident that restoration of fall flows on the lower Cosumnes River is a complex challenge. Changes that have been imposed on the groundwater system over many decades and that have adversely affected river flows can not easily be reversed in a few months or years. Demands on water are increasing and regional groundwater levels are further declining. Sensible management strategies will have to be developed within that context. This report can serve as a starting point for such a task. General recommendations for management can be concluded from the findings. These recommendations, however, have to be seen as general guidelines for the development of more specific strategies rather than as means to an end. Specific strategies may need additional analyses of local conditions and more specific assessment of potential impacts of implemented changes that were beyond the scope of this study. The following is a list of general recommendations developed from the results of this study:

- ***Flow augmentation:*** in times when flows received from the upper watershed fall below the critical threshold of approximately 55 cfs at Michigan Bar (MHB) flows could be augmented with water from Folsom South Canal (FSC). FSC is located 13 miles downstream of Michigan Bar. Based on the estimated average seepage loss per river mile of 1.5 cfs, augmentation from FSC could ensure sufficient flows at McConnell down to flows of 35 cfs at MHB. If flows fall below 35 cfs at Michigan Bar, flows could be enhanced with augmentation from Sly Park Reservoir in the upper watershed. An optimized combination of releases from Sly Park Reservoir and Folsom South Canal could keep the river open for fish migration throughout a wide range of flow conditions in the fall. Additional benefits to the long term recovery of groundwater levels could be achieved from additional seepage induced from augmented flows.
- ***Increasing net recharge:*** any efforts to increase net recharge to the regional groundwater system would benefit the recovery of regional groundwater levels and hence enhance the possibility to reduce seepage losses from the river channel by extending or stabilizing connected river reaches. In particular, the reaches upstream of Dillard Road and downstream of Twin Cities Road would benefit from such efforts. Increases in net recharge could be achieved by substituting groundwater pumping with surface water sources (in lieu recharge) or artificial recharge of surface water. High proportions of fine grained sediments and a complex alluvial fan stratigraphy in the lower Cosumnes basin will pose restrictions on the feasibility of artificial recharge. The river channel could be used for recharge efforts in combination with flow augmentation. Such recharge operations will be most successful

with enhanced knowledge of the three-dimensional hydrostratigraphy, including the interconnectedness of the aquifers on which success of artificial recharge schemes will depend.

- ***Natural recharge from inundated floodplains:*** efforts in recent years to restore a natural flood regime on the lower Cosumnes has resulted in extended areas of the floodplain being inundated during the winter season. These areas of the floodplain can provide significant additional sources for groundwater recharge. Further work is needed to quantify local recharge rates on the floodplain and to assess their potential for regional groundwater level recovery. However, preliminary simulations with the regional groundwater model, making simplifying assumptions of uniform and steady recharge from floodplains during periods of inundation, indicate that recharge from these areas could raise groundwater levels around the river significantly. This in turn would promote growth of riparian vegetation that would consume much of the groundwater. Further analysis are needed here to better understand the interplay between groundwater, surface water, and riparian vegetation in a heterogeneous, three-dimensional hydrologic system.
- ***Monitoring and further analyses:*** During the course of this study monitoring efforts and field investigations were conducted to compliment the numerical analyses. Results from these efforts revealed local information like the seasonal development of perched aquifers above the regional water table, estimates of travel times of river water to the water table through a thick unsaturated zone, significant variations in seepage rates over small scales and evidence for gaining river reaches at the upper and lower ends of the river, which was not completely represented in the coarser regional numerical analyses. This information can be of great importance for the development of specific management strategies especially if easy, regional solutions are not at hand. It is therefore recommended that monitoring efforts be continued and that more detailed investigations of geologic factors affecting the exchange between the river and the aquifer be conducted. Monitoring should include monthly or at least seasonal readings of groundwater levels around the river, quasi continuous measurements of groundwater levels and river stage at certain sites, and synoptic measurements of river flows at various locations along the river. Geologic factors that need further analyses are hydraulic parameters of varying stream bed materials and the extend and effects of certain low permeability layers that outcrop in the river bed. The development of a local scale (river reach) numerical model that can incorporate this information has been initiated and should be further pursued.

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