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WEAP21 – A Demand-, Priority-, and Preference-Driven Water Planning Model

Part 2: Aiding Freshwater Ecosystem Service Evaluation

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Abstract: *Potential conflicts arising from competing demands of complex water resource systems require a holistic approach to address the tradeoff landscape inherent in freshwater ecosystem service evaluation. The Water Evaluation and Planning model version 21 (WEAP21) is a comprehensive integrated water resource management (IWRM) model that can aid in the evaluation of ecosystem services by integrating natural watershed processes with socio-economic elements that include the infrastructure and institutions that govern the allocation of available freshwater supplies. The bio-physical and socioeconomic components of Battle Creek and Cow Creek, two tributaries of the Sacramento River of Northern California, USA, were used to illustrate how a new hydrologic sub-module in WEAP21 can be used in conjunction with an imbedded water allocation algorithm to simulate the hydrologic response of the watersheds and aid in evaluating freshwater ecosystem service tradeoffs under alternative scenarios.*

Keywords*: integrated watershed management, ecosystem services, salmon restoration, irrigation, hydropower*

Introduction

The planning of water resource systems requires a multi-disciplinary approach that brings together an array of technical tools and expertise along with parties of varied interests and priorities. Often, the water management landscape is shaped and influenced by a set of linked physical, biological, and socioeconomic factors that include climate, topography, land use, surface water hydrology, groundwater hydrology, soils, water quality, ecosystems, demographics, institutional arrangements, and infrastructure (Biswas, 1981; Loucks, 1995; Bouwer, 2000; Zalewski, 2002). The human demand for water, whether direct, such as domestic use or for irrigating crops for food, or indirect, such as hydropower generation or recreation, gives rise to a tradeoff landscape that increasingly seeks to balance water for human and ecosystem needs. One way of expressing this tradeoff among uses has been through the development of an ecosystem services approach, which is meant to describe both the conditions and the processes through which ecosystems sustain and fulfill human life (Daily, 1997).

Ecosystems maintain biodiversity, produce goods and services, and perform life-support functions. Freshwater aquatic ecosystem services include flood and drought alleviation, waste assimilation and purification capacity, and recreational opportunities. Goods include water for irrigation and domestic use and harvestable aquatic species (Loomis et al., 2000). Specific examples for the Sacramento River basin are shown in Table 1 and are typical of river basins. Despite their great value, the human record of stewardship of ecosystem goods and services has been poor. Largely out of a lack of understanding, or through knowingly ignoring or underestimating their real value, humans have often destroyed or impaired the ability of ecosystems to continue providing important services. In some areas, we now find ourselves attempting to turn back the clock and restore, often at great cost and with limited success, services that previously were freely available (e.g., current reforestation efforts, wetland restoration, invasive species elimination from communities that previously provided erosion control, wildlife habitat restoration, or any number of other services) (Mooney and Hobbs, 2000; NRC, 1992; Strange et al., 2002; Lackey, 2002; 2003).

Table 1. Some major goods and services provided by aquatic ecosystems of the Sacramento Watershed and its tributaries

Extractive	*In situ*
Water for agriculture	Aquatic-based recreation
Water for domestic consumption	Flood/drought mitigation
Water for industry	Soil Fertility/Regeneration
Harvestable fish/wildlife	Water for fish and wildlife habitat
	Water for hydro power
	Sediment/nutrient transport
	Water quality improvement

These reformulations often lead to conflicting viewpoints, where "one person's stressor might be another person's service." For example, in situations where the use of the basic resource such as water is at or near capacity, competition among service users is likely to occur. From the aspect of any one user, the allocation of that resource to another competing service can be viewed as a stressor. For example, water diverted for agriculture provides a service; however, it may limit the amount of water available for other needs. Thus, agricultural use of the water is both a service to farmers and those dependent on the goods produced and a stressor to natural systems through changes in the quantity and quality of water as a result of its agricultural use. The ability to capture this competitive interaction is important to understanding the relative trade-off between the different ecosystem services. At the core of this process is the hydrologic cycle, a central feature of the model developed in this work and applied in this paper.

Brief Summary of WEAP21

The Water Evaluation and Planning Model Version 21 (WEAP21) is an integrated water resource management (IWRM) tool designed to evaluate user-developed scenarios that accommodate changes in the bio-physical and socio-economic conditions of watersheds over time (see Yates et al., this issue; Raskin et al., 1992). One of WEAP21's strengths is that it places the demand side of the water balance equation on a par with the supply side. The data structure and level of detail may be easily customized to meet the requirements of a particular analysis and to reflect the limits imposed when data are limited. WEAP21 can describe the water-related infrastructure and institutional arrangements of a region in a comprehensive, outcome-neutral, model-based planning environment that can illuminate strategies and help evaluate freshwater ecosystem services. This capability is powerful in reducing potential conflicts among users in a study area through, for example, scenario-based gaming approaches.

Operating on the basic principle of water balance accounting, WEAP21 can address a range of inter-related water issues facing municipal and agricultural systems, including multiple surface/groundwater sources, sectoral demand analyses, water conservation, water allocation priorities, conjunctive use, general reservoir operations, and financial planning. The water system is represented in terms of its various supply sources (e.g., soil moisture, surface water, groundwater, desalinization plants, and water reuse elements); related infrastructure for withdrawal, transmission, and wastewater treatment; water demands (both instream flow requirements and off-stream consumptive uses), and demand-side management; associated capital and operation and maintenance costs; pollution generation; and simple in-stream water quality.

The advancements of WEAP21 have been based on the premise that at the most basic level, water supply is defined by the amount of precipitation that falls on a watershed or a series of watersheds, with this supply progressively depleted through natural watershed processes, human demands and interventions, or enhanced through watershed accretions. Thus, WEAP21 adopts a broad definition of water demand, where the watershed itself is the first point of depletion through evapotranspiration via surface-atmosphere interactions (Mahmood and Hubbard, 2002). These processes are governed by a water balance model that is used to define watershed scale evaporative demands, rainfall-runoff processes, groundwater recharge, and irrigation demands. These are linked to the stream network and water allocation components via the WEAP21 interface, where a stream network tracks water allocations and accounts for streamflow depletions and accretions.

Hydrologic Models of Cow and Battle Creek

Two small sub-catchments of the Sacramento watershed of northern California, USA were chosen to evaluate

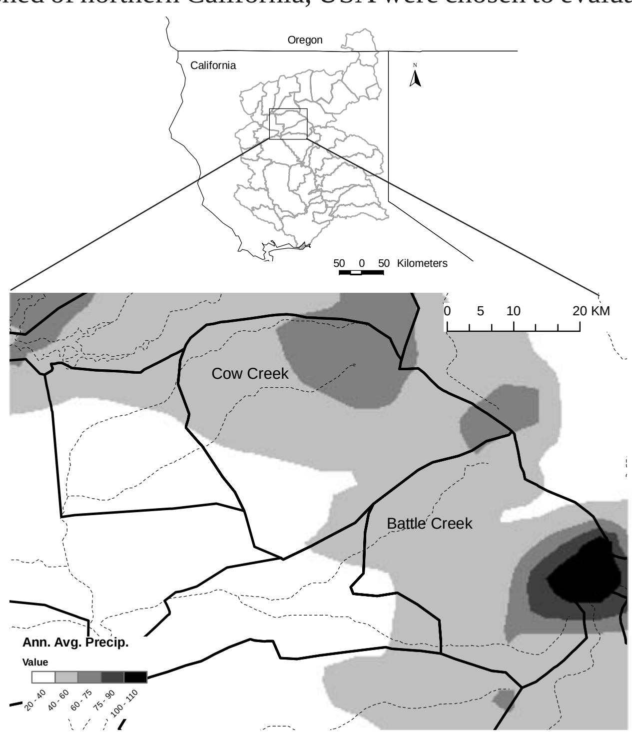


Figure 1. Location and subdivision of Cow Creek (Upper and Lower) and Battle Creeks (Upper and Lower) and the annual average precipitation (inches) for the period 1961 – 1990 (Daly et al., 2001)

the surface-hydrologic, groundwater, water temperature, and allocation models developed in WEAP21 and to illustrate how the model could be used to help evaluate the tradeoffs among a watershed's ecosystem services. The two catchments combine to define the United States Geological Survey's eight-digit Hydrologic Unit Code (HUC) classification (18020118). Interestingly, although Battle and Cow Creeks are in close proximity to one another and are climatologically similar, their hydrologic responses are quite different, primarily because of different geologic histories. The Battle Creek catchment was influenced by volcanic deposition, most notably Mount Lassen, which has given rise to a prolific underground spring system that yields high summer baseflows with reduced seasonal and interannual variability. Cow Creek, Battle Creek's northern neighbor, was not as geologically influenced by these historic volcanic episodes. Its hydrologic response is similar to many Sacramento tributaries, which includes high late winter and spring peak flows and low summer baseflows. Figure 1 shows the geographic location of these watersheds, with an estimate of the average annual precipitation between 1961 and 1990.

The eight-digit Cow-Battle HUC was sub-divided into five smaller, irregular sub-catchments that defined the upper and lower portions of the watersheds. The upper catchments are dominated by winter precipitation and spring snowmelt, while the lower catchments, which extend out across the Central Valley, are warmer and have a minimal snowmelt contribution. The sub-catchments were further subdivided into several land covers fractions (evergreens, deciduous trees, shrubs, grassland, and pasture), which are the computational elements of the conceptual water balance model (Yates et al., this issue). Table 2 shows the total area of each sub-catchment, with estimates of the percent land cover fraction for each. In this modeling exercise, we've assumed that only Lower Cow has irrigated pasture, covering about 7 percent or 3,300 hectares of its total land area, estimated from the United States Geologic Survey's National Land Cover Dataset (Homer et al., 2003).

The two-layer soil moisture scheme was applied to three of the four sub-catchments, including Upper Cow, North and South Forks of Upper Battle, and Lower Battle; while Lower Cow applied the one-layer scheme that was linked to an alluvial groundwater aquifer with surface-subsurface interaction (Yates et al., this issue). The model was run on a monthly time step and tracked the relative

Table 2. Total sub-catchment areas and the percentage of land cover designated for each of the sub-catchments of Cow and Battle Creeks

	Upper Cow	*Lower Cow*	*SF Upper Battle*	*NF Upper Battle*	*Lower Battle*
Area (km^2)	960	480	325	325	400
Deciduous	10	15	5	5	3
Evergreen	60	15	75	75	75
Shrubs	10	21	15	15	15
Grass	20	42	10	10	7
Irrig. Pasture	0	7	0	0	0

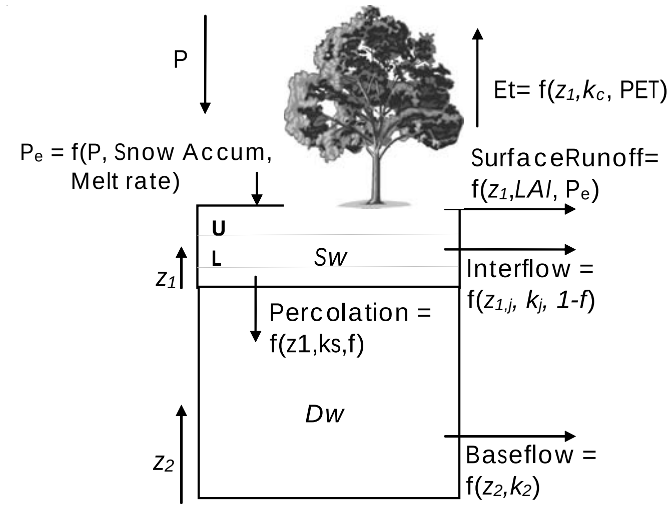


Figure 2. Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type, j

storage, z_j and z_2, based on water balance dynamics that include infiltration, evapotranspiration, surface runoff, interflow, percolation, and baseflow (Figure 2). The climate forcing data consisted of total monthly precipitation and average monthly temperature, relative humidity and wind speed taken from Mauer et al. (2002). The schematic of these watersheds are shown in Figure 3 as they are depicted in WEAP21.

The conceptual water balance model requires several parameters for each land cover fraction *j*. This includes

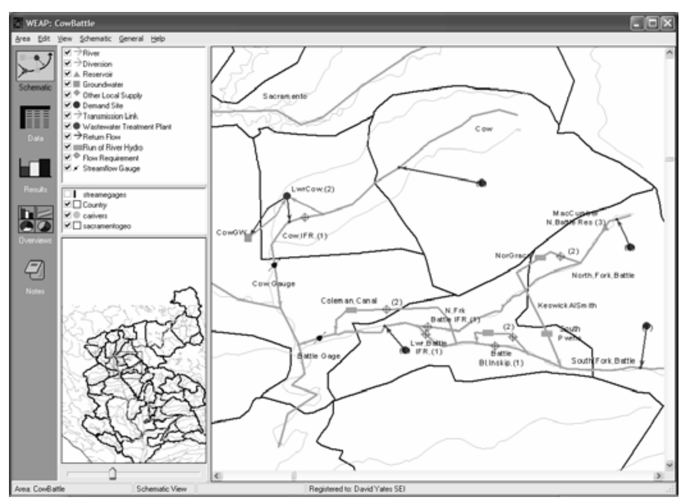


Figure 3. The WEAP21 interface and schematic of the Cow-Battle watersheds, showing the hydrologic and infrastructural linkages. The dots with single connecting lines to the rivers represent the spatial watershed elements. The symbols labeled IFR are the in-stream flow requirements. The dark dots with lines near the confluence with the Sacramento are the stream gage locations. The groundwater monitoring well of Cow Creek is the labeled and marked with a dark circle, while WEAP's representation of its alluvial aquifer is indicated by the rectangle. The triangle is the MacCumber/North Battle Creek reservoir.

estimates of leaf area index (LAI_j), which is used to specify the hydrologic response of the upper soil moisture store and crop coefficients ($k_{c,j}$) for describing potential evapotranspiration requirements. Total soil moisture storage capacity, Sw_j (mm), is conceptualized as an estimate of the rooting zone depth, while the parameter, k_j (mm/month), is an estimate of the root zone hydraulic conductivity (mm/time). The water balance model was run on a monthly time step, with precipitation given as a total accumulation (mm/month) as apposed to an "average day of the month" (mm/day) and so hydraulic conductivity of the upper (k_j) and lower (k_2) stores is the maximum possible water flux at full storage, when z_j and z_2 equal 1.0. These conductivities should not be considered saturated hydraulic conductivities in the strictest sense, which are usually prescribed in units of in length/day (Rawls et al., 1993). The parameter, f_j, is a quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions upper store discharge water either horizontally or vertically.

The period of October 1965 to September 1998 is used to simulate the monthly hydrologic response of these two watersheds. Both Cow and Battle Creeks have a United States Geological Survey stream gage near their confluence with the mainstem of the Sacramento River below Redding, CA. These were used to compare the modeled versus observed streamflows. The mean monthly precipitation and runoff hydrographs from these two tributaries, scaled by their representative area, are given in Figure 4. Note the striking difference in the hydrologic response of these two watersheds: Cow Creek has low summer baseflows, and Battle Creek has high summer baseflows. This difference occurs despite quite similar average monthly rainfall patterns observed over the watersheds during this period.

The Cow Creek alluvial groundwater aquifer was assumed to extend throughout most of the Lower Cow subcatchment. The following assumptions, based on Geographical Information System (GIS) analyses, were made regarding the parameterization of the Lower Cow alluvial aquifer: 1) the lateral aquifer extent, w_d, is approximately 8 km from the central stream channel; 2) the stream-aquifer interface length, l_d is 20 km; 3) the wetted stream depth, d_w is a constant 0.5 meter; and 4) the hydraulic conductivity of the alluvial aquifer is assumed to be 40 m/month with a porosity of 0.1 (Yates et al., this issue).

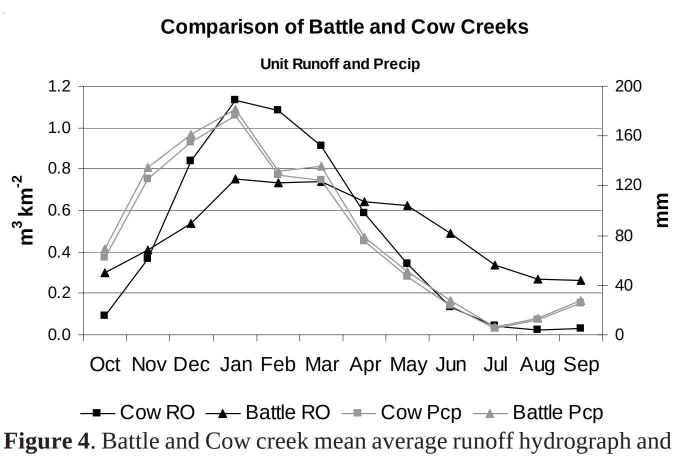


Figure 4. Battle and Cow creek mean average runoff hydrograph and precipitation for the period 1965 to 1998

Model Calibration of Watershed Responses

Model calibration was done manually via trial and error, seeking to minimize the root mean square error (RMSE); maximize the correlation coefficient, R; and reproduce the average annual flow volume for both Cow and Battle Creeks. Because the calibration was done manually, the entire period of 1965 to 1998 was used to evaluate model performance. The calibration procedure began by approximating the values of Sw_j and LAI based on estimates from referenced sources (Jackson et al., 1996; Allen et al., 1999; Scurlock et al., 2001; Gordon et al., 2003). The lower storage zone, Dw for Upper and Lower Battle Creek and Upper Cow Creek were arbitrarily set at 5000 mm. Calibration proceeded by making initial estimates of k_2, k_j, and f_j, and subsequently adjusting the parameters to improve the RMSE, R, and annual average flow volume metrics.

For each sub-catchment, the initial estimates of k_2 were made by separating the baseflow and computing an average monthly equivalent water depth. With Battle Creek as an example, streamflow data that encompasses both Upper and Lower Battle Creeks had an average monthly baseflow volume of $20x10^6$ m^3 for the period 1965 to 1998. It was assumed that the baseflow contribution from the Upper Battle Creek watershed was 75 percent of the watershed's total, with a contributing area of 600 km^2; while Lower Battle Creek accounted for 25 percent of the baseflow and a contributing area of 330 km^2. For Upper Battle Creek, the equivalent baseflow depth is then ($20E10^6$ m^3 * 0.75)/600 km^2 or 25 mm, while for Lower Battle Creek the equivalent baseflow depth is ($20E10^6$ m^3 * 0.25)/330 km^2 or 15 mm. The discharge rate from the lower store is given as, $k_2 * z_2^2$, so if average relative storage, z_2 is assumed to be 25 percent for both the Upper and Lower Battle Creek lower stores, then a first estimate for Upper Battle's lower store hydraulic conductivity is, $k_2 \approx 25/0.25^2$ or 400 mm/month, while for Lower Battle Creek, $k_2 \approx 15/0.25^2$ or 240 mm/month.

A similar procedure was followed for estimating initial values of k_j, although it was estimated using the difference between the observed, average monthly baseflow and the monthly average peak discharge. So for Battle Creek, the average monthly peak winter runoff volume for the period 1965 to 1998 was approximately 60E6 m^3, which is 40E6 m^3 in excess of the 20E6 m^3 baseflow. Again, it was assumed that the excess runoff contribution from the Upper Battle Creek watershed was 75 percent of the watershed's total, with a contributing area of 600 km^2, so the equivalent runoff depth was estimated as

Table 3. Initial and final calibration parameters used in the hydrologic model. *LAI* and *Rd* are land cover specific; with values applied to each land cover

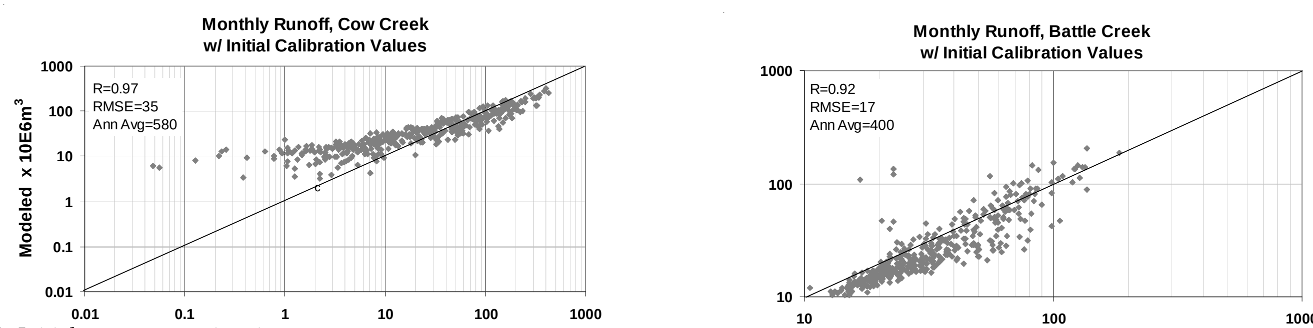
Initial	*Deciduous*	*Evergreen*	*Shrubs*	*Grass*[2]
LAI_j	3.0^t	4.6	1.7	2.0
Sw_j	1500	1200	900	700
	Upper Cow	*Lower Cow*[3]	*Upper Battle*	*Lower Battle*
F	0.4	0.6	0.4	0.6
k_j	200	120	138	83
k_2	150	-	350	240
Dw	5000	-	5000	5000
z_2	0.15	-	0.25	0.25
Final	*Deciduous*	*Evergreen*	*Shrubs*	*Grass*[2]
LAI_j	3.0^t	4.6	1.7	2.0
Sw^j	900[c]	720[c]	540[c]	455[c]
	Upper Cow	*Lower Cow*[3]	*Upper Battle*	*Lower Battle*
F	0.9	0.6	0.2	0.2
k_j	30	60	200	130
k_2	300	-	455	312
Dw	500	-	5000	5000
z_2	0.10	-	0.25	0.25

Notes: [t] Includes seasonal variability; [2] Irrigated pasture has a 30 percent higher R_d value to reflect the fact that it is usually ripped 500 mm to fracture the soil and improve infiltration. The lower store parameter values were not used in Lower Cow Creek since this sub-catchment is linked to an interactive aquifer. [c] Only Cow Creek's R_{dj} values were adjusted, while Battle Creek's final values were those used in the initial calibration.

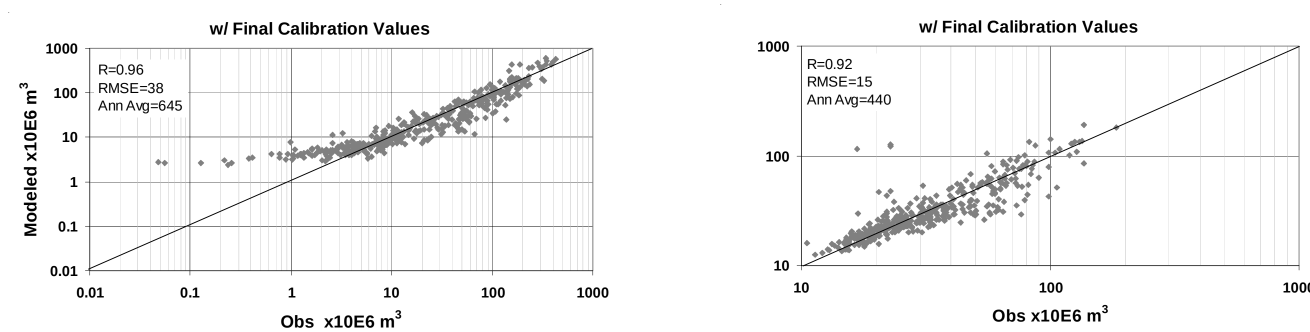
($40E10^6$ m^3 * 0.75)/600 km^2 or 50 mm, while the Lower Battle Creek equivalent baseflow depth was ($40E10^6$ m^3 * 0.25)/330 km^2 or 30 mm. Discharge rate from the upper store of each land cover fraction, *j* is given by, $k_j * z_{1,j}^2$, so if $z_{1,j} \approx 60$ percent for both the Upper and Lower Battle Creek upper stores for all land cover types during peak winter runoff, then a first estimate for Upper Battle's upper store is, $k_j \approx 50/0.60^2$ or 138 mm/month, while for Lower Battle Creek $k_j \approx 30/0.60^2$ or 83 mm/month. A similar procedure was followed for estimating the initial model parameters for Cow Creek, with values for both basins summarized in Table 3a.

The initial values of f_j for Upper and Lower Battle Creek were 0.4 for all sub-fractions, *j* which assumes that 40 percent of the monthly discharge from the upper store is interflow that contributes directly to streamflow, while the remaining 60 percent recharges the second store. For Upper and Lower Cow Creeks, the initial values of f_j were 0.6 for all sub-fractions, as it is assumed that a larger percentage of the upper store discharges immediately to the river, while 40 percent was assumed to be deep recharge of the second store.

Figure 5a shows log-log scatter plots of the monthly observed versus modeled flow volumes and the three summary statistics (*R*, RMSE, and annual average volume) for the period 1965 to 1998 based on the initial parameter values given in Table 3a for both Battle and Cow Creeks. The mean annual observed flow volume for the period 1965 to 1998 was 640x10E6 m^3 and 460x10E6 m^3 for Cow and Battle Creek, respectively. For Cow Creek, peak simulated discharge volumes tended to be under-predicted; while low flow volumes, particularly those below about 40x10E6 m^3, were over-predicted and the model tended to under



a) Initial parameter estimation



b) Final parameter estimation

Figure 5. Scatter plots and summary statistics of initial (a) and final (b) calibration of monthly flow volume (*10E6 m^3) for Cow Creek (left panels) and Battle Creek (right panels). Inset within each plot are the monthly correlation coefficient (R), the root mean square error (RMSE, *10E6 m^3) of the monthly flow, and the model estimate of the annual average runoff (*10E6 m^3)

perform in reproducing extreme low flows. For Battle Creek, the initial parameterizations led to under-predicted low flows, while flow volumes above approximately 80x10E6 m^3 tended to be more accurately reproduced.

From the initial simulations of Cow Creek flow, it was clear that recharge to the second store was too great, likely because of erroneous estimates of the storage capacities and an over estimation of this layer's ability to drain through to the sub-surface. Recall that Cow Creek was not as influenced by volcanic deposition when compared with Battle Creek. The Sw_j parameter for the Upper and Lower Cow Creek land use fractions were finally reduced by 60 percent relative to their initial values, and the hydraulic conductivity reduced to 60 mm/month and 50 mm/month for the upper and lower stores, respectively. Finally, a larger fraction of the upper store was allowed to become immediate runoff and not sub-surface recharge, thus f_j was increased to 0.7. Note the second store's hydraulic conductivity, k_2, value was increased while the total storage capacity was decreased by a factor of 10 to 500 mm. The initial relative storage, z_2, was reduced to 0.10. The parameters were adjusted to these values to reflect the fact that Cow Creek exhibits very little sub-surface storage and appears to drain rapidly.

An important calibration criterion was to ensure that neither the upper nor lower stores accumulated mass over the 33 year simulation period. Figure 6 shows the average values of z_2 for Upper Cow and Battle Creeks using the final parameter values (Table 3b) over the simulation period. Indeed, neither trace indicates any major storage trend. Figure 5b again shows the monthly flow estimates as scatter plots and the other calibration values (*R*, RMSE, and annual average volume) based on the final parameters used in calibration and summarized in Table 3b. Note the model still tended to over predict the extreme low flows of Cow Creek, although there is marked improvement. There is also improvement in the estimate of the annual average flow volume and the RSME values.

For Battle Creek, no change was made to the Sw_j values; rather the upper and lower stores' hydraulic conductivity rates were increased by 50 percent and 30 percent relative to their initial values, respectively. Likewise, the flow fractions, f_j were reduced to 0.2 for both Upper and Lower Battle Creek to reflect greater seepage to the second store. No other changes were made to the Battle Creek parameterization, and Figure 5b compares the monthly flow estimates to observations on the log-log scatter plot, along with the other criterion using the final parameter values for Battle Creek. The simulation of both the high and low Battle Creek flow volumes was agreeable with historical observations, with noted improvements in the annual average flow volume and a reduction in the RMSE value.

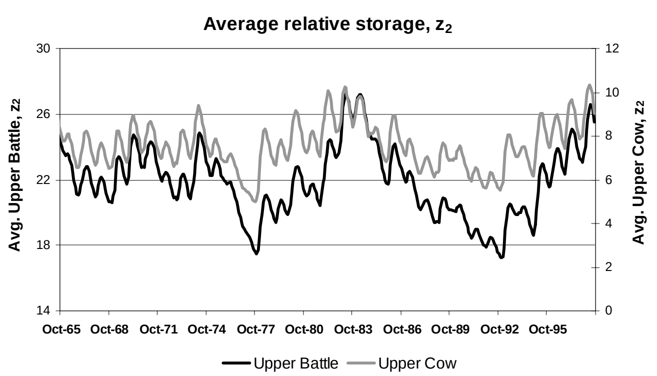


Figure 6. Simulated average relative storage, z_2, for Upper Battle (left scale) and Upper Cow (right scale) creeks using the final calibration parameters given in Table 3b

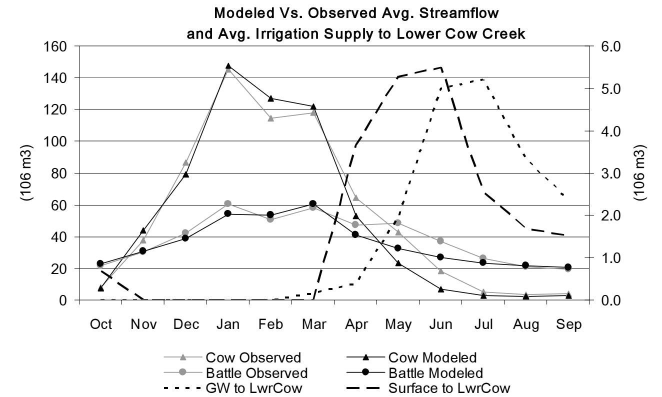


Figure 7. Monthly mean streamflow for Battle and Cow Creeks (left scale), and the average irrigation volume applied to the Lower Cow sub-catchment (right scale) from the groundwater aquifer (GW to LwrCow) and the surface water (Surface water to LwrCow). All were averaged over the period October 1965 to September 1998.

In summary, the WEAP21 hydrologic sub-module did an adequate job of reproducing most of the variability and the low flow characteristics of both watersheds, with a noted inability to capture the extreme low flows of Cow Creek. Using a mean monthly flow time series (Figure 7), the model did not accurately replicate the high late spring baseflows for Battle Creek, particularly May and June; the model tended to overestimate the early winter streamflow on Cow Creek; and the model underestimated its late spring flow. In spite of these shortcomings, the physical hydrologic component of WEAP21 was capable of capturing the most important hydrologic processes that dominate these two watersheds.

The Alluvial Groundwater Aquifer of Cow Creek

Recall from Figure 3 that Lower Cow is characterized as having an alluvial aquifer from which water can be pumped to meet summer irrigation requirements. Figure 8 shows observed groundwater elevations for a monitoring well (California Department of Water Resources, Well #31N03W29N001M) located in the Redding groundwater basin in the Lower Cow Creek sub-catchment, compared with model estimates of relative groundwater levels (e.g. l_d, height above river) for the final calibration simulation. The streambed is approximately 390 meters above sea

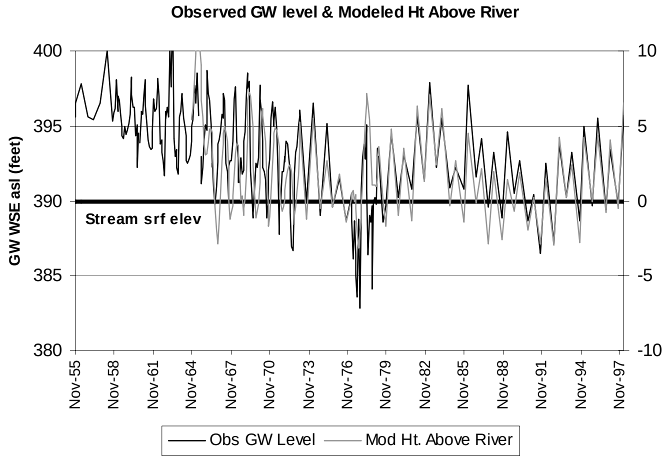


Figure 8. Observed water surface elevation (WSE) for California State Well Number 31N03W29N001M (dark line) and the modeled height above river (HAR) for the Cow Creek aquifer (light line). The Cow Creek stream surface elevation is identified at 390 m asl.

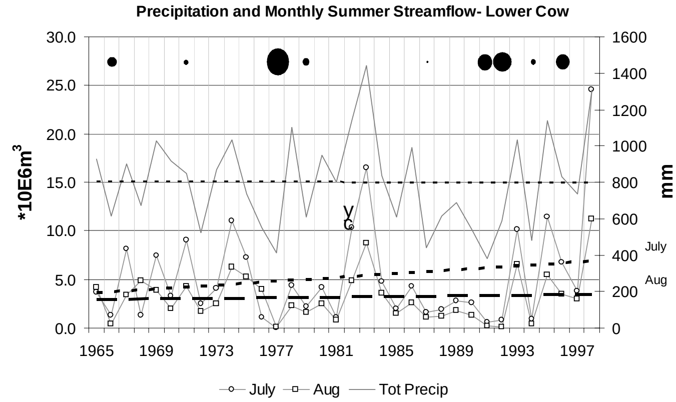


Figure 9. July and August observed streamflows in Lower Cow Creek for the period 1965 to 1998, and the total annual precipitation in the Lower Cow Creek watershed for the same period. The dashed lines are the linear trends for each series. The dark circles are model results, indicating the years and the relative volume of the in-stream flow requirements (IFR) that were unmet relative to 1977, the year of maximum unmet IFR.

level (asl), with groundwater levels slightly elevated relative to the major Cow Creek streambed, although it appears that in dry years the groundwater table can become lower than the riverbed (Figure 8).

In general, the model's simulation of groundwater levels compared favorably with the observed well levels, exhibiting similar seasonal variability and capturing the general inter-annual trend. The large seasonal variability of observed groundwater levels in the Lower Cow Creek implies large hydraulic conductivity rates of its alluvial aquifers. These high rates suggest considerable late winter and early spring percolation to the underlying aquifer, relatively rapid horizontal discharge of this infiltrated water to the river in late spring, and a reduction in the groundwater gradients relative to the stream bed. These reduced groundwater gradients lead to lower summer baseflows in the mid and late summer.

Together, these observations suggest that Cow Creek is a marginally gaining river along its lower reaches in normal years and a losing stream during extended dry periods. No well pumping data are available in the region to help understand its role in stream-aquifer dynamics. It is interesting to note that the well data reproduced in Figure 8 reveals a general decline in groundwater levels from the mid 1950s to the 1970s which have never recovered, suggesting that groundwater pumping has impacted the aquifer and well levels. Although there is no long-term trend in precipitation from the 1950s through the 1990s, there are certainly wet and dry cycles that exhibit a strong correlation with the summer low flows (Figure 9), while there appears to be an upward trend in the July streamflow. This is perhaps explained by the pumping of surface supplies for irrigated agriculture in the spring and the subsequent slow return of this irrigation water to the river in the summer, leading to enhanced baseflows. Note that this trend is not as strong by August.

Cow Creek Agriculture and In-stream Flow Requirements

In addition to the *base* scenario used in model calibration, two additional scenarios were created to investigate the role of irrigated agriculture on Cow Creek hydrology. The first scenario assumed an increase in irrigated acreage of 35 percent (*+35%-irrigation*), while the second scenario assumed a 50 percent reduction (*-50%-irrigation*) in irrigated acreage. Annually, pasture in the Central Valley requires nearly 1,400 mm of irrigation water, assuming it is applied using a flooding technique and to a mature, developed stand (Forero et al., 2003). Watering begins in April with the grass harvested in June and the re-growth subsequently irrigated and grazed from July through October. September and October require about 300 mm of water, with none applied through the winter. The base scenario resulted in the delivery of approximately 40 million m^3 of water per-year, supplying the 3,300 hectares of pasture approximately 1,200 mm annually, which is slightly lower than the 1,400 mm typically required. Irrigated pasture in Lower Cow Creek was configured in WEAP21 to be either supplied by surface water drawn from the stream or by groundwater pumped from the alluvial aquifer. In WEAP21, the preferences were set so that irrigation demand would be first satisfied by the surface supply ($Pe = 1$), and then by the groundwater supply ($Pe = 2$) only when the surface water was physically unavailable or the in-stream flow requirement was unmet. The in-stream flow requirement (IFR) was given a higher priority ($Pr = 1$) than the irrigation demand of Lower Cow ($Pr = 2$).

The high spring flows of Lower Cow Creek provided an adequate surface supply to meet the early season irrigation demands for both scenarios (Figure 7). The allocation algorithm appropriately drew water first from the surface supply ($Pe = 1$). As summer progressed, the flows were typically too small, thus supply was increasingly drawn from the Lower Cow alluvial aquifer (*Pe = 2*) to meet the summer irrigation demands and attempt to satisfy the in-stream flow requirements. Note that no physical limit (e.g. pumping capacity) is placed on the amount of groundwater that can be lifted for irrigation. Irrigation in the base scenario reduced the average annual runoff by about 3 percent, but demand is always fully met through a combination of surface and groundwater supplies, while the IFR is periodically violated in late summer/early fall of low flow years (Figure 9).

Figure 10 shows the percentage difference of streamflow among the three scenarios, given as $\Delta_{s,k} = [(Q_{s,k} - u_k)/u_k] * 100$, where $u_k = 1/3\ \Sigma(Q_{s,k})$, $Q_{s,k}$ is the Cow Creek streamflow near the confluence with the Sacramento for scenario *s* of month *k,* and u_k is the average monthly streamflow of the three scenarios. Of particular note, the lowest July baseflows correspond to the *base* scenario (e.g. 3,300 hectares of irrigated pasture), while the highest summer flows tend to correspond to the *-50%-irrigation* scenario until late summer. The base scenario led to the extraction of spring surface supplies that are not large enough to contribute to late summer baseflows. As summer ensued, streamflows were insufficient to meet irrigation demands and groundwater was pumped in support of irrigation requirements (Figure 7). The combination of these two processes leads to a lower groundwater table in the summer and thus lower baseflows.

The *+35%-irrigation* scenario had the largest reduction in flows relative to the other scenarios from October to June, due to higher irrigation demands of both surface and groundwater supplies in early and mid-summer. Surface water withdrawals for irrigation in the late spring/early summer would normally pass out of the basin, but instead slowly returned to the river from the upper soil moisture storage and from a recharging aquifer until July. These processes increased streamflow in mid summer for the *+35%-irrigation* scenario, but as irrigation requirements diminished in early fall, the groundwater contribution to streamflow decreased, and a depressed groundwater table produced declining streamflows in the fall and winter seasons. This result appears consistent with observations, such as the trend of increasing mid-summer streamflow in Cow Creek, but an absence of this trend in late summer (Figure 9). The *-50%-irrigation* scenario had the highest spring to mid-summer streamflows, but late summer and early fall flows were lower than the base scenario, as irrigation return flows in the base scenario supported higher late summer and fall flows.

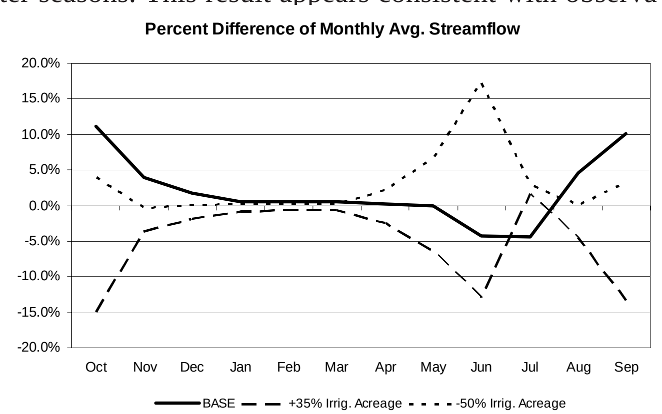


Figure 10. The percent deviation of streamflow relative to the average of all three monthly values

From the perspective of aquatic ecosystem services in Cow Creek, these scenarios imply subtle differences. The WEAP21 mode results suggest that irrigated pasture has increased the watershed's annual average evaporative loss by about 6 percent. This translates into a roughly 3 percent decline in the average flow volume downstream at Cow Creek's confluence with the Sacramento River and an approximate 0.6 meter drop in the mean groundwater elevation. Thus, irrigated agriculture occurring on tributary after tributary would have broad scale implications on overall watershed hydrology. However, this additional evaporative demand is consumptively used for pasture production which is an aquatic ecosystem service in its own right, and cannot be disregarded.

The above analysis highlights the potential benefits of using WEAP21 to develop conjunctive use strategies for meeting irrigation demands using both surface and ground water resources. Figure 10 suggests that WEAP21 can be used to determine thresholds of irrigation volume needed to enhance late summer baseflow, since the watershed acts as a storage buffer that captures earlier "excess" summer irrigation water. Conversely, model results also suggest that additional irrigation does not necessarily translate into enhanced baseflows, since under heavy irrigation (the *+35%-irrigation* scenario), increased baseflows were shown to only occur during a sort period in mid-summer, as depressed groundwater tables could not continue to support higher late summer flows. Understanding these interactions on streamflow is important in developing strategies to reduce the impacts or even benefit from irrigated agriculture. We now turn our attention to Battle Creek.

Battle Creek Hydropower and Chinook Salmon

Prior to hydropower development, Battle Creek provided a continuous stretch of prime habitat for anadromous Chinook salmon from its confluence with the Sacramento River upstream to natural migration barriers. Several small diversion dams built for hydropower production in the 1900s effectively moved the natural migration barrier downstream. In the 1940s, the Coleman fish hatchery was developed on the lower reaches of Battle Creek to mitigate the impacts on fish from these and other developments such as Shasta Dam on the upper Sacramento.

In spite of the changes to natural flows, Battle Creek is still regarded as a unique salmon producing watershed because of the relatively large numbers of Chinook salmon that historically spawned there and because of its potential to accommodate all four runs of the Chinook. For example, the only other population of winter-run Chinook salmon outside of Battle Creek occurs in the Sacramento mainstem, downstream of the Shasta Dam. The majority of the population spawns in areas of the Sacramento where high water temperatures periodically threaten these fish. In the event that water temperatures are lethal during a drought on the Sacramento River, the winter run Chinook would be impaired. Therefore, restoration of Battle Creek stream habitat would help support the winter-run salmon, because it is unlikely that Battle Creek habitat would be simultaneously impacted by the same high temperature conditions that could occur on the Sacramento River, giving the winter-run Chinook a spawning alternative (US DOI, 1996).

The unique hydrology of Battle Creek gave rise to considerable investments in hydropower infrastructure and major alterations in watershed dynamics over the years. The Battle Creek hydropower projects produce an annual average output of approximately 250,000 MWh that is almost all run-of-river generation. Two small storage reservoirs on the North Fork provide about 150 million m^3 (approximately 150,000 acre-feet) of storage, which is approximately 40 percent of Battle Creek's average annual flow.

There are plans underway to remove some of these diversion dams, restoring approximately 64 kilometers (40 miles) of river reach while trying to minimize the impact on hydropower production (USBRMP, 2001). In addition to restricting migration access, these diversion dams reduce the flow to less than 10 percent of the summer normal low flow, leading to higher summer water temperatures in the downstream reaches. The combination of these factors has dramatically reduced the available cold-water habitat. Spawning and egg incubation of Winter-run Chinook are optimal at a water temperature of about 14.5 °C. Water temperature greater than about 17.0 °C may be lethal to the eggs and juvenile fish (Meehan and Bjornn, 1991).

The WEAP21 model is used to evaluate two of the alternatives being proposed for restoration and to illustrate the ability of the model to evaluate their tradeoffs. Figure 3 shows a simplified WEAP21 schematic of the Battle Creek Watershed, and the major diversions, powerhouses, and canals that crisscross the basin. These include the MacCumber and North Battle Creek Reservoirs which have been combined as a single facility, and three diversion canals, including Keswick/Al Smith, Inskip, and the Coleman canal and their associated hydropower facilities. Notice that the Keswick/Al Smith Diversion takes water from the North Fork and moves it across the basin to the South Fork of Battle Creek. All scenarios assume in-stream flow requirements have the highest priority (*Pr = 1*), but currently the actual value of this requirement is remarkably low: 0.08 m^3/s (3 cfs) on the North Fork, and 0.14 m^3/s (5 cfs) on the South Fork above their confluence. Hydropower production is given a secondary priority after the in-stream flow requirements.

Comparisons are made among the potential for habitat restoration as measured by streamflow and stream water temperature, hydropower reductions, and operational changes on the MacCumber/North Battle Creek Reservoir complex. Most of the alternatives to restore riverine habitat are centered on the removal of some or all of the diversion dams, although one alternative does call for the placement of fish ladders and screens at these diversions to improve upstream accessibility and simultaneously increase IFRs. In WEAP21, this alternative scenario (*Alt 1*) constitutes higher North and South Fork IFRs of 1.4 m^3/s (50 cfs) for all months. A second alternative (*Alt 2*) includes the higher IFRs, the removal of the Inskip and Coleman diversion dams, and the realignment of the north-south carrier canal so that it is linked directly to the Coleman canal. Alternatives 1 and 2 are essentially the same for the North Fork, since *Alt 2* only includes removal of dams on the South Fork.

Figure 11 shows the mean distribution of temperatures along both the North and South Forks reaches for all three scenarios. The current diversion regime (base scenario) leads to the highest North Fork temperatures in the summer, since less water remains in the North Fork due to South Fork diversions for hydropower generation. Consequently, most of the South Fork river water remains cooler in the summer as compared to its North Fork neighbor because the South Fork includes both North and South Fork water that periodically mixes at high volumes. However, after water is diverted at the Coleman Canal diver-

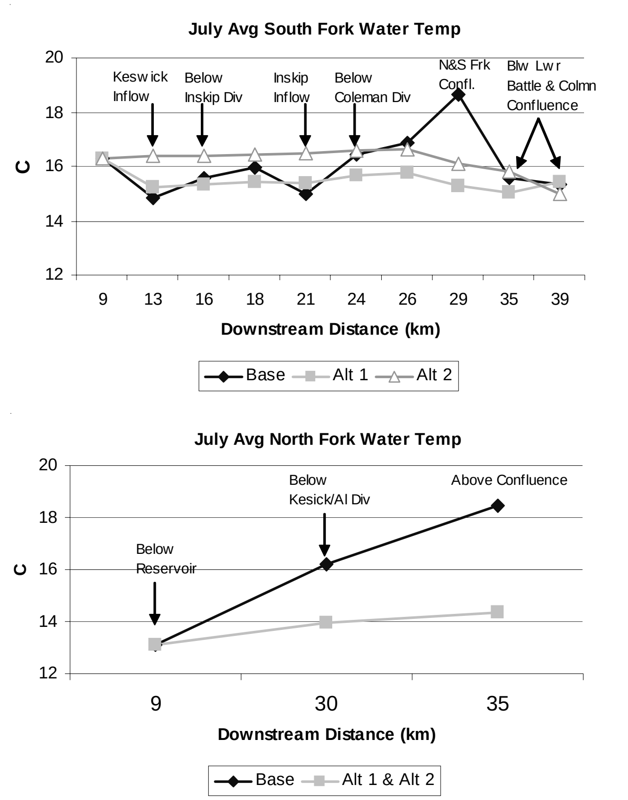


Figure 11. Average in-stream water temperature in July for the Base, Alternative 1 (*Alt 1*), and Alternative 2 (*Alt 2*) along the stream channels for both the South and North Forks of Battle Creek

sion point, the flow volume remains small until far downstream. Thus, even after the North and South Fork junction, the water temperatures remain elevated due to low flow conditions, as a majority of the flow remains in the Coleman canal.

If the installation and maintenance costs of fish ladders and screens are not considered, and if it is assumed they would be effective in providing suitable and abundant habitat for spawning salmon, then *Alt 1* is arguably the best in terms of total service provision. Hydropower production is reduced by about 15 percent on an average annual basis due to higher in-stream flow requirements while water temperatures are reduced substantially on the North Fork (Figure 11). By simply raising the in-stream flow requirements for both forks, as given by both scenarios, streamflow temperatures are reduced below the 17º C threshold. The *Alt 2* scenario does lead to a more dramatic reduction in hydropower production, about 47 percent on an annual average basis. Recall that for the *Alt 2* scenario, the Inskip power plant is removed and no additional water is transferred to the Coleman Canal from the South Fork. Note in Figure 11, that the *Alt 2* scenario actually yields higher average water temperatures in the upper reaches of the South Fork when compared to the base scenario and the *Alt 1* scenario, although still below the 17º C threshold. This is because no water is diverted from the North Fork to the South Fork and thus there is no mixing of larger water volumes along the South Fork reaches.

Summary

The utility of the WEAP21 model to integrate both the bio-physical and socio-economic elements of a watershed has been demonstrated for the Cow and Battle Creek tributaries of the Sacramento River of Northern California, USA. For Cow Creek, the utility of WEAP21's physical hydrology model was highlighted through both simulation of the watershed's hydrology and the irrigation of pastureland, while WEAP21's allocation algorithm was simultaneously used to supply demand from a combination of surface and groundwater supplies. The supply was determined based on user-assigned preferences and the priority to meet in-stream flow demands first and irrigation requirements second. By changing the amount of irrigated area in the watershed, the model was capable of investigating the subsequent impacts that irrigation might have on streamflow and groundwater elevations, which have well documented influences on both in-stream and riparian ecosystem service and function.

Battle Creek is unique due to its volcanic origin and year-round, cold, and plentiful streamflows. Such coldwater streams and rivers have historically provided habitat for winter-run and spring-run Chinook salmon, both listed as either endangered of threatened. However, hydropower facilities built in the 20th century have led to substantial alterations in the streams hydrologic and ecological function by introducing barriers to migration and unfavorable water temperatures. Battle Creek represents an important opportunity to restore stream habitat, similar to that of the upper Sacramento River that were lost after the construction of Shasta Dam in the 1940s.

The integrating nature of the WEAP21 model was used to evaluate the current conditions and multiple alternatives that are being considered to restore the habitat of the North and South Fork reaches of Battle Creek. The hydropower facilities and their production parameters as well as the natural and man-made hydrologic components of the watershed were integrated into the WEAP21 model. The model was capable of replicating the altered flow regime of the watershed and estimating the hydropower production and associated water temperatures. Two restoration scenarios were run, which included a fish ladder and fish screen scenario that implied raising the in-stream flow requirements (IFR), while the second alternative included the removal of diversion dams and higher IFRs. The trade-offs between improving in-stream flow conditions (e.g. both volume and temperature) were contrasted with the reduction in hydropower production.

The applications presented in this paper are not unique – these types of tradeoffs are made in basins all over the world – sometimes explicitly, but very often without a strong understanding of the tradeoffs. The potential to apply the new WEAP21 model, which simultaneously and seamlessly integrates watershed hydrologic processes with an allocation algorithm, has been demonstrated and shown to be a useful in developing an improved understanding of both the ecosystem services provided throughout a watershed, and the tradeoffs of alternative systems of management.

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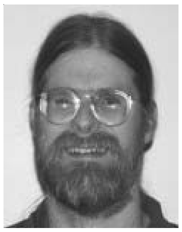

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References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1999. "Crop evapotranspiration: Guidelines for computing crop water requirements." FAO Irrigation and Drainage Paper 56. Rome: FAO.

Biswas, A. 1981. "Integrated water management: Some international dimensions." *Journal of Hydrology* 51, No. 1-4: 369-79.

Bouwer, H. 2000. "Integrated water management: Emerging issues and challenges." *Agricultural Water Management* 45, No.3: 217-28.

Daily, G. C., ed. 1997. *Nature's services: societal dependence on natural systems*. Washington, DC: Island Press.

Daly, C., G.H. Taylor, W. P. Gibson, T.W. Parzybok, G. L. Johnson, P. Pasteris. 2001. "High-quality spatial climate data sets for the United States and beyond." *Transactions of the American Society of Agricultural Engineers* 43: 1957-62.

Forero, L., B. Reed, K. Klonsky, and R. DeMoura. 2003. "Sample Costs to Establish and Produce Pasture Sacramento Valley-Flood Irrigation." Sacramento: University Of California, Cooperative Extension, Pa-Sv-03.

Gordon, W.S., and R.B. Jackson. 2003. "Global Distribution of Root Nutrient Concentrations in Terrestrial Ecosystems." Data set. Available on-line [http://www.daac.ornl.gov]. Oak Ridge, Tennessee, USA: Oak Ridge National Laboratory Distributed Active Archive Center.

Homer, C. C. Huang, L. Yang, B. Wylie, and M. Coan. 2003. "Development of a 2001 National Landcover Database for the United States." *Photogrammetric Engineering and Remote Sensing* 70: 829-40.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E.-D. Schulze. 1996. "A global analysis of root distributions for terrestrial biomes." *Oecologia* 108: 389-411.

Lackey, R.T. 2002. "Restoring wild salmon to the Pacific Northwest: framing the risk question." *Human and Ecological Risk Assessment* 8, No. 2: 223-32.

Lackey, R.T. 2003. "Pacific Northwest salmon: forecasting their status in 2100." *Reviews in Fisheries Science* 11, No. 1: 35-88.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich. 2000. "Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation study." *Ecological Economics* 33: 103-17.

Loucks, D. 1995. "Developing and implementing decision support systems: A critique and a challenge." *Water Resources Bulletin* 31, No. 4: 571-82.

Mahmood, R. and K. Hubbard. 2002. "Anthropogenic land-use change in the North American tall grass-short grass transition and modification of near-surface hydrologic cycle." *Clim. Res.* 21, No. 1: 83-90.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*15: 3237-51.

Meehan, W.R., and T.C. Bjornn. 1991. "Salmonid distributions and life histories." In W.R. Meehan, ed. *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitat*. American Fisheries Society Special Publication 19.Bethesda, MD, USA: American Fisheries Society.

Mooney, H.A., and R.J. Hobbs. 2000. *Invasive Species in a Changing World*. Washington, DC: Island Press.

National Research Council (NRC). 1992. *Restoration of Aquatic Ecosystems. Science, Technology and Public Policy*. Washington, DC: National Academy Press.

Raskin, P., E. Hansen, Z. Zhu, and D. Stavisky. 1992. "Simulation of Water Supply and Demand in the Aral Sea Region." *Water International* 17, No. 2: 55-57.

Rawls, W., L. Ahuja, D. Brakensiek, and A. Shirmohammadi. 1993. "Infiltration and soil water movement." In D. Maidment, ed. *Handbook of Hydrology*. New YorkL McGraw Hill.

Scurlock, J.M.O., G.P. Asner, and S.T. Gower. 2001. *Worldwide Historical Estimates and Bibliography of Leaf Area Index, 1932-2000*. ORNL Technical Memorandum TM-2001/268. Oak Ridge, Tennessee, USA: Oak Ridge National Laboratory.

Strange, E., H. Galbraith, S. Bickel, D. Mills, D. Beltman, and J. Lipton. 2002. "Determining ecological equivalence in service-to-service scaling of salt marsh restoration." *Environmental Management* 29: 290-300.

United States Bureau of Reclamation Mid-Pacific Region (USBRMP). 2001. *Battle Creek Salmon and Steelhead Restoration Project*. Scoping Report. Sacramento, CA, USA: US Department of Interior, USBRMP.

US DOI. 1996. *Recovery plan for the Sacramento/San Joaquin Delta native fishes*. Sacramento, CA, USA: U.S. Fish and Wildlife Service.

Yates, D., J. Sieber, J., D. Purkey, and A. Huber-Lee. 2005. "WEAP21: A Demand, priority, and preference driver water planning model. Part 1: Model Characteristics." *Water International* 30, No. 4: this issue.

Zalewski, M. 2002. "Ecohydrology- the use of ecological and hydrological processes for sustainable management of water resources." *Hydrological Sciences Journal* 47, No. 5: 823.