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EVALUATING WATER ALLOCATIONS FOR DROUGHT MANAGEMENT

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Abstract: Water supplies and allocations for the Klamath River, OR and CA were evaluated using SIAM (Systems Impact Assessment Model), a decision support system developed by U.S. Geological Survey. SIAM is a set of models in a windows interface that provides water supply and delivery in a managed river system, predicts water quality and simulates fish production. SIAM was used to explore the potential for changing river and reservoir system operations to improve downstream water quality under drought conditions. The Klamath River Basin has experienced drought conditions in three of the past ten years i.e., 1992, 1994, and 2001. Hydrologic input and flows for 1992 hydrology were used as a surrogate for a series of management alternatives reducing water delivery and use for irrigation, power production, and endangered species in both the lake and riverine segments of the Basin. Resource managers in the Klamath Basin have used SIAM to determine the impacts of specific legal and institutional flow constraints during droughts and to identify potential adverse water quality consequences.

INTRODUCTION

Originating in southern Oregon, the Klamath River joins with its main tributary, the Trinity River, as it flows through northern California and west to the Pacific Ocean. A schematic for the flow network is provided in Figure 1. The demand for water in the basin has dramatically increased since the late 1980's, with the listing of endangered species for native lake sucker species in Upper Klamath Lake, OR and declining anadromous fish populations in the mainstem Klamath River downstream in California. Water use issues in the Klamath Basin are further complicated by unresolved interstate, intrastate, and Native American reserved water rights. Tension among water users, including four Native American Tribes, the agriculture community and hydropower interests create a challenge for resource management. Managers must now balance water use among a variety of natural resource benefits, while still meeting contractual or other legal obligations. Flug and Scott (1998) provide a more detailed history of water development in the Klamath Basin.

Since 1994, scientists at the USGS Fort Collins Science Center have worked to develop the Systems Impact Assessment Model (SIAM), a decision support system. SIAM integrates water quantity, water quality, habitat, and fish production components to quantify the biological, physical, chemical and economic outcomes from changes in water management operations in the Klamath Basin (Bartholow, 1998). An extensive series of model verification, calibration and validation was applied to SIAM. The purpose for these individual models and integration within SIAM is for use by resource managers in the evaluation of alternative water management operational schemes for the conservation, protection, and restoration of both lake and anadromous fish species.

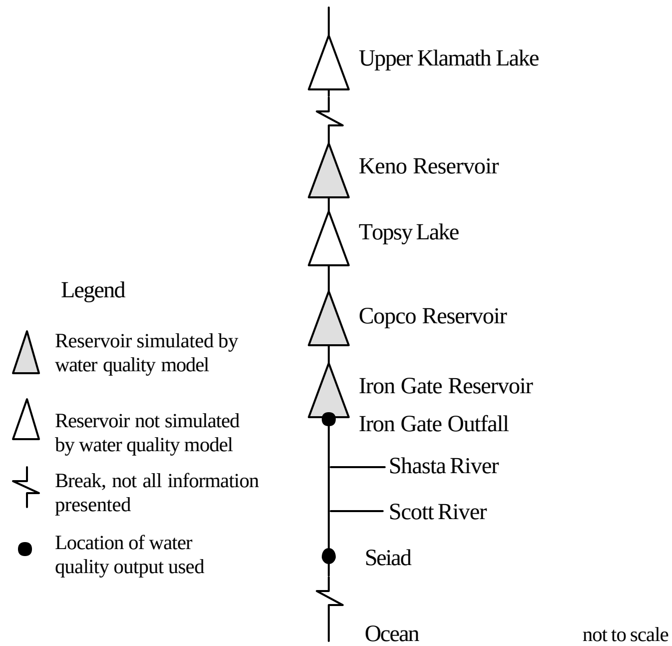

Figure 1. Water Quantity and Quality Flow Network, Klamath River.

Alternative water management scenarios were developed by the authors to simulate drought conditions as a surrogate for flows experienced during 2001. These scenarios and simulations help determine whether changes in Klamath River system operation can alleviate some of the flow constraints, as well as, water quality-related stresses (elevated temperature and decreased DO) experienced by anadromous fish. Alternative management strategies included changes in the target reservoir storage levels, water deliveries, and instream flow releases. The USGS study area modeled is 410 km of the mainstem Klamath River from Upper Klamath Lake in Oregon to the Pacific Ocean in California. Simulation of the alternatives were made using the decision support system SIAM as an interface for the water quantity network model MODSIM, the HEC-5Q water quality model, and SALMOD which tracks causes of mortality and estimates the number of surviving fish.

Klamath River Basin: Upper Klamath Lake (UKL) was naturally composed of and surrounded by extensive marsh and wetland areas. Large portions of these natural wetlands were later drained and converted to cultivatable agricultural lands. The Bureau of Reclamation (BOR) manages the Klamath Reclamation Project that now annually diverts on average 493 x 10^6 m^3 to 73,000 ha of cultivated project lands, while the annual returns or accretions average 290 x 10^6 m^3. Thus, agricultural and wildlife refuge diversions accounted for an annual average net consumptive use of 203 x 10^6 m^3. UKL is part of the Pacific Flyway and had the reputation as the largest North American habitat for migrating waterfowl (Bellrose, 1942; Baldassarre and Bolen, 1994). Two species of lake suckers in UKL, the shortnose (*Chasmistes brevirostris)* and Lost River (*Deltistes luxatus)* are currently listed as endangered species.

Water resources in the Klamath Basin are limited to annual precipitation, mostly from spring snowmelt. A summary of minimum, maximum, and average annual inflow to UKL is given in Table 1. The largest impoundment in the Basin is UKL, which on average holds less than a one-year storage capacity. Therefore, nearly all the water entering UKL in a given year is released for agricultural, municipal, hydropower, and instream uses. The lack of multi-year storage increases competition among water resource needs for the limited annual water supply. However, the upper basin provides considerable system flexibility with respect to water storage and diversion, and therefore, the greatest potential for water management.

Table 1. Annual Inflow into Upper Klamath Lake (UKL) in 10^6 m^3.

Minimum (1992)	1994	2001	Average (1906-2001)	Maximum (1956)
712	796	945	1637	3058

The five in-series reservoirs within the USGS study area are shown in Figure 1. Link River Dam (circa 1895) impounds UKL in the upper basin, followed by Keno (1967), J.C. Boyle or Topsy Lake (1958), two Copco dams (1917) and Iron Gate Dam (1962). PacifiCorp operates hydropower projects on four of these reservoirs. Keno Dam has no hydropower facilities. The total operational storage of the reservoirs included in the network flow model (i.e., Keno, J.C. Boyle, Copco and Iron Gate) provide 16.7 x 10^6 m^3 or about 1% of average annual inflow to UKL. The additional active storage in UKL brings the total active system water storage to approximately 617 x 10^6 m^3 or 37% percent of average inflows. Copco is a peaking release power plant with minimal ability to ramp releases, i.e., either up or down, from current operating levels. In 1962, Iron Gate Dam (IGD) was built as a re-regulating reservoir for Copco's peaking power releases and a Federal Energy Regulatory Commission (FERC) minimum flow release schedule was imposed. The dams serve as a barrier to anadromous fish during spawning runs. Since the early 1970's, populations of coho, steelhead and fall Chinook salmon have generally decreased in the Klamath Basin.

Thermal stress during spring, summer and fall months is believed to play a major role in declining anadromous fish populations in the Klamath Basin (W.M. Keir Associates, 1991; Williamson and Foote, 1998; McCullough, 1999). Chinook salmon life stages in the Klamath River study area encompass spawning, egg incubation, emergence, smoltification, and out-migration. Temperature requirements vary for each of these life stages and activities (Levy and Slaney, 1993). Many salmonid species have maximum growth rates in the range of 15 to 17 °C (McCullough, 1999). However, at temperatures above this range, fish grow at slower rates, are vulnerable to predation, more susceptible to disease, and overall experience higher mortality (Spence, *et al.,* 1996). Water temperature in the mainstem Klamath River reached 15 °C in mid-May during 1996-1998 (Campbell, 2001). Spawning cues and success are also affected by temperature. Chinook salmon may require temperatures below 16 °C before spawning occurs and temperatures in excess of 14.5 °C can cause egg mortality (McCullough, 1999). The water quality (temperature and DO) for both chronic and acute threshold values, selected by the authors for the simulations presented here, are summarized in Table 2. Field sampling and data collection indicates that these values are often exceeded in the summer months in the Klamath River.

Table 2. Water Quality Thresholds for Salmonid Stress.

Constituent	Chronic	Acute
Temperature	greater than 15 °C	greater than 20 °C
DO	less than 7 mg/L	less than 5 mg/L

Water Quantity and Quality Models: A network-based water resources allocation and planning model, MODSIM, was configured to the Klamath River Basin for simulation. Numerous water management alternatives are anticipated for further analysis with respect to flow diversions, return flows, reservoir storage levels, instream flow demands, as well as other physical and institutional constraints. A prioritization scheme is used in MODSIM water allocations. Instructions for modeling a flow network using the MODSIM computer algorithm are given by Fredericks and Labadie (1995) and Labadie (1988).

MODSIM is applied to simulating river and reservoir systems operation, from UKL downstream to the Pacific Ocean on a monthly time step. A simplified flow network for this application is provided in Figure 1. Inputs to MODSIM utilize measured (i.e., historic records) or synthetic values for inflows and reservoir operations (i.e., storage and release) on the mainstem Klamath River. Other major tributaries (Shasta, Scott, Salmon, and Trinity Rivers) are not modeled except as inflow points using USGS gage records at or near their confluence with the Klamath River. Scott and Flug (1998) and Flug and Scott (1998) provide more specifics of the flow network for the Klamath River, calibration and validation, as well as the use of this simulation model for analysis. Opportunities to re-configure or modify components for simulation include changing reservoir storage levels, evaluating different hydrologic sequences, adjusting agricultural diversions, and redefining recommended instream flow demands.

Water quality is evaluated using the HEC-5Q model, developed by the U.S. Army Corps of Engineers at the Hydrologic Engineering Center at Davis, California (USACE, 1986). The model has a long history of supported use, is in the public domain and can simulate both rivers and reservoirs. The water quality constituents simulated with HEC-5Q in this study are water temperature and dissolved oxygen (DO). The model simulations provide mean daily water quality, using monthly flows and reservoir storage computed by MODSIM, combined with daily average meteorological data. Mean monthly flows are disaggregated into equal daily-average flow values for HEC-5Q and daily reservoir storage is also generated. This disaggregation is a reasonable representation of summer base flow below Iron Gate Dam. However, in the spring, when peak flows pass over the spillway, the disaggregation method is less representative of actual operations. DO is simulated using HEC-5Q's simplified computation that includes biological oxygen demand (BOD), sediment oxygen demand (SOD) and re-aeration. The simplified DO simulation predicts general trends in DO that are within a mean absolute error of 1-2 mg/L for the mainstem Klamath River. Hanna and Campbell (2000) provide more information on the implementation of HEC-5Q for the Klamath, including data sources and calibration details.

Temperature and DO values, for both chronic and acute thresholds, were used to develop additional water quality metrics that relate to fishery impacts. The metric of degree day above threshold is commonly used for fisheries-related mesohabitat condition description. A degree day is the sum of the difference in daily average temperature and the criteria for each day that the threshold is exceeded. A similar metric was developed for a dissolved oxygen day (DO day), where a DO day is the sum of the difference between daily average DO and the criteria for each day that the threshold is exceeded. Computations of degree day and DO day for chronic and acute thresholds are compared and used to judge the merit of each alternative as compared to the base or other water management alternative. The threshold values are not absolute standards for salmonid health, but rather are guidelines that allow for the relative comparison of water management alternatives.

WATER MANAGEMENT ALTERNATIVES

Simulations under drought year scenarios for the Klamath River Basin include: 1) modified instream flows below Iron Gate Dam (IGD), using Federal Energy Regulatory Commission (FERC) or National Marine Fisheries Service (NMFS) minimum flow recommendations, or other targets designed to offer full protection (FP) for spawning and fry life stages of fall Chinook salmon and a modified full protection schedule (MFP); 2) simulating the effects of drought years such as 2001 and 1992; 3) reducing agricultural and wildlife refuge diversions in the upper basin BOR project area; and 4) changing reservoir storage levels, particularly in support of the two listed UKL endangered species as recommended by the US Fish and Wildlife Service (FWS) Biological Opinion (BO). Two minimum instream flow demand schedules below Iron Gate Dam and two other flow recommendations are given in Table 3. These flows range from fifty to seventy-five percent of the long-term average annual release (1927 x 10^6 m^3) of water from Iron Gate Dam.

Table 3. Instream Flows Below Iron Gate Dam (IGD).

Option	Monthly Flows in m^3/sec, Water Year Schedule												Annual Flow
	O	N	D	J	F	M	A	M	J	J	A	S	10^6 m^3
FERC	37	37	37	37	37	37	37	28	20	20	28	37	1016
NMFS	37	40	48	54	59	63	67	59	51	37	31	34	1503
FP	34	35	37	37	51	57	57	57	42	28	28	33	1286
MFP	34	35	37	37	42	45	45	45	23	23	25	28	1089

All alternatives for water management under simulated drought conditions use the 1992 water year hydrology. However, adjustments in water operations were made by manipulating priorities for demand schedules within MODSIM, to favor either meeting the water level targets for UKL or the instream flow schedule below IGD. Simulations are organized in two groupings based on target water levels for UKL. The 1992 grouping uses the actual historic monthly water levels as existed in the 1992 water management operation at UKL. The second 2001 group uses target water levels for UKL as recommended by the BO, to protect endangered species in the lake. Other differences between the two groupings include other UKL storage targets and full protection flow schedules (FP and MFP) below IGD for some additional 2001 simulations. In both the 1992 and the 2001 scenario groupings some simulations reduced to zero the upper basin diversions to agricultural project lands; these are simulations that attempt to meet target water levels in UKL and instream schedules below IGD. A summary table of the alternatives simulations analyzed in this paper is presented in Table 4, with additional comments given when each simulation is discussed in the results section that follows.

Table 4. Summary of Drought Water Year Simulation Alternatives.

Scenario	UKL Target	Below IGD Schedule	Agricultural Demands	Highest Priority
92B1 = 1992 Base	1992 Actual	FERC	1992 Schedule	UKL, then Ag. Demands
92B2	1992 Actual	FERC	1992 Schedule	Flows Below IGD
92N1	1992 Actual	FERC	None	Flows Below IGD
01B1 = 2001 Base	BO	FERC	1992 Schedule	UKL & IGD
01B2	BO	FERC	1992 Schedule	Flows Below IGD
01N1	BO	FERC	None	UKL & IGD
01N2	BO	FERC	None	Flows Below IGD
01N3	Held High	FERC	None	Flows Below IGD
01N4	Held High	FP	None	Flows Below IGD
01N5	Held High	MFP	None	Flows Below IGD

BO: Fish and Wildlife Service Biological Opinion
Held High: Water levels that keep storage high, for release late in the year
FERC: Federal Energy Regulatory Commission
FP: Full Protection for spawning and fry fall Chinook salmon
MFP: Modified Full Protection schedule

EVALUATION OF SIMULATION RESULTS

Simulations conducted using the MODSIM model maintained mass balance of water, although differences exist in monthly agricultural water deliveries, monthly flow releases and reservoir storage levels at most locations. These variations are largely due to the significant differences in target reservoir storage levels (i.e., volume of water) in UKL and target demands for instream flows below IGD (i.e., total discharge) that pass downstream to the Pacific Ocean. Simulation alternatives in MODSIM used different priorities to force operations that match the UKL storage levels in some scenarios and in other scenarios, priorities that attempt to meet the instream flows below IGD. Water quality variations then result from changes in the quantity, timing, mass storage, residence time, mixing and release of stored water.

Analysis of Water Quantity Simulation Results: A plot of the MODSIM simulated water levels in Upper Klamath Lake for several alternatives is given in Figure 2. The 92B1 alternative is representative of the 1992 grouping, which uses the FERC instream flow schedule as targets and the actual 1992 storage levels on UKL. All three 1992 simulations exhibit almost identical monthly storage levels in UKL throughout the year. UKL storage levels match the actual 1992 water levels for the 1992 group of simulations because the priorities used in the model were not inferior to agricultural water demands for those runs. Water allocations met the UKL water storage levels but either shorted agriculture deliveries or released instream flows below IGD that were less than the FERC minimum recommended flows (this is clearly visible in Figure 3 for scenario 92B1). The 1992 group of alternatives uses a set of UKL target water storage levels that allow for more drawdown (i.e., lower water surface levels) in all months except January through April, as compared to the 2001 group of scenarios, which use the BO or another synthetically high set of target water storage levels. This more liberal target for drawdown in UKL yields water in quantities great enough to supply demands other than UKL target levels for lake fish species. Some water remains available for meeting limited agricultural demands or for downstream instream flows. Further analysis of the instream flows below IGD, as given in Figure 3, clearly indicates that water to meet the FERC instream flow recommendations was not available under the 92B1 scenario. The simulation results presented in Figures 2 and 3 for this 1992 base alternative (scenario 92B1) match the actual historic values observed in water year 1992; the minimum instream flows below IGD were not met that year but water was delivered to meet the agricultural demands. The below IGD flows for Scenario 92B2 as shown in Figure 3 are equal to the FERC instream flow recommendations. Further analysis of information from scenarios 92B2 and 92N1, but not shown here, indicates that some limited quantities of water are available for agricultural deliveries while meeting the instream flow recommendations below IGD (particularly in June, July, and August).

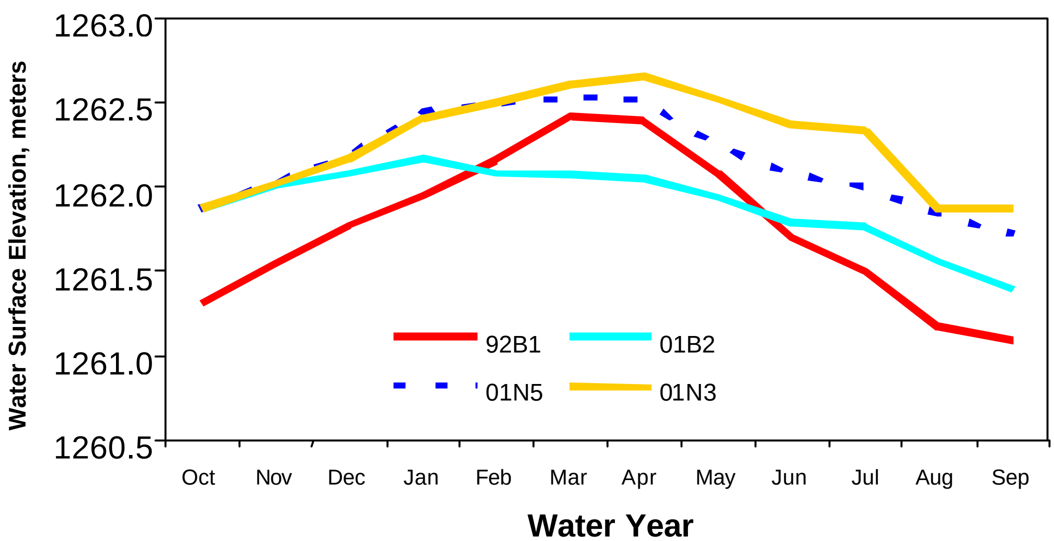

Figure 2. Upper Klamath Lake Simulated Elevations for Four Alternatives.

The 01B2 simulation results for UKL water levels shown in Figure 2 comes close to matching the FWS Biological Opinion (BO) for target reservoir storage levels in UKL, but falls a little short in August and September. This demonstrates the difficulty in managing limited water supplies during drought water years while attempting to meet instream flow demands and elevated upstream reservoir storage levels. There is not adequate water to meet all of these targets during low water years (i.e., drought conditions of 1992 or 2001). Based on these simulation results, no scenarios are presented here which attempt to meet the much higher instream flow demands associated with the NMFS minimum instream flow schedule previously presented in Table 3. The plot of flows below IGD for scenario 01N2, shown in Figure 3, indicates the quantity of water that would be available for agricultural delivery after meeting the UKL BO targets and the FERC minimum instream flow recommendation below IGD. This quantity is indicated by the higher flows, from January through April, as compared to the plot for scenario 92B2, which just matches the FERC recommendations.

Other simulations were identified by the authors and are presented here, using synthetic targets for UKL and Full Protection (FP and MFP) flow recommendations below IGD as previously defined. The plots in Figure 2 for scenarios 01N3 and 01N5 are the result of simulations that use higher target water levels for UKL most of the year, in an attempt to force the simulation to hold water in the upstream reservoir for release later in the year to meet the higher summer instream flow targets (FP or MFP). Even with the synthetic target for UKL, these drought year simulations still short the instream flow target for FP (scenario 01N4) from June through September. Thus, the scenario 01N5 offering a reduced FP (i.e., the MFP target schedule for instream flows) was created to identify exactly what instream flows can be provided during this surrogate 2001 simulation. The simulation for scenario 01N5 is still short of the MFP target schedule for September. The instream flows for these two synthetic simulations are also shown in Figure 3. Lack of adequate water supplies to meet all of the demands for UKL, agriculture and instream flow emphasizes the role for simulation modeling and the SIAM decision support system for evaluating tradeoffs in resource management decision making.

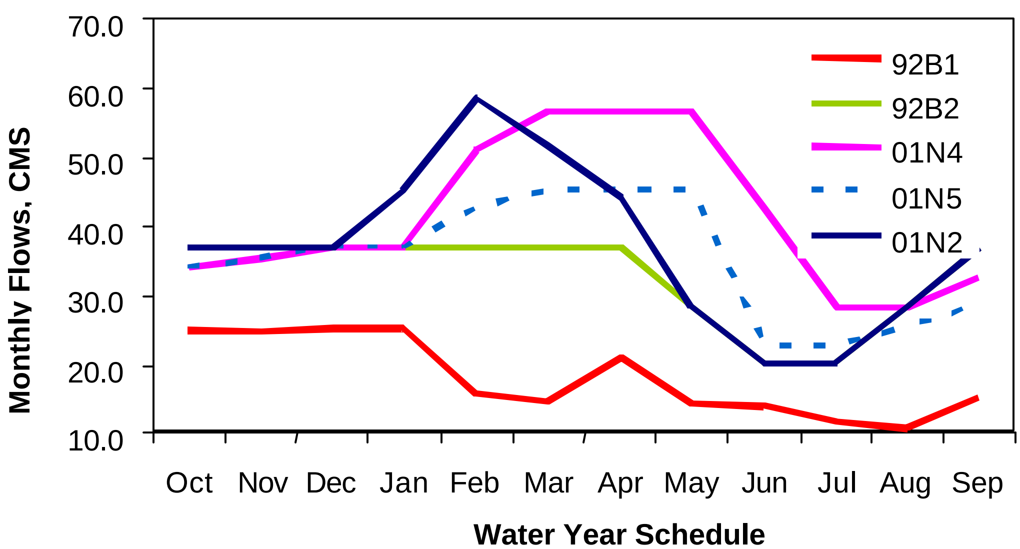

Figure 3. Simulated Instream Flows Below Iron Gate Dam (IGD) in m^3/sec.

<u>Analysis of Water Quality Simulation Results:</u> For mean daily temperatures, similar results were observed in the water quality model outputs in comparing the respective 1992 and 2001 groups of scenarios. Figure 4 therefore only presents the mean daily temperature plots for the three 1992 water management simulation alternatives. Reflecting back on the below IGD instream flow values shown in Figure 3, the larger downstream discharges from March through September actually result in increased water temperatures below IGD. These higher flows and temperatures correspond to simulation alternatives (i.e., scenarios) in which agricultural water deliveries were reduced to zero and operations provided increased instream flows below IGD. The warmer water persists further downstream to Seiad and beyond. Figure 5 shows the corresponding mean daily temperature plots downstream at Seiad Valley, where temperatures exhibit much greater daily variation (i.e., flashiness) and reservoir water release has less influence. Increases in water temperature are largely due to decreased reservoir retention times, which allow warm surface water to pass through the reservoirs and limit the time available for in-reservoir processes to affect water temperatures. Thus, water temperature varies more directly with air temperature (Campbell, *et al.*, 2001). The increased instream flows downstream below IGD must therefore draw water from the much smaller Iron Gate Reservoir in combination with passing downstream the warmer seasonal tributary surface inflows.

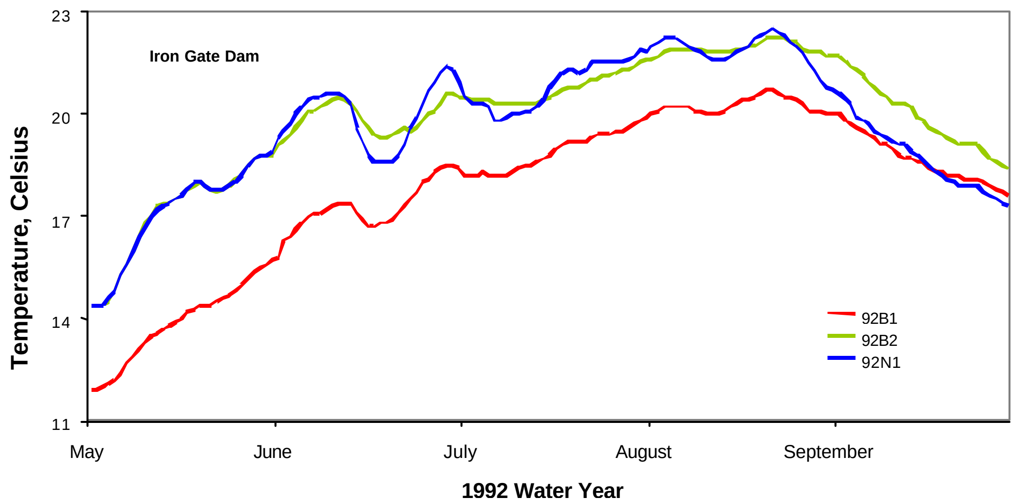

Figure 4. Simulated Mean Daily Temperatures Below Iron Gate Dam.

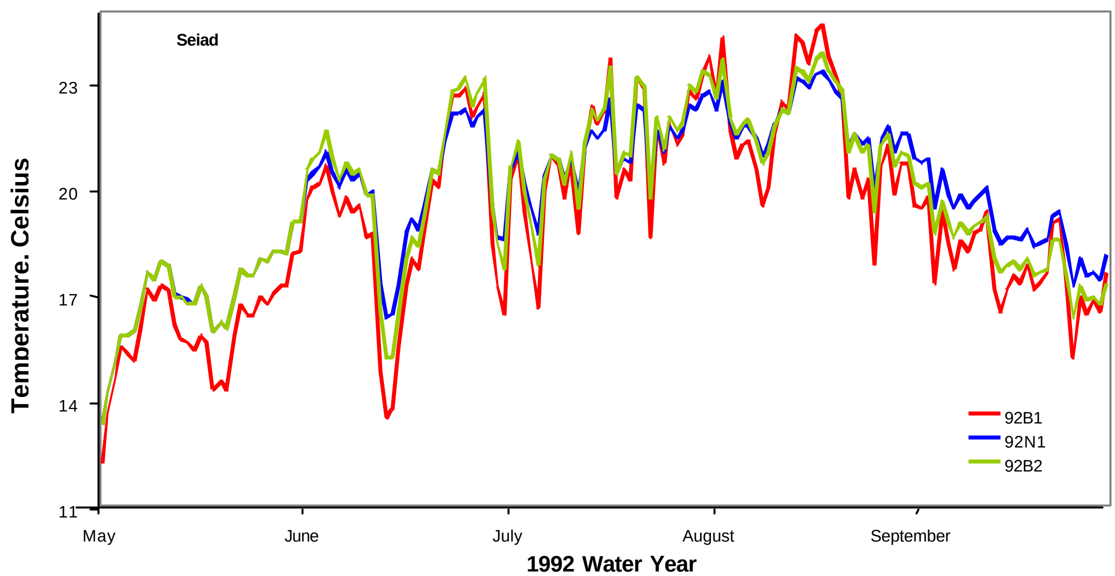

Figure 5. Simulated Mean Daily Temperatures at Seiad Valley.

Results for the temperature metrics of chronic and acute degree day values computed are summarized in Table 5 for several scenarios in both the 1992 and 2001 groups of simulation alternatives. In comparing the metrics for all scenarios presented to the 92B1 base simulation, it is clear that the larger instream flows, delivered below IGD from April through September, significantly increases both the chronic and acute number of degree days recorded below IGD. Remember that the 92B1 scenario yielded instream flows that were well below the FERC recommended schedule. The influence on chronic degree days continues further downstream at Seiad where higher values also exist for all but the 92 B1 base alternative. However, for the other 1992 scenarios, there is little additional influence in acute degree days at Seiad due to larger instream flow discharges. As water flows downstream other tributary inflows, including cooler water from numerous seeps and springs, enter the mainstem Klamath River and help alleviate elevated water temperatures to a limited degree. As a reminder, these metrics are only recommended for use in comparing water management alternatives and are not suggested for use in direct correlation to salmonid health or mortality.

Table 5. Simulated Temperature Metrics at Two Downstream Locations.

Scenario	Chronic, degree days		Acute, degree days	
	Below IGD	Seiad	Below IGD	Seiad
92B1	511	681	8	116
92B2	768	762	96	107
92N1	799	779	97	122
01B2	738	748	91	134
01N4	794	795	117	134
01N5	784	769	104	138

All of the water management alternatives simulated and discussed here had similar results on DO, i.e. increased water temperature resulted in lower DO values. However, in all simulations, DO was always above the criterion of 7 mg/L and therefore the results are not shown here.

SUMMARY AND CONCLUSIONS

Integrated water quantity and quality computer simulation models provide a useful tool for analysis of water management alternatives in the Klamath River Basin. The drought water management alternatives described and analyzed here demonstrate the use of such models for management decision making and decision support. Results presented clearly indicate that adequate water does not exist in low flow years to meet target water storage levels on Upper Klamath Lake for endangered lake fish species, to satisfy minimum recommended instream flows below Iron Gate Dam for anadromous fish, and supply other traditional and contractual water deliveries (e.g., agriculture). The simulations also provide quantitative and analytic information that rejects a common belief among many resource conservationists in the Klamath Basin that increasing mainstem flows will automatically improve water quality conditions for salmonids. Evidence presented here indicates that for the drought conditions and alternatives presented, increased instream flows actually increase mean daily temperature, and both chronic and acute degree days below Iron Gate Dam. Further downstream, at Seiad, higher flows also continue to exhibit increases in the number of chronic degree days, with little or no effect on acute degree days. These simulation results illustrate the need for analysis with respect to the spatial and temporal extent of water quantity and quality impacts, as some areas may experience improved conditions at the sacrifice of degradation either upstream or downstream or during other seasons in the year.

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