JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 17 2009

RESHAPING THE ANNUAL HYDROGRAPH AT IRON GATE DAM TO BENEFIT ANADROMOUS FISH POPULATIONS IN THE KLAMATH RIVER, CA

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A decision support system that integrates hydrology, water quality and anadromous fish production has been developed for the mainstem Klamath River, Oregon and California, USA. The Systems Impact Assessment Model (SIAM) analyses identified a recurring annual hydrograph shape for Iron Gate Dam releases that consistently yielded greater predicted fish production estimates. Applying the altered flow pattern in some simulations resulted in increased fish production estimates ranging from 3 to 605 % compared to an unaltered or historical hydrograph. Altering the Iron Gate Dam hydrograph may provide a positive management tool for increasing the production of Chinook salmon in the mainstem Klamath River.

INTRODUCTION

The U.S. Geological Survey (USGS) has been developing and applying a DSS (decision support system) for the mainstem Klamath River since 1996. SIAM (Systems Impact Assessment Model) consists of a set of three hierarchically coupled mechanistic models that predict water quantity, quality and fall Chinook salmon fish production (Campbell et al., 2001; Bartholow et al., 2003). The model was designed and developed to evaluate water management alternatives in any regulated river basin but currently is specific to the Klamath River. The model domain varies in longitudinal scope. The water quantity and quality models encompass the Klamath River from Upper Klamath Lake, OR to the mouth near Klamath, CA; however, the fish production model is limited to the river reach from Iron Gate Dam, CA to the Scott River confluence (Figure 1) because fish habitat has been consistently described only in that Klamath River reach.

Two key elements in the Klamath River mainstem are instream flows and water temperature as they affect anadromous fish populations (William M. Kier Associates, 1991). Both upstream and downstream water uses are constrained by threatened and endangered species requirements (US Fish and Wildlife Service, 1988; National Marine Fisheries Service, 1997). The Bureau of Reclamation has a large (220,000 acre) irrigated agriculture project in the Klamath Basin that uses water stored mainly in Upper Klamath Lake (US Bureau of Reclamation, 2000). Two lake-resident species of suckers in Upper Klamath Lake, the Lost River sucker (*Deltistes luxatus)* and the shortnose sucker (*Chasmistes brevirostris),* are protected by a Biological Opinion that restricts Upper Klamath Lake (UKL) water surface elevation changes (US Fish and Wildlife Service, 2002). In the lower basin below Iron Gate Dam, anadromous fish including coho (*Onchorhynchus kisutch)* and steelhead (*O. mykiss),* are threatened and abundance of these salmon as well as fall Chinook (*O. tshawytscha)* have been declining for many years (William M. Kier Associates 1991; National Marine Fisheries Service, 1997). NOAA Fisheries has subsequently issued a biological opinion on the impacts of on-going Klamath Project operations on coho with a recommended flow schedule below Iron Gate Dam (NOAA, 2001).

Drought in recent years has exacerbated conflicting needs for water resources in the Klamath Basin with fish kills occurring in both the upper and lower Klamath Basin in the past 10 years (Williamson and Foote, 1998; Perkins et al*.,* 2000; California Department of Fish and Wildlife, 2003; Lynch and Risley, 2003). Further complicating water resource issues in the Basin, the four hydropower dams on the Klamath River operated by PacifiCorp, Inc., are undergoing a FERC (Federal Energy Regulatory Commission) re-licensing review. Many water management alternatives are being vigorously discussed, including adding storage capacity to existing reservoirs, decommissioning some or all of the dams, pumping ground water to augment instream flows, and permanently or intermittently fallowing farm land.

SIAM has the capability of simulating the response of flows, reservoir storage, temperature and fish production for many water management alternatives that emulate conditions previously mentioned. Adding storage capacity to Upper Klamath Lake, dam removal, adding a cool water inflow source as a surrogate for using groundwater to augment instream flows and reducing irrigation deliveries as a surrogate for taking acreage out of production have all been simulated using SIAM (Hanna and Campbell, 2000; Campbell et al*.,* 2001; Bartholow et al., 2005). In addition, an automated SIAM utility was developed to investigate the effects of different flow schedules below Iron Gate Dam on fall Chinook salmon production. The SIAM utility was based on earlier work by Bartholow and Waddle (1995) for the stand-alone fish production model on the Trinity River, CA.

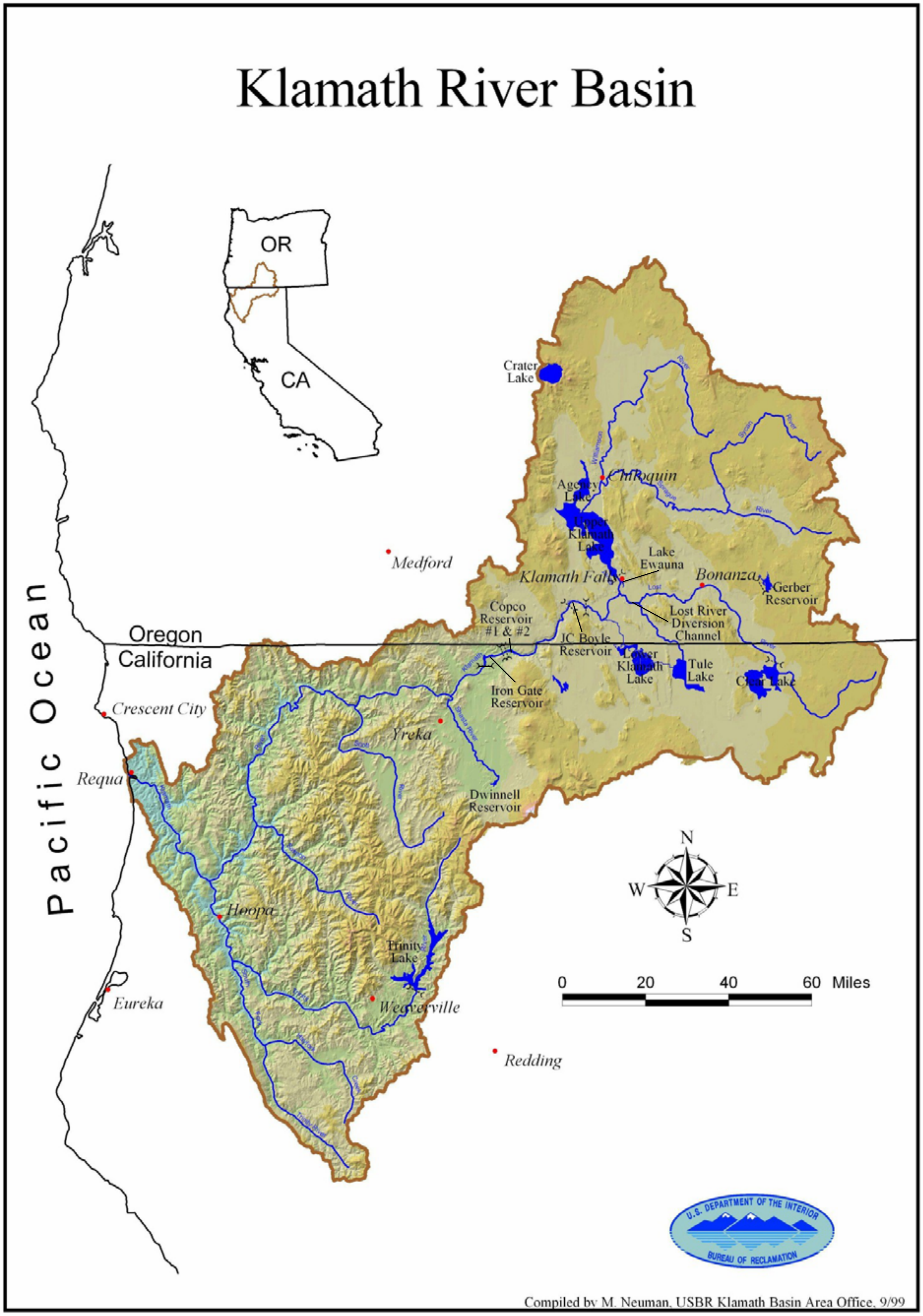

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Figure 1. Klamath River Basin, Oregon and California, with mainstem dams.

We applied the automated utility program to run SIAM iteratively varying the flow in 200 cfs increments to all of the years selected for the hydrograph pattern analysis. The program continues to run as long as some variation in flow for one or more months of the water year increases predicted fish production values. The final output from the utility program is a set of flows for a particular water year that yields the greatest fish production in the Klamath River study area. Evaluation of Klamath River flows predicted to increase Chinook production by this iterative process yielded an annual hydrograph pattern for Iron Gate Dam releases that seemed to consistently predict increased numbers of juveniles outmigrating to the Pacific Ocean. This hydrograph pattern was converted from absolute monthly flow values to a monthly percent of total annual flow. The altered hydrograph's shape was dissimilar to historical Iron Gate Dam operations. Fall flows were lower, compared to the historical 1961-2005 shape, and the spring peak was higher and of longer duration (Figure 2). The lower fall flows in SIAM appear to maximize spawning habitat and provide lower water temperatures early in the spawning season. Higher spring flows that extend into May in these SIAM simulations, may provide more rearing habitat for juvenile salmonids and also allow more rapid egress from the freshwater habitat to the ocean, thus decreasing thermal stress and exposure to disease.

We decided to test a variety of hydrological and meteorological category combinations to verify whether simulations using the altered hydrograph actually resulted in predictions of more fall Chinook salmon juveniles outmigrating from the Klamath River reach between Iron Gate Dam and the Scott River confluence.

METHODS

SIAM Models

SIAM, v. 4.0 was used for all simulations presented here. The DSS consists of modeling components for flow (MODSIM), water quality (HEC-5Q) and fish production (SALMOD).

These three models, MODSIM , HEC-5Q and SALMOD, were seamlessly coupled using a user-friendly interface, the Systems Impact Assessment Model (SIAM; Bartholow et al., 2005).

The SIAM interface handles the formatting of input and output data files from each individual model and disaggregates or aggregates the time step differences among the models. For example, MODSIM is a monthly time step model. When MODSIM data is passed to HEC-5Q, a daily time step model, the monthly data is disaggregated into the appropriate number of equal daily increments. When HEC-5Q output data is passed to SALMOD, the daily time steps are aggregated into an appropriate number of weekly increments. SIAM and a stand-alone version of SALMOD, along with their documentation, can be downloaded from the USGS website (http://www.fort.usgs.gov).

MODSIM, an off-the-shelf network water quantity simulation model (Labadie, 1988; Dai and Labadie, 2001), was applied to the Klamath River Basin to evaluate potential water management alternatives. MODSIM is a planning model used for interconnected and managed water systems with numerous reservoirs, diversions, and return flows. The model realistically allocates water using a prioritization algorithm that considers reservoir operating rules and physical constraints, instream flow requirements, and agricultural or other demands. Using historical monthly flow and reservoir operations records, MODSIM simulates river and reservoir operation from UKL downstream to the Pacific Ocean. The Klamath's major tributaries (Shasta, Scott, Salmon, and

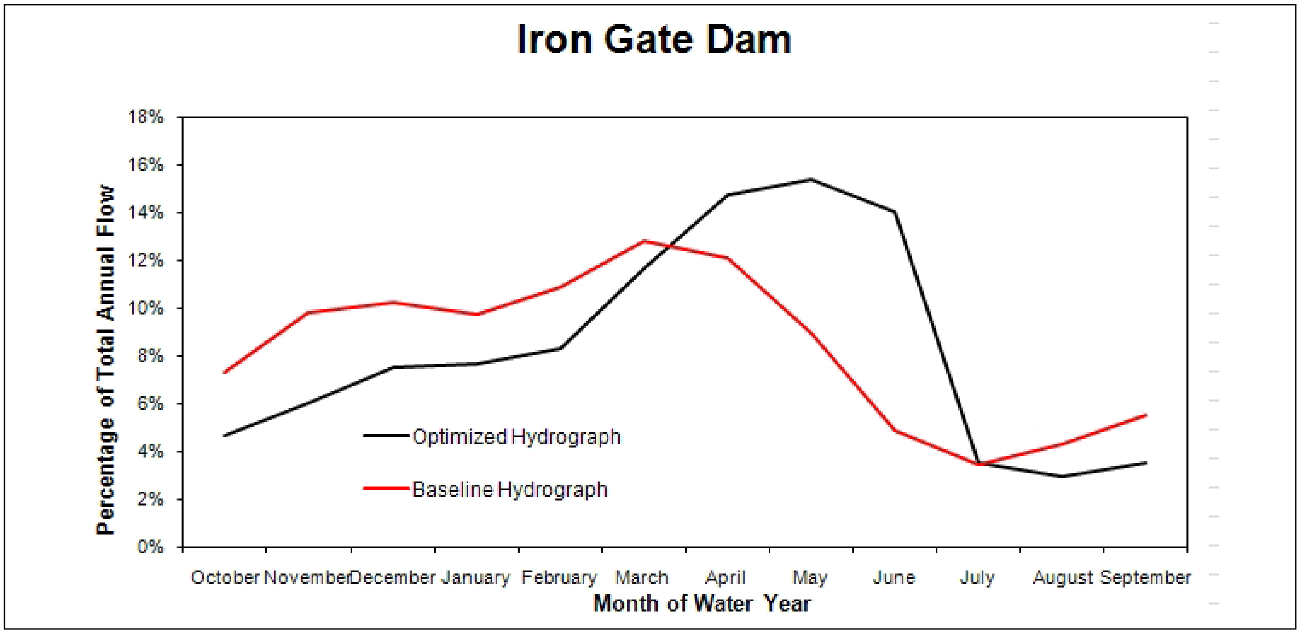

Figure 2. Comparison of two hydrograph patterns for Iron Gate Dam releases, the historical average of nine different year types and an altered (percent of total annual flow) hydrograph distributed over the 12 months of the water year for those same years.

Trinity Rivers) were modeled only as inflows using USGS gage records at or near their confluences with the Klamath. Details of this MODSIM model calibration and application may be found in Scott and Flug (1998).

HEC-5Q, another publicly available model (USACE, 1986), was used to simulate mean daily water temperature given Klamath River flows and reservoir operations from MODSIM. HEC-5Q is a one-dimensional model that simulates water quality in reservoirs vertically from the surface to the bottom and longitudinally in rivers. Mean monthly flows were converted to equal daily values by dividing by the number of days in each month (disaggregated) and combined with daily average meteorological data, including air and dew point temperatures, wind speed, and cloud cover. Flow and meteorology inputs then drive the HEC-5Q model in simulating all four Klamath River hydropower reservoirs in series. Single-day time step constraints in HEC-5Q required simplifying JC Boyle Reservoir and Copco #2's forebay to wide river reaches because these small reservoirs had short hydraulic residence times that became computationally unstable under high flow conditions.

The uniform monthly flow disaggregation represented stable flow conditions well, but was somewhat less descriptive of conditions during winter peak flow events and necessarily introduced steps at month boundaries. Fortunately, model tests verified that the simple disaggregation we used had only a negligible effect on release temperatures below the reservoirs due to their homogenizing effects. For example, we compared Iron Gate release temperatures for two simulations for a wet year, 1982, one using mean daily flows from the disaggregation and one using measured daily flows to capture larger amplitude day-to-day flow variations when they occurred. The maximum single-day difference in predicted release temperatures was 0.8°C in February, though the average absolute daily difference was 0.1°C, leading us to conclude that using simple disaggregation would not prejudice our results. A complete description of the HEC-5Q numerical modeling methods, data requirements and details of the Klamath River model calibration and application may be found in Hanna and Campbell, 2000.

SALMOD simulates population dynamics for freshwater salmonids; no population dynamics are included for ocean habitat. Though the model is applicable for both anadromous and non-anadromous salmonids, this document will only discuss the anadromous life history implementation. The model is fully described in Bartholow et al. (1993, 2001); only an outline of the model is presented here.

The model's premise is that egg and fish mortality are directly related to spatially and temporally variable micro- and macrohabitat limitations, which themselves are related to the timing and amount of streamflow and other meteorological variables. SALMOD is a spatially explicit model (Dunning et al., 1995) where habitat quality and carrying capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which serve as spatial computation units in the model. The model tracks a population of spatially distinct cohorts (fish in a stock born in the same year) that originate as eggs and grow from one life stage to another as a function of water temperature in each computational unit. Individual cohorts either remain in the computational unit in which they emerged or move, in whole or in part, to nearby units. Model processes include spawning (with redd superimposition), incubation losses (such as redd scour or dewatering), growth (including egg maturation), mortality due to water temperature and other causes, and movement (freshet-induced, habitat-induced, and seasonal). All model processes can potentially occur simultaneously.

The model is organized around events occurring during a biological year beginning with spawning and typically concluding with fish that are physiologically 'ready' (e.g., pre-smolts) swimming downstream toward the ocean. It operates on a weekly time step for one or more biological years. Input variables (e.g., streamflow, water temperature, number and distribution of adult spawners) are represented by their weekly average values. The study area is separated into individual mesohabitat types (e.g., pools, riffles, or runs) categorized primarily by channel structure and hydraulic geometry but modified by the distribution of features such as fish cover. Thus, habitat quality in all computation units of a given mesohabitat type changes similarly in response to discharge variation.

Fish cohorts are tracked by life stage and size class within the spatial computation units. Streamflow and habitat type determine available habitat area for a particular life stage for each time step and computation unit. Habitat area (quantified as weighted usable area, or WUA) is computed from flow: microhabitat area functions are developed empirically or by using the Physical Habitat Simulation System (PHABSIM; Milhous et al., 1989) or similar model. Habitat capacity for each life stage is a fixed maximum number (or biomass) per unit of habitat area available. Thus, the maximum number of individuals that can reside in each computation unit is calculated for each time step based on streamflow, habitat type, and available microhabitat. Fish from outside the model domain (from stocking, hatchery production, or tributaries) may be added to the modeled stream at any point in their life cycle.

Models like SALMOD are attaining confirmation in the scientific literature. For example, Capra et al. (1995), has demonstrated that spawning habitat availability reductions over continuous 20-day periods correlate well with production of 0+ trout. Building on Capra's work, Sabaton et al. (1997) and Gouraud et al. (2001) have further explored the field of limiting factors, both microhabitat and macrohabitat, using population models markedly similar to SALMOD, with some promising results.

MODEL CALIBRATION AND VALIDATION

Details of independently calibrating and validating (confirming) both MODSIM and HEC-5Q for the Klamath River have been reported elsewhere (Scott and Flug, 1998; Hanna and Campbell, 2000) and are only summarized here. MODSIM was calibrated for 1970-79 because this period contained relatively complete data records representing a variety of low, average, and high water supply years. Model calibration was considered excellent, with less than 0.1% difference in flows on an annual basis at three USGS gaging locations. Validation focused on the period 1980-89, also containing a representative mix of hydrologic years, and was satisfactory with average monthly and yearly flow differences well below 1.0%. Over the full period simulated, the root mean squared error (RMSE) between the simulated daily flows passed to the HEC-5Q model disaggregated from MODSIM and measured daily flows below Iron Gate was 34 cfs (ranging from 5 cfs in November to 74 cfs in September).

The HEC-5Q model was calibrated for 1996 and validated using 1997 and 1998 data sets, again dictated by the availability of good in-reservoir and in-river data. The model performed well with r^2 values of 0.85 to 0.97 depending on the year, and mean absolute errors of 0.9 to 1.0°C. However, the model performed somewhat less well for the entire 43 year data set, with a maximum mean absolute error of about 1.4°C depending on the geographic location, though the r^2 values remained quite high (e.g., $r^2 = 0.96$, $n = 7354$, $p < 0.001$ below Iron Gate Dam). Mean absolute error was better than average immediately below Iron Gate on an annual basis (1.1°C), with individual absolute monthly errors ranging from 0.9°C in August to 1.7°C in February. Measured water temperature data were intermittent during the bulk of the historical record (roughly 1963 to 1980), with changes in measurement techniques during the period, potentially explaining some differences.

Data and Parameter Sources for SALMOD

SALMOD has not yet been fully calibrated and validated for the Klamath River SIAM application. There are two primary sources for initial parameter values for fall Chinook modeling on the Klamath River. The first is from the Trinity River flow evaluation (U.S. Fish and Wildlife Service and Hoopa Valley Tribe, 1999), which in turn was an outgrowth of the work done by Williamson et al. (1993) and Bartholow et al. (1993). The second source stems from work by Kent (1999) and Bartholow (2002) who applied SALMOD for fall Chinook (and other races) on the Sacramento River below Shasta Dam. Both of these applications have added credence to parameter values, strengthened confidence in the model's predictive utility, and supplemented the analysis toolbox. Second, because there is never a full complement of values available for any site-specific model application, literature values developed for other rivers or related species must be used. Therefore, for this analysis, fish production estimates, although presented as "numbers" of fish should be considered as a relative comparison between simulations only, not accurate estimates of the true numbers of fish in the Klamath River during the historical period of record 1961-2005.

Hydrograph Analysis Simulations

The representative hydrological and meteorological years selected for this analysis were low, average and wet hydrology and cool, average and warm meteorology. Table 1 shows the water years chosen to represent the meteorology, and hydrology categories. SIAM has a 45-year period of record from 1961-2005. Representative years for hydrology were selected based on total April - September inflow volume to Upper Klamath Lake. Representative years for meteorology were selected based on average June air temperatures. SIAM baseline simulations, i.e., historical

Table 1. SIAM simulation matrix for Iron Gate Dam flow redistribution analyses.

Meteorology ‘Type’ Average June Air Temperature		Cool 16°C	Average 18°C	Warm 20 °C	Average Annual UKL Inflow (AF)
Hydrology ‘Type’	Dry	1981	1988	1977	275 x 10^3
	Average	1976	1978	1985	530 x 10^3
	Wet	1971	1982	1998	780 x 10^3

operations were simulated on each of the years and then simulations with the annual flow were redistributed according to the alternative flow release pattern previously identified. Table 2 shows the altered hydrograph pattern by month.

A total of 18 simulations were generated using SIAM, a baseline and an alternative hydrograph redistribution simulation for Iron Gate Dam releases using each water year listed in Table 1. Hydrograph alternative simulations were identical to the baseline except that total annual flow was allocated based on the monthly percentage distribution (Table 2). The SIAM model was configured to ensure that the desired flow releases were simulated and all resulting production estimates were tabulated.

Table 2. Iron Gate Dam annual flow redistribution percentages by month of water year.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
5.3	7.6	10.6	7.8	7.3	9.3	12.6	13.5	11.5	4.4	4.8	5.5	100

SIMULATION RESULTS

Baseline and the alternative flow pattern hydrographs at Iron Gate Dam for the three dry water year types simulated are displayed in Figure 3. The range of meteorological conditions from cool to warm is represented by the baseline traces in each figure with 1981 as a cool, dry year type, 1988

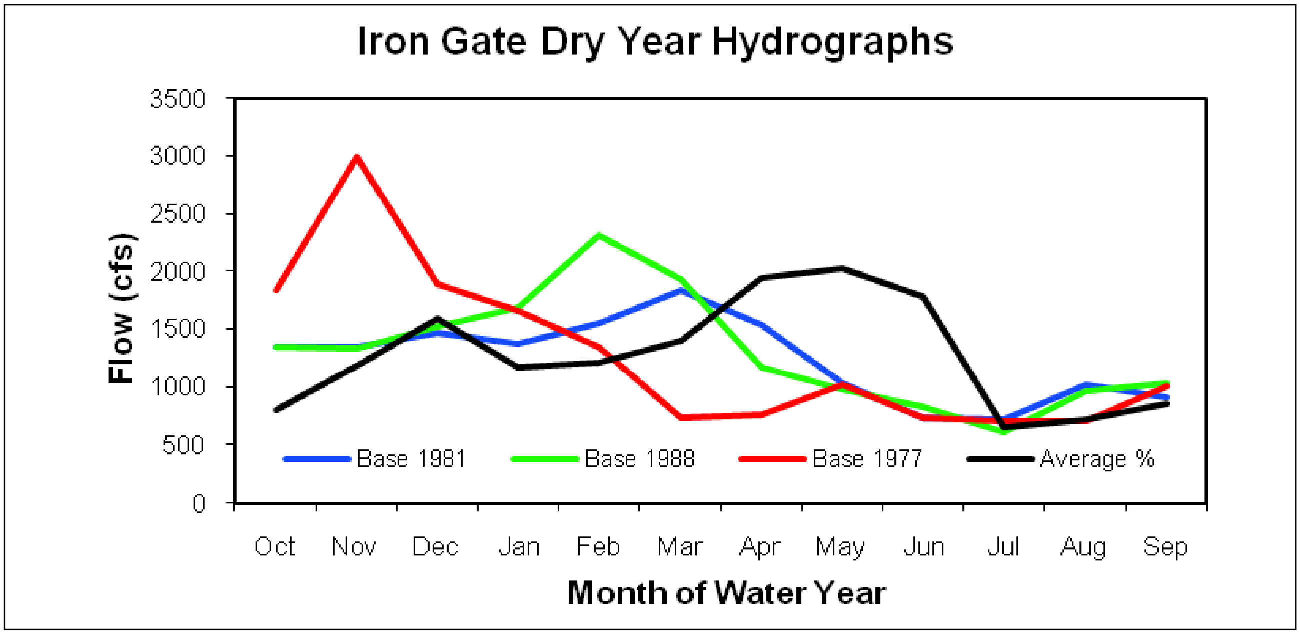

Figure 3. Iron Gate Dam hydrographs for dry water years with cool, average, and warm meteorological conditions from left to right, respectively; contrasted with an altered hydrograph.

as an average, dry year type, and 1977 as a warm, dry water year type. Meteorological year types were separated by about 2 °C in their maximum June air temperature as shown in Table 1.

The historical baseline traces in Figure 3 indicate the variability in the Iron Gate hydrograph. Releases from Iron Gate Dam in these three dry water years also show considerable inter-annual variation with 1977 having some peak flow in November, 1988 having a peak in February, and 1981 having a very small peak in December and a slightly higher peak in March. In contrast, the alternative flow distribution curve has the characteristic shape with a peak in December and then an extended peak from March – June. The alternative flow hydrograph provides about 47% of the total annual flow volume for the year in those 4 months. The small peak in December provides about 11% of the total annual flow volume and likely represents a general pattern in the Klamath Basin of late fall/early winter storm events.

In the three average water year historical baseline traces displayed in Figure 4, the persistent fall/winter peak associated with storm events is also readily apparent, and in two of the three years, a spring snow melt peak can also be discerned, although it occurs much earlier than the peak spring flows in the alternative flow distribution hydrograph.

It is still possible to see some peaks in fall flows in the wet year historical baseline hydrograph traces in Figure 5, although all of these water years have much greater spring flows, compared to the alternative flow distribution hydrograph. In two of the years, 1971 and 1982, the spring peak occurred earlier in the spring, although in 1998, the peak in May coincided with the peak at the same time for the alternative flow distribution hydrograph. In these wet water years, spring snowmelt or spring rains were major drivers for the shape of the historical baseline hydrographs.

The effect of redistributing the annual hydrograph on predicted fish production, expressed as the number of fall Chinook salmon juveniles outmigrating to the Pacific Ocean, is summarized in Table 3. The predicted number of fall Chinook salmon outmigrants was always increased by redistributing Iron Gate Dam flow releases. In some years, the change was very striking (1985) and in other years (1998) there was little difference between the historical baseline prediction and the

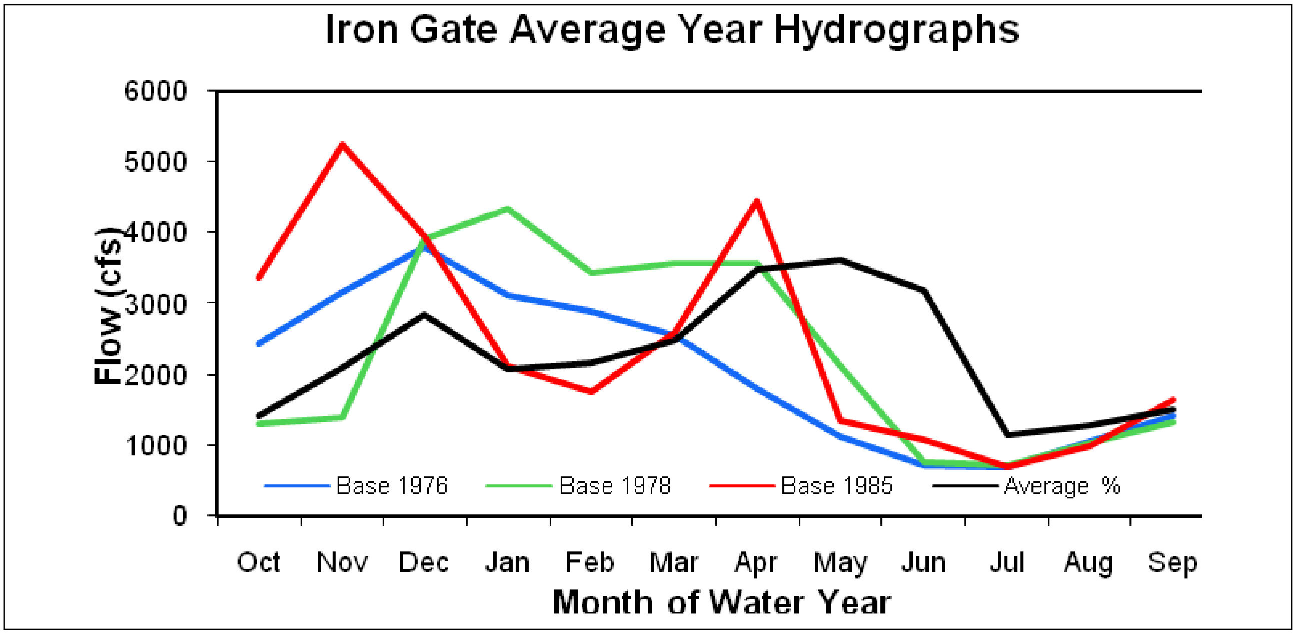

Figure 4. Iron Gate Dam hydrographs for average water years with cool, average, and warm meteorological conditions from left to right, respectively; contrasted with an altered hydrograph.

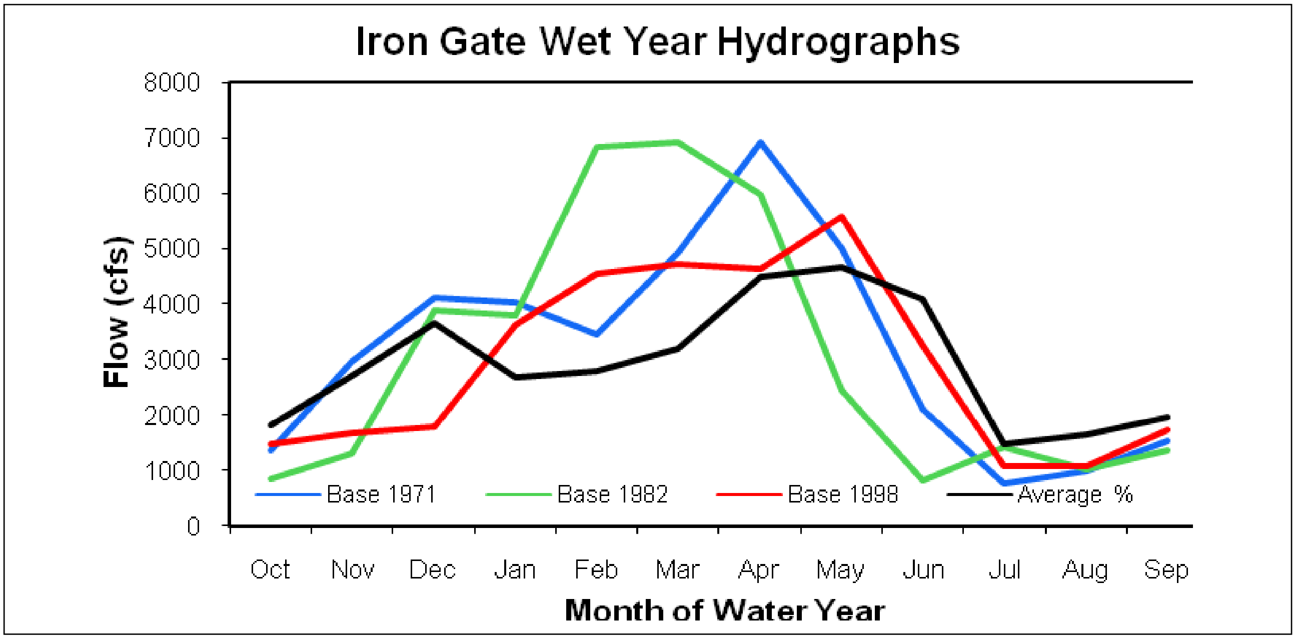

Figure 5. Iron Gate Dam hydrographs for wet water years with cool, average, and warm meteorological conditions from left to right, respectively; contrasted with an altered hydrograph.

altered flow distribution pattern outmigrant predictions. SIAM simulations using the altered flow distribution generally predict greater improvement in outmigrant numbers in dry and average hydrological years than in wet years.

In addition to the nine water years used for the basic analysis, a full SIAM 45-year simulation 1961-2005 for both historical and the altered flow distribution schedule below Iron Gate Dam was conducted. The predicted number of fall Chinook salmon outmigrants for both simulations is displayed in Figure 6. In all years, the altered flow distribution prediction was greater than the historical baseline, although in some years the differences were small. In certain years, such as 1963-1965 and 1985 the traces are widely divergent. The effects of extended drought in the Klamath Basin from 2001-2005 may also be reflected in the general declining trend in predicted outmigrant numbers in both simulations. When the water supply is limited, rearing habitat is much reduced in the spring, sometimes by as much as 50-70%. Several consecutive years when

Table 3. Percent change in the predicted number of fall Chinook salmon outmigrants resulting from applying the percent redistribution hydrograph to annual Iron Gate Dam flow releases for the nine meteorological and hydrological year type combinations.

Year	Meteorology Category	Hydrology Category	Baseline Number	Redistribution Number	Percent Change
1981	Cool	Dry	1475	1724	16.9%
1988	Average	Dry	1550	2110	36.2%
1977	Warm	Dry	1068	1945	82.1%
1976	Cool	Average	1562	2657	70.0%
1978	Average	Average	2059	2362	14.7%
1985	Warm	Average	362	2550	604.7%
1971	Cool	Wet	2292	2615	14.1%
1982	Average	Wet	2090	2521	20.6%
1998	Warm	Wet	2563	2640	3.0%

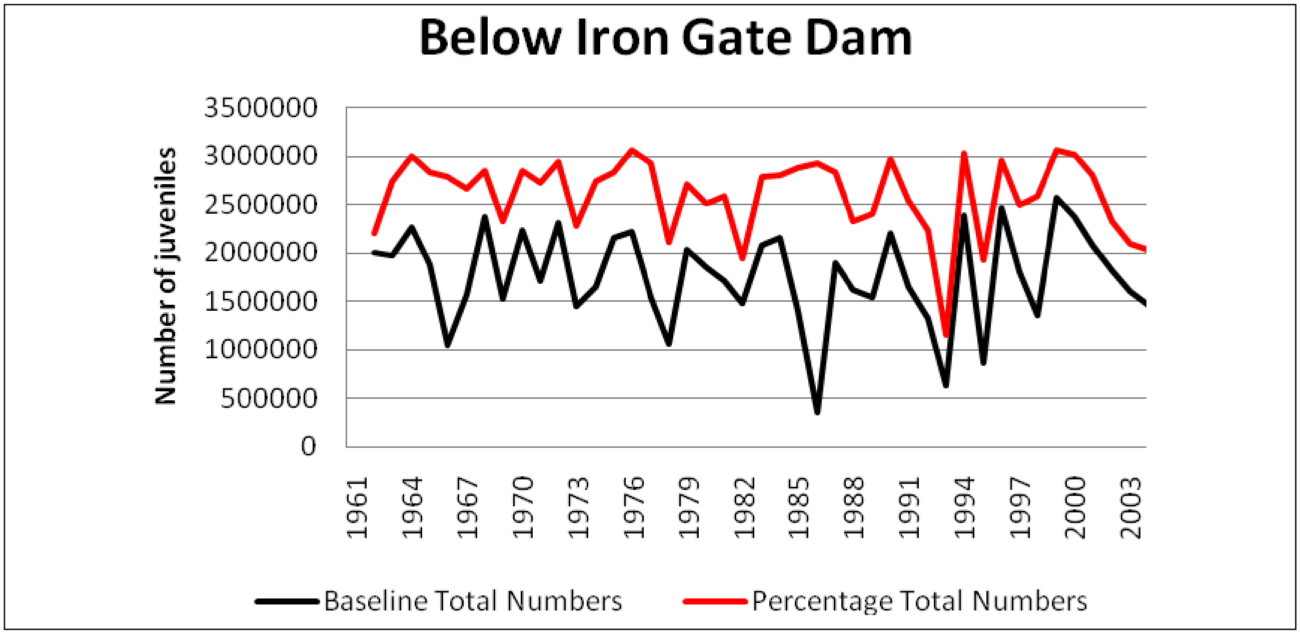

Figure 6. A comparison of predicted fall Chinook salmon outmigrants for two 45-year SIAM simulations 1961-2005 for the Klamath River below Iron Gate Dam.

conditions are sub-optimal can result in the declining trend observed in both the baseline and altered flow distribution simulation curves for predicted salmon outmigrant numbers (Figure 6).

DISCUSSION

There is a consistent difference between the predicted production of fall Chinook salmon outmigrants between the baseline and altered simulations. When the estimates diverged, e.g. 1985 (Figures 4 and 6), the difference was related to reduced spawning habitat when November flows below Iron Gate Dam exceeded 5000 cfs in the historical baseline simulation.

Reproduced here is a figure from Bartholow and Henricksen, 2006 depicting the habitat availability for various life stages of fall Chinook salmon in the study reach from Iron Gate Dam downstream to the Scott River confluence in the Klamath River (Figure 7). Spawning habitat area is severely reduced above 4000 cfs in this river reach. If these estimates, based on PHABSIM (Physical Habitat Simulation) measured depth and velocity measurements by the U.S. Fish and Wildlife Service, are credible, then the same may be true for 1963-1965.

An examination of USGS gaging station daily flow values for 1963 to 1965 indicates that during peak spawning (mid-October to mid-November), flows in 1963 were generally above 2,500 cfs, greatly reducing spawning habitat (Figure 7). In 1964, fall releases were generally below 2,500 cfs, but spring flows were generally less than 2,000 cfs and therefore, rearing habitat for fry, and smolts was reduced by 30-60%. In 1965, spawning flows were suitable, but on December 22, 1964 discharge below Iron Gate Dam was 25,000 cfs and remained greater than 10,000 cfs for an entire week. These flows are high enough to scour eggs from redds below Iron Gate Dam. USGS estimates that bed load movement begins at about 14,000 cfs in this river reach (R. Milhous, USGS – retired, pers. comm.). Generally high flows were experienced during the winter with more than 30 days occurring in January and February that were approximately 10,000 cfs. In April and May, 1965, flows were generally less than 2000 cfs. In 1965, it appears that habitat for egg, fry, smolt life-stages of fall Chinook salmon may have been adversely affected by unsuitable flows for much of that water year.

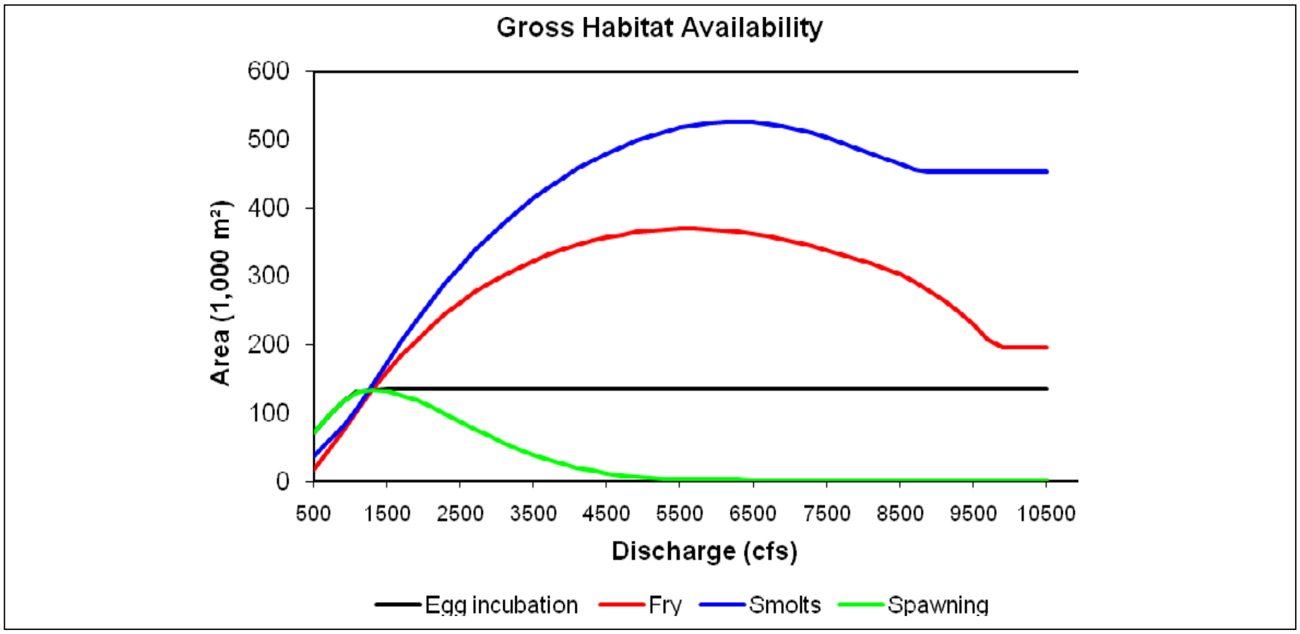

Figure 7. Gross habitat availability as a function of discharge through the Klamath River study area - Iron Gate Dam downstream to the Scott River confluence. Accretions and the effects of water temperature have been ignored in this graph (Bartholow and Henriksen, 2006).

The effects of extended drought are clearly apparent in the downward trend in predicted fish production displayed in Figure 6 for the period 2001-2005. Low flows affect all freshwater life stages of fall Chinook salmon. Referring to Figure 7, spawning habitat area is diminished below 1000 cfs and above 1700 cfs, with maximum habitat at about 1500 cfs. Egg incubation habitat is not affected by flow changes as strongly, as long as redds are not dewatered. Rearing habitat is reduced below about 3500 cfs and above about 8000 cfs for the fry life state. Smolt habitat is decreased below about 5500 cfs and above 8500 cfs although only slightly.

During the period 2001-2005, flows were sometimes greater than the optimal habitat area for spawning and fell far short of the maximum rearing habitat for both fry and smolt life stages of fall

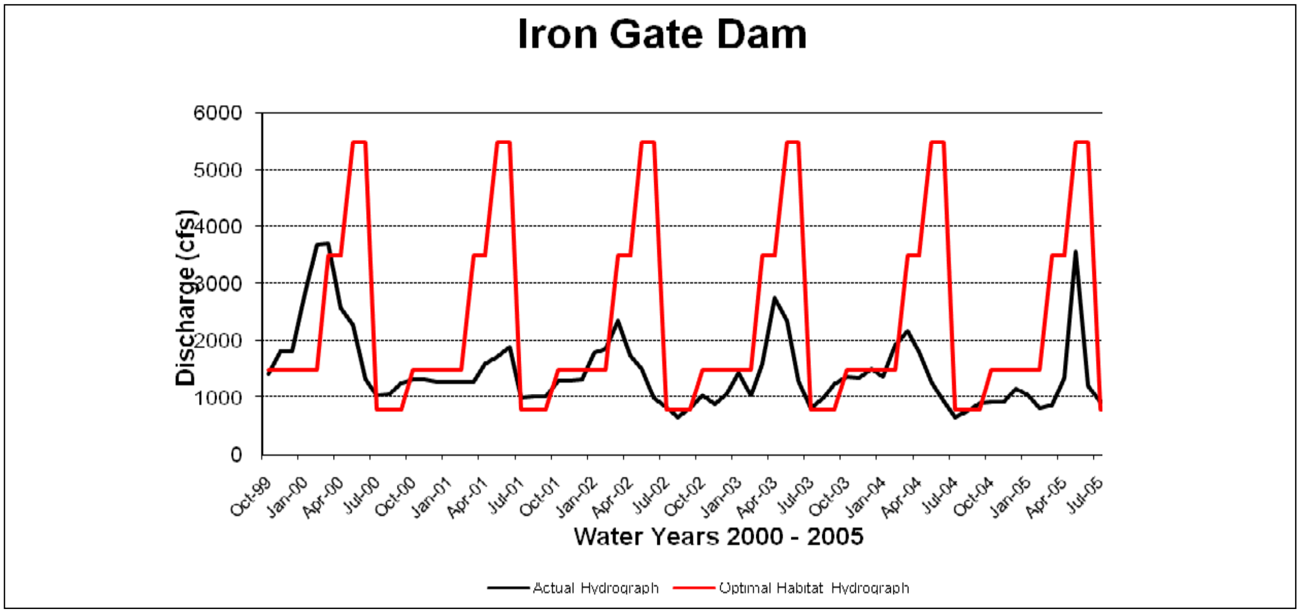

Figure 8. Comparison of Actual versus optimal habitat hydrograph for the Klamath River below Iron Gate Dam during the period 2000 – 2005.

Chinook salmon in this Klamath River reach (Fig 8). In 2005, even spawning habitat was decreased in the fall with flows around 1000 cfs and rearing habitat for fry being particularly limited. Drought conditions can severely impact fish production through lack of available habitat for the freshwater life stages of fall Chinook salmon.

All of the years from 2000 to 2005 were at or below the 25th percentile in terms of total annual discharge from Iron Gate Dam. They ranged from 2005 at the 9th percentile to 2003 at the 25th percentile and are among the lowest flow years during the entire period we examined from 1961-2005. Only 1992, 1994, 1991, and 1981 experienced lower flows and none of those were consecutive years. Certainly conditions for successful fall Chinook salmon production have been constrained by lack of water supply during the recent past. However, Chinook salmon populations are reported as declining throughout the Columbia, Klamath and Great Basins (Thurow et al., 1997; NRC, 2004). Thurow et al. (1997) report that “Both forms of Chinook salmon are absent from more than 70%...of their potential ranges and all are approaching extirpation in portions of their remaining ranges”. The authors emphasize that because these ecosystems have been altered significantly “areas supporting strong populations or multiple species will be critical for conservation management.” Although the National Research Council (2004) reports that “Chinook salmon were and continue to be the most abundant anadromous fish in the Klamath basin...”, they also state that “Virtually all populations of anadromous fishes have declined considerably from their historical abundances...” and “The main-stem Klamath River has become a challenging environment for anadromous fishes because of decreased flows and increased summer water temperatures.”

In all of the simulations evaluated in this exercise, real-world constraints such as the lake surface elevation targets for Upper Klamath Lake as specified in the U.S. Fish and Wildlife Service 2001 biological opinion (USFWS, 2001) for endangered lake suckers, water surface elevations required for maximal hydropower production below Copco and Iron Gate Reservoirs, and undepleted agricultural diversions were not imposed. If these constraints were imposed, in most cases, predicted fall Chinook salmon production could be greatly reduced. An example of this is displayed in Figure 9 where three simulation results are contrasted for water year 2000, a hydrologic year very close to the 50th percentile for total annual discharge from Iron Gate Dam in the SIAM data base.

Examination of simulation output results indicates that the altered hydrograph simulation allowed Upper Klamath Lake to exceed flood stage (>4143.3 ft) in February, March, and April, 2000. The additional 202,521 AF in storage allowed all agricultural and reservoir storage downstream storage targets to be met during the water year. In reality, Upper Klamath Lake cannot exceed flood stage and there is little alternative storage available in the current highly regulated Klamath system.

The surrogate simulation successfully allows Upper Klamath Lake water surface elevation targets to be met (Figure 9) and keeps the downstream power production reservoirs at or just above the levels needed to produce hydropower, but in order to meet higher Iron Gate Dam releases for better predicted fish production values, agricultural deliveries must be curtailed. Table 4 shows the months during the irrigation season when agricultural diversions were curtailed in the surrogate simulation. The total delivery shortage in the surrogate simulation was just over 60,000 acre-feet. The US Bureau of Reclamation and several Klamath Irrigation Districts operate a water bank where

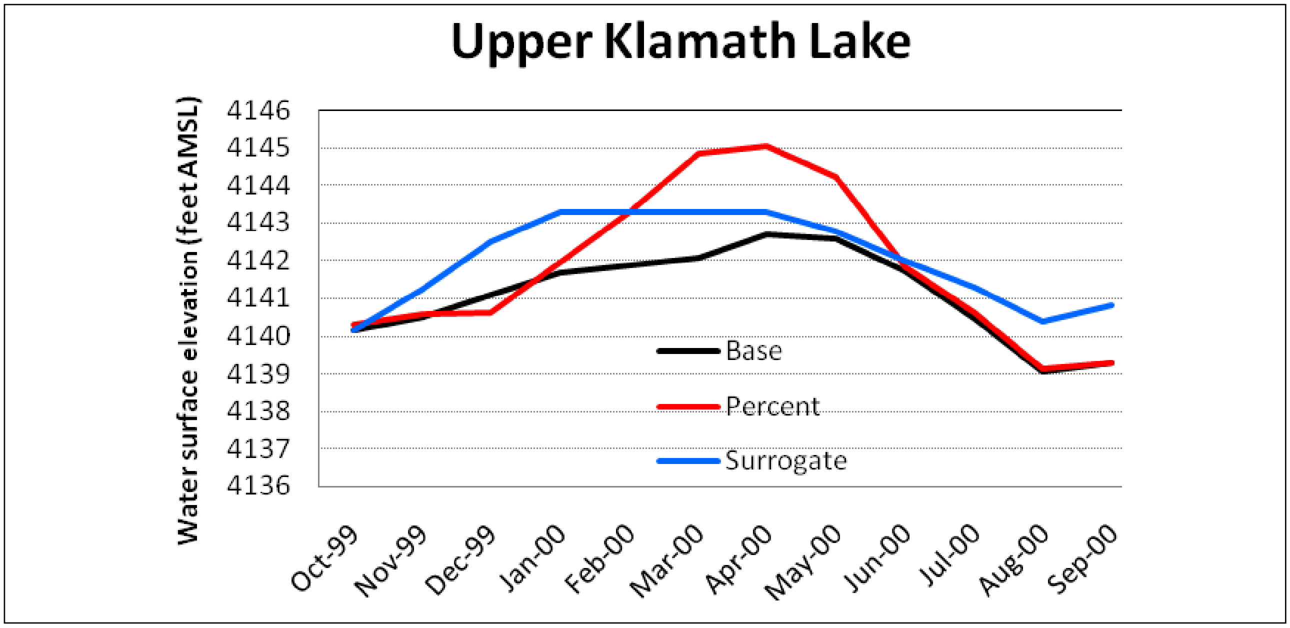

Figure 9. Water Year 2000 lake surface elevations in Upper Klamath Lake compared to a percent of total annual flow scheme and a surrogate simulation that complies with a biological opinion for Upper Klamath Lake (USFWS, 2001) and the Klamath River below Iron Gate Dam (NMFS, 1997).

additional water supply is gained by forgoing water use and small storages in two low lying seasonal wetlands (Agency Lake and Running Y Ranches). The combined supply for the water bank is approximately 100,000 acre-feet. Since the agricultural diversion shortage in the surrogate simulation is less than might be available through the water bank, we considered the simulation feasible under real world conditions.

The most important criterion for success, is whether or not the SIAM model would predict more fish production under the flows delivered at Iron Gate Dam for the surrogate simulation. Figure 10 compares fish production predictions for the three simulations. Although the surrogate simulation predicts fewer exiting fall Chinook salmon than the altered hydrograph simulation, both of these simulations still exceed fish production predicted for the baseline WY 2000 simulation. The altered hydrograph simulation is approximately 26% greater than the historical baseline fish production prediction and the surrogate simulation is still about 17% greater than historical baseline. Given the declining trend in predicted fall Chinook salmon production over the past 7 years 1999-2005, (Figure 6), a 17% positive change in predicted fish production would be highly desirable, particularly if that change could occur year in and year out.

Table 4. Agricultural diversion demands 'shorted' by the SIAM surrogate simulation for WY2000. Depletion amounts are acre-feet of water calculated by subtracting delivery amounts for the month from the historical WY2000 deliveries.

WY 2000	A-Canal	Lost River	North Canal	ADY Canal	Annual Shortage
Shortage (Acre Feet)					
April	0	7067	3823	4383	
May	3635	3236	3660	6881	
June	3971	0	6109	9803	
July	0	0	4462	3084	
Total	7606	10304	18054	24151	60114

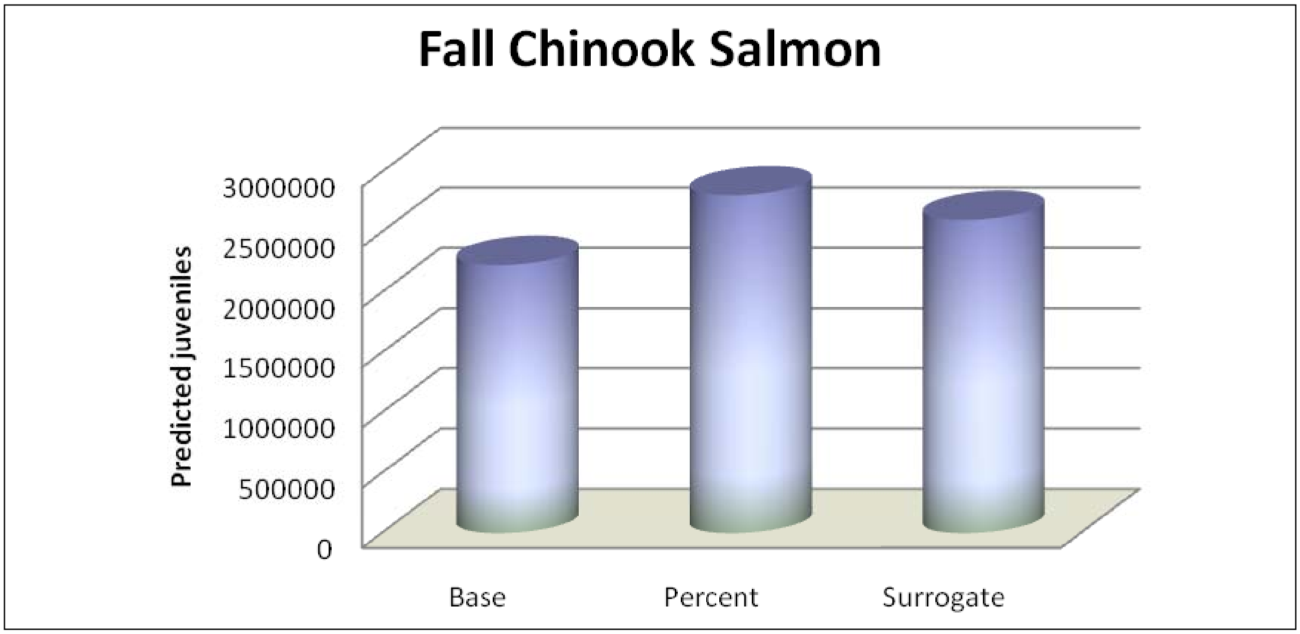

Figure 10. Comparison of fall Chinook salmon fish production predicted by three simulations for WY 2000, a historical baseline, an altered hydrograph at Iron Gate Dam simulation, and a surrogate simulation that achieves water surface elevation constraints for Upper Klamath Lake, JC Boyle, Copco and Iron Gate Reservoirs for hydropower production, and Iron Gate Dam flow targets to benefit anadromous fish production. Note that in the surrogate simulation, some agricultural deliveries could not be met and the use of a water bank would be required.

SUMMARY

The SIAM decision support system predicts that there is some potential for improving fall Chinook salmon production by altering the historical flow release patterns for Iron Gate Dam on the Klamath River mainstem. Opportunities for altering the Iron Gate Dam flow regime are greatest in low and average hydrological years because water storage in the Klamath system is limited to Upper Klamath Lake and a few small wetland areas in the upper basin. Upper Klamath Lake has no multi-year storage capability and generally passes all inflow received minus agricultural consumptive use downstream through the system during a yearly cycle.

The SIAM model predicted that re-distributing the total annual flow on a percentage basis, with most of the flow released during the spring, rather than the winter months (as has typified the historical flow regime in the Klamath River) was the flow regime that most favored fall Chinook salmon production. The effect of this shift in the proportion of total annual flow to the spring months apparently would provide greater predicted rearing habitat for fry and smolt life stages of fall Chinook salmon.

A closer look at historical predictions of fish production indicates that high or irregular flows during the spawning season may be particularly detrimental to year class success because in the study reach from Iron Gate Dam to the confluence of the Scott River, spawning habitat is severely reduced when flows exceed approximately 4000 cfs. Low flows in spring (<2000 cfs) are predicted to substantially reduce juvenile fall Chinook salmon rearing habitat.

If the fish production model within SIAM is generally indicative of factors that either favor or may adversely impact various life stages of fall Chinook salmon in the Klamath River, then this information may provide insights to resource managers in determining Iron Gate Dam flow release patterns that tend to consistently favor anadromous fish production. The difficulty will be in meeting the constraints for the biological opinion for endangered lake suckers, the biological opinion for coho salmon, hydropower production and agricultural deliveries. The example presented here for WY 2000 indicated that only a portion of the predicted maximum benefit of 26% increase in fish production could be provided when most of the constraints were met in the SIAM simulation 17%). Additional creative approaches, such as off-stream storage in historic wetlands to store abundant winter flows for later use to meet agricultural demands or downstream release for anadromous fish, could provide the predicted maximum benefit for increased fall Chinook salmon production. It may also be possible to develop water-year specific hydrographs rather than to apply a single percentage-based hydrograph.

USGS does not recommend specific resource management actions. We focus on providing information through model simulation results to assist managers in planning yearly or multi-year strategic actions to meet management objectives for a variety of resource benefit uses. In the Klamath River basin, those resource benefits vary widely with space, time, and management purview. SIAM is a modeling tool that may provide insights, illustrate consequences of potential decisions, and allow rapid assessment and exploration of effects of flow changes on water quality and fall Chinook salmon fish production in the Klamath River. If the Klamath River basin is one of those “areas supporting strong populations or multiple species...critical for conservation management...” (Thurow et al., 1997), then perhaps SIAM can provide meaningful, rapid, and objective analyses that can be utilized to manage these dwindling populations.

ACKNOWLEDGMENTS

We wish to thank Jonathan Friedman, Research Hydrologist, USGS, friedmanj(at)usgs.gov, and Jon Hendrikson, Hydrologist, USACE, jon.s.hendrikson(at)usace.army.mil for review and comments that greatly enhanced this manuscript.

REFERENCES

Bartholow, J. 2002. Modeling Chinook salmon with Salmod on the Sacramento River, California. Project completion report. Revised. 97 p. plus appendices.

Bartholow, J.M., J. Heasley, R.B. Hanna, J. Sandelin, M. Flug, S. Campbell, J. Henriksen, and A. Douglas. 2003. Evaluating Water Management Strategies with the Systems Impact Assessment Model: SIAM Version 3. U.S. Geological Survey, Fort Collins Science Center Open File Report 03-82. Fort Collins, Colorado. March 2003. 128 pp. Available on the Internet at http://www.fort.usgs.gov.

Bartholow, J., J. Heasley, J. Sandelin, B.A.K. Coughlan, J. Laake, and A. Moos. 2001. Salmod: A Population Model for Salmonids: User’s Manual. Version W3. USGS/FORT Internal Publication. 76 pp. Also available over the Internet at http://www.fort.usgs.gov.

Bartholow, J.M., and J. Henriksen. 2006. Assessment of factors limiting Klamath River fall Chinook salmon production potential using historical flows and temperatures. USGS Open File Report 2006–1249. U.S. Geological Survey, Fort Collins, Colo. 129 p

Bartholow, J.M., J.L. Laake, C.B. Stalnaker, and S.C. Williamson. 1993. A Salmonid Population Model with Emphasis on Habitat Limitations. Rivers. 4(4:265-279.

California Department of Fish and Wildlife. 2003. September 2002 Klamath River Fish Kill: Preliminary Analysis of Contributing Factors. Northern California-North Coast Region. 57 pp.

Campbell, S.G., Hanna, R.B., M. Flug and J.F. Scott. 2001. Modeling Klamath River system operations for quantity and quality. ASCE Journal of Water Resources Planning and Management. September/October 2001:284-294.

Capra, H., P. Breil, and Y. Souchon. 1995. A new tool to interpret magnitude and duration of fish habitat variations. Regulated Rivers: Research & Management 10:281-289.

Dai, T., and J.W. Labadie. 2001. River basin network model for integrated water quantity/quality management. Journal of Water Resources Planning and Management 127(5:295–305.

Dunning, J.B. Jr., D.J. Stewart, B.J. Danielson, B.R. Noon, T.L. Root, R.H. Lamberson, and E.E. Stevens. 1995. Spatially explicit population models: Current forms and future uses. Ecological Applications, 51:3-11.

Flug, M., and J.F. Scott. 1998. Modeling and Management of Water in the Klamath River Basin: Overcoming Politics and Conflicts. In: ASCE 1998 International Water Resources Engineering Conference Proceedings, "Water Resources Engineering 98", Abt, S.R. et al. (Editors), American Survey of Civil Engineers, VA, Vol. 1, 938-943.

Gouraud, V., J.L. Bagliniere, P. Baran, C. Sabaton, P. Lim, and D. Ombredane. 2001. Factors regulating brown trout populations in two French rivers: Application of a dynamic population model. Regulated Rivers: Research & Management 17:557-569.

Hanna, R.B., and S.G. Campbell. 2000. Water Quality Modeling in the Systems Impact Assessment Model for the Klamath Basin – Keno, Oregon to Seiad Valley, California. USGS Open File Report 99-113. 82 pp.

Kent, J.J. 1999. Application and sensitivity analysis of a salmonid population model for the Sacramento River, California. Master's Thesis, Colorado State University, Fort Collins, Colorado. 79 pp.

Labadie, J.W. 1988. Program MODSIM: River basin network flow model for the microcomputer. Department of Civil Engineering, Colorado State University, Ft. Collins, Colorado.

Lynch, D.D., and J.C. Risley. 2003. Klamath River Basin Hydrologic Conditions Prior to the September 2002 Die-Off of Salmon and Steelhead. U.S. Geological Survey Water-Resources Investigations Report 03-4099, Portland OR. 10 pp.

Milhous, R.T., M.A. Updike, and D.M. Schneider. 1989. Physical habitat simulation system reference manual - Version II. Instream Flow Information Paper No. 26. Washington, DC: U.S. Fish and Wildlife Service (Biological Report 89[16]). v pp.

National Marine Fisheries Service (NMFS). 1997. Endangered and Threatened Wildlife and Plants: Threatened Status for the Southern Oregon/Northern California Coast Evolutionarily Significant Unit of Coho Salmon. 50 CRF Part 17. Federal Register. 6211:33038-33039.

NOAA. 2001. National Oceanic and Atmospheric Administration Fisheries (NOAA Fisheries). Biological Opinion. Ongoing Klamath Project Operations. NOAA Fisheries Southwest Region , National Oceanic and Atmospheric Administration , Long Beach, CA. April 6, 2001. [Online]. Available: http://swr.ucsd.edu. [January 28, 2002].

National Research Council. 2004. National Research Council of the National Academies. Endangered and Threatened Fishes in the Klamath River Basin: Causes of Decline and Strategies for Recovery. National Academies Press, Washington, DC. 397 pp.

Perkins, D.L., J. Kann, and G.G. Scoppettone. 2000. The Role of Poor Water Quality and Fish Kills in the Decline of Endangered Lost River and Shortnose Suckers in Upper Klamath Lake. U.S. Geological Survey, Biological Resources Division Report Submitted to U.S. Bureau of Reclamation, Klamath Falls Project Office, Klamath Falls, OR 97603. Contract 4-AA-29-12160. 39 pp.

Sabaton, C., L. Siegler, V. Gouraud, J.L. Bagliniere, and S. Manne. 1997. Presentation and first applications of a dynamic population model for brown trout, *Salmo trutta* L.: aid to river management. Fisheries Management and Ecology 4:425-438.

Scott, J.F., and M. Flug. 1998. Modeling With MODSIM: Klamath River Basin Water Quantity for Protecting Fish and Other Resource Values. In: First Federal Interagency Hydrologic Modeling Conference Proceedings, Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data, Las Vegas, Nevada. April 19-23, 1998; Vol 2, 8-103 - 8-110.

Trihey and Associates. 1996. Instream Flow Requirements for Tribal Trust Species in the Klamath River. Prepared on behalf of the Yurok Tribe. March. 43 pp.

Thurow, R.F., D.C. Lee, and B. E. Rieman. 1997. Distribution and Status of Seven Native Salmonids in the Interior Columbia River Basins and Portions of the Klamath River and the Great Basins. North American Journal of Fisheries Management. 17:1094-110.

USACE. 1986. U.S. Army Corps of Engineers. HEC-5 Simulation of Flood Control and Conservation Systems, Appendix on Water Quality Analysis. 220pp.

???U.S. Fish and Wildlife Service. 1988. Endangered and Threatened Wildlife and Plants: Determination of Endangered Status for the Shortnose Sucker and the Lost River Sucker. 50 CFR Part 17. Federal Register. 53137:2130-27134.

USFWS. 2001. U.S. Fish and Wildlife Service Biological/Conference Opinion Regarding the Effects of Operation of the Bureau of Reclamation's Klamath Project on the Endangered Lost River Sucker *(Deltistes luxatus),* Endangered Shortnose Sucker *(Chasmistes brevirostris),* Threatened Bald Eagle *(Haliaeetus leucocephalus),* and Proposed Critical Habitat for the Lost River/Shortnose suckers. Klamath Falls, OR : Klamath Falls Fish and Wildlife Office . [Online]. Available: http://www.usbr.gov [August 18, 2001].

U.S. Fish and Wildlife Service and Hoopa Valley Tribe. 1999. Trinity River Flow Evaluation, Final Report. 307 pp plus appendices.

William M. Kier Associates. 1991. Long Range Plan for the Klamath River Basin Conservation and Fishery Restoration Program. Prepared for the Klamath River Basin Fisheries Task Force. January, 1991. 271 pp. plus appendices.

Williamson, J.D., and J.S. Foote. 1998. FY98 Investigational Report: Diagnostic Evaluation ofMoribund Juvenile Salmonids in the Trinity and Klamath Rivers (June-September, 1998U.S. Fish and Wildlife Service, California-Nevada Fish Health Center, Anderson, CA. December, 1998. 13 pp. plus appendices.

Williamson, S.C., J.M. Bartholow, and C.B. Stalnaker. 1993. Conceptual model for quantifying pre-smolt production from flow-dependent physical habitat and water temperature. Regulated Rivers: Research & Management. 81&2:15-28.

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