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ENVIRONMENTAL ASSESSMENT

Predicting the Thermal Effects of Dam Removal on the Klamath River

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ABSTRACT / The Klamath River once supported large runs of anadromous salmonids. Water temperature associated with multiple mainstem hydropower facilities might be one of many factors responsible for depressing Klamath salmon stocks. We combined a water quantity model and a water quality model to predict how removing the series of dams below Upper Klamath Lake might affect water temperatures, and ultimately fish survival, in the spawning and rearing portions of the mainstem Klamath. We calibrated the water quantity and quality models and applied them for the hydrometeorological conditions during a 40-year postdam period. Then, we hypothetically removed the dams and their impoundments from the models and reestimated the river's water temperatures. The principal thermal effect of dam and reservoir removal would be to restore the timing (phase) of the river's seasonal thermal signature by shifting it approximately 18 days earlier in the year, resulting in river temperatures that more rapidly track ambient air temperatures. Such a shift would likely cool thermal habitat conditions for adult fall chinook (*Oncorhynchus tshawytscha*) during upstream migration and benefit mainstem spawning. By contrast, spring and early summer temperatures could be warmer without dams, potentially harming chinook rearing and outmigration in the mainstem. Dam removal might affect the river's thermal regime during certain conditions for over 200 km of the mainstem.

The Klamath Basin, lying in northern California and southern Oregon, USA (Figure 1), historically produced large runs of chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead trout (*O. mykiss*), and other species that enlivened subsistence, sport, and commercial fisheries. Hydropower construction, water diversions for agriculture, mining, timber harvest, overfishing, loss of genetic integrity, disease, and climatic fluctuations attributable to El Niño are all considered contributors to the decline in the Klamath River fishery (Brown and others 1994). Despite hatchery and habitat restoration programs, and increasingly restrictive harvest regulations, salmonid populations have continued to decline in the Klamath Basin. The best quantitative information available indicates a halving of spawning run sizes since the late 1970s (USDOI 1985).

Water temperatures play a crucial role in physiological development, seasonal event timing, behavior, and survival for all cold-blooded aquatic organisms and are viewed as an obstacle to fish recovery on the mainstem Klamath River (California State Senate 1963; USDOI 1985; Klamath River Basin Fisheries Task Force 1991). Water temperature below the lowest of the Klamath's mainstem dams (and the current upstream limit of salmon migration) is known to regularly exceed 22–26°C in the summer and fall. These temperatures are clearly stressful for salmonids (Brett and others 1982; Myrick and Cech 2001) and could be acutely lethal or exclusionary (Eaton and others 1995, but see Williams 1995), especially in combination with diseases known to be present in the Klamath River (USEPA 1974; Williamson and Foott 1998). Episodic fish kills have occurred on this river (Foott and others 1999), most recently resulting in widespread publicity in the popular press. Although we do not know whether water temperature was a direct causative factor in recent kills, temperature is certainly one of many elements contributing to a stressful environment in this river at certain times of the year.

The series of hydropower facilities on the mainstem Klamath River (Figure 1) are currently undergoing a Federal Energy and Regulatory Commission (FERC) relicensing review. One option being considered is partial or complete removal of the four hydropower facilities below Link River Dam on Upper Klamath

KEY WORDS: Klamath River; Dam removal; Thermal regime; Phase shift; Recovery distance; Anadromous fish

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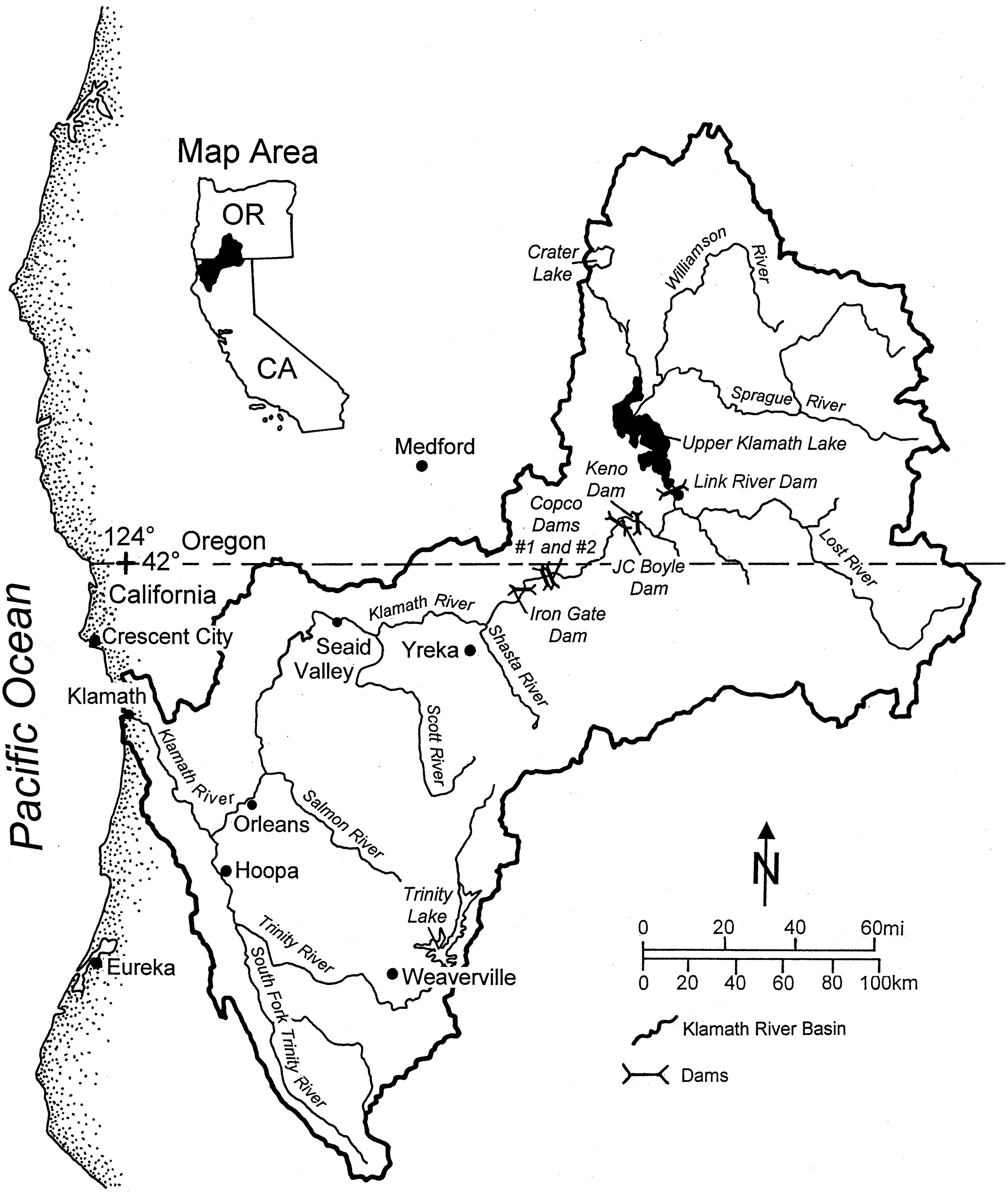

Figure 1. Klamath River Basin, Oregon and California, and approximate location of power-producing facilities on the mainstem. (Map adapted with permission from the Water Education Foundation, Sacramento, California.)

Lake (UKL). The principal objectives of dam removal are to provide access to more miles of spawning, rearing, and migration corridor habitat for anadromous salmonids (fish that grow in the ocean and return to fresh water to spawn) and to foster improvements to the river's water quality.

Much is known about changes in water temperature that accompany reservoir construction. Many researchers have supplied quantitative predam and postdam data for specific projects (Sylvester 1963; Ward 1963; Jaske and Goebel 1967; Moore 1967; Lavis and Smith 1972; Crisp 1977; Wunderlich and Shiao 1984; Cowx and others 1987; Webb and Walling 1988), whereas others have described thermal changes on a more conceptual level (Ward and Stanford 1982; Poff and Hart 2002). In general, thermal effects and their causes are well understood. Reservoirs store not only water but also heat. Thus, the reservoir acts as a buffer that reduces both the annual amplitude of, and daily fluctuations in, downstream temperatures because the reservoir's mass warms and cools more slowly than the free-flowing river. For the same reason, reservoirs delay the annual thermal signature such that those periods of warmest and coolest temperatures occur later than ''normal'' due to the gradual expenditure of stored heat (or cold). The exact magnitude of these changes depends on several factors: (1) the volume, surface area, and depths of impoundments; (2) the depth of water withdrawals from dams; and (3) the rate of withdrawals compared with unregulated flows. The distance these effects can be measured downstream depends largely on impoundment discharge, but is typically less than 50 km (Palmer and O'Keeffe 1989).

Only recently has much serious attention been given to understanding the thermal consequences of reservoir removal (Bednarek 2001; Gregory and others 2002; Hart and Poff 2002; Horne and others 2004). Although few removal projects have been studied explicitly for temperature changes (Pawloski and Cook 1993; McRae and Edwards 1994), it is reasonable to expect from first principles that water temperatures would return to a close semblance of predam conditions, barring other landscape-scale changes to the watershed (Hart and others 2002). Unfortunately, good thermal records are not available on the Klamath River prior to dam construction. The US Geological Survey (USGS) did collect daily maximum and minimum temperature data at several river locations during the early postdam period from approximately 1964 to 1981; this dataset has been supplemented in recent years (e.g., Campbell 2001). Additional studies have been done on the Klamath to understand the effects of alternative flow regimes on downstream temperatures and other water quality parameters, but only with the dams in place (Deas and Orlob 1999; Hanna and Campbell 2000; Lowney 2000; Campbell and others 2001).

Objective

Because any improvement in water temperatures might aid the recovery of anadromous salmon on the Klamath River (Klamath River Basin Fisheries Task Force 1991), we wanted to quantify changes to the river's thermal regime from Upper Klamath Lake to near the Pacific Ocean without the series of impoundments below UKL. To address this objective, we used a decision support model, the System Impact Assessment Model, SIAM Version 3.75 (Campbell and others 2001; Bartholow and others 2003), to simulate water temperatures in the mainstem Klamath below UKL if the dams were removed. Our intent was to examine a long period of record to represent the full range of hydrometeorological conditions, both seasonally and annually. Although our database covered water years (running from October to September) 1961–2001, we chose to start our comparisons after Iron Gate Dam was fully functional in 1962. Additionally, we wanted to determine the approximate length of river that might be affected if the dams were removed and to make a preliminary assessment of the potential that any temperature changes might have on chinook salmon, the most abundant salmon in the mainstem Klamath.

Study Area

Thermal Setting

The Klamath River is situated far enough north (42°N) to support a variety of cold-water fish. However, the Cascade and Siskiyou mountain ranges isolate much of the upper basin from moderating coastal weather. This isolation, combined with relatively low elevations along the river below UKL, serve to position the Klamath on an ecological ''edge'' with respect to thermal conditions. Temperatures in the Klamath and nearby streams are elevated with a greater frequency and remain elevated for a longer time than waters in adjacent basins. In particular, summer highs in the Lower Klamath Basin might exceed 26.6°C more than 10 days per year in contrast to most coastal drainage basins—both north and south of the Klamath—that never exceed this temperature (Blakey 1966). Wet winters are followed by hot, dry summers. Water warmed by impoundments, water diversions, warm agricultural return flows, and channel modifications have been cited as factors contributing to high mainstem temperatures (USDOI 1985; Klamath River Basin Fisheries Task Force 1991).

Historical Watershed Development

The Upper Klamath Basin was naturally composed of extensive wetlands, once having a reputation as the largest North American habitat for migrating waterfowl. Over the past 150 years, human alterations have extensively transformed the landscape, watershed, and rivers (Flug and Scott 1998). Land-use changes include fur trapping that removed beavers, dredging for gold, commercial timber harvest, and commercial fishing. In 1905, the US Bureau of Reclamation was authorized to develop the Klamath Reclamation Project to support water management for agricultural development. Link River Dam was constructed in 1921 at the outflow from Upper Klamath Lake to enhance water storage in the naturally formed UKL. Along with the construction of dams, dikes, and water delivery canals came extensive drainage of natural wetlands and marshes to create arable lands. Since 1958, the Klamath Reclamation Project has supplied an average of 493×10^6 m^3 of water annually to 73,000 ha of fertile land.

There are four hydropower facilities on the mainstem Klamath River: Link River Dam just below UKL, J.C. Boyle Dam (1958), Copco (1917), and Iron Gate Dam (1962). Two other structures, one forming Lake Ewauna and one at Keno Dam, control the river slightly, but they produce no hydropower. Iron Gate Dam, a reregulation facility for peaking hydropower operations just upstream at Copco, required a FERC license that established a minimum flow release schedule. Flows were increased and modified under US Fish and Wildlife Service (FWS) Biological Opinions of 1992 and 1996 and continue to be reevaluated. The minimum discharge regime at Iron Gate has had the effect of producing higher daily minimum but lower summer average flows than pre-Iron Gate conditions (National Biological Service 1995). Iron Gate Dam is now the terminus for anadromous spawning runs in the Klamath River.

Existing Water Supply and Management

The relative values of watershed inflows and ungauged hydrologic accretions are shown in Table 1. Flows relative to Seiad Valley are shown because this is the river segment most likely to be affected by thermal changes if dams were removed. Because UKL can at best control 48% of the flow to Seiad Valley, unmanaged tributaries and accretions reduce the opportunity to substantially alter flows in this river reach. Annual inflows to Upper Klamath Lake are highly variable (Table 2). The smaller UKL outflows reflect water deliveries to the Klamath Reclamation Project, although some agricultural return flows reenter the Klamath River downstream. UKL inflows combined with substantial middle- and lower-basin accretions (most notably the Shasta, Scott, Salmon, and Trinity rivers) make the Klamath the third largest discharge into the Pacific Ocean in the conterminous United States. It is interesting to note that the net consumptive use of water delivered to Klamath Reclamation Project lands amounts to less than 2% of the Klamath River's ocean discharge.

A summary of reservoir capacities (Table 3) highlights the relative importance of Upper Klamath Lake for water management. In Table 3, the maximum storage values represent the total storage possible for each lake or reservoir. Dead storage is the volume that remains impounded below the level of existing outlets. Therefore, active storage represents the ''manageable'' volume of water for each reservoir. The 1962–2001 operating storage values in Table 3 represent the volumes that were actually used during this period. These smaller volumes reflect contemporary operations that meet agricultural deliveries, provide hydraulic head to generate hydropower, maintain water levels and habitat for fish in UKL, and support minimum flows below Iron Gate Dam.

A range of computed hydraulic residence times for water to move through each reservoir is given in the last column of Table 3. These residence times are based on the maximum storage for each reservoir divided by a range of low, average, and high monthly flows from the 1962–2001 period of analysis. For residence times greater than 1 month, computations were based on the approximate number of months representing that residence time. For example, if an approximate residence time of 6 months was calculated, then a 6-month flow period for low, average, and high discharge conditions was taken from the flow record to generate the range given in Table 3.

None of the reservoirs is suitable for temperature control. The reservoirs below UKL are small, have outlet structures located in the epilimnion, and have short hydraulic residence times (Table 3). For example, the average residence time in Iron Gate Reservoir is less than 2 weeks (~13.8 days), severely limiting its potential to influence water quality, and specifically water temperature, in unregulated downstream sections of the river. Although the reservoirs exhibit thermal stratification during the summer, the cool water mass below the epilimnion in each reservoir is limited. Intensive modeling estimates of Iron Gate Reservoir suggest that careful water withdrawal through multiple vertical outlets would

Table 1. Average annual flow into and down the Klamath River

Location	Average annual Klamath River flow (1962–2001)		
	Flow in 10^6 m^3/yr	Flow as % of Seiad Valley, California, flow on the Klamath River	Flow as % of Klamath, California, flow on the Klamath River
UKL inflows	1,666	48	11
Accretions	437	12	3
Shasta River	172	5	1
Accretions	521	15	3
Scott River	572	16	4
Klamath River at Seiad Valley, California	3,502	100	22
Salmon River	1,656	NA	11
Accretions	2,595	NA	16
Klamath River at Orleans, California	7,753	NA	49
Trinity River	4,332	NA	28
Accretions	3,683	NA	23
Klamath River at Klamath, California (near the Pacific Ocean)	15,768	NA	100

Note: Accretions are ungauged hydrologic inputs to the Klamath River. NA means not applicable.

only decrease outflow temperatures for a brief period (no more than 1.5 months), and then only by about 1–2°C, before the reservoir would mix to near-surface temperatures (Mike Deas, Watercourse Engineering, personal communication). UKL is large but quite shallow, with an average depth of only 3 m, precluding effective stratification.

In addition to the limited size of all system reservoirs below UKL, recent operating constraints make the Klamath essentially a run-of-the-river system. Total basinwide storage on average can accommodate only about 5 months' UKL inflow (total active storage from Table 3 divided by the average UKL inflow from Table 1). Using more typical operating storage values, only 2.5 months' storage is accessible. In other words, year-to-year carryover storage to meet both agricultural and in-stream flow demands is generally not available to provide water during low water years or low-flow summer months when upstream and instream demands compete. For example, Figure 2 illustrates the monthly discharge variation at Iron Gate Dam for the period modeled. The variation from extremely low summer flows to high peak flows helps explain the wide range of hydraulic residence times given in Table 3, and the relatively high winter flows signal the lack of systemwide storage.

Table 2. Annual water year flows at two major reservoirs on the Klamath River in 10^6 m^3

	Minimum (1992)	Average (1962–2001)	Maximum (1965)
UKL inflow	708	1666	2615
UKL outflow at Link River Dam	488	1329	2213
Releases below Iron Gate Dam	572	1915	3286

Methods

Water Quantity and Quality Models

MODSIM (Labadie 1988; Dai and Labadie 2001), a network water quantity simulation model developed at Colorado State University, was applied to the Klamath River Basin to evaluate multiple water management alternatives. MODSIM is a water resources planning model developed for interconnected and managed water systems with numerous reservoirs, diversions, and return flows. The model is designed to allocate water consistent with the hydrological, physical, and institutional aspects of a river basin. It employs a prioritization scheme to simulate flows throughout the system under different water management alternatives consisting of reservoir operating rules and constraints, instream flow requirements, agricultural demands, and other water allocations.

We used MODSIM to simulate river and reservoir operation from UKL downstream to the Pacific Ocean using a monthly time step. Inputs to MODSIM were derived from historical records and/or simulated flows for the upstream portion of the basin consistent with data from the US Bureau of Reclamation's planning models. Major tributaries (Shasta, Scott, Salmon, and

Table 3. Reservoir storage volumes and calculated hydraulic residence times for a range of storage definitions and a range of flows on the mainstem Klamath River

Reservoir	Maximum storage (10^6 m^3)	Dead storage (10^6 m^3)	Active storage (10^6 m^3)	1962–2001 operating storage (10^6 m^3)	Computed hydraulic residence time (days) Low — average — high
UKL — Link River Dam	776.8	176.3	600.5	276.5	45.8 — 170.2 — 400.5
Lake Ewauna	1.2	0	1.2	0.1	0.1 — 0.9 — 4.4
Keno Reservoir	22.8	0	22.8	4.3	1.1 — 5.7 — 64.7
J.C. Boyle Reservoir (Topsy Lake)	4.2	0	4.2	1.9	0.2 — 0.9 — 4.9
Copco Lake	57.8	0	36.3	34.5	2.5 — 11.0 — 59.4
Copco #2 forebay	0.1	0	0.1	0	0.0 — 0.0 — 0.1
Iron Gate Reservoir	72.5	15.7	56.8	28.7	3.1 — 13.8 — 74.4
Total Storage	935.4	192.0	721.9	346.0	—
Total system residence time	All storage bodies				52.8 — 202.5 — 608.4
	All storage below UKL				7.0 — 32.3 — 207.9

Trinity Rivers) were not modeled except as inflows, using USGS gauge records at or near their confluence with the Klamath. Scott and Flug (1998) and Flug and Scott (1998) provided more specifics concerning the flow network for the Klamath River.

To evaluate water quality, we used the HEC-5Q model to simulate mean daily water temperature from UKL to the ocean. HEC-5Q is a one-dimensional model developed by the US Army Corps of Engineers (USACE 1986). The model simulates water quality in reservoirs vertically from the surface to the bottom, and in rivers longitudinally downstream. Data required by HEC-5Q included daily average discharge and temperature for all inflowing water and daily average meteorological data (including air and dew point temperatures, wind speed, and cloud cover). Riparian shading was not included because median channel widths are greater than 30 m, indicating little shading from that source. All four Klamath River hydropower facilities in series were modeled in HEC-5Q along with major tributary inflows. Single-day time-step constraints in HEC-5Q required simplifying the smaller J.C. Boyle Reservoir and the Copco #2 forebay to wide river reaches because their operational pools exchange more than once per day. A full description of these methods can be found in Hanna and Campbell (2000).

We linked the MODSIM and HEC-5Q models together using decision support software (SIAM) described by Bartholow and others (2003). This software supplied all the required data, unit conversions between the models, simulation options, and display features. We fed the MODSIM-generated monthly flow and reservoir storage values, disaggregated to daily averages, into the HEC-5Q model. Disaggregation represented ordinary regulated flow conditions well, but was less accurate in representing unregulated winter peak flows. Fortunately, model simulations demonstrated that the effect of disaggregation on predicted water temperatures was negligible.

Model Calibration and Validation

Model calibration and validation provided confidence in the models' simulations of different hydrologic and meteorologic conditions. Calibration and validation steps for MODSIM and HEC-5Q were performed independently. The period 1970–1979 was selected for MODSIM calibration because it contained a variety of low, average, and high hydrologic years, as well as relatively complete data records. Calibration included setting reservoir "target" storage levels to historical values and comparing the model's simulated downstream flow releases to historical recorded flows at three USGS gauge locations. Differences between modeled and gauged flows for the calibration period at these locations are presented in Table 4. Model calibration was considered excellent, with less than 0.1% difference in flows on an annual basis at all three gauging locations. Validation focused on the period 1980–1989, which also contained a representative mix of hydrologic years. Validation was also considered excellent, with average monthly and yearly differences well below 1.0%. A few anomalies occurred in specific months and were readily explained by documented changes in normal reservoir operations.

The HEC-5Q model simulation for temperature was calibrated for 1996 and validated using 1997 and 1998

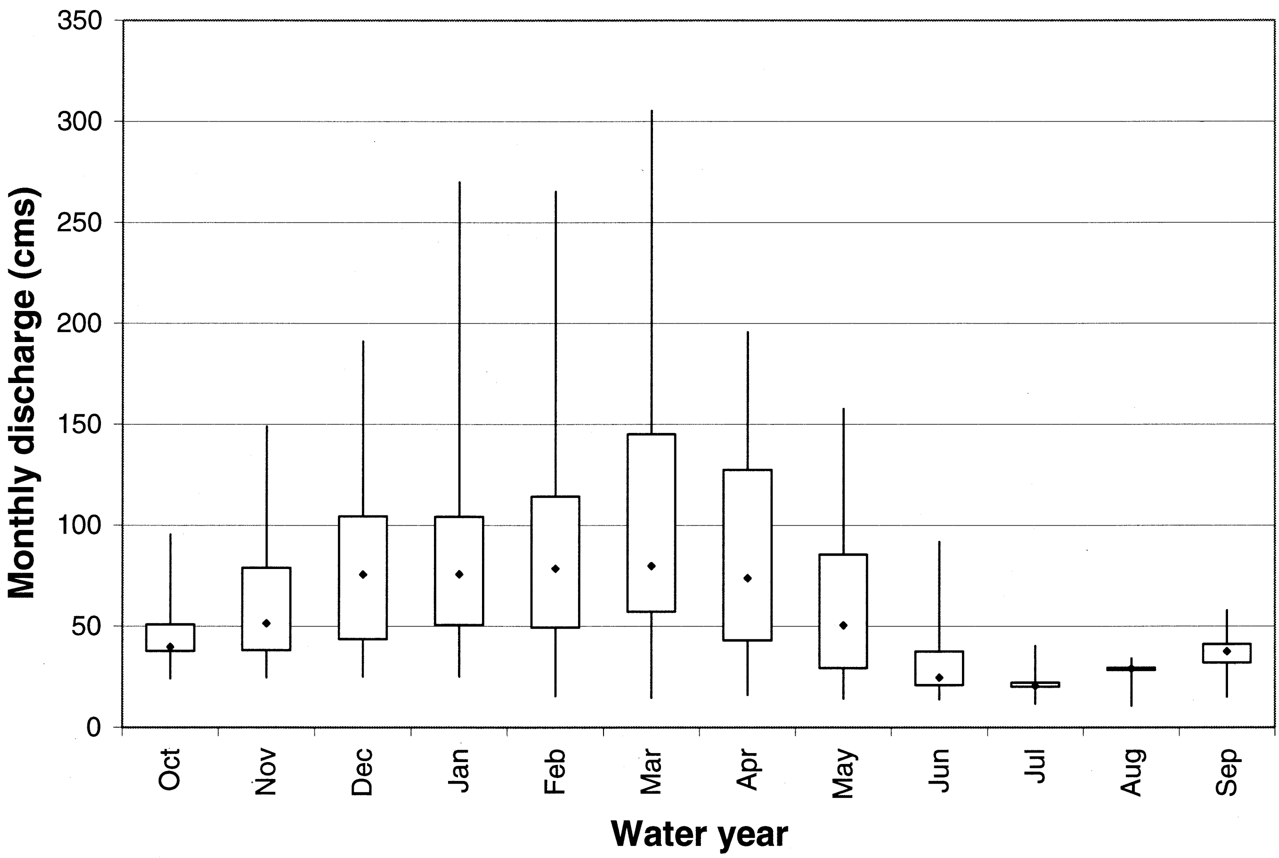

Figure 2. Whisker plot of historical Iron Gate Dam monthly releases for the period 1962–2001 showing maximum, 75th percentile, median (♦), 25th percentile, and minimum monthly discharges (m^3/s) through the water year.

measurements because these were years when the best data were available for both reservoir and river locations. Goodness-of-fit values for model calibration and validation are presented in Table 5. Table 6 provides goodness-of-fit statistics over the entire 40-year period we subsequently simulated at seven specific locations. The largest error we found was near the ocean (Klamath, California), which could be due to estuarine tidal influence we did not model. Additional sources of error include gaps in historic meteorological data (especially cloud cover), disaggregating monthly flows into daily values, HEC-5Q's failure to incorporate longitudinal dispersion in the reservoirs and river, the model's inability to handle topographic shading, and changes in methods for stream temperature measurement during the period simulated. The mean absolute error (MABSE) associated with our water quality model for the 40-year period (~1.8°C) was in line with modeling applications for total maximum daily load (TMDL) analyses, which are generally between 0.5°C and 2.0°C (Paul Wiegand, National Council for Air and Stream Improvement, Corvallis, Oregon, personal communication). During the summer (1 May–30 September), when we had the most complete measured data for 1962–2001, mean daily temperatures predicted by SIAM were within ±0.4°C at the Iron Gate Dam location, ±0.8°C at the Seiad location, and ±1.3°C near the ocean. Using only the most contemporary measured data (1996–2001, overlapping the model's calibration and validation periods), differences were even smaller.

The HEC-5Q model performed well in capturing the essence of the river's seasonal thermal signature under existing conditions as signified by the highly significant r^2 values (e.g., $r^2 = 0.95$, $n = 7627$, $P < 0.001$ at Iron Gate Dam in Table 6). However, because temperature predictions for any single day at any single location contain more uncertainty (±1.8°C), we have generally limited our analyses and resulting conclusions to the identification of temperature changes at longer timescales over multiple years. Additional information on the calibration and validation of HEC-

Table 4. Calibration (1970–1979) of the MODSIM water quantity model for discharge at three locations on the Klamath River

Stream gauge location	Average monthly difference (10^6 m^3)	Yearly average difference (10^6 m^3)	Maximum monthly difference (10^6 m^3)
Keno Dam	0.144	1.732	1.384
Iron Gate Dam	0.154	1.857	1.430
Seiad Valley	0.195	2.344	3.356

Table 5. Water quality model (HEC-5Q) calibration and validation goodness-of-fit statistics for water temperature for the Klamath River modeling domain Keno Dam, Oregon, to Seiad Valley, California

MABSE (°C)			r^2		
Calibration	Validation		Calibration	Validation	
1996	1997	1998	1996	1997	1998
1.0	1.04	0.90	0.90	0.85	0.97

Note: Mean absolute error (MABSE) is a measure of the deviation of the model prediction from the measured data.

Table 6. Spatial goodness-of-fit comparison between simulated and observed mean daily water temperatures (°C) over the water year 1962–2001 time period

Location	Distance from mouth (km)	Dates of measured data	No. of days of measured data (n)	r^2	MABSE (°C)
Keno Dam	376.9	1996–2001	1197	0.950	1.74
Upstream of Copco Dam	327.9	1996–1999	591	0.935	1.77
Iron Gate Dam	308.4	1963–1980; 1996–2001	7627	0.953	1.55
Seiad Valley, California	210.5	1963–1979; 1998–2000	6038	0.946	1.62
Orleans, California	95.3	1966–1982	5282	0.946	2.12
Young's Bar	54.7	1999–2001	395	0.885	1.36
Klamath River at Klamath, California (near the Pacific Ocean)	4.5	1966–1981	4477	0.901	2.23

Note: MABSE refers to the mean absolute error at each location.

5Q at many locations on the Klamath River, including dissolved oxygen and conductivity not discussed here, can be found in Hanna and Campbell (2000).

Biological Thresholds and Evaluation Metrics

Predicting the magnitude of thermal change if the dams were removed would not tell us whether those changes were biologically meaningful. To add to this perspective, we used the maximum recommended temperature from the ranges for three life stages of salmon (USEPA 2003) for the periods of the year they apply (Table 7). Fall chinook salmon are the most studied species throughout the basin due to their overall commercial and subsistence importance. Although timing can vary, peak fall chinook immigration occurs from September through November (as their name implies), with mainstem spawning in October and November. Egg incubation extends from October through February, with fry emergence beginning in February. Juveniles emigrate principally as pulses the following April and May, although a percentage of these fish exit in June or over summer until the next fall, depending on annual meteorologic and hydrologic conditions.

We also used three synthetic metrics to reveal biologically relevant differences between scenarios. One is a computation of degree-days that integrates the total exposure (both intensity and duration) of water temperatures that might adversely affect fish (Armour 1991). As used here, a degree-day is an aggregate measure of thermal stress, calculated as the sum of the differences of mean daily temperature above a specified temperature criterion for a specified time period. We selected 15°C as a chronic high-temperature threshold and 20°C as an acute high-temperature threshold based on values reported by USEPA (2003)

Table 7. Recommended temperature ranges and time periods used as guidelines for biological evaluation

Life stage	Mean daily temperature range	Time period
Spawning and egg incubation	4–14°C	1 October–15 April
Juvenile rearing	12–15°C	1 February–1 July
Adult migration	15–20°C	15 August–15 December

Note: The upper limit of each range reflects the maximum recommended temperature for each West Coast salmon life stage (USEPA 2003). Time periods were adapted for fall chinook salmon on the Klamath River from unpublished data (Shaw and others 1997). The spawning temperature range also protects *in vivo* eggs.

and McCullough (1999). Both the chronic and acute thresholds are below lethal temperatures for most salmon life stages. However, temperatures above these values are associated with progressively adverse effects such as suboptimal growth rates, reduced swimming performance, increased disease risk, and impaired smoltification (USEPA 2003). As an example of our degree-day calculation, 16°C for 1 day would equate to 1 chronic degree-day and 17°C for 3 days would be 6 chronic degree-days.

A second metric we employed was the number of days during the year when water temperatures exceed the recommended temperatures given in Table 7. We refer to this as ''annual exposure,'' which is meant to isolate the duration of stressful temperatures for salmon life stages. The final metric we employed was a measure of macrohabitat suitability, namely, the average number of river kilometers less than or equal to the maximum recommended temperatures. This final metric provided a way to judge spatial, rather than temporal, effects. Degree-days, annual exposure, and macrohabitat suitability indices were used not as absolute standards for water quality or salmon health, but rather as relative guidelines to compare water management alternatives.

Simulation Methodology

Two SIAM simulations were generated and compared. One simulation mimicked the postdam 1962–2001 historical period, reproducing historical flow and storage values with all impoundments and agricultural diversions in place. This simulation, referred to as ''*With Dams*,'' predicts temperature within previously discussed confidence limits. The second simulation, ''*Without Dams*,'' used the same governing hydrologic and meteorologic data, but reservoirs below Upper Klamath Lake were set to a small fixed capacity of 1000 m^3, effectively eliminating them from the water quality simulation. These two simulations differed only in the presence or absence of storage reservoirs; therefore, simulated differences in water temperature can be attributed to that change alone. Historical agricultural diversions still occurred in the *Without Dams* simulation, although we recognize that without the head provided by Keno Dam, existing water diversions would be impacted. Because temperature differences with and without these diversions were negligible (<0.1°C), our results and discussion are confined solely to the *With* and *Without Dams* simulations. (The *Without Dams* scenario did predict a minor increase in available water because reservoir evaporation was eliminated, but this difference also proved negligible in temperature predictions.)

Results

Graphing 40 years of model results does not clearly distinguish differences in the two simulations. Therefore, a representative portion of the results is displayed in Figure 3 that compares predicted mean daily water temperatures with and without dams below the Iron Gate Dam site for the shorter period, water years 1996–2001. It is obvious from Figure 3 that annual maximum temperatures differ between the two simulations. Less obvious, but still apparent, is the shift (delay) between the two traces. In the *With Dams* simulation, temperatures are slightly warmer in the fall and winter (when ambient temperatures are falling) and cooler in the spring and summer (when ambient temperatures are rising) compared to the *Without Dams* simulation. The *With Dams* simulation also shows the reservoirs' influence in dampening daily temperature variability.

We computed temperature differences between the two simulations over the whole 40-year period. The reservoirs collectively dampen the predicted single-day annual maximum temperatures immediately below the Iron Gate site on average by about 2.4°C, from 23.4°C to 21.0°C, although they slightly increase the overall annual average temperature at the same site (0.25°C). By maximizing the $lag_{n\text{-days}}$ correlation between the *With* and *Without Dams* traces for the 40-year period, we found that the annual temperature cycle below the Iron Gate site shifted an average of about +18 days between the two simulations; that is, on an annual basis, the seasonal ''sine curve'' of water temperatures *with* the dams, including both summer maxima and

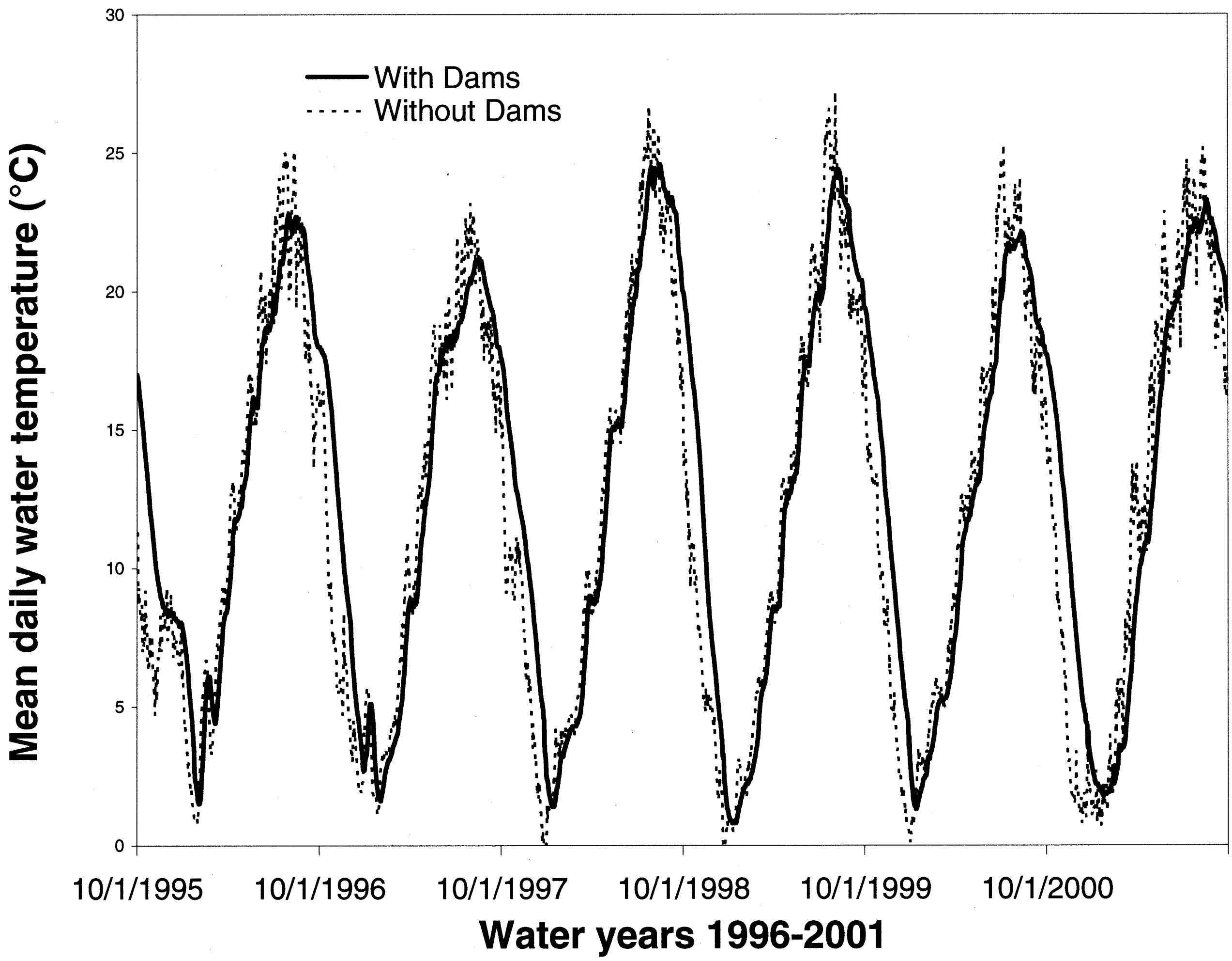

Figure 3. Comparison of simulated mean daily water temperatures at the Iron Gate Dam site in two different SIAM simulations for a recent portion of the 40-year simulation period.

winter minima, occurs about 18 days after they would *without* the dams. This phase shift is easily seen in an annual graph of predicted monthly average temperatures at the Iron Gate site (Figure 4). Careful inspection of Figure 4 reveals that the phase shift is not uniform throughout the year; it is of longer duration during the fall low-flow period (3–4 weeks) and shorter in the higher-flow spring and early summer (2–3 weeks).

The average time advancement for the single-day summer maxima in the *Without Dams* scenario was +21 days. However, there was a large variation in exactly when single-day summer maxima would fall during any given year, ranging from an 11-day negative shift to a 69-day positive shift. Basically, in the *Without Dams* scenario, the whole river becomes much more responsive to ambient meteorology, specifically air temperature. Without the dams supplying their more time-integrated release temperatures, simulated maximum annual temperatures vary more directly with the exact sequence of each year's daily meteorologic driving variables.

At Seiad Valley, 98 km downstream from Iron Gate Dam, the upstream reservoirs' influence is largely attenuated, with ambient meteorology dominating the thermal signature. However, there is still a difference between the *with* and *without* dams simulations (e.g., water year 1996) (Figure 5). Over the 40-year period, predicted mean temperatures at this site are about the same (11.3°C *With Dams* vs. 11.0°C *Without Dams*), but the average annual maximum temperature is 1.3°C higher in the *Without Dams* simulation, slightly less difference than what was found at the Iron Gate site. As at Iron Gate, fall/winter temperatures are cooler and

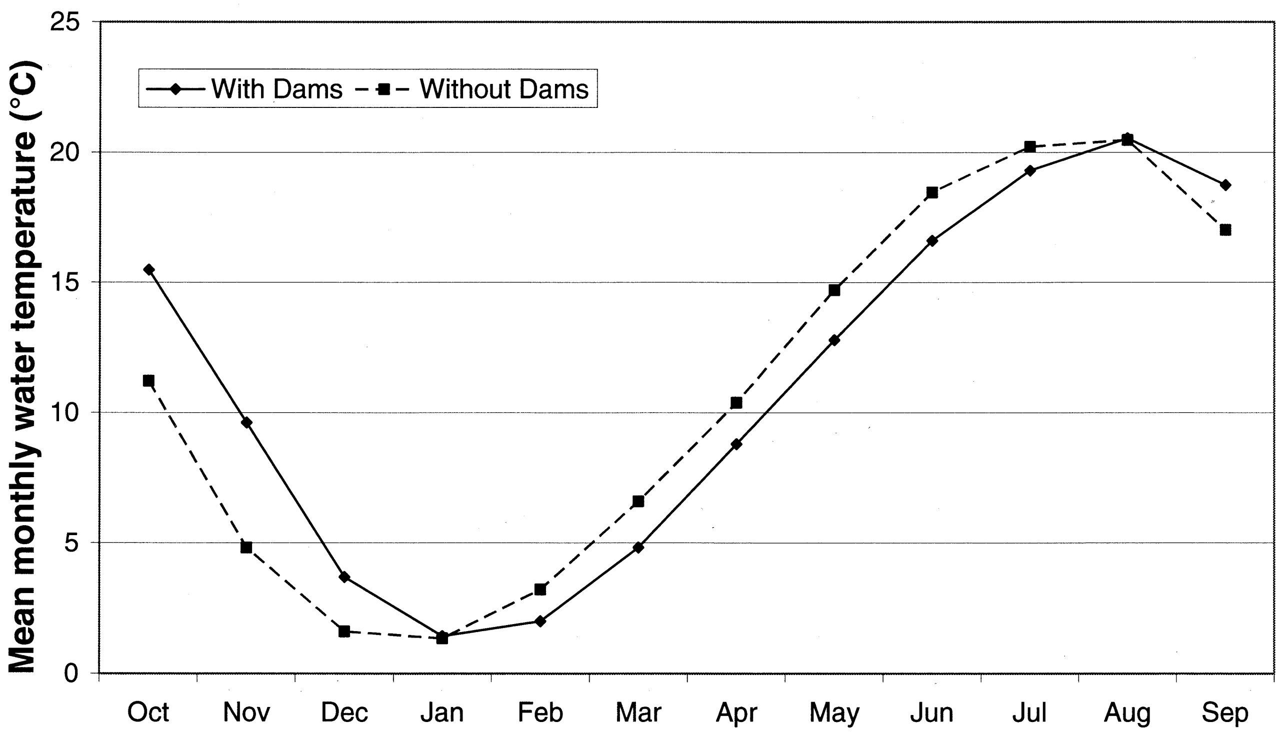

Figure 4. Comparison of predicted mean monthly water temperatures between the *With Dams* and *Without Dams* scenarios averaged over the 40-year period at the Iron Gate Dam site.

spring/summer temperatures are somewhat warmer in the *Without Dams* compared to the *With Dams* simulations.

Further downstream near the ocean, *With* and *Without Dams* temperatures still differ between the simulations, but they are minor. Average mean daily temperatures over the 40-year period are 11.9°C for the *With Dams* simulation and 11.7°C for the *Without Dams* simulation. Average annual maximum temperatures are 0.4°C warmer in the *Without Dams* simulation compared to the *With Dams* simulation. There is a slightly cooler fall/winter and warmer spring/summer trend without the dams in place, as noted upstream at Iron Gate Dam and Seiad Valley.

Two typical longitudinal profiles from Upper Klamath Lake to the river's mouth for both simulations are shown in Figure 6. Temperature discontinuities are clearly visible at the reservoir locations, but are also evident at major tributary junctions. The top part of Figure 6 shows that the two simulations are much the same throughout the river during early summer, whereas the bottom part of the figure indicates wide divergence immediately below the impounded sections during the fall, but a steady convergence as the river approaches the ocean. For example, the October plot in Figure 6 shows *Without Dams* temperatures about 5°C cooler below Iron Gate Dam, tapering to only about 1°C cooler near the ocean.

Table 8 compiles mean annual chronic and acute degree-days for the *With* and *Without Dams* simulations over the entire 40-year simulation period at three locations on the Klamath River. Below Iron Gate Dam, the incidence of chronic degree-days indicative of thermal stress increases by about 8% in the *Without Dams* simulation, whereas the number of acute degree-days increases by 110%. At Seiad Valley, the number of chronic degree-days increases only slightly, but acute degree-days increase about 38%. Near the ocean, chronic degree-days again increase just slightly, but acute degree-days increase about 16%. The degree-day metrics confirm that exposure to chronic temperatures remains about the same between the two simulations, but predicted exposure to the higher acute temperatures is much greater in the *Without Dams* scenario.

Annual exposure, indicative of the duration of thermal stress for salmon, is summarized in Table 9. For spawning/egg incubation and adult migration, the *Without Dams* simulation predicts fewer days above the recommended maximum temperature. However, the *Without Dams* simulation predicts more days outside the recommended maximum temperature for juvenile rearing. Using this metric, the *Without Dams*

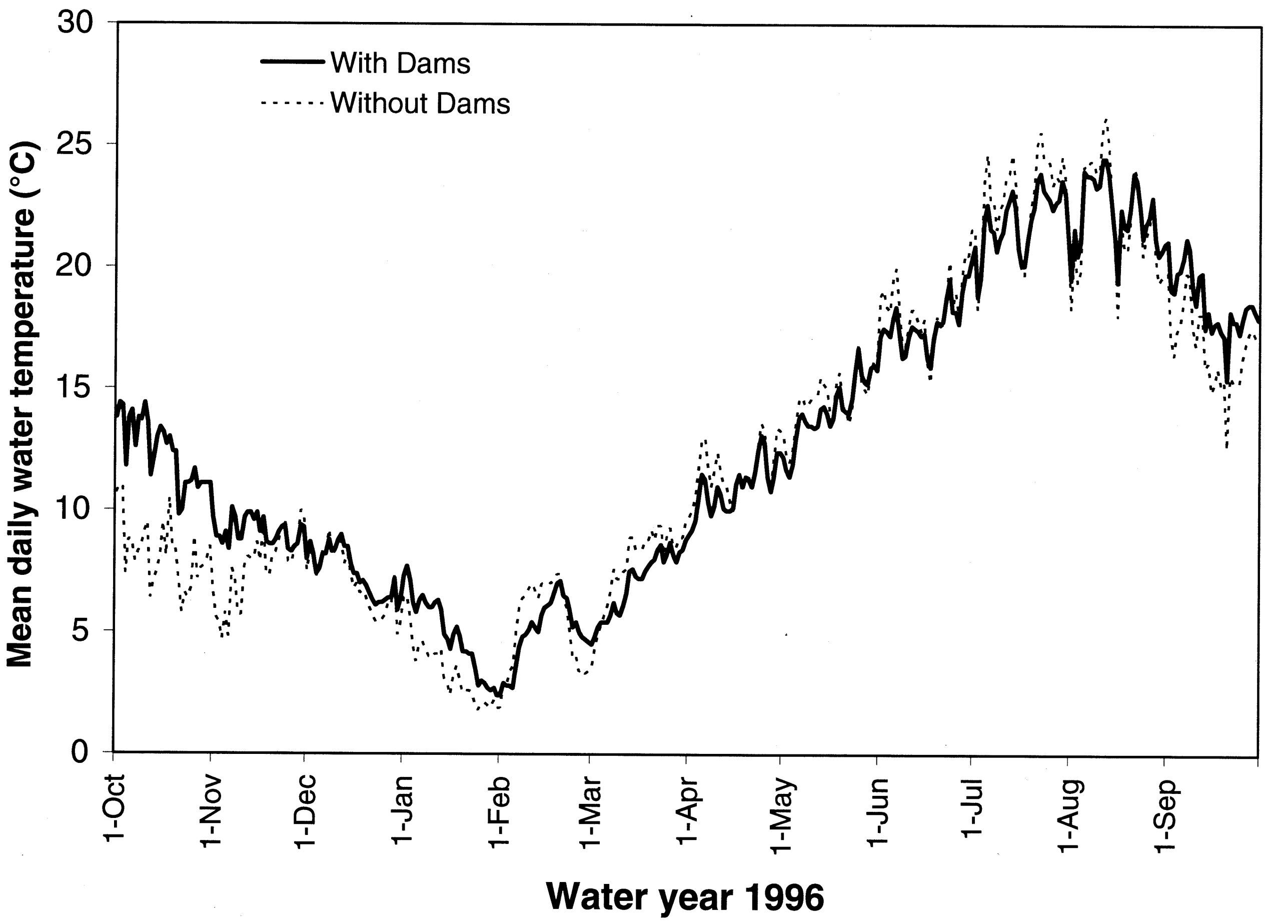

Figure 5. Comparison of predicted mean daily water temperatures at Seiad Valley in two different SIAM simulations for water year 1996.

simulation seems to provide thermal benefits to two of the three life stages of fall chinook salmon we examined, whereas the *With Dams* simulation seems to provide thermal benefits for the juvenile rearing life stage.

Figure 7 integrates many simulation results at a single location over 1 year (1996). This graph highlights periods when the recommended maximum temperatures (Table 7) are exceeded for the various life stages of fall chinook. In early fall, predicted temperatures in the *Without Dams* simulation are cooler than the maximum recommended values for spawning and egg incubation. In spring and early summer, predicted temperatures in both simulations are warmer than recommended for juvenile rearing, but somewhat cooler with the dams in place. Then, in late summer, predicted temperatures are warmer than recommended for adult migration for part of the year in both simulations. In this latter case, the *With Dams* predicted temperatures are higher, and elevated temperatures persist longer, than in the *Without Dams* simulation.

The SIAM macrohabitat metric integrates results through space for the Klamath River mainstem from Iron Gate Dam to the ocean. This metric calculates the total amount of river corridor habitat available above or below a specified temperature. As with other indices from the SIAM model, this metric has limitations. For example, the metric calculates the total length of suitable river habitat over the entire reach from Iron Gate Dam to the ocean without regard to where that habitat is located. Therefore, the metric provides no information about whether there might be a thermal migration barrier or other form of habitat fragmentation.

For fall chinook spawning and egg incubation, the recommended maximum temperature is 14°C (Table 7). The amount of predicted habitat available in the Klamath River from the macrohabitat index for the

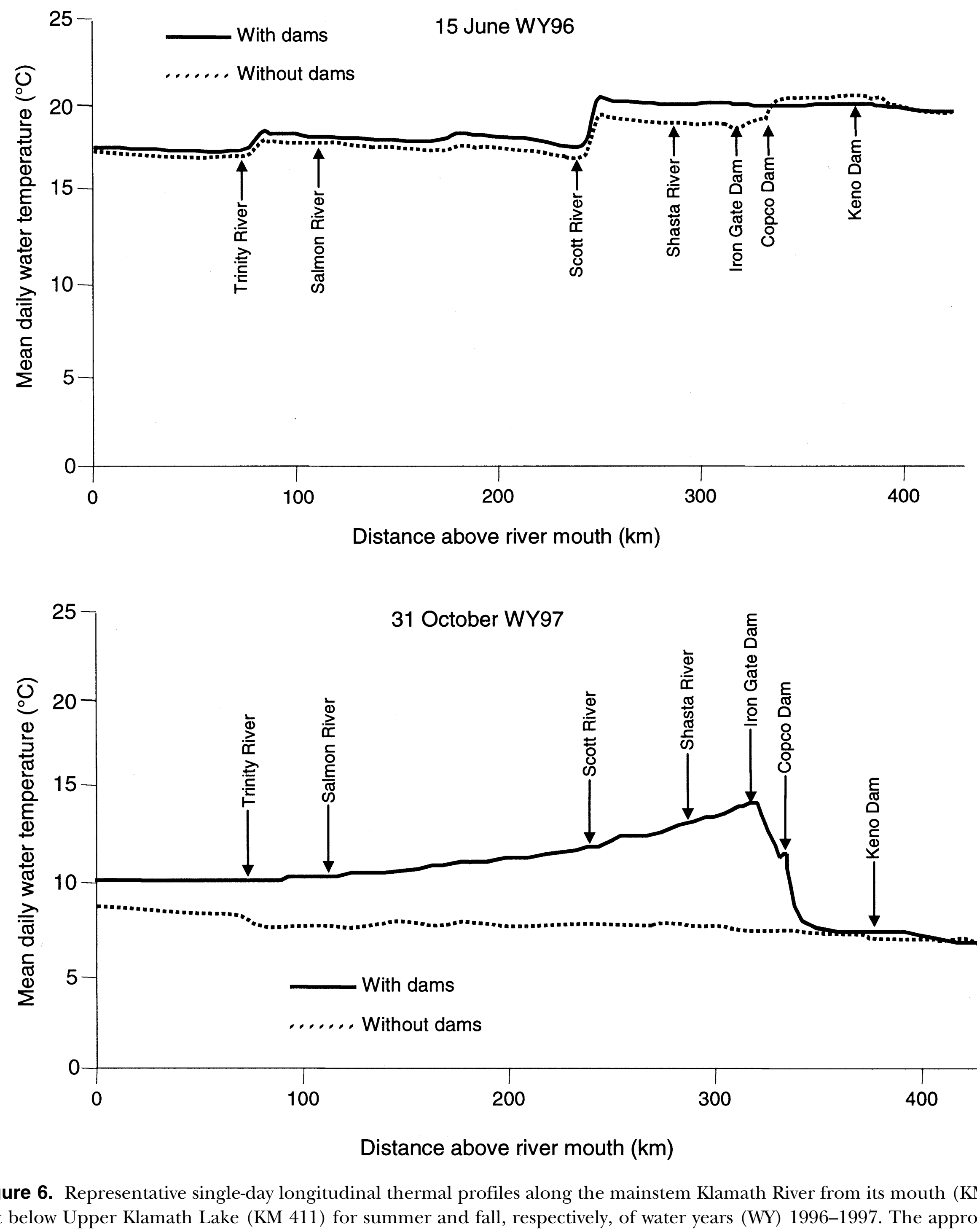

Figure 6. Representative single-day longitudinal thermal profiles along the mainstem Klamath River from its mouth (KM 0) to just below Upper Klamath Lake (KM 411) for summer and fall, respectively, of water years (WY) 1996–1997. The approximate locations of major tributaries and dam sites are indicated on the profiles.

month of October during the period 1996–2001 averages 137.1 km (44% of the total length of river from Iron Gate downstream) in the *With Dams* simulation and 224.8 km (73%) in the *Without Dams* simulation. In the other months, November through mid-April, virtually all river corridor habitat, 306.7 km, was below the recommended 14°C temperature maximum in these two simulations during the 1996–2001 period.

Table 8. Mean annual chronic and acute degree-days (DD) at Iron Gate Dam, Seiad Valley, and near the ocean at Klamath, California, for the *With* and *Without Dams* simulations for the period 1962–2001

	With Dams		*Without Dams*	
Location	Chronic DD (>15°C)	Acute DD (>20°C)	Chronic DD (>15°C)	Acute DD (>20°C)
Iron Gate Dam	482	48	519	101
Seiad Valley	460	69	467	95
Klamath River at Klamath, California (near the Pacific Ocean)	439	55	449	64

Table 9. Average annual number of days that temperatures exceed the maximum recommended temperature during time periods for three life stages of fall chinook salmon at three locations on the Klamath River, California, for the period 1962–2001

	Iron Gate		Seiad Valley		Klamath, California	
Life stage (time period)	*With Dams*	*Without Dams*	*With Dams*	*Without Dams*	*With Dams*	*Without Dams*
Spawning and egg incubation (1 Oct.–15 Apr.)	30	12	19	10	15	11
Juvenile rearing (1 Feb.–1 July)	49	60	48	53	53	58
Adult migration (15 Aug.–15 Dec.)	33	23	28	23	21	19

For fall chinook juvenile rearing, the recommended maximum temperature is 15°C. The amount of predicted habitat available from February through July begins to decrease slightly in April, but is severely curtailed beginning in May. Just 118.4 km (39%) of available river corridor habitat is predicted for the *With Dams* simulation and 88.6 km (29%) is predicted for the *Without Dams* simulations of the 1996–2001 period. In July, for both the *With* and *Without Dams* simulations, the predicted available habitat below 15°C is zero. For fall chinook migration, the maximum recommended temperature is 20°C. The amount of predicted habitat available in the Klamath River mainstem is very limited at the beginning of the spawning run. From August 15 to September 1, the *With Dams* simulation predicts just 32 km (10%) of available habitat below 15°C and 60.1 km (20%) for the *Without Dams* simulation of 1996–2001. The macrohabitat index information corroborates the mean daily temperature predictions presented in Figure 7.

Discussion

Because the *With* and *Without Dam* simulations in our analysis differed only in the presence or absence of reservoirs, we have assumed that differences in predicted water temperatures, and in metrics derived from them, provide reasonable estimates of thermal effects if Klamath River dams were removed. Averaging model results over the 40-year simulation period reveals underlying temperature differences while reducing the influence of daily prediction inaccuracy. Our results are, for the most part, consistent with existing literature discussed at the beginning of the article, indicating that the simulations represent the essence of the underlying processes governing the influence of reservoirs on downstream water temperatures. Our results are also quite similar to a modeling study comparable to ours on a Michigan river by Horne and others (2004), who found small (<1°C) absolute temperature changes with simulated dam removal, but increased day-to-day variation and a return to a ''natural'' seasonal variation.

Magnitude of Thermal Effects

Collectively, it appears that the series of impoundments below Upper Klamath Lake warm downstream waters slightly on an average annual basis compared to the *Without Dams* condition. However, the reservoirs reduce both day-to-day temperature variability and annual maximum temperatures immediately below the

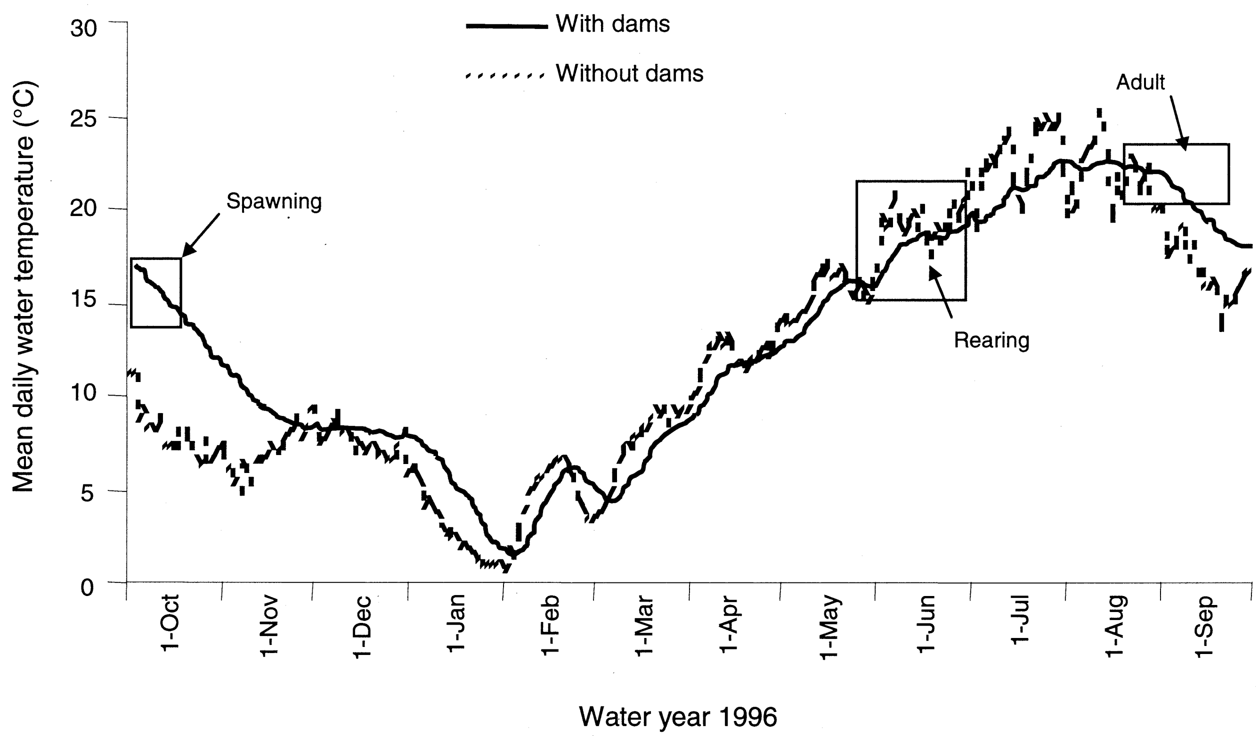

Figure 7. Annual time series of predicted mean daily water temperatures for water year 1996 at the Iron Gate Dam site for the *With Dams* and *Without Dams* simulations. Boxes indicate times when recommended temperature guidelines from Table 7 have been exceeded for three life stages of fall chinook salmon (after Armour 1991).

dams and for some distance downstream. All of the thermal differences are predicted to be greatest immediately below the lowest impoundment, Iron Gate, and become dampened in the downstream direction.

Because we modeled mean daily water temperature, we did not make predictions about maximum daily water temperature. However, in reviewing available temperature measurements on the Klamath River, we found that maximum daily water temperatures are highly correlated with mean values, and average about 0.4°C above the mean below Iron Gate Reservoir and 1.6°C above the mean at the free-flowing Seiad Valley site in August. Thus, it is reasonable to expect that, without the reservoir's dampening effect, daily temperature fluctuations would increase by about 1.3°C on the mid-Klamath during the hottest part of the year.

Thermal Phase Shift

Klamath River impoundments appear to delay the normal progression of water temperatures by about 18 days on an annual basis. It is tempting to relate this 18-day phase shift to the hydraulic residence time of the two lowest impoundments (13.8 days for Iron Gate and 11.0 days for Copco, totaling ~25 days on average). Variation in monthly reservoir throughput and incomplete mixing could easily explain the difference. As we have seen (Figure 7), this phase shift might be important biologically because the reservoirs deliver temperatures much warmer than recommended through the fall upstream migration and spawning period. The situation is reversed in the spring and early summer, when the reservoirs supply cooler temperatures than would be present without the impoundments in place, potentially reducing juvenile growth rates, yet possibly mitigating temperatures for outmigrating juveniles.

An intriguing aspect of the thermal phase shift might relate to the run timing for fall chinook immigration into the Klamath River. Snyder (1931) indicated that peak immigration occurred in mid-August between 1919 and 1930, whereas the California Department of Fish and Game (2003) reports that immigration now peaks in early September. In some Alaskan streams, chinook salmon runs are delayed by a month in tributaries influenced by lakes exhibiting increased fall and winter temperatures, which might shorten hatching and emergence time for developing eggs (Burger and others 1985). Quinn and Adams (1996) report that run timing for sockeye salmon (*Oncorhynchus nerka*) on the Columbia has apparently shifted about 1 week earlier in the year following closure of Bonneville Dam. However, they speculate that run timing for this species of salmon is more related to photoperiod than to water temperature. Early migration timing, of unknown stimulus, is associated with high mortality of sockeye salmon on the Fraser River in British Columbia (Cooke and others 2004).

The shift in peak immigration timing for Klamath River fall chinook is about the same duration as the thermal phase shift we found, although this could simply be coincidental or due to other factors. However, if spawn timing were to revert to an earlier date if dams were removed, and if juvenile growth were increased sufficiently by the somewhat warmer water available in the early spring, one might speculate that peak juvenile outmigration could also shift to an earlier date. If so, juveniles could avoid the high late-spring/early-summer water temperatures they currently experience.

Recovery Distance

One area where our results differed unexpectedly from previous literature was in the distance thermal effects persisted below the reservoirs under certain circumstances. Our modeling indicated that impoundment-generated temperature differences could persist over 300 km from Iron Gate Dam to the ocean at certain times of the year. Most of the time (e.g., 15 June 1996; Figure 6), predicted temperature differences between our two simulations were small (<1°C) for much of the lower Klamath River. Below the confluence with the Trinity River, the influence of reservoir operations on predicted temperatures appeared to be greatly attenuated. This is consistent with the literature and with one Klamath River model with a finer time step than we used that indicated ''negligible'' differences below the Trinity River when comparing simulations similar to ours (Mike Deas, Watercourse Engineering, personal communication).

However, simulation results for some late-fall conditions (e.g., bottom part of Figure 6) indicated substantial differences in predicted temperatures for the *Without Dams* simulation (≥2°C) compared to the *With Dams* simulation from Copco Dam downstream to the confluence with the Trinity River. These results are contrary to findings of Palmer and O'Keeffe (1989), who derived an empirical formula relating discharge and longitudinal recovery distance (i.e., how far downstream from a perturbation the effect could be measured) from a variety of study sites around the world. The Palmer and O'Keeffe formula {distance (km) = 35.5 $\log_e$(discharge (m^3/s))]} predicts that temperature perturbations originating at Iron Gate would likely be measurable for only about 110 km downstream.

In the 31 October case we presented, Iron Gate Dam releases of 38 m^3/s constituted about 31% of the flow at the ocean, slightly greater than average for all Octobers in our simulation period. Further, the Klamath River from Iron Gate to the Trinity River is confined within relatively narrow bedrock canyons with negligible groundwater accretions. Below the Trinity, stream width increases substantially, but the width-to-deepest-depth ratio remains almost constant from Iron Gate downstream to the ocean, indicating that the rate at which heat is gained (or lost) might remain roughly proportional solely to the mainstem's temperature instead of other physical factors, such as air temperature. Thus, it is plausible that periods with essentially constant hydrologic and meteorologic conditions for the approximately 3-day travel time from Iron Gate to the ocean would result in simulated temperature differences that persist far downstream, especially in the fall, when reservoir temperatures deviate markedly from ambient stream temperatures.

It is reasonable to expect that recovery distance is a function of discharge volume, tributary accretions and their temperatures, and the reservoirs' antecedent thermal conditions (Preece and Jones 2002). On balance, we suggest that our simulations are realistic at least 110 km below Iron Gate. Below this point, prudence suggests that our simulation results are provocative, but uncertain, down to the Trinity River, 238 km below Iron Gate, and should be confirmed using different techniques. Our results should be discounted when the river enters the tidal zone 282 km downstream because different physical processes govern water temperatures below that point.

Biological Effects

The evaluation metrics we used mirrored the spring versus fall changes in water temperature previously discussed, but offer additional insights relative to salmon-specific requirements. The degree-day metric integrates both the intensity and duration of water temperatures that might adversely affect fish, although like any integrative index, it can mask important properties of the individual components. This metric indicates that exposure to temperatures associated with chronic thermal stress for chinook salmon would change little *without* the impoundments, whereas exposure to temperatures associated with acute thermal stress are predicted to increase by a large percentage.

The thermal exposure metric quantifies the duration of conditions unfavorable to salmon life stages. This metric indicated that water temperature conditions for adult migration, spawning and egg incubation are better (i.e., fewer days above the recommended maximum temperature for those life stages) in the *Without Dams* predicted results. However, for the juvenile rearing life stage, the *With Dams* simulations predict fewer days above the maximum recommended temperature, especially immediately below the Iron Gate Dam site.

The final metric we evaluated was the longitudinal extent of suitable macrohabitat in the Klamath River for the various life stages of salmon. We identified potential biological bottlenecks for all three life stages of fall chinook. Predicted temperatures exceed maximum recommended temperatures for spawning and egg incubation in October, juvenile rearing in May and June, and adult migration from mid-August through mid-September. In comparing the *With* and *Without Dams* simulations, potential biological habitat bottlenecks for spawning and egg incubation life stages are less extensive in the *Without Dams* simulation; for juvenile rearing they are less extensive in the *With Dams* simulation, and for the adult migration life stage, they are less extensive in the *Without Dams* simulation.

Conclusion

Anthropogenically induced changes in the Klamath watershed over the past 200 years, such as timber harvest, mining, agriculture, and other human activities, have substantially altered the landscape of the basin (William M. Kier Associates, Inc. 1991). Simply removing the dams would not likely restore the thermal regime in the Klamath River to pre-European settlement conditions. However, the observed delay in the seasonal thermal signature at Iron Gate Dam would be eliminated by dam removal, and temperatures during the upstream migration and spawning period would improve substantially without the impoundments. On the other hand, already high temperatures during the spring and early-summer juvenile rearing period might be further increased if dams are removed. All predicted effects are greatest immediately below the reservoirs and become smaller in the downstream direction. In summary, our results indicate that there might be both thermal benefits and detriments to chinook salmon resulting from dam removal.

From this analysis, we cannot say whether overall chinook production would be increased, decreased, or remain the same. Once calibrated, we plan to use SIAM's more mechanistic fish production model (SALMOD) to better quantify cumulative thermal effects on salmon production. Such an analysis, however, would still leave unanswered questions about how a thermal phase shift might affect chinook behavior and would not address impacts to species having different life-history traits and thermal requirements. We also want to be clear that our simulations did not address other important changes expected if dams were removed, such as fish access to additional aquatic habitat, restored sediment transport, and other water quality characteristics like dissolved oxygen below the reservoirs (Bednarek 2001). In addition, we did not attempt to evaluate other flow regimes since Upper Klamath Lake remained operational and continued to supply agricultural diversions, and associated return flows, in both of our simulations. There well might be opportunities to manage the reservoirs differently to alter downstream thermal regimes. All of these subjects remain for additional investigation.

Water management decisions must fully consider alternatives, trade-offs, spatial and temporal effects, and the occasional counterintuitive consequences that result from changing system operations in a regulated river such as the Klamath. The application of a decision support system (SIAM, in this instance) and careful examination of the output can provide valuable insights to the decision-making process. USGS has been involved in studies on the Klamath River for several years, working to improve data quality and predictive models of water quantity, water quality, and anadromous fish production. Our goal is to provide information to assist resource management agencies in making their decisions; USGS makes no recommendations as to the appropriateness or lack of appropriateness of dam removal on the Klamath River.

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