

## Recent Water Temperature Trends in the Lower Klamath River, California

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**Abstract.**—Elevated water temperatures have been implicated as a factor limiting the recovery of anadromous salmonids in the Klamath River basin. This article reviews evidence of a multi-decade trend of increasing temperatures in the lower main-stem Klamath River above the ocean and, based on model simulations, finds a high probability that water temperature has been increasing by approximately 0.5°C/decade (95% confidence interval [CI] = 0.42–0.60°C/decade) since the early 1960s. The season of high temperatures that are potentially stressful to salmonids has lengthened by about 1 month over the period studied, and the average length of main-stem river with cool summer temperatures has declined by about 8.2 km/decade. Water temperature trends seem unrelated to any change in main-stem water availability but are consistent with measured basinwide air temperature increases. Main-stem warming may be related to the cyclic Pacific Decadal Oscillation, but if this trend continues it might jeopardize the recovery of anadromous salmonids in the Klamath River basin.

The Klamath River basin (Figure 1) straddles the border between the states of Oregon and California. The basin drains an area of over 40,000 km<sup>2</sup> through varied landscapes. The upper reaches, above river kilometer (RKM) 375 (as measured from the outlet to the Pacific Ocean), are characterized by rain-shadowed lowlands holding extensive lakes and relic marshlands arising from a border of low mountains. The Klamath River drains these relatively flat valleys, flowing over 400 km through a tall, coastal mountain range that contributes several major tributaries from the flanks of dormant volcanoes and finally emptying through dense forests along the coastal plain into the Pacific Ocean. The middle and lower portions of the river (below RKM 308) are largely constrained within bedrock canyons and interspersed with minor alluvial reaches. Flows vary widely throughout the year; peak flows generally occur in December and January, and the lowest flows extend from June through September. Summer low flows below a series of hydropower facilities on the main-stem Klamath River are often held at Federal Energy and Regulatory Commission (FERC) mandated minima, about 20 m<sup>3</sup>/s. Accretions are substantial along the river, however: average annual flows grow from 1,666 × 10<sup>6</sup> m<sup>3</sup>/year as the river drains the upper basin to 15,768 10<sup>6</sup> m<sup>3</sup>/year near the ocean. Historic hill slope and

in-channel gold mining, extensive logging, and middle-basin hydropower development, coupled with wetland draining and diversions for agriculture in the upper basin, comprise the major watershed manipulations.

At approximately 42°N, the Klamath River basin is situated far enough north to support a variety of coldwater fishes. However, the isolation of the upper basin from moderating coastal weather and frontal movement, the rapid 550-m drop in the river's elevation below Upper Klamath Lake compared to the surrounding terrain, and main-stem flows that originate from this very large (24,000–36,000 ha) and shallow (3 m) water body, all serve to position the Klamath River on an ecological "edge" with respect to water temperatures for coldwater fishes. Measured U.S. Geological Survey (USGS) gauge data reveals that mean monthly temperature in the lower Klamath River, the only portion currently accessible to anadromous salmonids, generally ranges from 3–6°C in January to 20–22.5°C in July or August. Monthly average daily maximum temperature is commonly above 23°C except in areas immediately below hydropower reservoirs or near the ocean. Temperature in the Klamath River is elevated with a greater frequency and remains elevated for a longer time than temperatures in adjacent coastal anadromous streams. Summer maxima in the lower Klamath River basin below the Trinity River confluence (RKM 70; Figure 1) may reach 26.6°C for up to 10 d/year, in contrast to most other nearby coastal rivers, both north and south of the Klamath River, that never exceed this temperature (Blakey 1966).

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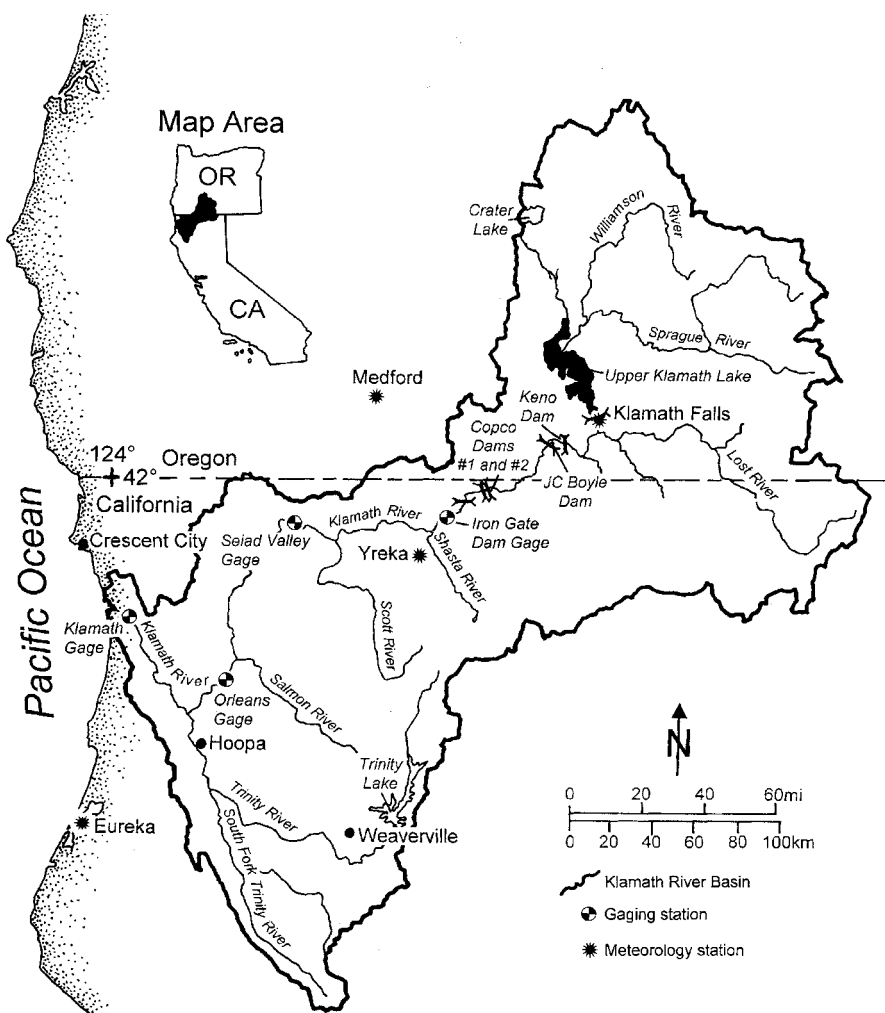


FIGURE 1.—Map of the Klamath River basin, Oregon and California, showing the approximate locations of major dams, water temperature gauges, and meteorological stations. The map was adapted with permission from the Water Education Foundation, Sacramento, California.

Elevated temperature is clearly problematic for salmonids (Brett 1952; USEPA 2003). Nehlsen et al. (1991) listed various salmonid stocks as either extinct or at risk in the Klamath River and two of its California tributaries, the Shasta and Scott rivers, along with many other coastal and inland streams. High temperature is among the many concerns for the successful recovery of salmonids in the Klamath River below Iron Gate Dam, the current upstream terminus of anadromous salmonid migration (CH2M Hill 1985; Klamath River Basin Fisheries Task Force 1991). Elevated temperatures have taken on a greater significance recently because of their potential link to disease outbreaks

affecting both adult and juvenile salmonids in the Klamath River (Lynch and Risley 2003).

Researchers at the USGS were asked by the Klamath River Basin Fisheries Task Force to put together a decision support system (DSS) that links Klamath River basin hydrology, water quality, and fish production to create a better understanding of the range of water management opportunities and their potential consequences. Prior to the modeling effort, we reviewed the available data, concentrating on hydrology, water quality, species life history, and channel morphology. The resulting unpublished review confirmed the frequent occurrence of stressful temperatures for salmonids, and

also suggested a basinwide warming of river temperatures of between 0.4°C and 0.6°C per decade. However, the estimated trend contained a large degree of uncertainty due to limitations inherent in the measured water temperature record, specifically the short duration of and large gaps in thermograph records, as well as ordinary intra-annual variability.

As a component of the DSS, a water temperature model was subsequently completed for approximately 400 km of the main-stem Klamath River from Upper Klamath Lake in Oregon to the river's mouth in California, incorporating the best meteorologic and hydrologic data readily available for the 40-year postdam period, water years (WY) 1962–2001 (Hanna and Campbell 2000; Campbell et al. 2001). This temperature model enabled a more complete estimation of mean daily water temperature in the lower Klamath River during periods of incomplete thermograph records, and features several biologically relevant metrics, such as degree-days, duration of high thermal exposures, and length of river with temperatures between specified values.

The objective of this article is to review measured data and model results for evidence, if any, of basinwide warming in the lower Klamath River below Iron Gate Dam during the postimpoundment period, 1962–2001. I assess historical water and air temperature records in the basin along with relevant hydrologic data, and evaluate the simulated water temperature and derived temperature metrics for trends.

### Methods

*Trend estimation.*—All measured data and simulation results (described below) were analyzed with statistical software developed by Battelle Pacific Northwest Laboratory (Gilbert 1987: Appendix B). The software performs a nonparametric analysis that uses the seasonal Kendall test (Hirsch et al. 1982) to estimate trends in the annual data and Sen's (1968) slope estimator for monthly data. These tests are appropriate because the data need not conform to any particular distribution and may contain embedded cycles or exhibit serial correlation (Gilbert 1987). Unlike ordinary least-squares trend estimation, these techniques are therefore unbiased by nonnormal outliers, are relatively insensitive to a moderate amount of missing data, and are less likely to be biased by extreme events at the beginning or end of the time series (Fox et al. 1990; USEPA 1998).

Both methods are related to one another and are

conceptually straightforward. The slopes of all possible data pairs (in time series order) are computed and ranked. From this ranked set, the median slope is the best estimate of the trend. Software output includes two-sided confidence intervals (CIs) about the "true" slope at the 0.05 level, obtained through nonparametric techniques developed by Sen (1968). Please refer to Gilbert (1987) for software details. Fox et al. (1990) performed a similar analysis to identify linear trends in another West Coast basin's streamflow and precipitation data. However, unlike Fox et al. (1990), I did not smooth any of the time series data.

*Historical water temperature records.*—The Klamath River basin contained 18 USGS water temperature gauges, each with differing periods of record (Table 1). Seventeen were for riverine stations and one represented Crater Lake, potentially useful because of its long-term data set. Daily maximum and minimum water temperature data for the 13 gauges having at least 10 years of data were extracted from the EarthInfo CD-ROM (EarthInfo, Inc. 1994), and were scanned to remove obvious transcription errors. Mean monthly water temperature was computed as the simple average of all measured minimum and maximum daily values if there were at least 25 d with measurements in that month; otherwise, the value was considered missing.

*Simulated river temperature and metrics.*—The System Impact Assessment Model (SIAM) DSS (Bartholow et al. 2003) was used to simulate mean daily water temperature on the main-stem Klamath River from Upper Klamath Lake to the ocean based on historical monthly flows and reservoir storage volumes (disaggregated to mean daily values) supplied by SIAM. Monthly flows and storage values were used because they meshed easily with the planning framework employed by the U.S. Bureau of Reclamation and because regulated flows in the Klamath River tend to be relatively constant from day to day except during large rainstorm events that generally occur in winter. The SIAM framework uses the U.S. Army Corps of Engineers Hydrologic Engineering Center's HEC-5Q model (USACE 1986) to estimate water temperatures. The HEC-5Q model is a one-dimensional model that simulates water quality in reservoirs vertically from the surface to the bottom and longitudinally downstream in rivers.

The data requirements for HEC-5Q are daily average temperature values of all inflowing waters and daily average meteorological data, including air and dew point temperatures, wind speed, and

TABLE 1.—Klamath River basin U.S. Geological Survey (USGS) gauges and data used in the preliminary scoping exercise. Estimated trends for stations with over 10 years of data were derived from Gilbert's (1987) technique. Trends in bold italics are statistically different from zero ( $P < 0.05$ ). The four main-stem Klamath River gauges used in subsequent analyses are shown in italics. All stations are in California except Crater Lake, which is in Oregon.

USGS gauge		Years of record	Years available	Estimated trend (°C/year)
Number	Name			
11530500	<i>Klamath River near Klamath</i>	1966–1981	16	0.050
11530300	Blue Creek near Klamath	1966–1978	13	0.000
11530000	Trinity River at Hoopa	1964–1984	21	<b>0.100</b>
11529000	South Fork Trinity River near Salyer	1963–1966	4	
11528700	South Fork Trinity River below Hyampom	1966–1979	14	<b>0.050</b>
11528500	Hayfork Creek near Hyampom	1961–1974	14	0.029
11528200	South Fork Trinity River near Hyampom	1961–1965	5	
11527000	Trinity River near Burnt Ranch	1962–1983	22	0.000
11525655	Trinity River below Limekiln Gulch	1985–1985	1	
11525600	Grass Valley Creek at Fawn Lodge	1985–1985	1	
11525500	Trinity River at Lewiston	1959–1983	25	0.010
11523000	<i>Klamath River at Orleans</i>	1966–1982	17	0.033
11522500	<i>Klamath River near Seiad Valley</i>	1964–1979	16	–0.014
11520500	Salmon River at Somes Bar	1966–1979	14	0.040
11517500	Shasta River near Yreka	1965–1979	15	–0.020
11516600	Cottonwood Creek at Hornbrook	1965–1971	7	
11516530	<i>Klamath River below Iron Gate Dam</i>	1963–1980	18	0.033
11492200	Crater Lake	1964–1993	30	<b>0.033</b>

cloud cover. Solar radiation is not a direct model input, but rather is calculated by a companion program based on the meteorologic data, time of year, and latitude. Boundary temperatures for unmeasured tributaries were derived from regression equations based on air temperature. A complete description of the methods used to set up the HEC-5Q model for the Klamath River can be found in Hanna and Campbell (2000).

The HEC-5Q model was calibrated for 1 year (1996) and validated for 2 years (1997, 1998) with the most reliable data available. Mean absolute errors were 1.0°C for 1996, 1.04°C for 1997, and 0.90°C for 1998. The model also performed well in capturing the essence of the river's seasonal thermal signature, as signified by the highly significant coefficient of determination ( $r^2$ ) values (e.g., below Iron Gate Dam:  $r^2 = 0.96$ ,  $n = 7,354$ ,  $P < 0.001$ ). Overall model bias was  $-1.1^\circ\text{C}$  at gauge locations from Iron Gate Dam downstream (i.e., the model underestimated temperatures slightly), although temperature predictions for any single day at any single location over the 40-year simulation period contained more uncertainty (average absolute mean daily error,  $\sim 1.8^\circ\text{C}$ ), especially near the ocean in the tidal zone (Bartholow et al., in press).

For this analysis, the model's goodness of fit to measured data was examined for a temporal trend in the residuals (measured minus simulated water

temperature values) that might inflate or deflate trend estimates. Monthly average residuals were calculated from daily values when there were 25 or more measured values per month, and were processed following Gilbert's (1987) methodology. In addition, the SIAM model was run to simulate a period of 10 consecutive years that had identical flow and meteorology regimes to see whether the modeled system might accumulate heat from year to year, falsely generating a trend due to a computation or implementation anomaly.

Daily water temperatures were simulated for the 40-year period, WY 1962–2001 (beginning the year after the last dam was put in place), and exported from SIAM for the four main-stem river locations highlighted in Table 1. In addition to river temperature, SIAM also calculated six biologically relevant metrics for the site immediately below Iron Gate Dam:

- (1) the annual number of degree-days exceeding  $15^\circ\text{C}$  (e.g., a mean daily water temperature of  $17^\circ\text{C}$  counts as 2 degree-days),
- (2) the annual number of non-overlapping events when water temperature exceeded  $15^\circ\text{C}$  for 7 d in a row,
- (3) the annual number of days when water temperature exceeded  $20^\circ\text{C}$ ,
- (4) the annual first day in spring when water temperature reached  $15^\circ\text{C}$ ,

- (5) the annual last day in fall when water temperature reached 15°C, and
- (6) the number of river kilometers from Iron Gate Dam to the mouth of the Klamath River with water temperature below 15°C averaged for the summer (1 May to 30 September).

The 15°C and 20°C thresholds in these metrics were chosen as representative of chronic and acute high temperatures for salmonids, based on values reported by the U.S. Environmental Protection Agency (USEPA 2003). Both thresholds are below lethal temperatures for most salmonid life stages, but they are associated with increasingly adverse effects such as sub-optimal growth rates, reduced swimming performance, increased disease risk, and impaired smoltification (USEPA 2003). Unlike Bartholow et al. (in press), who focused only on Chinook salmon *Oncorhynchus tshawytscha*, the first five metrics were calculated for the entire year because one or more life stages for all anadromous salmonids can occur in the Klamath River year-round (Leidy and Leidy 1984). Daily values for all temperatures and metrics were converted to average monthly values by use of utility programs and were subsequently processed with Gilbert's (1987) software.

*Historical air temperature and hydrology records.*—The HEC-5Q model uses daily average air temperature as one of its dominant inputs. The two closest air temperature stations to the main-stem Klamath River below Iron Gate Dam used by Hanna and Campbell (2000) were Yreka and Eureka, California; Yreka meteorology governs the upstream portions of the river and the maritime station at Eureka governs the river's lowest 50 km, approximately 32 km from the coast (per Lewis et al. 2000). However, because the Yreka station had missing data for air temperature and other required meteorological variables, Hanna and Campbell (2000) used regression techniques to translate some daily values from Medford, Oregon. To eliminate any possibility of contaminating this trend analysis with synthetic values, I used the most consistent source of raw data available (EarthInfo, Inc. 1995). Average monthly maximum and minimum air temperatures for Eureka, Yreka, and Medford and for Klamath Falls, Oregon, were extracted from this database for calendar years (CY) 1962 through 1993, the latest year available in the EarthInfo, Inc. (1995) database. Mean monthly air temperature values were computed from these values as before and were processed by use of Gilbert's (1987) methodology.

TABLE 2.—Estimated trends in simulated water temperature along the main-stem Klamath River and their 95% confidence intervals (CIs) for the 40-year period 1962–2001 ( $n = 480$ ). Trend estimates at all stations had  $P$ -values  $\leq 0.001$ . Note, however, that the most downstream station (Klamath River near Klamath) showed a significant trend in the analysis of measured less simulated residuals and was not considered trustworthy.

Station	Trend (°C/year)	95% CI
Klamath River below Iron Gate Dam	0.053	0.044–0.063
Klamath River near Seiad Valley	0.051	0.043–0.059
Klamath River at Orleans	0.048	0.039–0.057
Klamath River near Klamath	0.044	0.036–0.051

Another required input for HEC-5Q is hydrology. To detect whether water temperature trends might be due to changes in river flow, I examined the historical monthly average discharge records (WY 1962–2001) for Iron Gate Dam and processed these values by use of the same set of procedures applied to the other data.

## Results

### *Historical Water Temperature Records*

The historical gauge data for the 13 stations listed in Table 1 with more than 10 years of data implied an average basinwide warming trend of 0.026°C/year. However, estimated annual trends for individual stations (Table 1) and months (not shown) during the year varied widely. Two stations suggested small negative trends and two indicated no trend at all. Nine stations indicated positive annual trends. Only three stations (Crater Lake, South Fork Trinity River below Hyampom, and Trinity River at Hoopa) had trends that were statistically different from zero at the 0.05 level. If data from only these three stations are averaged, the estimated trend would be 0.06°C/year, but none of these stations is on the main-stem Klamath River and their period of record was inconsistent in both duration and timing. Thus, results from the historical temperature gauges were only *suggestive* of a trend, not statistically conclusive. Without the seemingly obvious trends evident by examining the simulation model's 40-year output (described below), this analysis would not have been continued.

### *Simulated River Temperature and Metrics*

Table 2 indicates that annual water temperature trends derived from HEC-5Q model results have been increasing at each of the four main-stem lo-

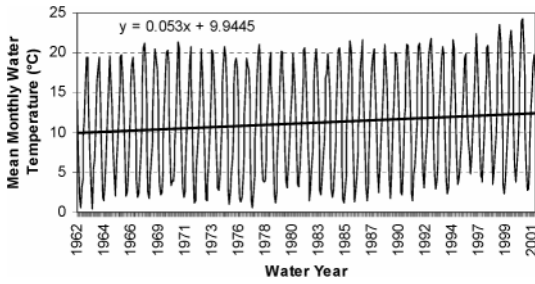


FIGURE 2.—Illustration of the increasing trend in simulated mean monthly water temperature below Iron Gate Dam on the main-stem Klamath River. Mean monthly values were computed from the HEC-5Q model's (USACE 1986) daily simulation results.

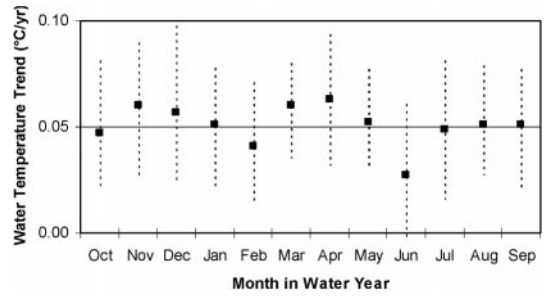


FIGURE 3.—Estimated monthly trends (with 95% confidence intervals) in the simulated mean monthly water temperature for the main-stem Klamath River near Seiad Valley from 1962 to 2001. June was the only month in which the trend was not significant at the 0.05 level. Mean monthly values were computed from the HEC-5Q model's (USACE 1986) daily simulation results.

cations but with slightly less of an increase in the downstream direction. Figure 2 provides an example of the trend observed for the river below Iron Gate Dam. Positive trends were found for each month of the year at all four stations (the Seiad Valley gauge trends are shown in Figure 3), and almost all months were significant at the 0.05 level. June trends were consistently non-significant.

Running the model for the consecutive 10-year period with identical annual flow regimes and meteorology indicated no interannual increase or decrease in thermal storage, confirming that the model's algorithms themselves were not falsely generating any trend. However, a careful examination of residuals (measured minus simulated temperatures) for the full historical period (1962–2001) did reveal some linear and cyclic trends. A small linear trend was identified at each of the four main-stem stations, but the residual trends at the three upstream-most stations were small (average, 0.003°C/year;  $n = 135\text{--}235$ ) and none were significantly different from zero at the 0.05 level when tested with Gilbert's (1987) technique. At the Klamath River near Klamath, California, the linear trend in residuals was large (0.032°C/year;  $n = 134$ ) and significantly different from zero. These results imply that the model does not introduce any significant trend of its own that would confound an estimate of basinwide warming at all but the most downstream, tidally influenced station. Because the inclusion of that station (Klamath River at Klamath) might influence reliable detection of basinwide trends, it was omitted from the remainder of the analysis.

Table 3 summarizes simulated temperature trends for the six different metrics at three stations along the main-stem Klamath River. Collectively,

these metrics indicated that (1) cumulative exposures to stressful temperatures have been increasing in both number and duration; (2) the length of the annual period of potentially stressful temperatures has been increasing (i.e., summer effectively starts earlier in the spring and extends longer into the fall); and (3) the average length of river with suitable temperatures has been decreasing. There was generally a decreasing rate of change

TABLE 3.—Estimated annual trends in metrics derived from simulated water temperature below Iron Gate Dam on the main-stem Klamath River and their 95% confidence intervals (CIs;  $P \leq 0.05$ ) for the 40-year period 1962–2001. See text for definitions of the calculated metrics. All metrics had 40 observations except for the spring and fall dates ( $n = 39$ ).

Metric	Site	Annual trend	95% CI
Degree-days (>15°C)	Iron Gate Dam	5.55	2.89–8.68
	Seiad Valley	5.94	3.97–8.42
	Orleans	5.99	3.67–8.50
Chronic events (weeks)	Iron Gate Dam	0.09	0.05–0.15
	Seiad Valley	0.08	0.04–0.11
	Orleans	0.07	0.00–0.13
Acute events (d)	Iron Gate Dam	1.09	0.56–1.73
	Seiad Valley	0.91	0.36–1.37
	Orleans	0.81	0.29–1.20
Spring date (d)	Iron Gate Dam	–0.44	–0.75 to –0.18
	Seiad Valley	–0.43	–0.72 to –0.14
	Orleans	–0.33	–0.64 to –0.05
Fall date (d)	Iron Gate Dam	0.46	0.22–0.71
	Seiad Valley	0.31	0.07–0.56
	Orleans	0.25	0.05–0.47
Length of river below Iron Gate Dam <15°C (km)	Downstream of Iron Gate Dam	–0.82	–1.29 to –0.40

TABLE 4.—Estimated trends in measured air temperature in or near the main-stem Klamath River and their 95% confidence intervals (CIs) for calendar years 1962–1993. All stations had  $P$ -values  $\leq 0.001$  except Yreka ( $P = 0.357$ ).

Station (months of data)	Trend (°C/year)	95% CI
Eureka, California (384)	0.056	0.042–0.066
Yreka, California (373)	0.000	–0.029–0.000
Medford, Oregon (366)	0.040	0.019–0.060
Klamath Falls, Oregon (382)	0.035	0.012–0.059

in these metrics in the downstream direction, although there were a few exceptions.

#### *Historical Air Temperature and Hydrology Records*

Estimated historical air temperature trends are given in Table 4. The variance in the estimated temperature trend was large across stations, and the Yreka station exhibited no air temperature trend at all. Interestingly, the rate of change appeared strongest at the downstream-most station, Eureka. This station's estimated trend was an increase of 0.056°C/year.

The estimated annual trend in discharge at Iron Gate Dam was quite small ( $-0.09$  m<sup>3</sup>/s per year) relative to typical flow rates ( $>28.32$  m<sup>3</sup>/s), but it was still significant (95% CI =  $-0.200$  to  $-0.024$  m<sup>3</sup>/s per year;  $P \leq 0.003$ ). Although several months showed some discharge trends approaching 1.4 m<sup>3</sup>/s per year, most were negligible. Because of the small magnitude of estimated annual change in flow, it appeared unlikely that hydrologic changes could be responsible for trends detected in water temperatures.

### **Discussion and Conclusion**

#### *Best Estimate of Warming Trends*

Thirteen USGS water temperature gauges had enough measured data to allow computation of trend statistics, but short records and large blocks of missing data resulted in few statistically significant trend estimates. A few stations with longer historical records did suggest a small, statistically significant warming trend beginning in the 1960s. In particular, Crater Lake (with the longest record) is well off the main-stem Klamath River and indicated a significant trend similar to on-river locations, suggesting that a warming trend, if present, might be basinwide and not related to any specific land use or water use factors. Because the records were short and incomplete, additional analysis was warranted. The best way to continue

the analysis was to use a water temperature model to, in essence, fill and extend the record.

Filling the data record via simulation eliminated some of the uncertainty associated with the handling of missing data in the statistical analysis, and extending the record well beyond what was historically available strengthened the statistical power to estimate mean trends and their CIs simply because of increased sample size (Gilbert 1987). However, the use of a simulation model potentially interjects uncertainty because the model itself must introduce no trend of its own. No significant trend in model residuals (measured minus simulated temperatures) through time was detected except at the downstream-most station near Klamath, California. For this reason and because this location was also influenced by unmodeled tides, this station was not used in drawing conclusions about Klamath River basin warming even though its estimated trend was quite similar to those of the other three stations.

Aggregating all other stations from Table 2, it is estimated from the filled record that the average trend in main-stem water temperatures has been 0.5°C/decade (95% CI = 0.42–0.60°C/decade;  $P \leq 0.001$ ) for the 40-year postdam period, 1962–2001. On average, this represents a 2°C increase during the period examined—a change with potentially significant ramifications for the aquatic community. This estimated trend is larger than that found for a British Columbia watershed by Morrison et al. (2002), who estimated a warming trend of about 0.22°C/decade from 1953 to 1998.

#### *Uncertainty Inherent in the Estimated Trend*

Many factors must be weighed when attempting to judge the uncertainty inherent in the trend estimate for the main-stem Klamath River. There are a variety of opinions about exactly which statistical methods possess the best “power” for attempts to tease trends from real-world data (US-EPA 1998). No trend estimation technique, including the software developed by Gilbert (1987), can fully quantify uncertainty. None are immune from problems associated with the analysis period and length (i.e., when the analysis begins and when it ends) (Williams 1991); none can completely factor out serial correlation (Fox et al. 1990); and none can address potential biases in measured or estimated time series data (Gilbert 1987). Further, trends in measured (not simulated) data may be influenced by improvements in measurement precision or technique through time or, in the case of meteorologic data, by anthropomorphic changes at

or near the location of instrumentation (Pielke et al. 2002).

Perhaps most importantly, this analysis relied heavily on a simulation model that, like all models, is an incomplete representation of reality and that exhibited a degree of serial correlation in the residuals that is probably indicative of the decadal-scale temperature oscillations widely reported in the literature on Pacific salmon (e.g., Beamish and Bouillon 1993). Though annual trend estimates at all stations listed in Table 2 were quite similar, they showed a small, unexplained decrease in the downstream direction. The apparent patterns in estimated seasonal or geographic trends could simply be random, but they might warrant further statistical analysis dealing with homogeneity, which was not explored here.

The bottom line is that the estimated trends for Klamath River basin warming in no way imply a permanent change in the system (Helsel and Andrews 1991), and the CIs about the estimate may be too narrowly prescribed. The analysis by Fox et al. (1990) that examined trends in San Francisco Bay outflows by use of similar procedures generated considerable discussion in the literature concerning statistical application, confidence in the results, and implications for the future (Helsel and Andrews 1991; Williams 1991; Fox et al. 1991a, 1991b). Further discussion of the current analysis may certainly be warranted.

#### *Likely Causes of the Warming Trend*

If there is a trend, what are its causes? Changes in hydrology have been found by some investigators to be related to regional climatic shifts, though generally at higher latitudes (Danard and Murty 1994; Morrison et al. 2002). However, there was very little indication that water temperature trends on the Klamath River were related to any systematic change in main-stem hydrology below Iron Gate Dam (although changes at a monthly scale may deserve additional attention). Instead, water temperature trends were supported by the estimates of basinwide air temperature warming that averaged 0.33°C/decade (95% CI = 0.11–0.46°C/decade) across all four stations in Table 4. Air temperature is very important in the HEC-5Q model both because it dominates mean daily heat exchange and because air temperature was used to calculate tributary inflow temperatures. Therefore, it is no surprise that any trend detected in air temperatures would have a direct effect on simulation-derived water temperature trends. Differences in the magnitude of estimated water and air temper-

ature trends may be explained by other meteorological parameters known to be important in determining mean daily water temperature (e.g., dew point temperature, solar radiation, and wind speed, none of which were investigated here). It is also possible that temperature trends could be influenced by cumulative watershed changes (e.g., timber harvest), but watershed condition was not a direct input for HEC-5Q simulations. More likely, the difference between air and water temperature trends simply reflects the aggregate uncertainty in each estimate.

It is interesting that the data for Yreka, the station closest to the geographic center of the basin, did not indicate a statistically significant trend in air temperature. Translating some meteorological data from Medford to use as input for the model could have influenced estimated water temperature trends from the model results, but evidence for erroneous water temperature predictions was lacking. Although Medford is outside the Klamath River basin proper (Figure 1), it is physically quite close to a large portion of the watershed contributing ungaged accretions that account for about one-half of the river's flow at the ocean (Bartholow et al., in press). Crater Lake is also in close proximity to Medford, and we know from the analysis of historical data that this station's lengthy record showed a detectable and statistically significant positive trend in water temperatures through time (0.33°C/decade; Table 1). Therefore, the use of Medford meteorological data as a surrogate for Yreka data when necessary may have been appropriate.

#### *Other Confounding Factors*

How can a 40-year warming trend be put in perspective? There is evidence that periodic high temperatures occurred in the Klamath River basin in the 1900s prior to 1962. Risley and Laenen (1999) looked at even longer-term air temperature records at Klamath Falls and established that there was no difference in the median annual air temperature for the periods 1922–1950 and 1950–1996. This appeared to be due largely to a series of very hot years occurring in the 1930s that rivaled, but did not exceed, air temperatures recorded in the 1990s. More generally, researchers have noted a recurring climatic pattern in North Pacific Ocean temperatures at decadal time scales that affect continental surface air temperatures. This pattern, aptly named the Pacific Decadal Oscillation (PDO), has been shown to correlate to varying degrees with shifts in salmon production



(Mantua et al. 1997). The correlation is stronger for Alaska's salmon stocks and weaker for stocks in Washington, Oregon, and California. The period examined in this paper, 1962–2001, spans a detected PDO crossover point (1977) from cooler to warmer weather (Mantua et al. 1997) and may be a contributing factor to the trend detected in the Klamath River data, although the coefficient of determination between an annual PDO index and Klamath Falls air temperature was not strong ( $r^2 = 0.2$ ). Nonetheless, if the polarity of the PDO shifts once again, periods of cooler weather may return to the Klamath River basin. If an additional warming trend was superimposed on the recurrent PDO signature, however, one would expect each succeeding air temperature peak and trough to be higher than the last. Klamath River basin waters would not likely continue warming at the same decadal rates reported here even if air temperatures continue to rise. Water temperature does not linearly parallel increases in air temperature but instead is S-shaped due to evaporative cooling and back radiation from the water's surface; above approximately 25°C, stream temperature begins to level with respect to rising air temperature, but not so much that it could not eventually reach 30°C or higher (Mohseni et al. 2002).

#### *Potential Significance of the Warming Trend*

Are the trends in water temperature important from a biological perspective? The various metrics derived from simulated water temperature (Table 3) point toward greater exposure (both in frequency and duration) to chronic and acute temperature thresholds that are potentially stressful to salmonids through both time and space. Below Iron Gate Dam, for example, considering both the onset of high temperatures in the spring and their conclusion in the fall, the period of the year when mean daily temperature exceeds 15°C has been increasing by 9 d/decade. This rate of change seems especially large, adding up to over 1 month during the 40-year period studied. In contrast, the decrease in average length of river with temperatures below 15°C (8.2 km/decade) does not appear to be as major an issue, but does demonstrate an incremental elimination of coldwater habitat.

In the Klamath River basin, elevated water temperatures can occur from May through October, a period of concern for many anadromous salmonids since eggs (deposited during fall spawning) and juveniles (out-migrating from late spring through summer) are thermally sensitive life stages. Upstream migrating and spawning adults may also be

affected during the late summer. The months of June–September exhibit exceedingly poor water temperatures for any overwintering salmonids at most main-stem Klamath River locations in most years. For example, the mean monthly maximum daily water temperature from the historical data collected at Seiad Valley from 1964 to 1979 was 23.3°C in July, and daily extremes were as high as 29.5°C. In short, water temperature in the lower main-stem Klamath River is currently marginal for anadromous salmonids; their thermal resource is being “squeezed” in both space and time. Even the winter period is not immune, as warmer waters would be expected to speed egg and alevin maturation rates and to advance hatching times (Crisp 1981). Southern Pacific coastal salmon streams (below 56°N) are typically viewed as offering a nurturing growth opportunity for young salmon, demonstrated by the fact that they migrate to the ocean as young-of-the-year instead of yearlings as is common above 56°N (Taylor 1990). However, rivers as warm as the main-stem Klamath River might instead be viewed as thermally adverse, essentially requiring out-migration to avoid early- or overwinter death unless rearing fish can locate and take advantage of thermal refugia or coolwater tributaries.

Several researchers have discussed potential impacts of climate change on fishery resources; trends found in Klamath River basin water temperature and associated metrics are reminiscent of those discussions. Meisner (1990) and Sinokrot et al. (1995) pointed to potential losses in thermal habitat associated with warming, and Chatters et al. (1995) projected salmonid population declines accompanying a 2°C rise in temperature. Other biological communities appear to be undergoing shifts in their geographic range (e.g., Edith's checkerspot butterfly *Euphydryas editha*; Parmesan 1996) or changes in life history timing (e.g., flowering times for British plants: Fitter and Fitter 2002) in presumed response to changing climatic conditions. If water temperature trends of the magnitude found for the main-stem Klamath River continue in future decades, some stocks may decline to levels insufficient to ensure stock survival, as was discussed by Chatters et al. (1991) for the Columbia River basin and Eaton and Scheller (1996) for cold- and coolwater guilds in general.

Selection of a single thermal threshold as an indicator of the time when stocks may disappear from a specific geographic area is problematic (Poole et al. 2001; Dunham et al. 2003), but Eaton et al. (1995) listed mean weekly temperatures of

23.4°C for coho salmon *O. kisutch* and 24°C for Chinook salmon as thresholds above which disappearance becomes increasingly likely. Both simulations and measured data suggest that waters in the main-stem Klamath River below Iron Gate Dam, particularly at Seiad Valley and Orleans, are already at or above the 24°C mean weekly threshold, although this is not the case at Iron Gate Dam. This does not mean that cooler Klamath River basin tributaries could not continue to produce salmon, but natural stocks that rely on the main stem as a migration corridor in times of seasonally high temperatures may not survive if they cannot adapt. Lawson et al. (2004) made a similar observation about the survival of coho salmon in Oregon streams north of the Klamath River basin.

No one can say whether warming trends will continue or predict the magnitude and time frame of such trends. It appears certain, however, that if warming does continue, recovery of naturally reared anadromous salmonids in the Klamath River basin may become increasingly problematic. For the moment, discussion about the future of salmon remains heated.

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