Lower Tuolumne River Water Temperature Modeling Study

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1 BACKGROUND

The Federal Energy Regulatory Commission (FERC) issued a July 16, 2009 order (128 FERC ¶ 61,035) wherein Ordering paragraph (F) directed the Turlock Irrigation District (TID) and the Modesto Irrigation District (MID) (the Districts) to develop a water temperature model in conjunction with instream flow studies of the lower Tuolumne River. As described by the July 16, 2009 Order, the goal of the temperature modeling study is "to determine the downstream extent of thermally suitable habitat to protect summer juvenile *Oncorhynchus mykiss* rearing under various flow conditions and to determine flows necessary to maintain water temperatures at or below 68 degrees Fahrenheit from La Grange Dam to Roberts Ferry Bridge." In response to the July 16, 2009 Order, the Districts proposed using a recently completed HEC-5Q water temperature model that was developed for the Tuolumne River and other tributaries of the San Joaquin River with CALFED funding (RMA 2008). A Draft Study Plan was distributed for Agency review on September 3, 2009. The Districts submitted the Final Lower Tuolumne River Water Temperature Modeling Study Plan (Stillwater Sciences 2009a) to FERC on October 14, 2009 along with documentation of Agency consultation, copies of comments and recommendations on the Draft Study Plan, and descriptions of how the agencies' comments and recommendations are accommodated by the Final Study Plan. Along with examination of the flow vs. temperature relationship for the benefit of *O. mykiss*, the Final Study Plan included scenarios intended to determine flows necessary to maintain seasonal water temperature objectives for specific life stages of both *O. mykiss* and Chinook salmon (*O. tshawytscha*) at various locations in the lower Tuolumne River. Additionally, the water temperature model predictions developed in this study will be used in conjunction with instream flow incremental methodology (IFIM) estimates of weighted usable area (WUA) for the benefit of these species, as described in a separate study plan (Stillwater Sciences 2009b).

In its May 12, 2010 Order (131 FERC ¶ 62,110) on Modifying and Approving Instream Flow and Water Temperature Model Study Plans, FERC approved the October 2009 Final Study Plan and provided for the Districts to file, for FERC approval, a request for extension of time as may be required by the timing of the May 12, 2010 Order. The Districts sent proposed revised schedules to the fishery agencies on May 28, 2010 and following a 30-day comment and review period, submitted this extension request to FERC on June 30, 2010. The FERC approved the extension request on July 21, 2010 and work was initiated in early August. Following a comment period for Agency review from December 11, 2010 to January 10, 2011, the final report will be prepared for submission to the FERC on March 12, 2011.

2 APPROACH AND STUDY QUESTIONS

The goal of the FERC-ordered water temperature modeling study is to test a series of flow scenarios to determine the flows needed to maintain specified water temperatures at particular river locations and seasonal windows relevant to life history requirements of California Central Valley steelhead (*O. mykiss*) and fall–run Chinook salmon (*O. tshawytscha*). The Final Study Plan (Stillwater Sciences 2009a) outlined an approach in which the existing HEC-5Q water temperature model would be validated by developing model predictions for flow and meteorological data corresponding to periods of measurement of *in situ* water temperature data not used in the initial model calibration.

To examine potential water temperature management scenarios for the benefit of lower Tuolumne River salmonids, two study questions were included in the July 16, 2009 Order:

1. What flows are required to maintain summer water temperatures (MWAT[1]) of 20ºC (68°F) or less downstream to Roberts Ferry Bridge at river mile (RM) 39.5?
2. What is the relationship between flow and water temperature at various time periods during the year in specified reaches of the lower Tuolumne River?

In addition to Study Question 1 above, four additional scenarios corresponding to Study Question 2 were recommended by the Agencies in their review of the Draft Study Plan that correspond to their recommended interim conditions for the protection of various life stages of *O. mykiss* and fall-run Chinook salmon.

3. What flows are required to maintain a summer MWAT of 18ºC (64.4ºF) downstream of La Grange Dam to Roberts Ferry Bridge (RM 39.5)?
4. What flows are required to maintain a MWAT of 18ºC (64.4ºF) downstream of La Grange Dam to the confluence with the San Joaquin River (RM 0) from October 15 to December 1?
5. What flows are required to maintain a MWAT of 13ºC (55.4ºF) downstream of La Grange Dam to Roberts Ferry Bridge (RM 39.5) from October15, to February 15?
6. What flows are required to maintain a MWAT of 15ºC (59.0ºF) downstream of La Grange Dam to the confluence with the San Joaquin River (RM 0) from March 20 to May 15?

In all, five scenarios were evaluated using the validated temperature model. Additional alternative scenarios (i.e., temperature, location, timing, etc.) may be evaluated in the future, following the completion of this study, drawing upon findings from the literature or field observations, such as information provided to FERC by the Districts, CCSF, and the Agencies. For example, IFIM estimates of WUA of suitable habitat meeting particular life-stage-specific criteria (i.e., depth, velocity, and substrate) will be developed in a separate IFIM Study (Stillwater Sciences 2009b), with these results superimposed upon areas meeting particular water temperature criteria to create an estimate of effective WUA, or EWUA.

[1] The maximum weekly average temperature, or MWAT, is calculated as the maximum 7-day running average of the daily mean temperatures for the period of record or a time period of concern (e.g., a salmonid life stage) (Brungs and Jones 1977).

3 STUDY AREA

As shown in Figure 1, the study area extends from La Grange Dam (RM 52.2) downstream to the San Joaquin River confluence (RM 0.0). The upper reach from La Grange to Roberts Ferry Bridge (RM 39.5) specified in the July 16, 2009 Order represents the downstream extent of most summer *O. mykiss* observations in past snorkel surveys (TID/MID 2009). It also contains the Dominant Spawning Reach (down to RM 46.6) and the Dredger Tailing Reach (down to RM 40.3) which typically have the majority of Chinook salmon spawning activity (McBain and Trush 2000). In order to examine water temperature objectives for upmigrating and outmigrating life stages of Chinook salmon (Scenarios 2 and 4, respectively), the study reach extends from La Grange Dam to the confluence of the San Joaquin River (RM 0.0).

4 METHODS

4.1 Validate Existing HEC-5Q Water Temperature Model

Documentation of the existing HEC-5Q water temperature model as provided in the Calibration Report (AD Consultants et al. 2009), as well as model input files, were used to evaluate the model calibration and uncertainty in modeled water temperature predictions. The HEC-5Q model was then validated using water temperature data not used in the original model calibration, as recorded by District thermographs at various locations in the lower Tuolumne River during 1996–2009.

Water temperatures have been recorded continuously by the Districts under their real time monitoring (RTM) program at various locations in the lower Tuolumne River since 1986 (TID/MID 2005). In addition the California Department of Fish and Game (CDFG) has deployed thermographs in the lower Tuolumne River at nearby locations since 1999 (Table 4-1). The periods of record for these data are also shown graphically in Figure 2. Although the HEC-5Q model primarily used CDFG thermograph data, examination of the temperature records included in the compiled HEC-5Q temperature model (called "HWMS") established that data at the Ruddy/Santa Fe Gravel plant location (RM 36.5) and at Shiloh Road (RM 3.5) are identical between the two data sets and that TID/MID data were used at these locations.

Table 4-1. Period of record summary for hourly water temperature data used to assess HEC-5Q model accuracy.

River mile	TID/MID location	CDFG location[1]	Hourly data period of record	
51.8	La Grange[2]		11/14/2001	Present
51.6		Riffle A1	7/27/2001	12/31/2007
50.7	Riffle A7		11/14/2001	Present
49.7		Riffle C1	3/1/2002	12/31/2007
49.1	Riffle 3B		12/10/1997	Present
47.5		Basso Bridge[2]	3/1/2002	12/31/2007
45.5	Riffle 13B		11/14/2001	Present
43.2		Riffle I2	12/19/2001	12/31/2007
42.9	Riffle 21		5/27/2004	Present
42.6		Riffle K1[2]	3/1/2002	12/31/2007
39.5	Roberts Ferry Bridge		8/11/1998	Present
38.0		7-11 Gravel[2]	3/1/2002	12/31/2007
36.5	Ruddy (Santa Fe) Gravel	Santa Fe Gravel	12/10/1997	Present
35.0		Riffle Q3	5/31/2002	12/31/2007
31.0		Hickman Bridge[2]	7/15/2002	12/31/2007
26.0		Fox Grove	9/9/2005	12/31/2007
23.6	Hughson WWTP		12/10/1997	Present
19.0		Mitchell Road	8/12/2005	12/31/2007
15.9		Modesto[2]	8/12/2005	12/31/2007
12.0		Carpenter Road	8/12/2005	12/31/2007
3.5	Shiloh Bridge	Shiloh[2]	12/11/1997	Present

[1] CDFG thermograph data included in HEC-5Q "HWMS" file distribution by RMA and AD Consultants
[2] Data used in initial HEC-5Q model calibration

As recommended by the Agencies, model performance was assessed using the following temperature modeling goodness of fit metrics, adapted from Theurer et al. (1984), using both 6-hr averaged (minimum time-step of the HEC-5Q model) and daily averaged thermograph data:

- Maximize the correlation coefficient ($R^2 \leq 1.0$) between modeled and observed water temperatures at individual thermograph locations, as well as across all locations not used in the original calibration data set.
- Determine the fraction of observed temperatures deviating from modeled temperatures by more than 0.5°C (0.9°F), 1°C (1.8°F), and 1.5°C (2.7°F)
- Determine any trends in the residual errors (observed minus modeled) either spatially (across several locations) or temporally (at individual locations).

If the goodness of fit results indicated large errors between observed and predicted temperatures, updated model uncertainty estimates could be developed for particular locations or times of year.

Goodness of fit metrics and other summary statistics and graphics used for model validation were generated using the "R" statistical software package (Bowman and Azzalini 1997).

4.2 Scenario Development and Model Simulations

The current FERC (1996) flow schedules and the actual flow releases during the 1996–2009 periods were simulated as part of the model validation exercise. The validated HEC-5Q model was then used to predict conditions relating directly to the initial scenario included in the July 16, 2009 FERC Order (see Section 2, Study Question 1), along with the four additional scenarios corresponding to Study Question 2 (see Section 2) as recommended by the Agencies pertaining to their interim conditions for the protection of various life stages of California Central Valley steelhead and fall–run Chinook salmon. The HEC-5Q model was used to determine the downstream extent of suitable water temperatures for these key species and life stages under normal and extreme meteorology as provided in the Calibration Report (AD Consultants et al. 2009) for the years 1980–2008.

5 RESULTS

The temperature model validation was initiated in June 2010 and completed in August 2010. Using the validated temperature model, initial scenario evaluation was conducted in August and September 2010. A progress report will be filed with FERC on November 9, 2009, followed by a draft report for Districts review by mid-November, a revised draft submitted for Agency review on December 10, 2010, and Final Report to the FERC on March 12, 2011.

The units of measure used to report water temperature in the text follow the convention used by the Agencies in their study plan recommendations. For example, goodness of fit metrics and error statistics refer to degrees Celsius (°C). Results of water temperature model simulations are presented in °C, followed by conversions to degrees Fahrenheit (°F) in parentheses. Because the HEC-5Q model output provides water temperatures in °F, some analyses are presented in °F, only.

5.1 Validation of Initial HEC-5Q Model Calibration

The Calibration Report (AD Consultants et al. 2009) provided with the model distribution shows that the modeled temperatures are consistently close to the temperatures actually observed at the seven "calibration" locations. This remains true for all 16 thermograph locations (designated as "HWMS") provided as background data in the model distribution (Figure 3). The Calibration Report uses the r-squared (r^2) statistic for the linear regression of modeled versus observed values, and this statistic was also calculated for the HWMS thermograph locations, using mean daily water temperatures (Table 5-1). Ordinarily one would also report the p-value for the regression fit, but in all cases this was numerically indistinguishable from 0 by the algorithm used in the R software (<2.2e-16). Another approach is to consider how the differences (modeled-observed water temperature) are distributed. Table 5-1 shows the mean and standard deviation of this difference, as well as the root-mean-square (rms) value, and Figures 4 and 5 show various order statistics (i.e., deviations by quartiles). Yet another way of looking at the model is to ask what fraction of the time the predicted value is within some deviation from the observed value. This is shown in the last three columns of Table 5-1 as "Percent Coverage." For example, at Riffle A1, the modeled daily mean temperature was within 1°C of the observed value for 96% of the time period simulated.

Table 5-1. Comparison of modeled and observed daily mean water temperatures at the CDFG (HWMS) thermograph locations.

Site	Days	r^2	Model-observed (°C)			Percent coverage [1]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
Riffle A1	1,553	0.67	0.14	0.49	0.52	64%	96%	100%
Riffle C1	1,486	0.87	-0.18	0.55	0.58	64%	90%	100%
Basso Bridge	1,532	0.95	-0.07	0.54	0.54	66%	91%	100%
Riffle I2	1,544	0.98	-0.21	0.56	0.59	59%	91%	99%
Riffle K1	1,787	0.98	-0.07	0.58	0.59	63%	92%	99%
7-11 Gravel	1,517	0.99	-0.17	0.55	0.57	64%	92%	98%
Santa Fe Gravel	1,458	0.98	-0.32	0.64	0.72	56%	84%	95%
Riffle Q3	935	0.99	-0.22	0.56	0.60	61%	91%	99%
Hickman Bridge	1,340	0.99	-0.36	0.56	0.67	54%	87%	98%
Fox Grove	700	0.98	-0.84	0.56	1.01	27%	68%	87%
Hughson WWTP	2,562	0.99	-0.67	0.64	0.93	35%	72%	90%
Mitchell Road	490	0.99	-0.69	0.41	0.80	36%	79%	97%

Site	Days	r²	Model-observed (°C)			Percent coverage [(1)]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
Modesto	1,861	0.98	0.03	1.12	1.12	36%	62%	82%
Carpenter Road	222	0.98	-0.08	0.89	0.89	44%	74%	91%
Grayson	183	0.97	0.01	0.83	0.82	49%	76%	91%
Shiloh	2,539	0.97	0.17	1.28	1.29	32%	58%	75%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Table 5-1 shows the r-squared statistic is considerably lower for thermograph locations at up-stream sites Riffle A1 and Riffle C1 than for other locations. However, this is merely a consequence of the fact that a much smaller range of temperatures are represented at these sites on an annual basis than for downstream locations. As can be seen in Figure 3, the modeled-observed pairs are clustered around the one-to-one (modeled = observed) diagonal to a broadly similar extent at all sites, meaning the magnitude of the error is similar at all locations. Table 5-2 shows similar results to those above based on a comparison of modeled and observed calibration results using 6-hour interval data.

Table 5-2. Comparison of modeled and observed instantaneous water temperatures (6-hour intervals) at the CDFG (HWMS) thermograph locations.

Site	Intervals	r²	Model-observed (°C)			Percent coverage [(1)]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
Riffle A1	6,233	0.63	0.14	0.59	0.61	61%	91%	99%
Riffle C1	5,982	0.84	-0.20	0.66	0.69	56%	86%	97%
Basso Bridge	6,144	0.85	-0.08	1.02	1.03	53%	82%	90%
Riffle I2	6,182	0.95	-0.21	0.88	0.91	43%	77%	92%
Riffle K1	7,157	0.97	-0.08	0.80	0.81	49%	81%	94%
7-11 Gravel	6,077	0.97	-0.18	0.92	0.94	44%	78%	91%
Santa Fe Gravel	5,837	0.98	-0.32	0.74	0.81	51%	82%	93%
Riffle Q3	3,750	0.99	-0.23	0.64	0.68	56%	87%	97%
Hickman Bridge	5,367	0.99	-0.37	0.64	0.74	51%	82%	95%
Fox Grove	2,810	0.96	-0.85	0.72	1.11	32%	62%	84%
Hughson WWTP	10,262	0.98	-0.67	0.75	1.01	33%	66%	87%
Mitchell Road	1,968	0.98	-0.69	0.53	0.87	35%	73%	93%
Modesto	7,482	0.97	0.01	1.21	1.21	33%	59%	78%
Carpenter Road	899	0.97	-0.08	0.93	0.93	42%	71%	90%
Grayson	746	0.96	0.00	0.94	0.94	41%	72%	89%
Shiloh	10,178	0.96	0.16	1.35	1.36	30%	56%	73%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Examination of the time series of observed and predicted water temperatures suggests the model tends to under-predict temperatures in the upper reaches of the river and to over-predict temperatures in the lower reaches. Figure 4 shows the deviation of model-predicted temperatures from observed temperatures is generally within ±1°F as an annual average but is most pronounced during June, when this discrepancy increases to nearly ±2°F. As discussed below, extending the comparison to the TID thermograph period of record reveals that this apparent discrepancy is related to the water year and meteorological conditions represented in the two datasets (Table 4-1).

5.2 Validation of HEC-5Q Model Against Data Not Used in the Initial Calibration

Table 4-1 shows there are a number of thermograph locations maintained by TID/MID under the Districts' RTM program covering portions of the 1999–2007 calibration period. These data provide an opportunity to evaluate model performance using data that have not contributed, even indirectly, to model calibration.

Thermographs associated with the RTM program are operated primarily in connection with river-wide monitoring for the benefit of Chinook salmon and *O. mykiss*, and consequently are concentrated in approximately the upper third of the lower Tuolumne River. The only stations used by the RTM program downstream of RM 25, at the Hughson Waste Water Treatment Plant (RM 23.6) and Shiloh Road (RM 3.5), are also included in the HWMS dataset. The RTM stations therefore provide less extensive geographical coverage in the lower portion of the river than do the HWMS stations. On the other hand, the RTM stations generally provide longer periods of record: in particular, the HWMS stations have no data for the upper half of the river before June 15, 2001 or between December 18, 2002 and July 21, 2004 (Figure 2).

Overall, the model fit shown in Table 5-3, as measured by r-squared, rms error, and the percent coverage statistics appears similar to the CDFG HWMS data summarized in Table 5-1 and indicates the model generally predicts water temperatures within 1–1.5°C. However, comparisons using the RTM data indicate that the model may systematically over-predict water temperature in the upper river in June by 1–2°F (Figure 5). This is the exact opposite of the results of the comparison using the CDFG HWMS data discussed above, which suggest that the model may systematically under-predict water temperature in the upper river in June (Figure 4). However, this apparent discrepancy turns out to be an artifact of the differences in the period-of-record of the two data sets (Table 4-1). Closer inspection of the full time-series of modeled and predicted temperature shows that the model tended to over-predict temperatures in the upper portions of the river in drier water year types (2002, 2003, and 2004), especially in the spring and summer, and to under-predict in wetter water year types (2005 and 2006). Direct comparison of temperature data from nearby locations yielded similar results and it is apparent that a number of flow-related artifacts appear in the calibrated model, likely due to the limited number of water-year types covered by the calibration data period of record. Only four water years (2002, 2005, 2006, and 2007) are covered very well by the HWMS thermographs in the upper river (Figure 2). Further, the HWMS period of record does not cover any of 2003 and gives only limited coverage of 2004.

Table 5-3. Comparison of modeled and daily mean water temperatures at the TID/MID (RTM) thermograph locations.

Site	Days	r^2	Model-observed (°C)			Percent coverage [1]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
La Grange	2,239	0.58	0.43	0.86	0.96	51%	77%	86%
Riffle A7	2,030	0.76	0.40	0.91	0.99	50%	73%	88%
Riffle 3B	2,497	0.95	0.54	0.58	0.79	43%	77%	96%
Riffle 13B	2,239	0.98	0.33	0.64	0.72	54%	84%	96%
Riffle 19	1,973	0.99	0.12	0.63	0.64	61%	88%	97%
Riffle 21	986	0.98	0.26	0.63	0.68	53%	88%	97%
Roberts Ferry Bridge	3,076	0.99	0.18	0.62	0.64	57%	89%	98%
Ruddy Gravel	3,287	0.99	0.22	0.68	0.72	56%	84%	95%
Fox Grove	179	0.98	-0.68	0.73	1.00	27%	76%	91%
Hughson WWTP	3,001	0.99	-0.59	0.68	0.91	40%	75%	91%
Shiloh Bridge	2,804	0.96	0.22	1.32	1.33	31%	55%	73%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Table 5-4 shows similar results based on a comparison of modeled and observed calibration results using 6-hour interval data.

Table 5-4. Comparison of modeled and observed instantaneous water temperatures (6-hour intervals) at the TID/MID (RTM) thermograph locations.

Site	Intervals	r^2	Model-observed (°C)			Percent coverage [1]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
La Grange	8,949	0.59	0.43	0.90	1.00	51%	75%	86%
Riffle A7	8,109	0.78	0.40	0.97	1.05	48%	74%	87%
Riffle 3B	9,973	0.94	0.54	0.74	0.91	46%	76%	90%
Riffle 13B	8,948	0.95	0.33	0.88	0.94	54%	78%	88%
Riffle 19	7,878	0.97	0.11	0.87	0.88	44%	76%	92%
Riffle 21	3,939	0.97	0.25	0.85	0.89	40%	73%	92%
Roberts Ferry Bridge	12,301	0.98	0.17	0.81	0.82	47%	79%	93%
Ruddy Gravel	13,129	0.98	0.23	0.79	0.82	50%	80%	92%
Fox Grove	717	0.82	-0.74	1.98	2.12	30%	57%	79%
Hughson WWTP	11,982	0.98	-0.59	0.82	1.01	37%	69%	88%
Shiloh Bridge	11,195	0.96	0.21	1.39	1.40	29%	53%	71%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

5.3 Discharge-Flow-Temperature Relationships

In direct response to the July 16, 2009 Order, the validated temperature model was used to examine the relationship between flow and water temperature at various time periods during the year in specified reaches of the lower Tuolumne River. It is apparent from the model validation results discussed above that the HEC-5Q model may systematically over- or under-predict water temperatures to some degree within portions of the lower Tuolumne River under various flow regimes and meteorological conditions. For this reason, it is important to gain a clearer understanding of the behavior of the model to better inform its use in evaluating the various temperature targets included in the Final Study Plan (Stillwater Sciences 2009a).

A non-parametric technique, kernel smoothing, was used within the "R" statistical software (Bowman and Azzalini 1997) to evaluate the temperature difference of observed and modeled temperatures as a function of river mile and Modesto flow for 1999–2007 across all HWMS and RTM thermograph locations (Figure 6). The results show that the calibrated model systematically over-predicts water temperatures throughout the river by 1–2°F at lower flows, except in the winter months, and under-predicts temperatures in the upstream and middle reaches by up to 2°F at higher flows from spring through summer. It should be pointed out, however, that the model fit lies within the 1–2°F uncertainty described in the Final Study Plan (Stillwater Sciences 2009a). For this reason, although model uncertainty shown in Figure 6 should be taken into consideration in setting potential flow requirements based upon water temperature, the existing HEC-5Q model should be considered validated for the purposes of examining the overall feasibility of meeting various temperature target scenarios included in the Final Study Plan.

5.4 Preliminary Evaluation of Flow Requirements to Meet Seasonal Water Temperature Targets

The primary approach used to address the second study question included in the July 16, 2009 Order was to simulate the variation of Don Pedro release flows over a large range of historical meteorological conditions in order to identify the expected flows necessary to meet various water temperature thresholds downstream. The water temperature standard chosen for this evaluation is the maximum value of the moving 7-day average temperature, i.e., the "maximum weekly average temperature" or "MWAT." It should be understood that the actual flows necessary to meet a given water temperature at a particular river location and time of year will depend, in general, on flows and temperatures upstream at a range of earlier times. An advantage of using weekly average values is that issues of travel time between release and compliance points, as well as autocorrelation of the flow and temperature combinations within the data record, can be plausibly ignored. However, because antecedent meteorology and reservoir operations affect the available storage volume and temperature structure of the reservoir, the model may substantially over- or under-predict actual water temperatures encountered under real-world reservoir operations. As noted in the Final Study Plan, since the reservoir operations component of the existing HEC-5Q model is not adequately reflective of actual basin hydrology and the Districts' operation of Don Pedro Reservoir, this study did not seek to address water storage and water delivery operations under various scenarios and water-year types (Stillwater Sciences 2009a).

To address the limitations above, the effects of a given release flow on downstream temperature were explored using the validated HEC-5Q model under the simplifying assumption that the release temperatures from Don Pedro reservoir are known and relatively stable from year-to-year. To de-couple reservoir operations from water temperatures entering the lower Tuolumne River, incoming flows to Don Pedro reservoir and downstream canal deliveries were artificially set to very large values within the model input data files. Figure 7 shows that average water temperatures entering the lower Tuolumne River from La Grange Dam would vary between 9.8ºC (49.7ºF) and 11.2ºC (52.2ºF) on an annual basis. All simulations used these temperatures at the upstream end of the modeled reach below La Grange Dam and then used the within-year meteorology to determine the downstream extent of various temperature values. Recognizing that reservoir operations may be specifically evaluated in the future to determine the feasibility of achieving various downstream temperature targets on a long-term basis, this allowed the HEC-5Q model to be used strictly as a reach-based temperature model for the purposes of this study.

As required under Ordering Paragraph (F) of the July 16, 2009 Order, we present model simulation results to determine the downstream extent of thermally suitable habitat to protect summer juvenile *O. mykiss* rearing under various flow conditions. The initial scenario evaluated includes an estimate of flows necessary to meet water temperatures below 20ºC (68°F) from La Grange Dam to Roberts Ferry Bridge at RM 39.5. In addition, the USFWS and other fishery resource agencies identified additional scenarios that were included in the Final Study Plan to evaluate seasonal temperature targets at other locations for the benefit of various life stages of *O. mykiss* and Chinook salmon.

5.4.1 Flows meeting a summer MWAT of 20ºC at Roberts Ferry Bridge

The initial evaluation scenario evaluated from the information requested in the 16 July 2009 Order was to determine the flow required to maintain a summertime maximum weekly average water temperature (MWAT) of 20ºC (68°F) or less downstream to Roberts Ferry Bridge (RM 39.5). The validated HEC-5Q model was used to evaluate this initial scenario. Results of this evaluation indicate that flows of 200–300 cfs will be required to regularly meet this condition, with 300–350 cfs required during the hottest years (Figure 8). Based upon this analysis, the summertime MWAT typically occurs in the second half of July in most years.

5.4.2 Flows meeting a summer MWAT of 18ºC at Roberts Ferry Bridge

In addition to the initial evaluation scenario included in the July 16, 2009 Order and described in Section 5.4.1 above, the first of four additional scenarios evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a summer MWAT of 18ºC (64.4ºF) from La Grange Dam downstream to Roberts Ferry Bridge (RM 39.5). Results of this evaluation indicate that flows of 200–300 cfs will be required to regularly meet this condition, with 400 cfs required during the hottest years (Figure 9). As with the 20ºC evaluation described above in Section 5.4.1, the summertime MWAT typically occurs in the second half of July in most years.

5.4.3 Flows meeting a fall MWAT of 18ºC at the San Joaquin River confluence from October 15 to December 1

The second additional scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a fall MWAT of 18ºC (64.4ºF) from La Grange Dam downstream to the confluence with the San Joaquin River (RM 0) from October 15 to December 1. Results indicate that flows of 150–400 cfs will be required to meet this condition during the second half of October of most years, with only 100 cfs or less required after November 1 (Figure 10). Based upon this analysis, the fall MWAT typically occurs at the beginning of this simulation period (October 15–22) in all years. It should be noted that meeting this temperature target from La Grange Dam all the way to the San Joaquin River confluence cannot be achieved under any flow release condition during mid-October of hotter years.

5.4.4 Flows meeting a fall/winter MWAT of 13ºC at Roberts Ferry Bridge from October 15 to February 15

The third additional scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a fall/winter MWAT of 13ºC (55.4ºF) from La Grange Dam downstream to Roberts Ferry Bridge (RM 39.5) from October 15 to February 15. Results indicate that flows of 300–500 cfs will be required to meet this condition during mid-October, falling below 200 cfs by mid-November (Figure 11). As stated above, the fall/winter MWAT typically occurs at the beginning of this simulation period (October 15–22) in all years.

5.4.5 Flows meeting a spring MWAT of 15ºC at the San Joaquin River confluence from March 20 to May 15

The last scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a spring MWAT of 15ºC (59ºF) from La Grange Dam downstream to the confluence with the San Joaquin River (RM 0) from March 20 to May 15. Results indicate that flows of 700–1,000 cfs will be required to meet this condition during mid- to late-March of most years (Figure 12). Based upon this analysis, the springtime MWAT typically occurs at the end of this simulation period (May 15) in most years. Meeting this temperature target from La Grange Dam all the way to the San Joaquin River confluence cannot be achieved under any flow release condition in any year modeled after mid-April.

6 DISCUSSION

The existing HEC-5Q water temperature model developed for the Tuolumne River was evaluated and independently validated for use in predicting downstream water temperatures in relation to flows released at La Grange Dam. Although the model validation results show that the model systematically over-predicts or under-predicts water temperatures in portions of the river during some seasons and within particular flow ranges, this variance lies within the 1–2°F uncertainty described in the Final Study Plan. Therefore the existing calibrated model, with the noted uncertainty, is considered validated for providing the results obtained in this study.

In all, five scenarios were evaluated using the validated water temperature model. Results of the model simulations indicate that flows of 200–300 cfs would be required to regularly meet year-round water temperature targets (MWAT) of 20ºC (68°F) and 18ºC (64.4ºF) or less downstream to Roberts Ferry Bridge (RM 39.5), except in the hottest years when slightly higher flows would be required during summer. Considering the model's systematic over-prediction of water temperatures in this portion of the river at flows of this magnitude in all but the winter months, actual flows required to meet these targets during most of the year could be lower than predicted by the model.

The three additional scenarios simulated by the model predicted the flows necessary to meet water temperature targets only during certain portions of the year. Because the hottest portion of the fall (October 15 to December 1) and fall/winter (October 15 to February 15) simulation periods typically occurs at the beginning of the period (October 15–22), more flow is required to maintain the water temperature targets during mid-October than in subsequent weeks. In the hottest years, the model predicts that an 18ºC (64.4ºF) MWAT target cannot be maintained downstream to the confluence with the San Joaquin River (RM 0) during mid-October under any flow release conditions. Flows required to meet fall and fall/winter temperature targets decline rapidly during late October and early November with the onset of cooler weather conditions. Model predictions indicate that from November 1–December 1, only 100 cfs or less is required to maintain an MWAT of 18ºC (64.4ºF) downstream to the confluence with the San Joaquin River (RM 0), and only 200 cfs or less is required to maintain an MWAT of 13ºC (55.4ºF) downstream to Roberts Ferry Bridge from mid-November to February 15.

As would be expected, water temperatures during the spring simulation period (March 20 to May 15) are highest at the end of the simulation period. Flows required to maintain an MWAT of 15ºC (59.0ºF) downstream to the confluence with the San Joaquin River (RM 0) therefore increase over the course of the spring. After mid-April, model predictions indicate that an MWAT of 15ºC (59.0ºF) cannot be maintained downstream to the confluence with the San Joaquin River under any flow release conditions.

The results of the model validation and simulations indicate that model predictions are appropriate for use in evaluation of effective weighted usable area (EWUA) as part of the Districts' instream flow (IFIM) study included in the July 16, 2009 Order. However, it should be stressed that the model results presented here are not suitable for establishing flow schedules on a long-term basis. As stated in the Final Study Plan, using the HEC-5Q model (or any water temperature model) as a predictive tool is limited by the availability of meteorological data corresponding to the conditions of interest (e.g., hottest week of spring or summer). Various reservoir operation and release scenarios may be simulated against the period-of-record meteorology to generate a range of predicted temperatures for various locations in the river under varying meteorologic conditions. At that time coordinated reservoir operations modeling should be conducted to determine corresponding long-term water storage estimates under various water-year types and climate change scenarios not addressed as part of this study.

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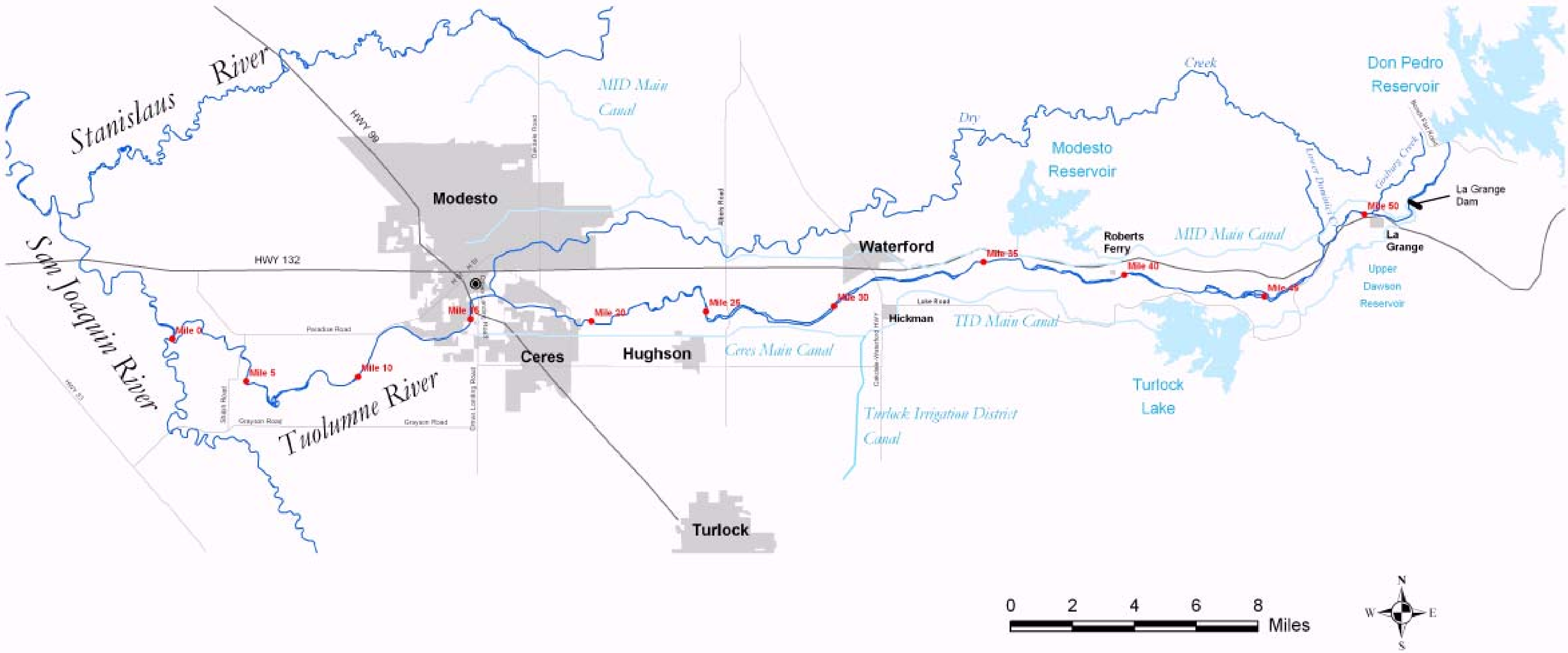

Figure 1. Vicinity map for the Tuolumne River water temperature modeling study.

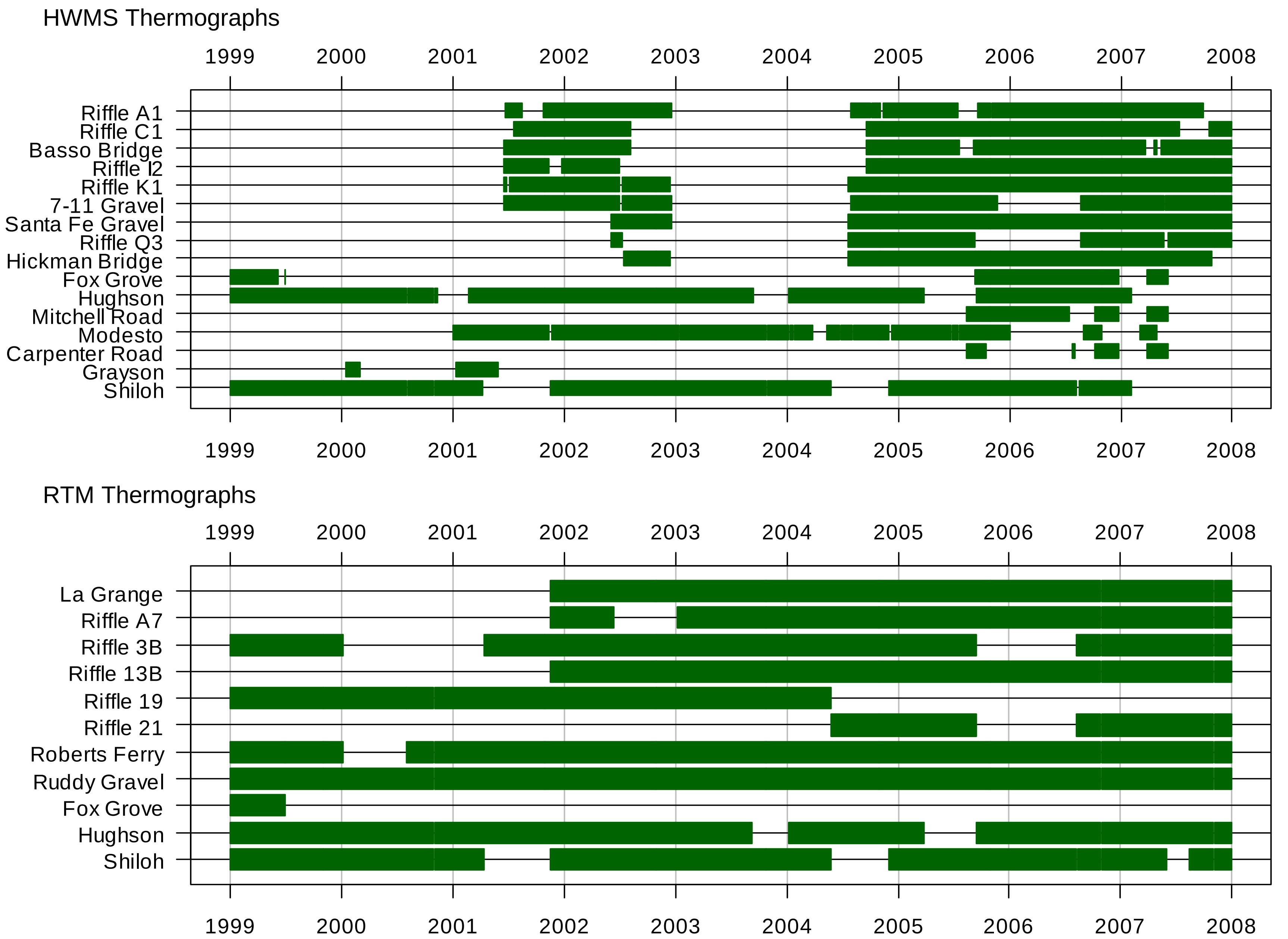

Figure 2. Dates represented by the CDFG ("HWMS") and TID-MID ("RTM") thermographs. Only days from 1/1/1999 through 12/31/2007, and for which 10 or more observations were recorded, are shown.

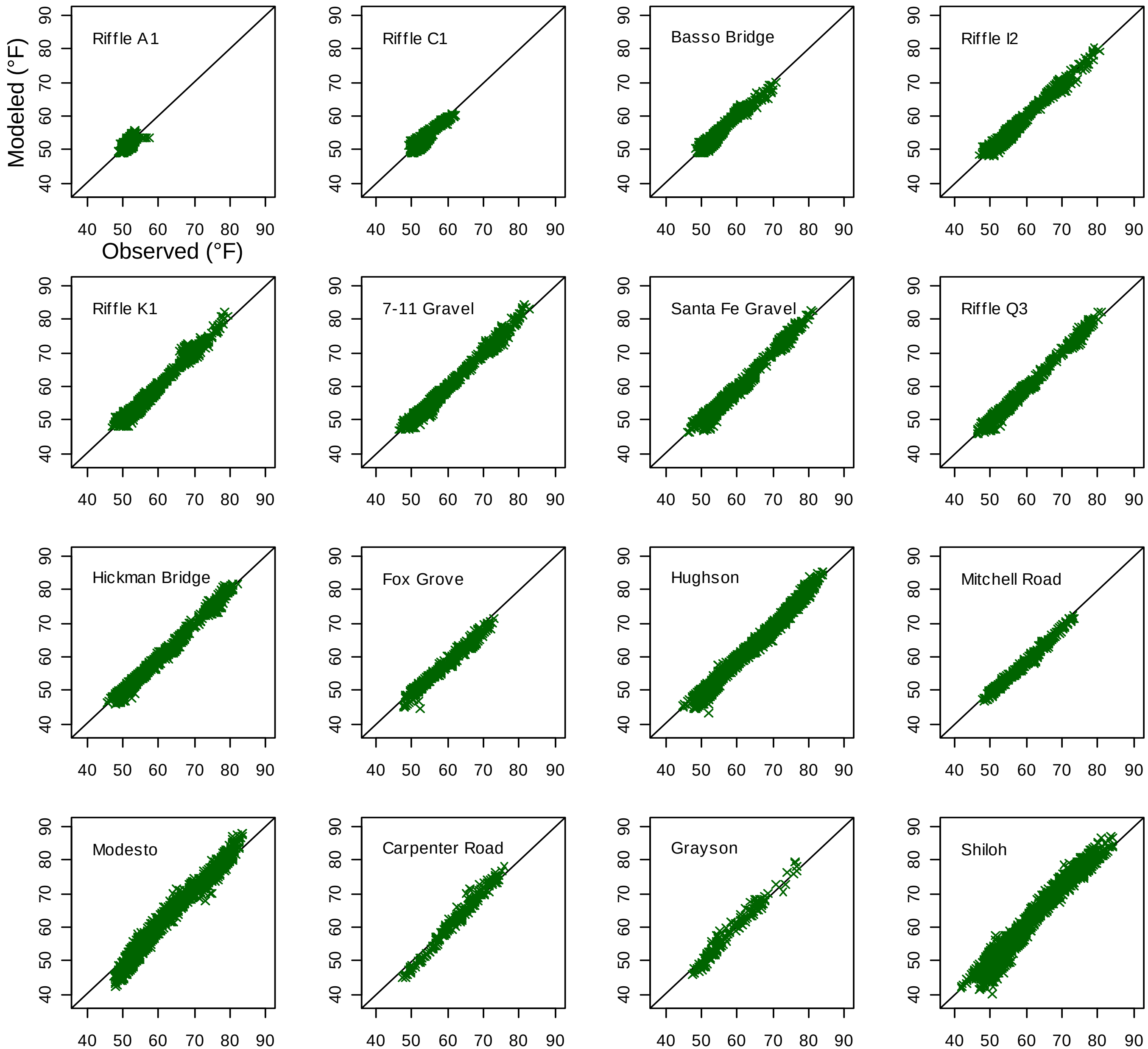

Figure 3. Modeled vs. observed mean daily water temperatures at various locations in the Tuolumne River below La grange dam. These are all the Tuolumne River comparisons directly accessible in the HWMS GUI. The historical values are mostly from CDFG thermographs.

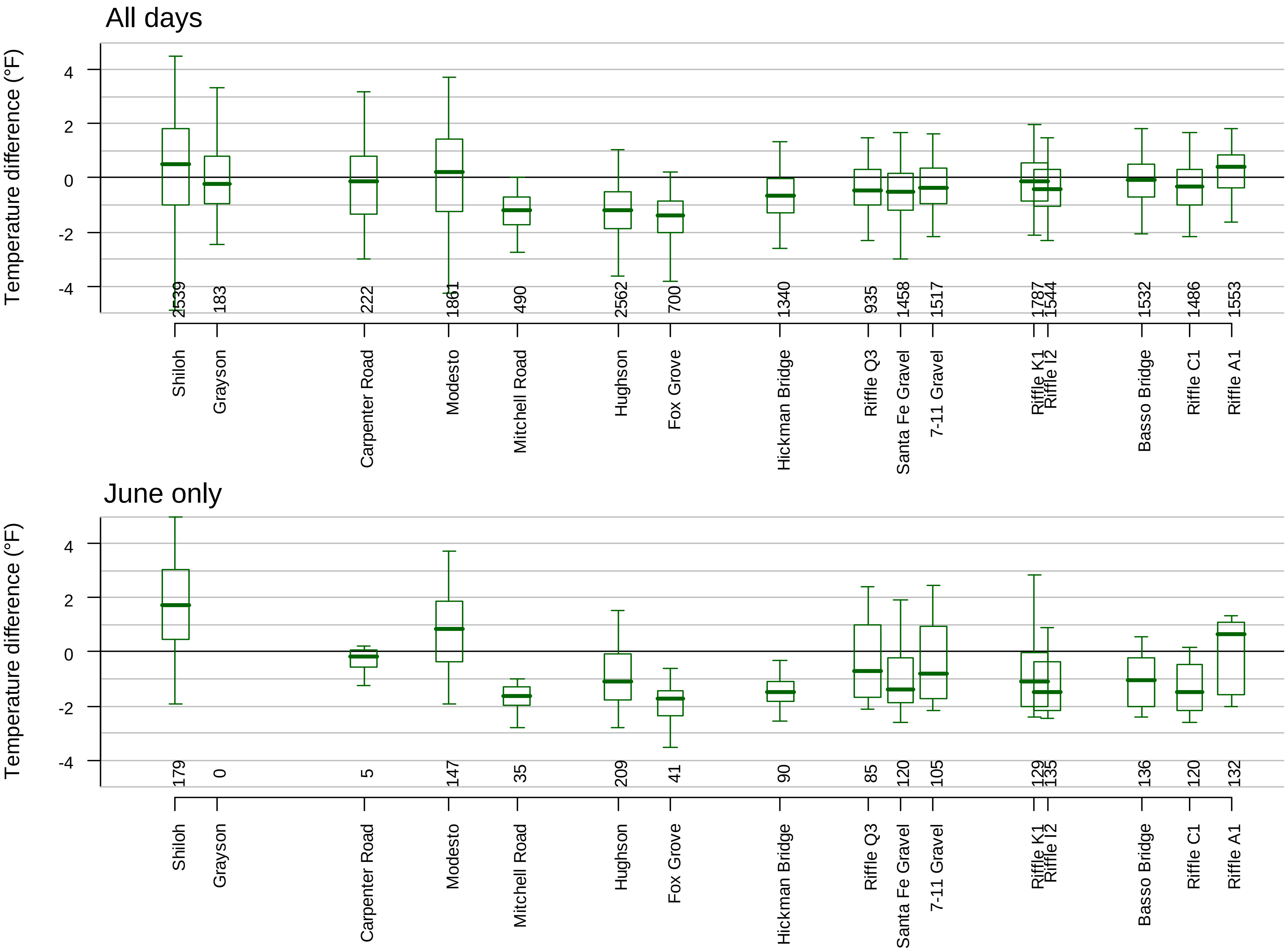

Figure 4. Difference (modeled - observed) between mean daily water temperatures at the CDFG ("HWMS") thermographs in the Tuolumne River below La Grange dam (1999-2007). Boxes show median, first, and third quartiles; whiskers show 2.5 and 97.5 percentiles.

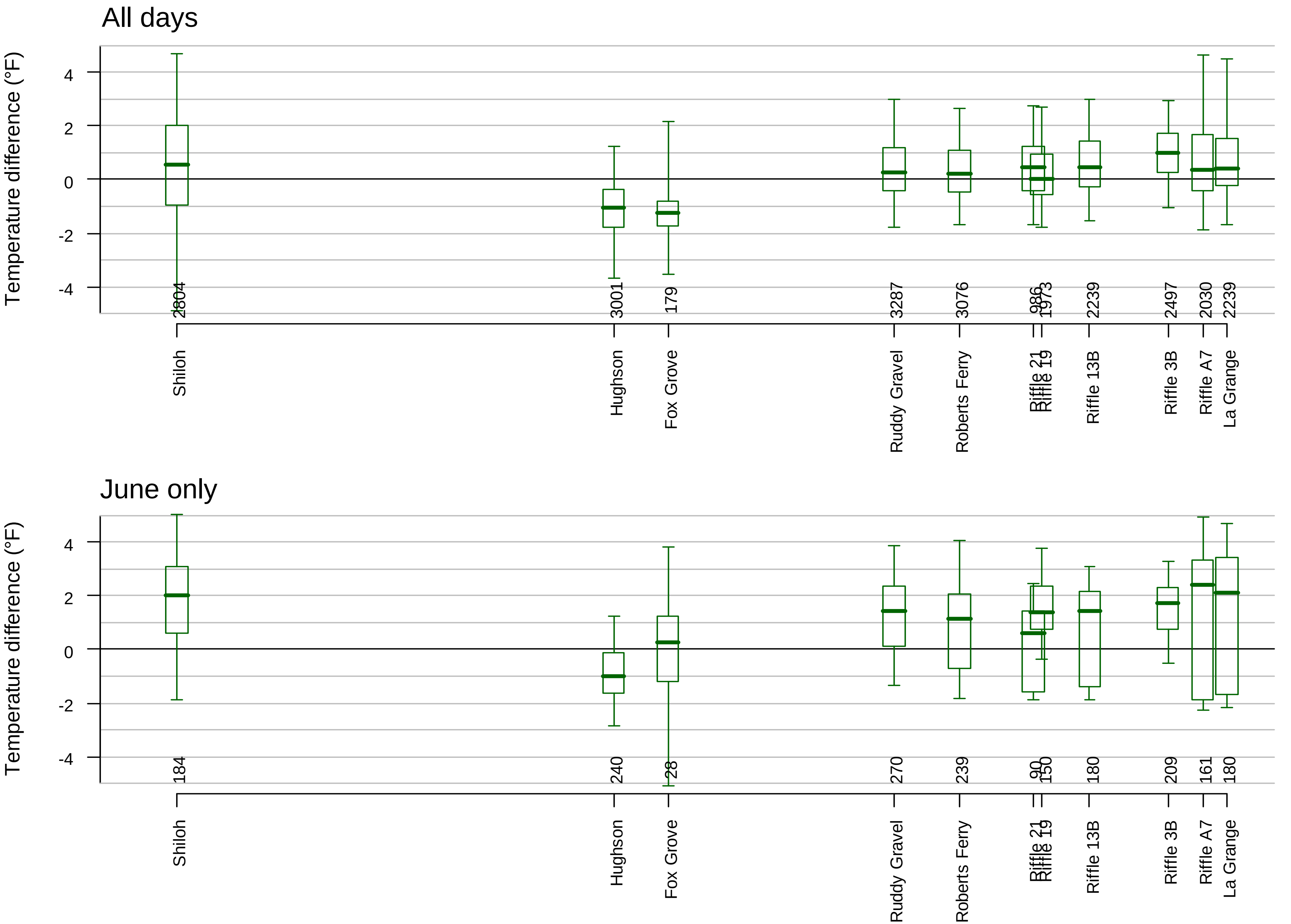

Figure 5. Difference (modeled - observed) between mean daily water temperatures at the TID-MID (“RTM”) thermographs in the Tuolumne River below La Grange dam (1999-2007). Boxes show median, first, and third quartiles; whiskers show 2.5 and 97.5 percentiles.

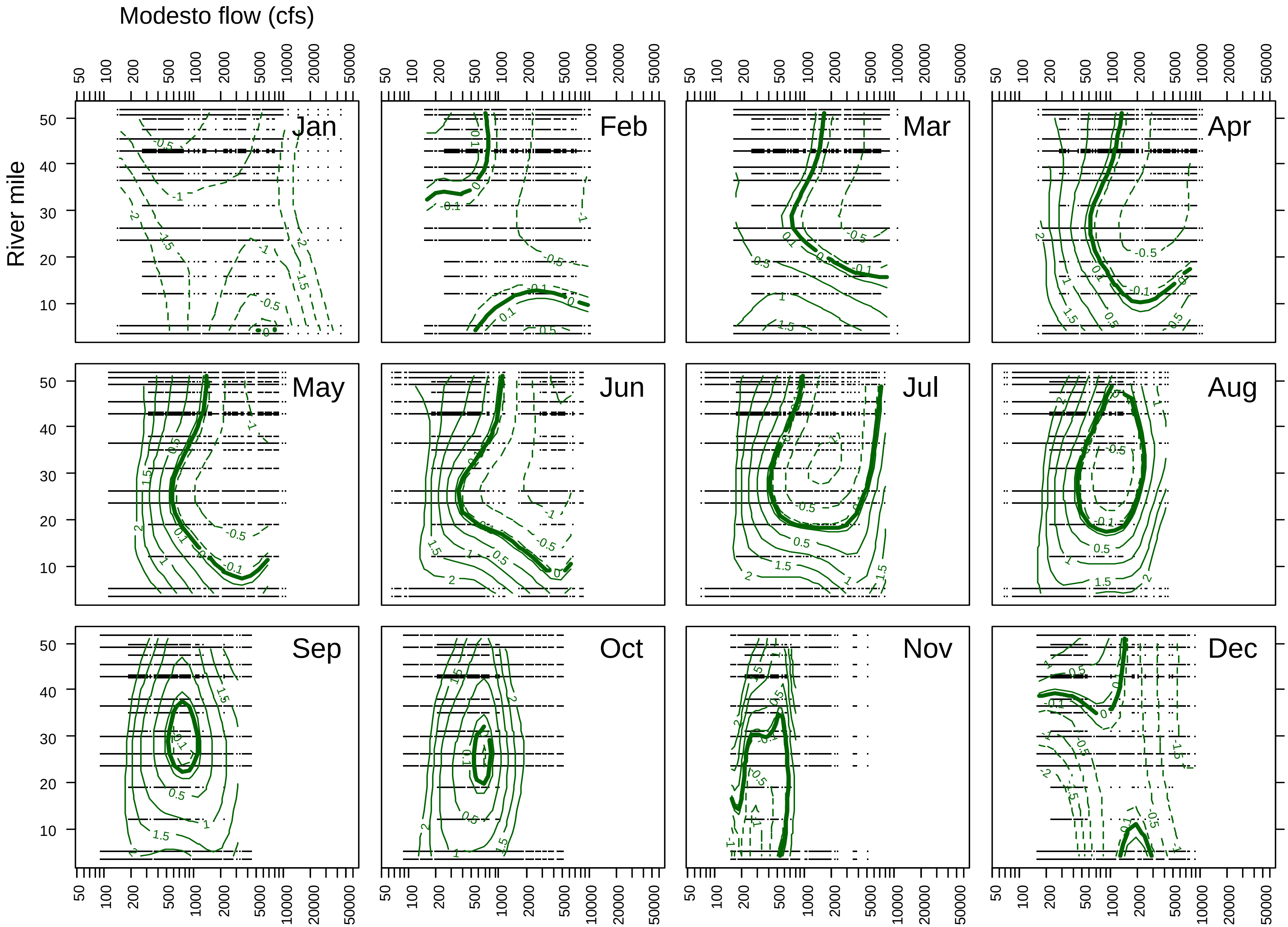

Figure 6. Discrepancy between modeled and observed water temperatures (modeled - observed, in °F), 1999 through 2007, for all HWMS and RTM thermographs, by month. Each observed combination of flow, location, and temperature difference is marked. The lines show isopleths of a surface fitted by non-parametric regression.

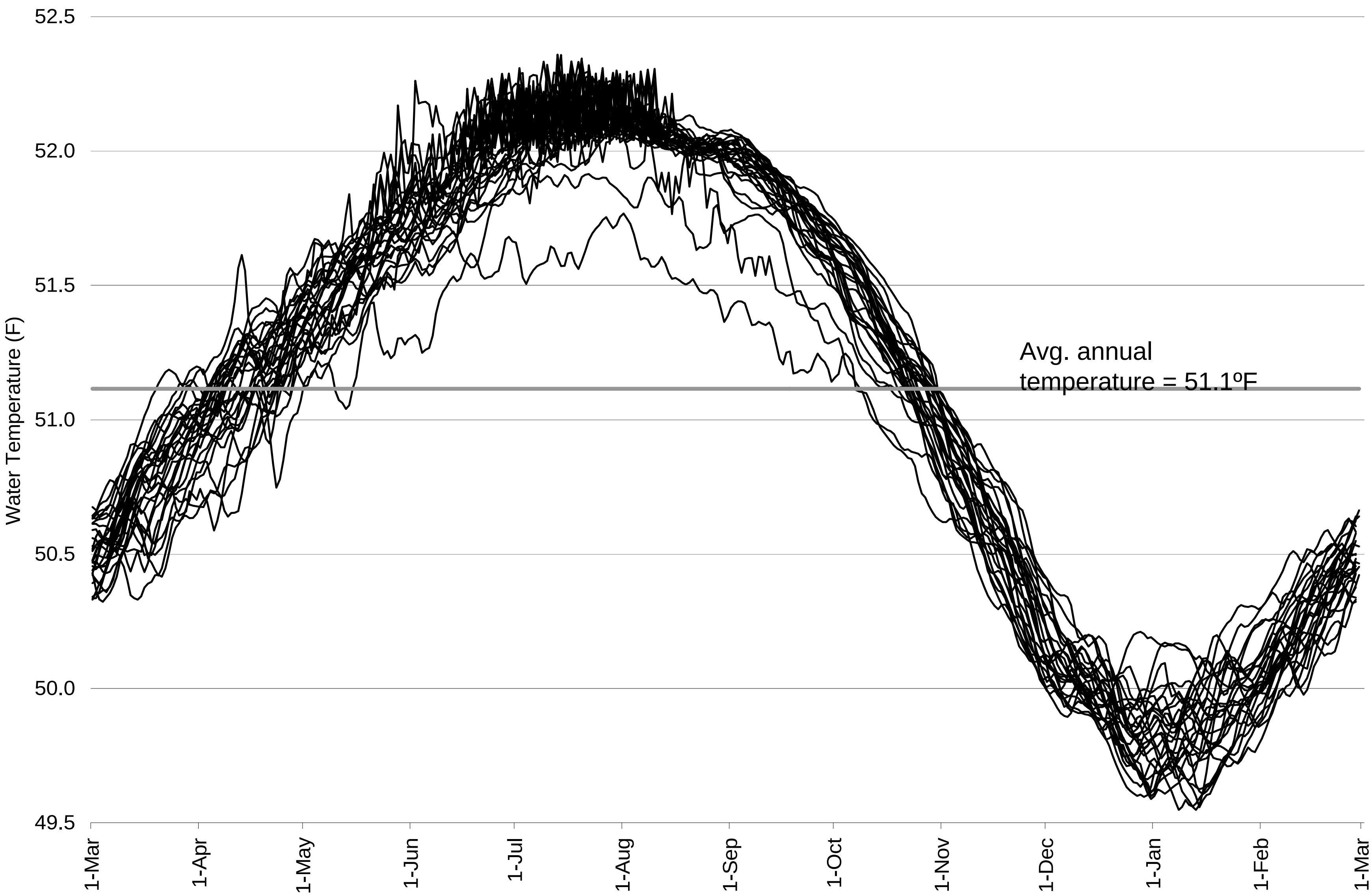

Figure 7. Estimated average daily water temperatures exiting La Grange Dam (RM 52) using period of record meteorology (March 1980 through December 2007).

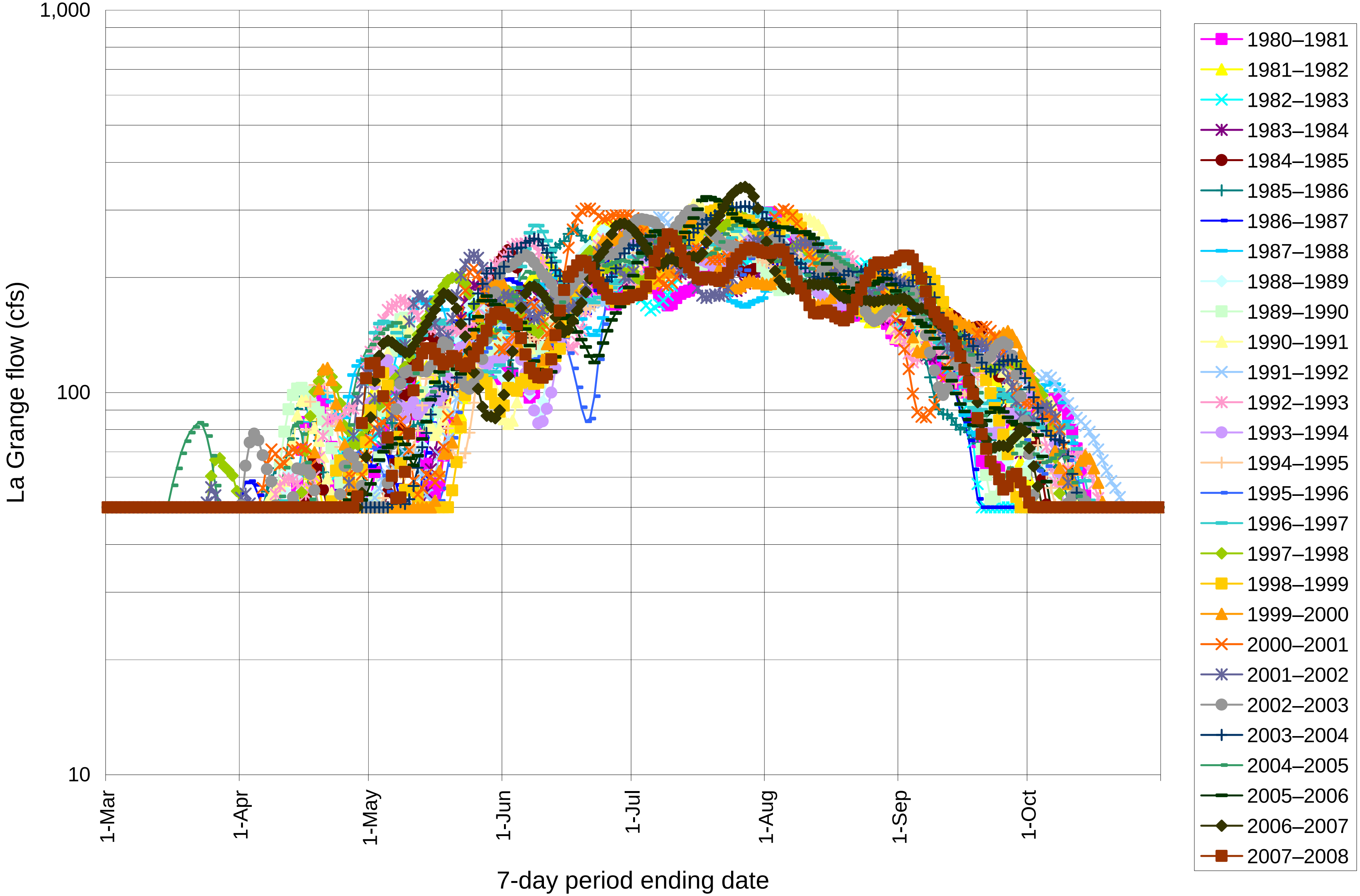

Figure 8. Simulation of flows required to maintain a summer MWAT of 20ºC (68ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5), for the period of record 1980-2007.

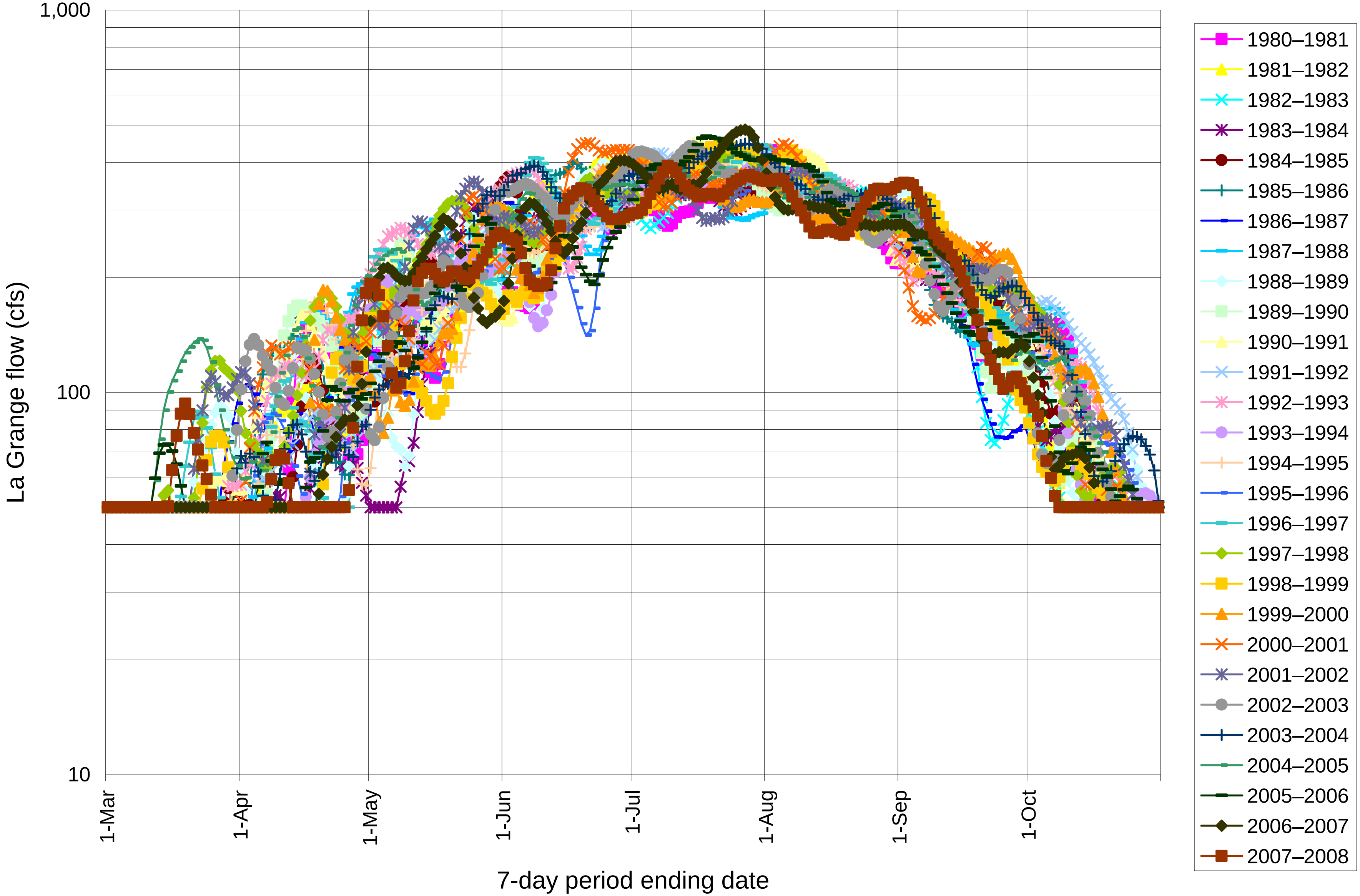

Figure 9. Simulation of flows required to maintain a summer MWAT of 18ºC (64.4ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5), for the period of record 1980-2007.

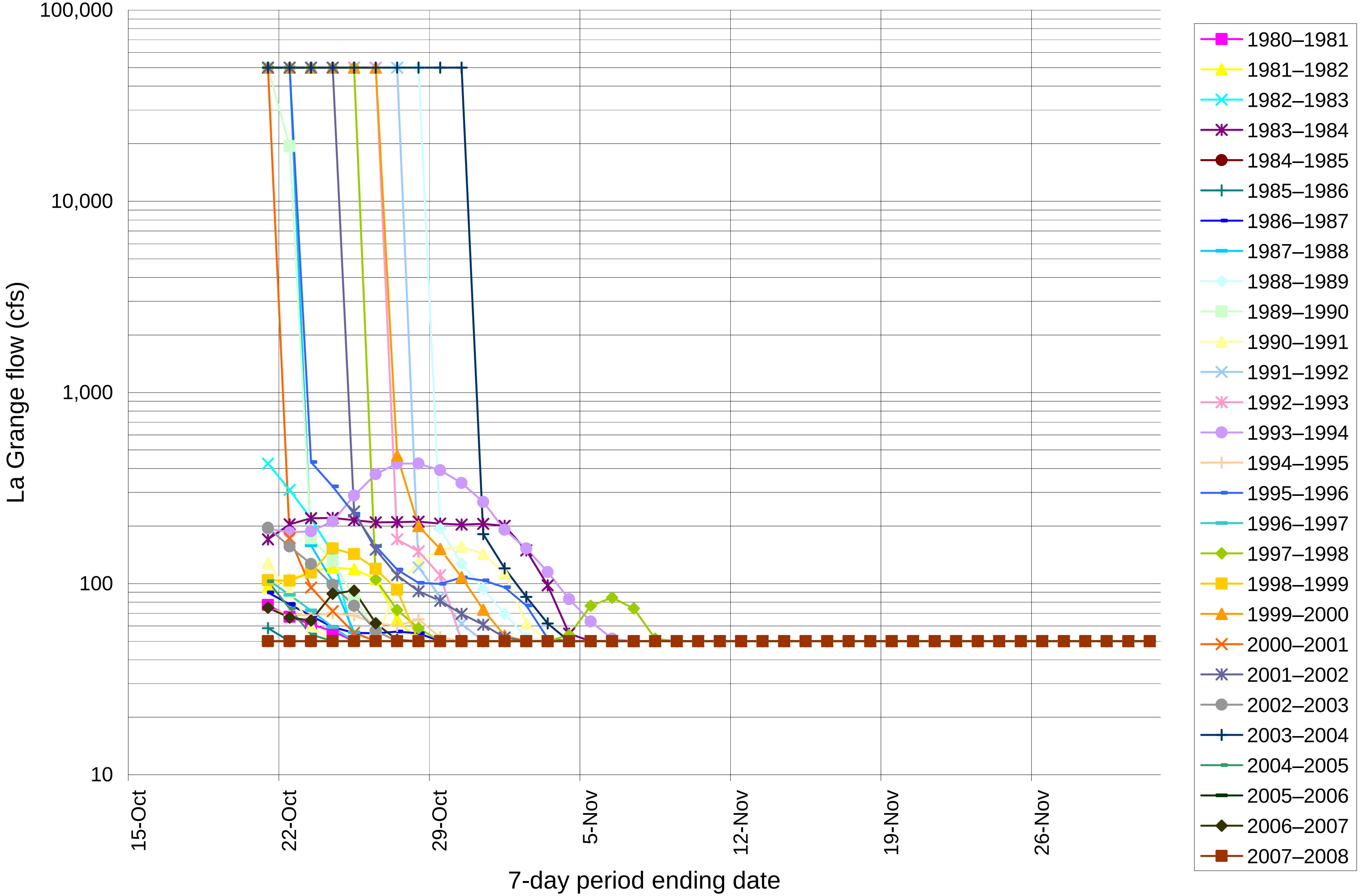

Figure 10. Simulation of flows required to maintain a fall MWAT of 18ºC (64.4ºF) downstream of La Grange Dam (RM 52) to the confluence with the San Joaquin River (RM 0) from October 15 to December 1, for the period of record 1980-2007.

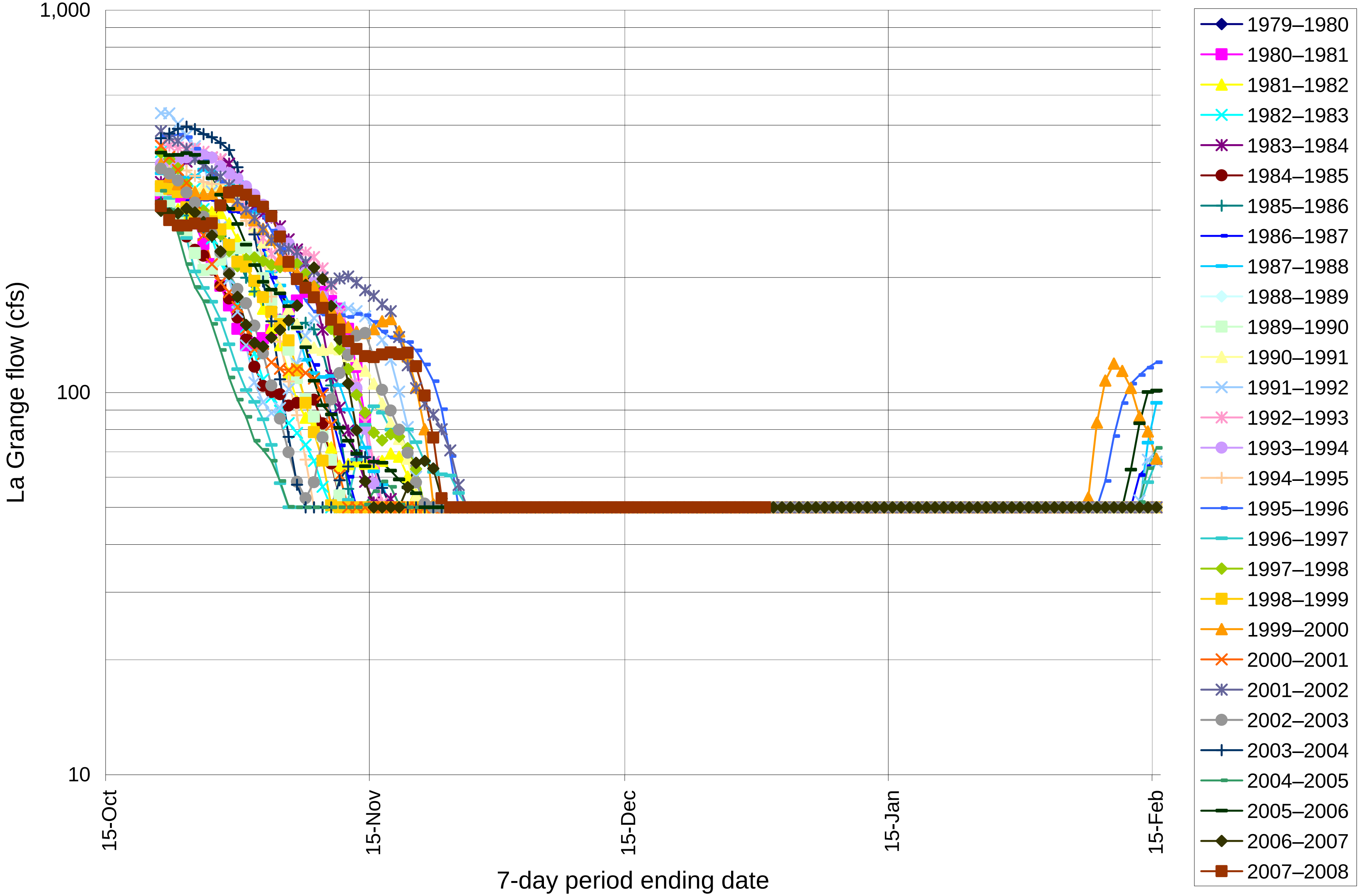

Figure 11. Simulation of flows required to maintain a fall/winter MWAT of 13ºC (55.4ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5) from October 15 to February 15, for the period of record 1980-2007.

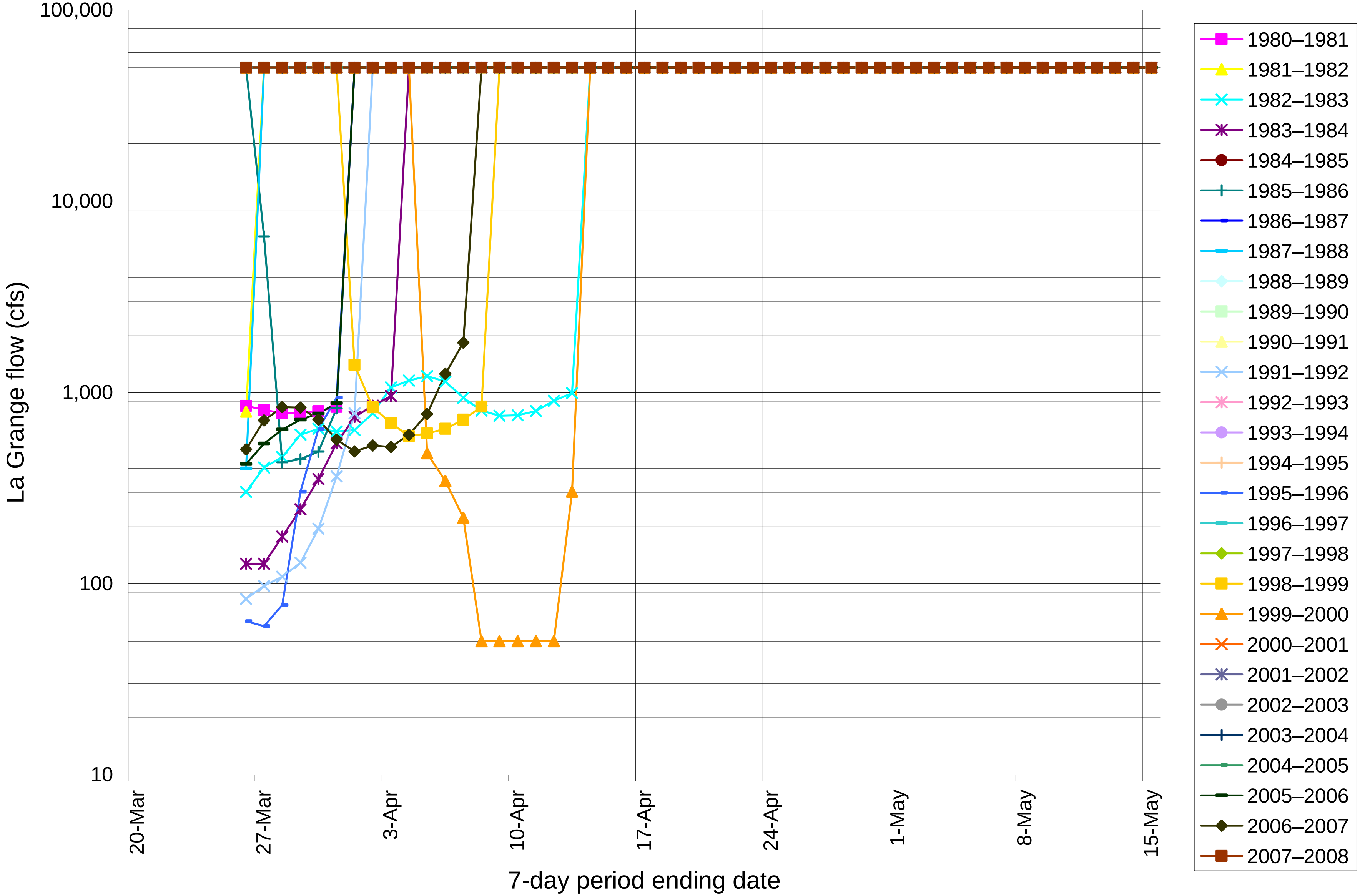

Figure 12. Simulation of flows required to maintain a spring MWAT of 15ºC (59ºF) downstream of La Grange Dam (RM 52) to the confluence with the San Joaquin River (RM 0) from March 20 to May 15, for the period of record 1980-2007.