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DEVELOPMENT AND APPLICATION OF A WATER TEMPERATURE MODEL FOR THE COLORADO RIVER BELOW GLEN CANYON DAM, ARIZONA

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ABSTRACT

Filling of Lake Powell upstream from Glen Canyon Dam during the 1970s transformed the seasonally warm Colorado River into a consistently cold river. The loss of seasonal variability in the downstream thermal regime has altered the biota of the river corridor, particularly native fishes and the aquatic food web. Predicting downstream water temperatures allows resource managers the ability to assess potential future influences of environmental and operational factors on downstream thermal environments. To support adaptive management below the dam, we developed an unsteady, one-dimensional water temperature model for the mainstem Colorado River ecosystem. Model development was achieved by linking existing unsteady-flow and constituent transport models. Model calibration and testing were accomplished using data from ongoing downstream temperature monitoring. The calibrated model was then used to evaluate downstream water temperature under a variety of fluctuating and steady flow regimes and across a range of annual release volumes and temperatures. Simulation results suggest that daily electricity load-following fluctuations (for the same volume) result in negligible differences in mainstem water temperature throughout the river corridor (avg. difference < 0.1 °C). However, dam release volumes associated with upstream reservoir storage do influence mainstem temperatures, with average temperature differences between low and high release volumes ranging from 0.5 °C to 2.6 °C moving downstream.

Key Words: Colorado River, Grand Canyon, water temperature, flow fluctuation, simulation modeling, adaptive management

INTRODUCTION

The condition of an aquatic ecosystem can be largely affected by water temperature; thus, water temperature is an important indicator of environmental quality (Gu and Li, 2002). Most biological processes and chemical reactions in a water body are influenced by temperature (Thomann and Mueller, 1987). In the Colorado River ecosystem (CRE), the evolution, distribution, and ecology of aquatic organisms and fish communities are fundamentally affected by water temperature. Native fish species, including the humpback chub (*Gila Cypha*), evolved in a seasonally warm and turbid riverine environment (Gloss and Coggins, 2005). The thermal regime of that environment has been altered significantly by the closure of Glen Canyon Dam (GCD).

Background

Closure of GCD in 1963 has resulted in significant changes to the physical processes and environments of the Colorado River downstream from the dam (see figure 1). Flow regulation by the dam raised annual minimum flows, reduced annual peak flows, and increased daily flow fluctuations in response to hydropower demand (Topping and others, 2003). Essentially, dam operations have transformed the Colorado River from a river with a seasonally variable hydrograph to a river with substantial daily variability but much less seasonal variability. The construction and operation of the dam has also affected the geomorphic characteristics of the Grand Canyon by trapping the upstream sediment load in the reservoir upstream of GCD (Lake Powell). Sediment entrapment in Lake Powell has led to the erosion and redistribution of downstream sand bars and other fine-grained deposits that have intrinsic biological, recreational, and cultural value (Topping and others, 2000; Rubin and others, 2002; Wright and others, 2005). Because a substantial portion of the sediment load of the Colorado River, including fine-grained silts, clays and organic matter, is deposited in the upper reaches of Lake Powell, water released from GCD is essentially clear and typically much less turbid than in pre-dam times.

Prior to flow regulation by the dam, mean daily water temperature at Lees Ferry, approximately 24 kilometers (15 miles) downstream, was 14 °C, ranging from 0 °C to 27 °C. From 1973-2003, GCD release temperatures averaged 9.3 °C, with fluctuations between 7 °C and 12 °C (Vernieu and others, 2005). Between 2003 and 2005, release temperatures warmed considerably as a result of a substantial water level drop in Lake Powell due to prolonged drought conditions in the Southwest U.S., with a maximum release temperature of 16.3 °C in October of 2005. Despite this recent warming trend, the thermal regime of the Colorado River below GCD remains markedly different from pre-dam patterns, most notably the consistent, cold dam releases and the highly reduced seasonal variability downstream.

The altered thermal regime in concert with modified flows, reduced organic inputs and decreased turbidity has affected the aquatic food web (Blinn and others, 1995; Shannon and others, 2001; Kennedy and Gloss, 2005), the native and non-native fish communities (Gloss and Coggins, 2005), and the terrestrial vegetation composition (Ralston, 2005). The operation of GCD has also affected cultural and recreational resources within the river corridor (Fairley, 2005; Kaplinski and others, 2005). In response to these impacts, various actions have been discussed within the Glen Canyon Dam Adaptive Management Program (GCDAMP) to alter water temperature conditions downstream. These actions include the alteration of dam operations, such as reduced summer flow volumes to promote downstream warming (Trammel and others, 2002) and dam modification, such as the construction of a selective withdrawal structure at the dam (Garrett and others, 2003).

Purpose and Scope

The purpose of this study was to develop a numerical model for the 386-kilometer (240-mile) mainstem reach of the Colorado River through the Grand Canyon that can accurately simulate mainstem river hydrodynamics and temperature, and to apply this model to 1) predict changes in water temperature that could result from proposed changes to dam operations or structural modifications to the dam, and (2) improve our current understanding of the complex physical processes controlling downstream thermal dynamics. This report addresses these goals by documenting the development, calibration, testing, and application of a one-dimensional water temperature model for the mainstem. The results presented herein are not directly transferable to nearshore environments in Grand Canyon, which may be important rearing habitat for juvenile native fishes. These environments may behave quite differently from the mainstem, particularly with respect to daily fluctuating flows. Modeling temperature dynamics in these nearshore environments is the subject of ongoing and future work, for which the one-dimensional mainstem model described here will provide important boundary conditions.

Model calibration was focused on calendar year (CY) 2000, and the calibrated model was then tested using data from CY 2005 (figure 2). CY 2000 was characterized by below-normal inflows into Lake Powell and slightly warmer than average air temperatures at Page, AZ and Lake Mead, NV. This time period also encompassed a wide range of discharge patterns, including steady releases of 226 cubic meters per second (cms) during the Low Summer Steady-Flow (LSSF) experiment and peak discharges above 850 cms, as well as elevated downstream temperatures during the summer months associated with the LSSF. CY 2005 was characterized by near-normal inflows into Lake Powell and slightly warmer than average air temperature in Page, AZ and Lake Mead, NV. This year had the highest GCD release temperatures ever recorded (16.3 °C) since monitoring began in 1988, as well as a wide range of discharge patterns including alternating two-week blocks of steady and fluctuating flows during the fall months.

METHODS

Model Description

The Colorado River mainstem thermal model was constructed by linking previously developed hydrodynamic and solute transport models. The model employs the unsteady-flow model (UNSTEADY) of Wiele and Smith (1996) and Wiele and Griffin (1997) to simulate mainstem hydrodynamics, and the hydrodynamic results (i.e. velocity, cross-sectional area, top width) are in turn used as inputs to drive water temperature simulations using the enhanced Branched Lagrangian Transport Model (BLTM) of Jobson and Schoellhamer (1993) and Jobson (1997). The UNSTEADY model is a reach-averaged, diffusion wave model of diurnal discharge wave propagation developed specifically for the Colorado River through the Grand Canyon and has been successfully utilized in a number of research applications within the Grand Canyon. The data used in the formulation of the UNSTEADY model include over 200 measured channel cross-sections developed by Wilson (1986), reach-averaged velocities taken from dye-tracing studies conducted by Graf (1995), channel slope, and stage measurements at permanent and temporary streamflow gaging stations within the Grand Canyon.

The BLTM model is capable of simulating the fate and transport of conservative and non-conservative water quality constituents in branched river systems, tidal canal systems, and deltaic channels and has found widespread use within the U.S. Geological Survey (USGS) over the past 15 years (e.g. Jobson, 1985; Graf, 1995; Ishii and Turner, 1996; Conrads and Smith, 1997; Feaster and others, 2003). The BLTM solves the one-dimensional, advective dispersion equation by using a Lagrangian reference frame in which the computational nodes move with the flow. The transport equation is solved for each of the constituents included in the simulations.

The BLTM uses an equilibrium temperature algorithm to simulate water temperature rather than requiring all of the meteorological parameters (air temperature, relative humidity, solar radiation, cloud cover, etc.) necessary to compute the surface heat exchange between the water and the atmosphere. The equilibrium temperature is defined as the water temperature at which there is no heat exchange across the water surface (Thomann and Mueller, 1987). Conceptually, a parcel of water has the potential to reach an equilibrium temperature when all meteorological conditions are held constant and the parcel will approach a water temperature representative of the ambient meteorological conditions (Jobson, 1980). The equilibrium temperature algorithm implemented by Jobson (1997) assumes that the equilibrium temperature of the air and the water are identical and that the air temperature varies as a sine function between the daily extremes. Given these assumptions, the time variation of the equilibrium temperature is computed in BLTM as:

$$T_e = T_a + \frac{K_a(T_h - T_l)}{2m_a(t_s - t_f)} * \cos(t + \theta) \tag{1}$$

where T_a is the air temperature, K_a is the heat exchange coefficient for the atmosphere, m_a is the mass per unit area of the atmosphere, T_h is the high air temperature extreme, T_l is the low air temperature extreme, t_f is the time of the first temperature extreme, t_s is the time of the second temperature extreme, t is the time, and θ is the phase angle ($3\pi/2$ if the first extreme is the minimum, and $\pi/2$ if the first extreme is the maximum temperature). Though we considered adding more rigorous water surface energy balance equations to BLTM, the results obtained during calibration and testing (described below) did not justify this additional effort.

Data Requirements

The boundary conditions for the flow and transport model include time series of discharge and water temperature at GCD. Hourly measurements of discharge from GCD were taken from records compiled by the Western Area Power Administration (http://www.wapa.gov/crsp/operatns/gcSCADAdata.htm) and used as inputs to the UNSTEADY flow model (see figure 2a). Hourly GCD release temperature records (figure 2b) were compiled from published records of water temperatures downstream from Glen Canyon Dam (Voichick and Wright, 2007). The meteorological data (air temperature and wind speed) used in this study were from the Page, AZ cooperative station (Station ID: 026180), obtained from the National Climatic Data Center, and from the Sentinel Island, Lake Mead meteorological station operated by the USGS Nevada Water Science Center (see figure 2c). Longitudinal dispersion factors were taken from dye-tracer studies conducted by Graf (1995).

MODEL CALIBRATION AND TESTING

The model was first calibrated for CY 2000 and tested for CY 2005 using only Page, AZ meteorological data and hourly water temperature data collected at six stations, ranging from Lees Ferry, defined as river kilometer (RK) 0, to the Diamond Creek confluence 364 kilometers downstream (water temperature monitoring sites described in Voichick and Wright, 2007). Water temperatures were calibrated by first systematically adjusting the free convection and mass transfer parameters within BLTM's wind function, derived by Jobson (1980), to minimize the mean absolute errors (MAE) of the estimates. The MAE is calculated as:

$$MAE = \frac{\sum|y - x|}{n} \tag{2}$$

where y is the modeled value, x is the observed value and n is the number of observations. BLTM's empirical wind function takes the form:

$$\psi = 3.01 + 1.13V \tag{3}$$

where Ψ is the wind function that gives evaporation in millimeters per day and V is the wind speed in meters per second. Ultimately, a free convection coefficient of 1.3 and a mass transfer coefficient of 1.13 yielded the best fit of the estimates to the observed water temperature data. Using these parameters, simulated water temperatures at six river locations showed similar trends in prediction errors using the calculated equilibrium temperatures, with underestimates (too cold) during the winter months and overestimates (too warm) during the summer months. The model calibration was further refined by adjusting the calculated equilibrium temperatures using the average date of estimated and observed water temperature convergence for all six locations. Calculated equilibrium temperatures for the winter time period were increased by 20% and decreased by 3% for the summer time period. The model was then tested for CY 2005 without further adjustment of the calibration parameters.

Summary statistics of model performance for both time periods at six river locations are presented in table 1. Results for RK 98 and RK 364 are also presented as annual time-series plots in figure 3. Measured and simulated water temperatures showed similar trends during CY 2000 and CY 2005. For the calibration period, MAEs ranged from 0.25 °C at RK 0 to 1.16 °C at RK 364 and maximum absolute errors ranging from 1.3 °C to 2.1 °C (table 1). The model slightly underestimated the daily variability in water temperatures at the four upstream locations (down to RK 140 – Phantom Ranch) and slightly overestimated the daily variability at the two locations downstream from RK140; in both cases, however, the MAEs in daily variability were less than 0.3 °C. For the testing time period, MAEs ranged from 0.21 °C to 0.70 °C and maximum absolute errors ranged from 0.8 °C to 2.3 °C (table 1). The MAEs for the calibration and testing time periods are comparable to each other and typically fall well below 1 °C, indicating that the model is relatively robust and that, in general, the model is capable of accurately simulating the temperature dynamics of the system.

One important trend common to both the calibration and testing datasets is increasing error with increasing distance downstream from GCD. Though one would expect model performance to deteriorate as the distance from boundary conditions increases, we hypothesized that a substantial portion of this error might be attributable to the representativeness of the Page, AZ meteorological data used as input into the model. Model simulations were conducted for both the calibration and testing periods incorporating Lake Mead meteorological data into the boundary conditions. This was accomplished by averaging hourly air temperatures and daily wind speeds from both meteorological stations to calculate a single time series of equilibrium temperatures used as input into the model. As expected, model performance improved slightly at the two monitoring locations in the western canyon but declined in the eastern canyon (see figure 1). The overall model performance did not improve enough to justify the additional complexity associated with the inclusion of the Lake Mead meteorological data stream. The current version of the model is not capable of handling multiple meteorological inputs. Future work may include the development of a routine to include variable meteorological inputs for different spatial locations within the study region.

MODEL APPLICATION

The model described above was previously used to evaluate the estimated effects of four long-term, experimental options for dam operations on the thermal regime below GCD in support of the GCDAMP (Grand Canyon Monitoring and Research Center, 2006). The options contained revised operating criteria for GCD and highly variable flow releases including variable release volumes, periods of steady and fluctuating flows, and variable ramping rates. Model results indicated that only small differences in daily mean mainstem water temperatures were expected to result from differences in flow releases; on average, the differences between options with similar total release volumes and without a selective withdrawal device were within the uncertainty of the model calculations (< 1 °C). On the other hand, simulation results indicated that differences in the total release volume and/or the use of a selective withdrawal structure can significantly affect downstream temperatures. These results prompted further modeling exercises that investigated how fluctuating and steady flows of identical release volumes impact mainstem thermal dynamics. The degree of daily electricity load-following in GCD releases and its effects on the downstream ecosystem are fundamental questions facing the GCDAMP because constraining daily fluctuations can have significant economic impacts.

The calibrated mainstem thermal model was used to simulate water temperatures for a 21-day period for 24 different scenarios. These scenarios simulated fluctuating versus steady flows of identical release volumes under three daily discharge ranges and four different release temperatures. Daily discharge ranges included (1) 141 -283 cms, (2) 141 – 425 cms, and (3) 141 – 566 cms. Release temperatures were 5 °C, 10 °C, 15 °C, and 20 °C. These daily flow regimes result in monthly flow volumes of 501,000 acre-feet, 611,000 acre-feet, and 830,000 acre-feet, respectively, and represent the range of release volumes encountered at GCD over the past several years (release volumes can be much larger during wet hydrologic conditions). Daily hydrographs for each range were taken from flows occurring within the last five years; steady-flow hydrographs were constructed using the mean daily discharge of each fluctuating regime repeated at an hourly time step. Similarly, the synthetic release temperatures (assumed constant in time for each simulation) bracket the mean annual release temperature, including lower and upper extremes that fall outside the range of historical dam releases but could potentially be met with the construction of a selective withdrawal structure. Equilibrium temperatures were estimated from the mean daily minimum and maximum air temperatures, times of those extremes, and mean daily wind speed for the Page, AZ weather station (Station ID: 026180) for the month of August, 1990-2005. All of the daily hydrographs, release temperatures and meteorological parameters were repeated daily for each 21-day simulation.

Model results were evaluated for the last 14 days of the simulation period in order to avoid the influences of the initial conditions. Summary statistics for simulated water temperatures at four mainstem sites with release temperatures of 5 °C, 20 °C, and the average of all four release temperatures are provided in table 2. Figure 4a shows simulation results for a 10 °C release temperature, where it is seen that there were very minor temperature differences between fluctuating and steady flows at all four sites, with mean differences below 0.1 °C at all sites and maximum differences ranging from 0.41 °C at RK 48 to 0.21 °C at RK 364. Similar differences were found for the remainder of the simulations with different release temperatures (see Table 2). Both the mean and maximum temperature differences for all sites decreased as release temperatures increased, with a mean difference of 0.10 °C and maximum difference of 0.31 °C for 5 °C releases and a mean difference of only 0.01 °C and a maximum difference of 0.13 °C for 20 °C releases. This is partially due to the larger difference between water temperatures and air temperatures at lower release temperatures, allowing for increased surface heat exchange and larger temperature gradients. The results also indicate that release volumes have a more substantial impact on mainstem temperatures than daily release patterns, with temperature differences between low and high volume releases ranging from 0.5 °C at RK 48 to 2.6 °C at RK 364. Figure 4b compares the differences between steady and fluctuating flows of the same volume with differences between low and high volume releases (501,000 and 830,000 acre-feet), illustrating the importance of release volume in comparison to daily flow variability.

This result is not particularly surprising when considered in the context of the dye-tracer studies of Graf (1995) who showed that steady and fluctuating flows of the same overall release volume result in nearly equivalent mean water velocities. Since mean water velocity is the primary driver of advective transport, large differences might not be expected for flows with similar values. However, fluctuating and steady flows also differ in the amount of surface area and volume available for surface heat exchange at a given location at a given time, such that simply assuming no change in temperature dynamics based on velocity alone would be tenuous. Also, dye studies were only conducted for a few different flows. In contrast, by holding the boundary conditions constant for each scenario and conducting many simulations, we were able to isolate the parameters of interest and develop a better understanding of the effects of flow the downstream thermal regime. Simulation capabilities that provide an improved understanding of the significant physical drivers in a complex system allow resource managers the ability to better assess potential future influences of environmental and operational factors on downstream thermal environments.

SUMMARY

We developed a one-dimensional model of water temperature along the mainstem Colorado River downstream from Glen Canyon Dam to the Diamond Creek confluence (RK 364). Data used in the calibration and testing included time-series of GCD discharge, GCD release temperatures, meteorological parameters from Page, AZ and Lake Mead, NV, water temperatures at 6 locations along the Colorado River corridor, and longitudinal dispersion factors from Graf (1995). The model was calibrated by minimizing the MAEs through systematic adjustment of model parameters. The calibrated model was then tested with no parameter adjustment to ensure accurate model performance under conditions different from the calibration period.

The model simulated water temperatures on both hourly and seasonal time scales with an acceptable level of error. The MAE statistics were well below 1°C for the calibration and testing periods using only Page, AZ meteorological data for all locations except at RK 364 where the error terms were slightly greater than 1 °C. The incorporation of Lake Mead meteorology resulted in small improvements (0.1 – 0.3 °C) in model performance in the western canyon, but slightly increased the error terms ($\leq$ 0.15 °C) in the eastern canyon.

The mainstem temperature model was used to simulate downstream thermal characteristics under a variety of daily fluctuating and steady flow regimes and across a range of release volumes and temperatures. The mean and maximum temperature differences between daily fluctuating and steady flows of identical release volumes were both below 0.5 °C. In contrast, simulated temperature differences between released flow volumes ranged from 0.5 °C to 2.6 °C. These results indicate that daily flow regimes appear to have a minor impact on mainstem temperature patterns and that flow volumes play a more substantial role than daily flow regimes in determining water temperature patterns downstream. We fully acknowledge that the opposite may be true for nearshore environments, because these environments can become nearly hydraulically isolated from the mainstem during steady discharges. Temperature modeling in these nearshore environments is the subject of ongoing and future work.

This model is part of a 3-tiered modeling suite designed to provide resource managers with the ability to assess potential future influences of environmental and operational factors on downstream thermal environments. A simplified, semi-empirical, monthly time step model (tier 1) has also been developed for initial scoping of alternatives (Wright and others, in review). More rigorous investigation of alternatives could then be undertaken with the one-dimensional, process-based model of the mainstem as described in this paper (tier 2). Finally, development of a system-wide nearshore water temperature model (tier 3) is ongoing and will be dynamically linked to the one-dimensional mainstem model to characterize low-velocity thermal environments, particularly backwaters, which may serve as essential rearing environments for juvenile fish.

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River Kilometer	Mean Absolute Error (°C)	Minimum Absolute Error (°C)	Maximum Absolute Error (°C)	Standard Deviation of the Absolute Error (°C)
		January 1, 2000 – December 31, 2000		
0	0.25	0.00	1.20	0.19
48	0.25	0.00	1.25	0.21
98	0.38	0.00	1.71	0.31
140	0.60	0.00	2.07	0.41
267	0.84	0.00	2.65	0.53
364	1.13	0.00	2.93	0.69
		January 1, 2005 – December 31, 2005		
0	0.21	0.00	1.21	0.16
48	0.34	0.00	2.07	0.28
98	0.41	0.00	1.98	0.34
140	0.46	0.00	2.00	0.35
267	0.59	0.00	1.91	0.42
364	0.70	0.00	2.11	0.49

TABLE 1. Summary goodness-of-fit statistics for simulated water temperatures at six mainstem sites below GCD ranging from Lees Ferry at RK 0 to Diamond Creek at RK 364, during calendar years 2000 (calibration) and 2005 (testing).

Daily Flow Range		River Km 48	River Km 98	River Km 204	River Km 364
		5 °C release			
141-283 cms	Mean difference (°C)	0.04	0.01	0.05	0.04
	Max	0.24	0.18	0.11	0.18
141-425 cms	Mean	0.02	0.15	0.15	0.09
	Max	0.38	0.45	0.47	0.28
141-566 cms	Mean	0.07	0.10	0.15	0.17
	Max	0.48	0.24	0.42	0.36
		20 °C release			
141-283 cms	Mean difference (°C)	0.01	0.01	0.01	0.04
	Max	0.13	0.06	0.07	0.05
141-425 cms	Mean	-0.01	0.05	0.01	0.05
	Max	0.23	0.11	0.13	0.06
141-566 cms	Mean	-0.01	0.04	0.03	0.10
	Max	0.3	0.16	0.16	0.10
		All releases (5, 10, 15, and 20 °C)			
141-283 cms	Mean difference (°C)	0.03	0.01	0.02	0.01
	Max	0.18	0.12	0.15	0.12
141-425 cms	Mean	0.01	0.01	0.07	0.04
	Max	0.31	0.28	0.30	0.17
141-566 cms	Mean	0.03	0.07	0.09	0.11
	Max	0.39	0.21	0.30	0.23

TABLE 2. Summary statistics for simulated water temperatures at four mainstem sites with release temperatures of 5 °C, 20 °C, and the average for all four release temperatures. Values for each daily flow range are the mean and maximum temperature differences (fluctuating minus steady) between fluctuating and steady flows in degrees Celsius and cms = cubic meters per second.

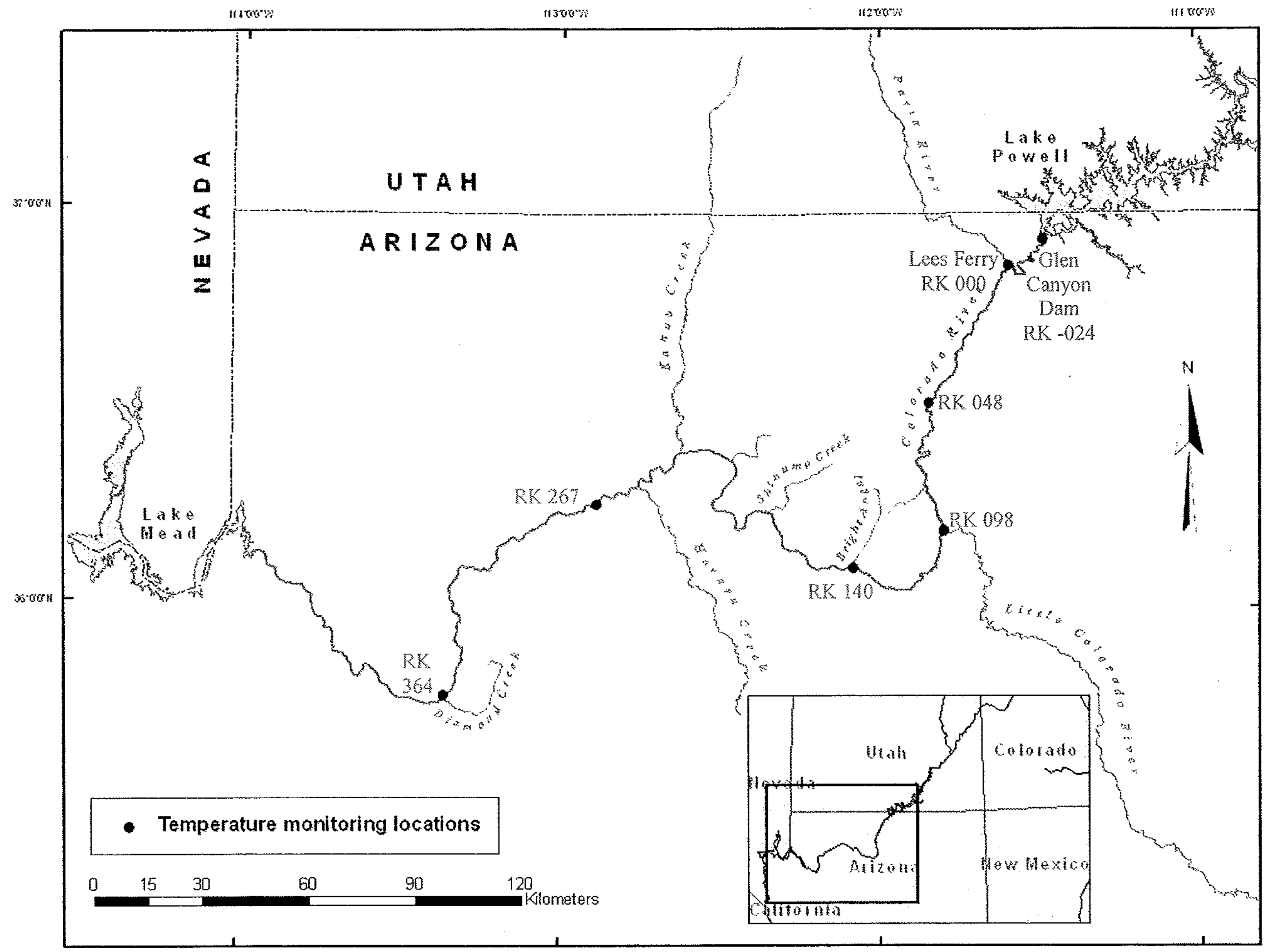

FIGURE 1. Map of the Colorado River and its tributaries between Lake Powell and Lake Mead, showing water temperature monitoring locations used in this study (RK = river kilometer).

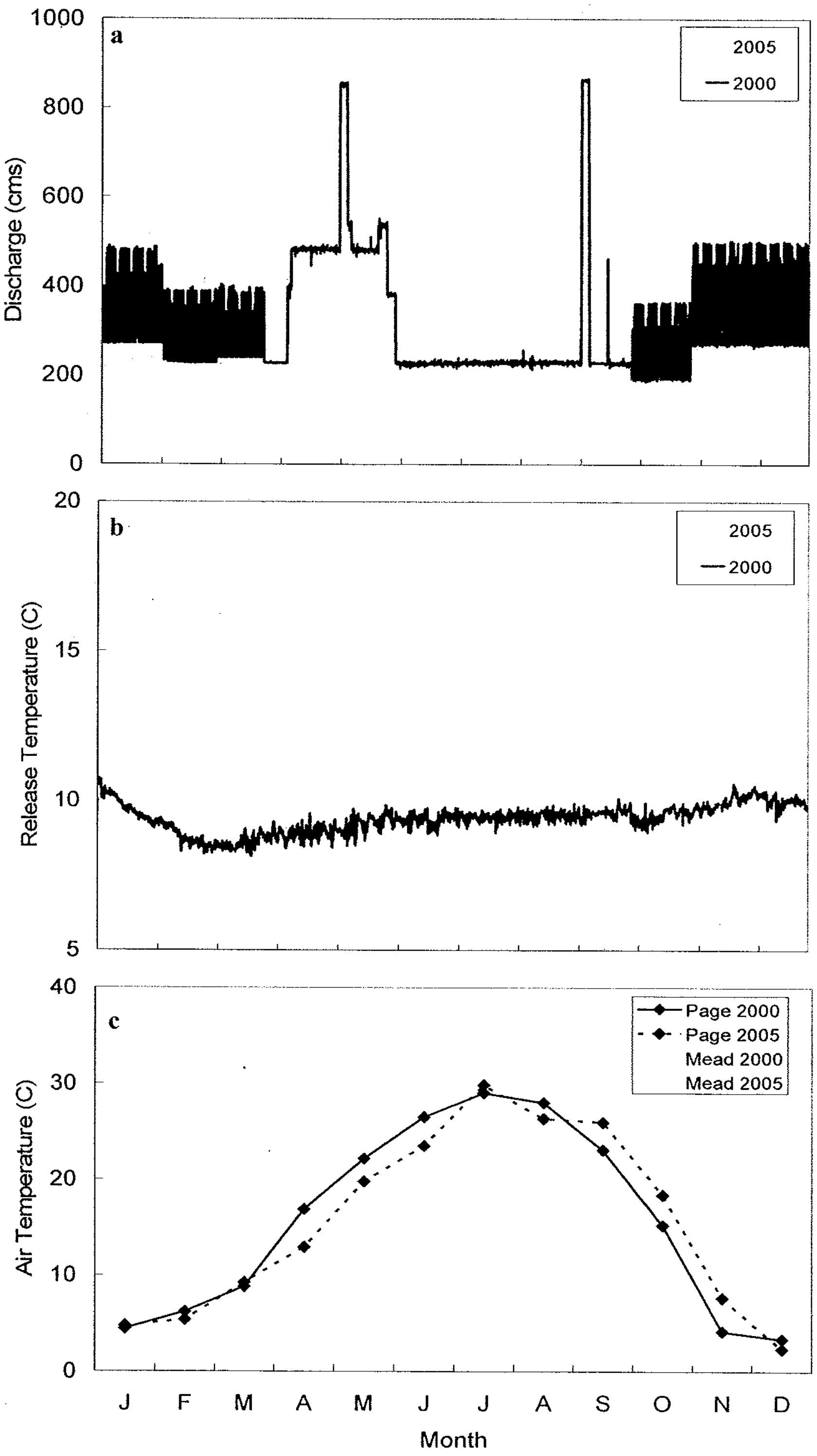

FIGURE 2. (a) Glen Canyon Dam hourly discharge and (b) release temperatures, and (c) monthly average air temperatures at Page, AZ and Lake Mead, NV for 2000 and 2005.

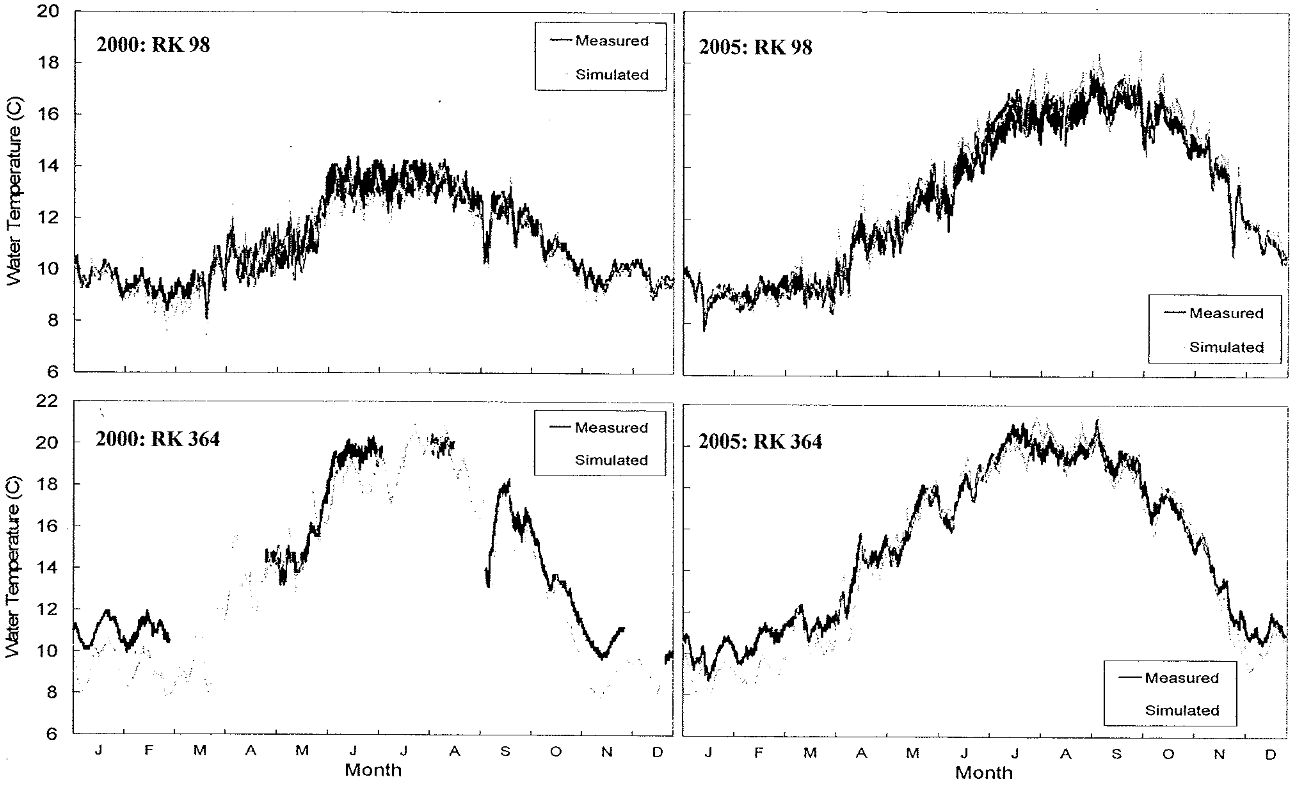

FIGURE 3. Measured and simulated water temperatures for the years 2000 and 2005 for two river locations, RK 98 (top) and RK 364 (bottom).

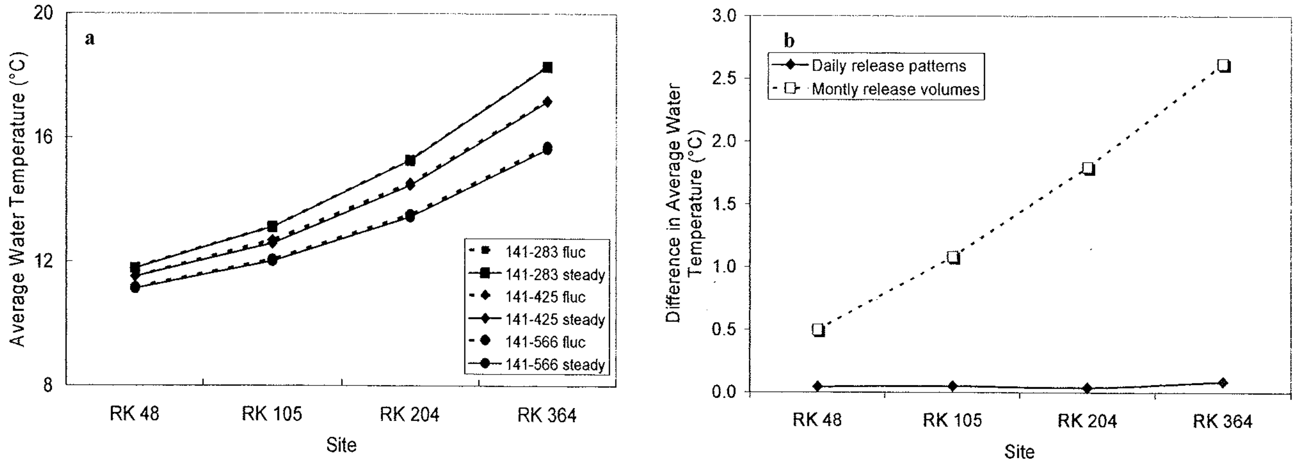

FIGURE 4. Mean simulated water temperatures at four sites (a) for daily discharge ranges of 141 - 283 cms, 141 - 425 cms, and 141 - 566 cms and a 10 °C release temperature. Solid lines represent steady flows, and dashed lines represent fluctuating flows. Panel b shows the mean simulated temperature differences between fluctuating and steady flows for the 141 – 566 cms daily discharge range (solid line) and the mean simulated temperature differences between low monthly release volumes (501,000 acre-feet) and high monthly release volumes (830,000 acre-feet) represented by the dashed line.