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A SIMPLIFIED WATER TEMPERATURE MODEL FOR THE COLORADO RIVER BELOW GLEN CANYON DAM†

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ABSTRACT

Glen Canyon Dam, located on the Colorado River in northern Arizona, has affected the physical, biological and cultural resources of the river downstream in Grand Canyon. One of the impacts to the downstream physical environment that has important implications for the aquatic ecosystem is the transformation of the thermal regime from highly variable seasonally to relatively constant year-round, owing to hypolimnetic releases from the upstream reservoir, Lake Powell. Because of the perceived impacts on the downstream aquatic ecosystem and native fish communities, the Glen Canyon Dam Adaptive Management Program has considered modifications to flow releases and release temperatures designed to increase downstream temperatures. Here, we present a new model of monthly average water temperatures below Glen Canyon Dam designed for first-order, relatively simple evaluation of various alternative dam operations. The model is based on a simplified heat-exchange equation, and model parameters are estimated empirically. The model predicts monthly average temperatures at locations up to 421 km downstream from the dam with average absolute errors less than 0.5°C for the dataset considered. The modelling approach used here may also prove useful for other systems, particularly below large dams where release temperatures are substantially out of equilibrium with meteorological conditions. We also present some examples of how the model can be used to evaluate scenarios for the operation of Glen Canyon Dam. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS: water temperature; modelling; Colorado River; Glen Canyon Dam

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INTRODUCTION

Closure of Glen Canyon Dam on the Colorado River in 1963 resulted in significant changes to downstream physical processes and environments in Grand Canyon, which have in turn affected biological and socio-cultural resources. Glen Canyon Dam has dramatically changed the flow regime of the Colorado River through Grand Canyon, transforming it from seasonally variable to highly variable on a daily basis (to satisfy electricity demand) with much less seasonal variability (Topping *et al*., 2003). The geomorphology of Grand Canyon has also been affected because the upstream sand load is now trapped in Lake Powell, the reservoir behind the dam, leading to erosion and redistribution of sandy deposits that have biological, recreational and cultural value (Rubin *et al*., 2002, Schmidt *et al*., 2004, Wright *et al*., 2005). Lake Powell also traps fine sediment that once kept the river turbid for most of the year. In contrast, the post-dam river runs clear for most of the year when tributaries are not flooding. Finally, hypolimnetic releases from the dam have resulted in a much less variable thermal regime, with water temperature significantly colder than pre-dam temperatures in the summer and warmer in the winter (Vernieu *et al*., 2005). The combination of altered flows, reduced allochthonous organic inputs, decreased turbidity and an altered thermal regime has led to a shift in the aquatic food web (Kennedy and Gloss, 2005). This, combined with the introduction of non-native fishes, has resulted in changes to the native fish community (Gloss and Coggins, 2005). Because of these impacts, dam operations have been modified in order to improve water temperature conditions downstream, for example by reducing flow volumes in the summer to promote downstream warming (Trammell *et al*., 2002). Also, construction of a selective withdrawal structure on the dam has been considered (Garrett, 2003).

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In this paper, we present a new model for estimating monthly average water temperatures along the mainstem of the Colorado River from Glen Canyon Dam to Spencer Canyon, approximately 421 km downstream (Figure 1). We use a relatively simple approach that estimates monthly average water temperature downstream of the dam based on monthly average release temperature, air temperature and flow volume. Model calibration and validation was carried out using water temperature data collected at several monitoring sites throughout the reach starting in 1988 (Voichick and Wright, 2007). Estimating monthly average temperatures is particularly suited to the Colorado River below Glen Canyon Dam because flow releases are scheduled on a monthly basis and are thus nearly constant for a given month. The goal of this work was to develop a simple model that can be used for initial investigation of alternative dam operations and/or structural modifications, which could then be further explored with a more standard unsteady state water temperature model (e.g. Anderson and Wright, 2007). To this end, we also present examples of using the model for these purposes.

METHODS

Background

Water released from Glen Canyon Dam typically comes from the hypolimnion of Lake Powell, resulting in significantly less seasonal variation in water temperature downstream, as compared to pre-dam conditions. Daily water temperature records from the Colorado River at Lees Ferry gage (USGS 09380000) beginning in 1948 show that pre-dam temperatures typically ranged from 0 degrees Celsius (°C) in the winter to 25–30°C in the summer; post-dam, temperatures have typically ranged from 8 to 12°C, until recently when drought conditions in the southwestern US have led to reduced water levels in Lake Powell and increased release temperatures (Figure 2).

Because air temperatures are typically greater than dam release water temperatures, water released from the dam tends to warm downstream as it travels between Lake Powell and Lake Mead. Monthly average water temperatures

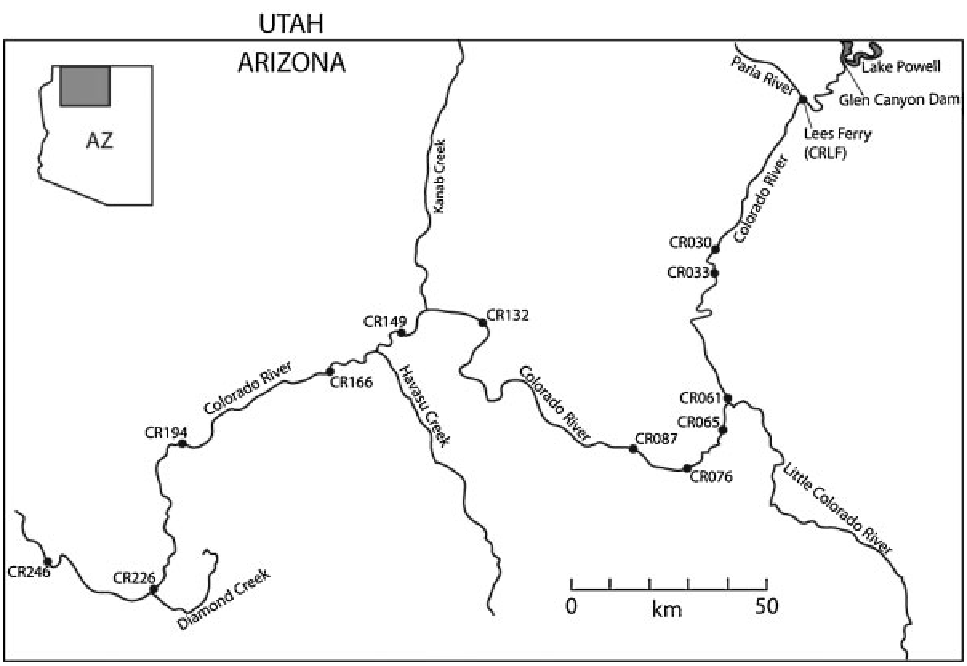

Figure 1. Map of the Colorado River below Glen Canyon Dam, northern Arizona, showing water temperature monitoring locations described in Voichick and Wright (2007). The naming convention is such that the number represents river miles downstream from Lees Ferry, which is about 15 river miles downstream from Glen Canyon Dam. Monitoring location CR246 is the downstream extent to which the model was applied

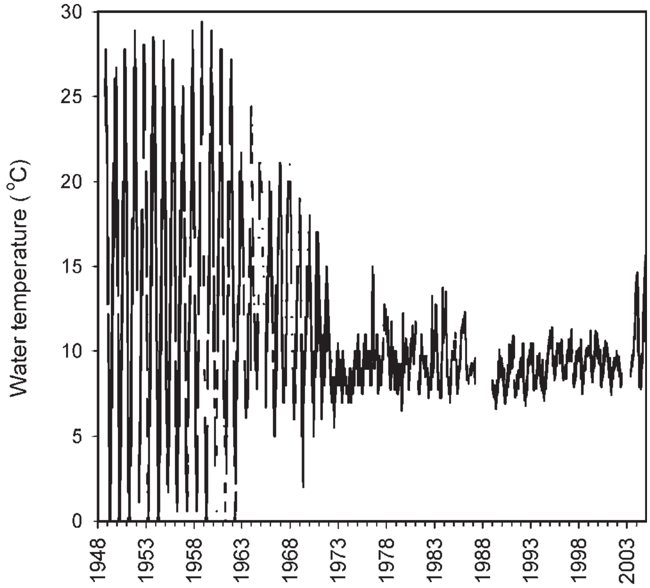

Figure 2. Daily water temperatures as measured at the Lees Ferry gaging station from 25 July 1949 through 30 September 2005. See Voichick and Wright (2007) for a detailed description of the data sources

for several months are shown in Figure 3(a), while Figure 3(b) shows the average downstream temperature gradient determined from the slope of a linear least-squares regression to the profile data in Figure 3(a) (only sites with periods of record greater than 10 years were used in this figure, see Voichick and Wright, 2007). These data indicate that summer months are characterized by significant downstream warming, winter months are characterized by small longitudinal temperature gradients (slight downstream cooling in December) and that average longitudinal temperature gradients may be reasonably approximated as constant.

Previous efforts to model water temperatures downstream from Glen Canyon Dam include Ferrari (1987) and Walters *et al.* (2000). Ferrari (1987) employed two methods to assess the effects of raising Glen Canyon Dam release temperatures, a graphical technique and the USEPA Qual-II model, but did not have the extensive dataset now available for model calibration and validation. Walters *et al.* (2000) used a Lagrangian tracking method to estimate downstream monthly average water temperatures. The basis for this method derives from the advection–dispersion-heat balance equations after assuming steady state conditions, complete vertical and lateral mixing in river cross-sections, advection dominating over dispersion (longitudinal) and a simplified expression for surface heat exchange, as follows:

$$U\frac{\mathrm{d}T(x)}{\mathrm{d}x} = K[T_e - T(x)] \tag{1}$$

where U is mean velocity, x is longitudinal distance, $T(x)$ is the monthly average water temperature at location x (in subsequent equations the dependence on x is assumed such that $T(x)$ is represented as T), K is a bulk surface-heat exchange coefficient and T_e is the equilibrium temperature (see, e.g. Thomann and Mueller, 1987). We have ignored the effects of tributaries in the formulation of (1) because, for our study reach, their flow volumes are too small and sporadic to have a large influence on mainstem monthly average temperatures. The equilibrium temperature is the temperature that would be achieved over a reach of infinite length (if meteorological conditions are constant), and the bulk surface heat exchange coefficient controls the rate at which downstream temperature changes occur when temperatures are below equilibrium; in general, both are complex functions of meteorological conditions (Thomann and Mueller, 1987).

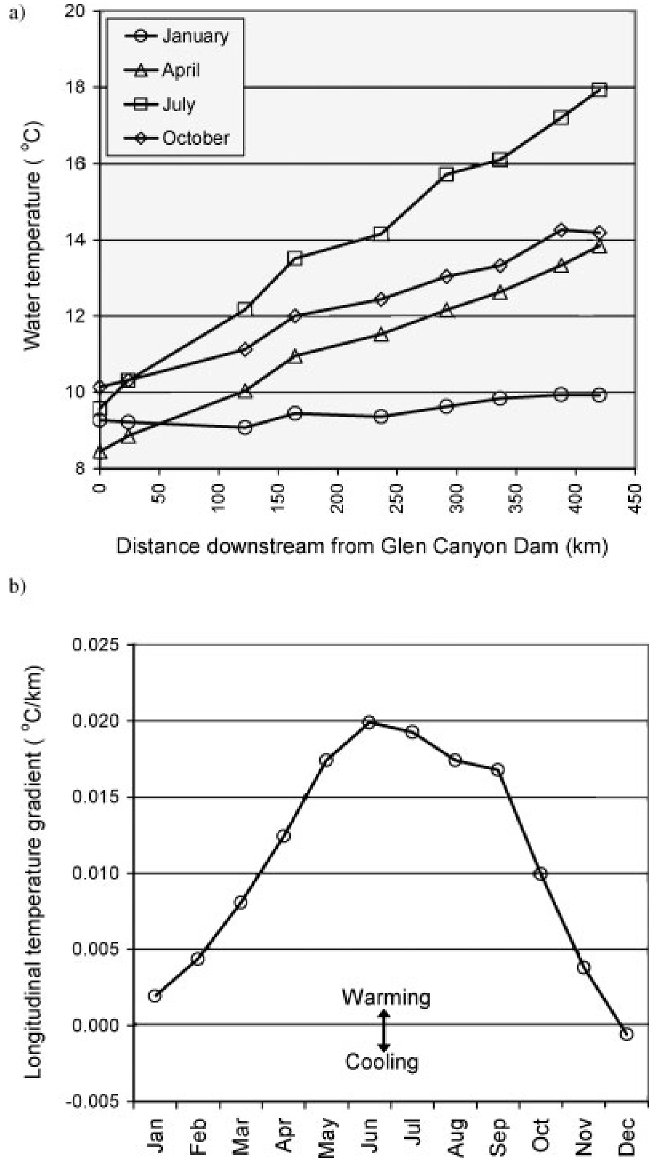

Figure 3. Monthly average water temperature longitudinal profiles for January, April, July and October (a), and longitudinal downstream temperature gradients for each month (b), based on sites with a 10-year or greater period of record. Refer to Voichick and Wright (2007) for exact period of record for each site. Temperature gradients were determined from linear least-squares regression to the profiles

Integrating Equation (1), under the constraint that U, K and T_e do not vary with x, and subject to the upstream temperature boundary condition yields

$$T = T_e + (T_o - T_e)\exp\left\{-\frac{K}{U}x\right\} \tag{2}$$

where T_o is the temperature at the upstream boundary (Glen Canyon Dam in this case). Though U, K and T_e likely vary substantially with x over short time scales, the analyses presented here support the assumption of constancy over monthly time scales. Walters *et al.* (2000) used this formulation along with monthly values for T_e and K

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determined by calibrating to observed water temperature data, but the methods and calibration are not described in detail and the complete, edited water temperature dataset has only recently been published and made available (Voichick and Wright, 2007).

Modelling approach

We follow a similar approach as Walters *et al.* (2000), but with one further key assumption that simplifies the determination of empirical coefficients considerably. The form of Equation (2) describes a longitudinal temperature profile that approaches the equilibrium temperature in an exponential manner; that is as the temperature approaches equilibrium, the rate of change decreases. Analyses of data downstream from Glen Canyon Dam, however, suggest that monthly average temperature gradients can be approximated as constant (see Figure 3(a)), particularly during summer months when warming is greatest. This suggests that, for the conditions measured in the post-dam era, flow volumes are large enough such that rapid adjustment to equilibrium does not occur. Rather, water temperatures tend to approach equilibrium gradually over a very long reach such that the temperature profiles are approximately linear over the ~400 km between Glen Canyon Dam and Lake Mead. Based on these observations, we propose a simplification to Equation (1) as follows:

$$U\frac{\mathrm{d}T}{\mathrm{d}x} = K[T_e - T_o] \tag{3}$$

$$T_e = T_{\mathrm{air}} + T_{\mathrm{shift}} \tag{4}$$

where T_{air} is the monthly average air temperature at Page, Arizona (NOAA/NWS Cooperative Observer Network Station ID 026180), and T_{shift} is an empirical temperature shift (assumed constant) that allows the temperature gradient to go to zero when the equilibrium temperature and release temperature are the same. That is, when $T_o = T_{\mathrm{air}} + T_{\mathrm{shift}}$ the system is at equilibrium and thus, on average, no net heat exchange occurs across the water surface (i.e. $\mathrm{d}T/\mathrm{d}x = 0$). Physically, the temperature shift accounts for the difference between the river's equilibrium water temperature, averaged over the entire reach and on a monthly basis, and the air temperature at the Page airport (the nearest meteorological station) which is located to the northeast of the reach at a higher elevation. Integration of Equation (3) and substation of Equation (4) yields

$$T = T_o + \frac{K}{U}x(T_{\mathrm{air}} + T_{\mathrm{shift}} - T_o) \tag{5}$$

The forms of Equations (3) and (5) describe a constant temperature gradient and linear downstream temperature profile controlled by the ratio *K*/*U* and the difference between the equilibrium temperature and release temperature. This formulation is quite simple and yet it preserves enough physics to capture the primary phenomena that have been observed, namely (1) increased downstream warming when discharges are low owing to increased water residence time, captured through U in the denominator of Equation (5) and (2) increased warming when air temperatures are most different from release temperatures, captured through $T_{\mathrm{air}} - T_o$ in the numerator of Equation (5). The primary advantage of this formulation is that it allows for simple, direct determination of the empirical coefficients, as described below in the model calibration section.

Model calibration

Model calibration entails estimation of two parameters in Equation (5), K and T_{shift}. Once these parameters are estimated, monthly average water temperature profiles can be computed for a given release temperature (T_o), air temperature (T_{air}) and mean velocity (U). Thus, calibration requires a dataset of release temperatures, air temperatures, mean velocity and water temperatures at various locations along the river reach, all as monthly average quantities. Traditional calibration would proceed by varying the empirical parameters within a physically realistic range and comparing modelled versus measured downstream temperatures and attempting to systematically minimize the error between the two. Our approach allows for this error minimization to be accomplished through simple linear least-squares regression, as follows. Because the longitudinal temperature gradients are assumed to be constant, the model parameters can be estimated directly using measured longitudinal

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temperature gradients. This can be seen by combining Equations (3) and (4) and re-arranging slightly

$$U\frac{\mathrm{d}T}{\mathrm{d}x} = K(T_{\mathrm{air}} - T_o) + KT_{\mathrm{shift}} \tag{6}$$

In this form, the slope of the linear regression between $U\mathrm{d}T/\mathrm{d}x$ and $(T_{\mathrm{air}} - T_o)$ is equal to K and the y-intercept is equal to KT_{shift} Thus, the slope and y-intercept of the regression yield the two model parameters.

The data required for the use of Equation (6) to estimate the model parameters are: (1) measured longitudinal temperature gradients, which require measured temperatures at several locations along the river, (2) flow velocities, (3) air temperatures and (4) release temperatures, all as monthly average values. We assembled calibration and validation datasets using water temperature data from Voichick and Wright (2007), air temperature data from NOAA/NWS COOP station 026180 at Page, AZ (http://www.wrcc.dri.edu/summary/climsmaz.html, accessed 10 April 2008), and reservoir water release data from the Bureau of Reclamation (http://www.usbr.gov/uc/crsp/getsiteinfo, accessed 10 April 2008). Monthly average water releases were converted to mean velocity using the relationship developed by Wiele and Smith (1996) and Wiele and Griffin (1997) for their unsteady flow model for this reach of the Colorado River, $U = 0.021Q^{0.63}$, where U is mean velocity in metres per second ($\mathrm{m\,s^{-1}}$) and Q is water discharge in cubic metres per second ($\mathrm{m^3\,s^{-1}}$).

We split the dataset into calibration and validation by selecting even numbered years for calibration and odd numbered years for validation. The water temperature dataset began in 1988 when temperature monitoring began at the site immediately below the dam. The number of sites steadily increased through time until 2005 when the number of sites was reduced to eight (Figure 4). For calibration (even numbered years), longitudinal temperature gradients were computed for months with at least five sites in operation, using least-squares linear regression. The result was 73 months with the necessary information for evaluating K and T_{shift} from Equation (6), that is 73 months with values for U, $\mathrm{d}T/\mathrm{d}x$, T_{air} and T_o. Figure 5 shows $U \times \mathrm{d}T/\mathrm{d}x$, versus $(T_{\mathrm{air}} - T_o)$ along with the least-squares linear regression line slope and y-intercept. The high R^2 value of the regression (0.97) supports the hypothesis that downstream temperature gradients are primarily controlled by the mean velocity and the difference between air temperature and release temperature. The slope of the regression line sets $K = 6.51 \times 10^{-7}\,\mathrm{s^{-1}}$ and the y-intercept divided by the slope sets $T_{\mathrm{shift}} = 7.91^{\circ}\mathrm{C}$.

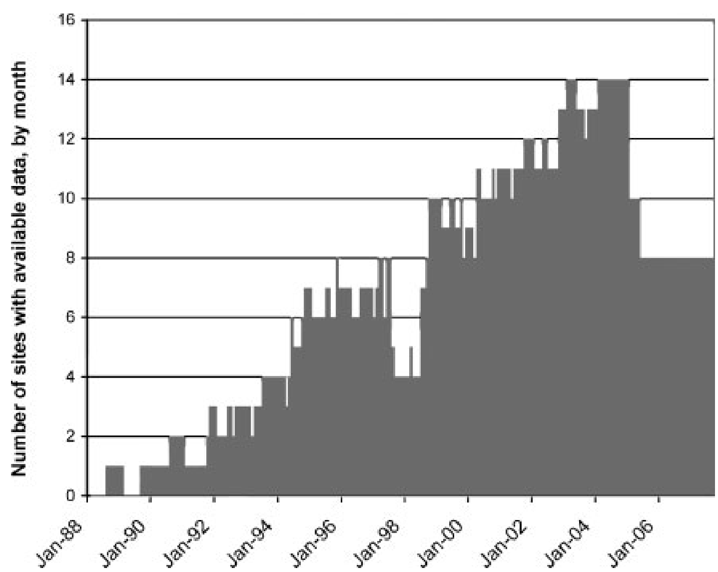

Figure 4. Number of sites with available water temperature data, by month, based on the Voichick and Wright (2007) dataset, including recent data from water years 2006 and 2007. Calibration was achieved using data from even-numbered years, with odd-numbered years reserved for model validation

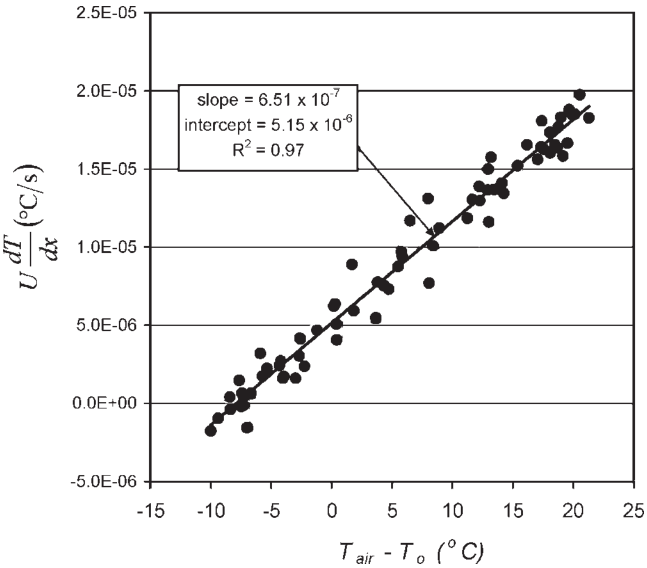

Figure 5. Linear least-squares regression around Equation (6) in order to calibrate the model empirical parameters, K and T_{shift}

RESULTS

Model validation

We reserved half of the water temperature dataset for validation of the model, using the calibrated parameters from the previous section. Insertion of these parameters and the relation between velocity and discharge into Equation (5) yields the final form of the model

$$T(x) = T_o + \frac{3.10 \times 10^{-5} x}{Q^{0.63}} (T_{\text{air}} + 7.91 - T_o) \tag{7}$$

where $T(x)$ is the water temperate at some distance x downstream from the dam (x in metres), T_o is the release water temperature, Q is the release water discharge (in $m^3 s^{-1}$) and T_{air} is air temperature at the Page weather station. All values are monthly averages and temperatures are in °C.

The validation dataset consisted of odd-numbered years from 1988 to 2007 (10 years). During this time period, there were as many as 14 sites in operation (Figure 4) at a given time (see Voichick and Wright, 2007, for periods of record for each site). The number of validation data points varies by site, since some sites have been in operation longer than others. Overall, there was a total of 690 validation data points, where each data point represents a monthly average water temperature at a given site, with a maximum of 94 points at the CRLF gage (Figure 1) and a minimum of 12 points at CR149.

Modelled temperatures were compared to the validation dataset by computing and analysing the residuals, that is the differences between the model and observations. We computed the signed errors, $\text{SE} = T_{\text{mod}} - T_{\text{obs}}$, and absolute errors, $\text{AE} = |T_{\text{mod}} - T_{\text{obs}}|$, where T_{obs} are the observed temperatures and T_{mod} are the modelled temperatures. The signed errors indicate whether or not there are any systematic positive or negative biases while the absolute errors provide an indication of the overall performance of the model.

Figure 6 shows the signed errors in a box-and-whisker plot for all measurement sites (whisker lengths are 1.5 times the interquartile range). The signed errors typically have medians close to zero (maximum of - 0.32°C at CR087), do not indicate any consistent positive or negative biases, and tend to increase downstream as expected since model errors should accumulate downstream. The longitudinal patterns that are apparent in Figure 6 could be the result of differential heating resulting from some reaches being wider than others (Schmidt and Graf, 1990) and/

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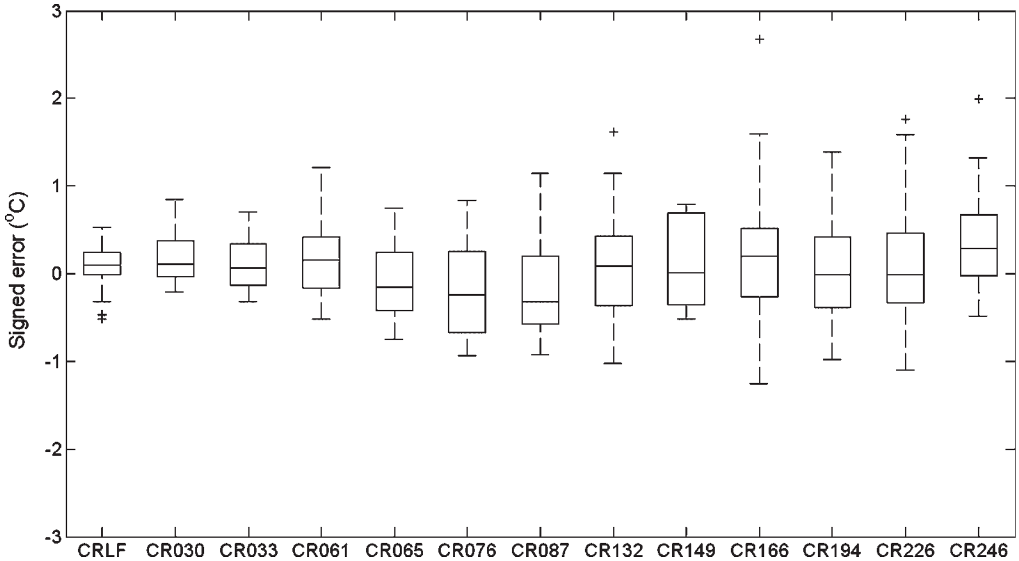

Figure 6. Differences between observed and modelled temperatures (signed errors) for each measurement site for the entire validation dataset

or variations in canyon orientation and exposure to sunlight (Yard *et al*., 2005). Overall, the signed errors suggest good agreement between the model and observations with maximum errors in the 2°C range.

The results of the absolute error analysis are shown in Table I which contains the mean and standard deviation of the absolute errors for each monitoring site. Table I also contains the number of observations available for each site within the validation dataset. As with the signed errors, the absolute errors tend to increase downstream, as expected. For all sites, the mean absolute errors (and standard deviations) are less than 0.5°C. The maximum errors tend to occur during fall low flow months, typically October–November, when the modelled temperatures tend to be greater than measured values at the most downstream sites. During these months, the rate of warming can be greater in the upper reaches than in the lower reaches (Figure 7); since the model assumes a constant rate of warming (or cooling) for the entire reach it cannot capture this effect. A more sophisticated model that accounts for longitudinal changes in heat flux would be required to capture these details, such as Anderson and Wright (2007).

Table I. Mean and standard deviation of absolute errors for each monitoring location for the validation dataset

Site identifier (see Figure 1)	Distance downstream from dam (km)	Mean AE (°C)	Standard deviation of AE (°C)	Number of observations
CRLF	25	0.17	0.14	94
CR030	74	0.24	0.22	32
CR033	79	0.25	0.19	29
CR061	124	0.33	0.25	93
CR065	130	0.39	0.23	32
CR076	148	0.47	0.27	39
CR087	165	0.45	0.26	77
CR132	238	0.46	0.33	61
CR149	265	0.41	0.29	12
CR166	293	0.49	0.43	63
CR194	338	0.43	0.34	50
CR226	389	0.46	0.38	71
CR246	421	0.49	0.46	37

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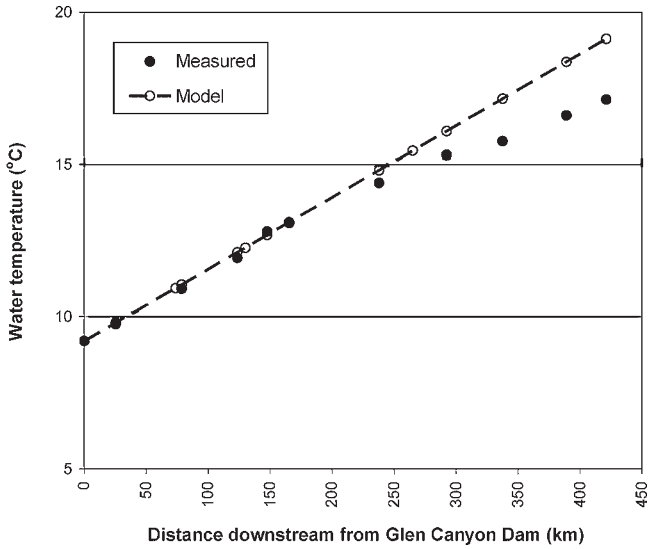

Figure 7. Measured and modelled temperatures for September 2001, illustrating a scenario resulting in the largest model errors in the lower reaches. The measured data indicate a decreased rate of warming in the lower reaches which cannot be captured by the model due to the assumption of a constant longitudinal temperature gradient

Example applications

The model, as presented in Equation (7), can be used to evaluate the interrelationships between the driving parameters, that is water discharge, air temperature and release temperature. To facilitate this type of use, Table II contains monthly average air temperatures from the Page, AZ NOAA/NWS COOP station (026180) for the period 1958–2007. As an example of how the model may be used, we developed contour plots of water temperature at two locations downstream from Glen Canyon Dam for a range of water discharge and a range of release temperatures (Figure 8). These two parameters were varied because they could potentially be manipulated through operation and/or modification of the dam, whereas air temperatures could not. Contour plots were developed for two locations: (1) at the mouth of the Little Colorado River approximately 125 km downstream from the dam (CR061 in Figure 1), and (2) 390 km downstream from the dam (CR226 in Figure 1). The calculations were made for typical historical

Table II. Monthly average air temperature at NOAA/NWS COOP station 026180 at Page, AZ for 1958 through 2007

Month	Air temperature (°C)
January	1.4
February	4.9
March	9.2
April	13.9
May	19.4
June	25.2
July	28.4
August	26.9
September	22.1
October	15.1
November	7.3
December	1.8

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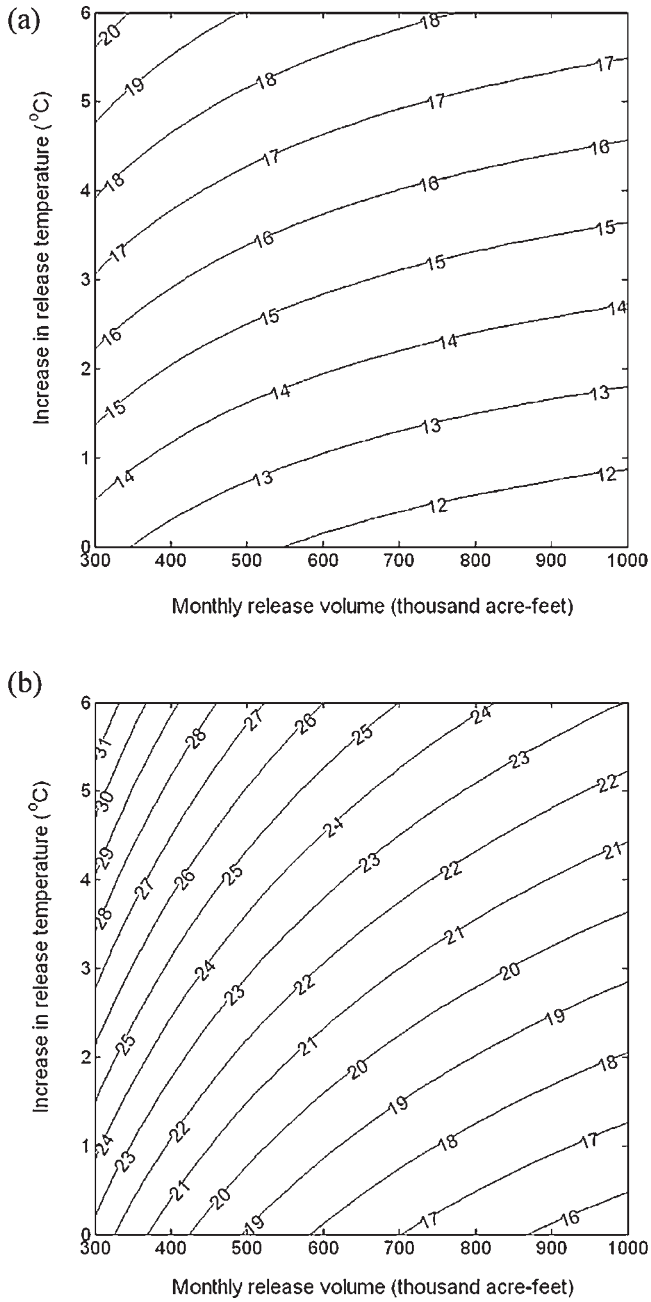

Figure 8. Contour plots of modelled temperatures at 125 km (a) and 390 km (b) downstream from Glen Canyon Dam for a range of monthly release volumes and increases in release temperatures. Simulations are for typical post-dam summer conditions with $T_{air} = 26°C$ and $T_o = 9°C$, thus the *y*-axis values represent an increase over 9°C in release temperature

conditions for summer periods, with an air temperature of 26°C and a release temperature of 9°C. In Figure 8, water discharge is presented as the monthly release volume in thousand acre-feet because this is the volume unit that is commonly used within the Glen Canyon Dam management and scientific program.

The temperature of the mainstem at the mouth of the Little Colorado River during the summer is important because endangered, juvenile humpback chub may be flushed from this tributary (where they spawn) during

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summer thunderstorm floods, possibly experiencing thermal shock due to differences between tributary and mainstem water temperatures (see, e.g. Gloss and Coggins, 2005). A potential application of Figure 8(a) could be to estimate the combination of conditions necessary, in terms of release volume and release temperature, to achieve a given monthly average temperature at this important location. For example, if 16°C during the summer was deemed an objective by resource managers, this contour could be traced in Figure 8(a) to determine the combination of release volume and release temperature required. It is apparent from Figure 8(a) that release temperature has a greater influence on downstream temperatures than release volume at this location.

Further downstream, it is seen that the effects of release volume become more important because water residence time is significantly longer. Water temperatures in these downstream reaches are important because of the potential for upstream migration of non-native warm water fish if water temperatures are increased through dam operations and/or dam modifications. The downstream location results also illustrate the limitations of this model, notably the very high predicted temperatures in the upper left hand corner of Figure 8(b). As detailed earlier, simplifications made in the model formulation preclude the ability of the model to approach equilibrium gradually, such that physically unrealistic modelled temperatures can result for conditions outside the range of conditions used in model calibration and validation.

CONCLUSIONS

Water released from Glen Canyon Dam is typically substantially colder than ambient air temperatures, particularly during summer months, owing to water releases from the reservoir's hypolimnion. Thus, water temperatures along the reach below the dam often exhibit downstream warming. An analysis of a large water temperature dataset for this reach indicates that these downstream temperature gradients can be approximated as linear, at least for monthly average values. This observation allows for substantial simplification of the standard heat balance equations, leading to a simple algebraic model wherein the longitudinal temperature gradient is a function of the amount of water released from the dam and the difference between air temperature and release water temperature.

The simplified model contains two empirical parameters that were calibrated using available water and air temperature data. Model validation indicated that there were no positive or negative biases in signed errors, and mean absolute errors were less than 0.5°C for all sites for the 421 km reach studied. Maximum errors (~2°C) tend to occur in the farthest downstream reaches during fall low flow months when the modelled temperatures tend to be greater than the observed temperatures.

Example applications were used to study the effects of various flow release volumes and release temperatures on downstream temperatures. These example applications illustrate how release temperatures tend to dominate water temperatures in the upstream reaches, whereas in the lower reaches of the study area the importance of the release volume increases substantially owing to longer travel times and the potential for increased heat exchange across the water surface.

Because of the simplified nature of the model, we envision it as being a useful tool for first-order analyses of alternatives for future operations and/or modifications of Glen Canyon Dam, such as a selective withdrawal structure, which could then be further analysed with a more complex, unsteady state model (e.g. Anderson and Wright, 2007). As shown in the previous section, the model can yield physically unrealistic results if applied to conditions that are outside of the calibration and validation dataset. Finally, the methods presented herein may also be useful for modelling water temperatures in other systems, particularly downstream from large dams where release temperatures are substantially out of equilibrium with meteorological conditions.

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