Effect of Glen Canyon Dam on the Temperature Regime of Colorado River

Kaveh Zamani
University of California, Davis

Effect of Glen Canyon Dam on the Temperature Regime of Colorado River

Kaveh Zamani, PhD Student, (kzamani@ucdavis.edu)

Department of Civil and Environmental Engineering, University of California at Davis

Abstract: Temperature of an aquatic body is a crucial factor which affects, vertical mixing, dissolved oxygen, and most of biological and biochemical processes. The natural temperature fluctuation in the Colorado River in the Northern Arizona altered after construction of Glen Canyon Dam due to hypolimnetic withdrawal from the Dam's reservoir, Lake Powell. Several managerial remedies were considered to modify the tail-water temperature to preserve native fish habitat. In this review, I discuss the basics governing equations of heat transport in water. Then I provide the characteristics of the pre/post dam, time-series of temperature downstream of Lake Powell. Finally I discuss a simplified model which was suggested to predict water temperature in the Colorado River, downstream of the Glen Canyon Dam.

1- Introduction

Water temperature represents one of the most important biophysical characteristics of surface water quality. Water temperature is a key factor in ecohydraulics and ecohydrology due to the several reasons:

1- Vertical water temperature profile affects the stratification.

2- Dissolved oxygen solubility in water is determined by the water temperature. Basically the warmer the water is meaning the less dissolved oxygen.

3- Large temperature change has profound effect on the aquatic species composition. Many aquatic species can only tolerate a certain range of temperature fluctuation.

4- Water temperature is important form industrial and recreational point of views.

5- Some processes such as volatilization, sorption of organic chemical to particular matter are function of water temperature. Temperature increase may lead to growth of toxic compounds.

6- Given that most of biochemical processes in a river are governed by temperature. Temperature drop can decrease reproductive rates in the riverine food chain.

The term "thermal pollution" is commonly used to describe water quality deterioration caused by input of hot/cold water in a water body. Because of the solar radiation, water temperature in surface streams naturally follows diurnal and seasonal pattern. However the closure of dam on rivers resulted in significant change to the downstream aquatic environment. As the regular water outlet facilities in most of the dams usually takes water from an elevation significantly lower than surface, the water released from a dam in to the downstream river is considerably cooler compare to pre-dam temperature is summers. While in winters the released water is warmer than the pre-dam natural condition. In the next section I briefly review the physical governing equations of temperature for rivers and lakes.

2- Governing equation of heat transport in surface water

Just analogues to the mass balance equation for a volume of water, "heat balance" can be written for the same volume. For a hypothetically well-mixed system, in a finite time, heat balance can be written as:

Accumulation = inflow – outflow ± heat exchange with surroundings

Accumulation refers to change of heat H in the system over the time t:

$$\text{Accumulation} = \frac{\Delta H}{\Delta t} = \rho C_p V \frac{\Delta T}{\Delta t} \tag{1}$$

where ρ is water density, C_p is specific capacity of heat, V is volume, and T is temperature of water. Inflow describes all local and nonlocal sources of heat entering the system of interst:

$$Inflow = Q\rho C_p T_{in}(t) \tag{2}$$

where Q is volumetric flow rate of all water sources entering the system and T_{in} is the average inflow temperature. In turn, outflow is the heat which is carried out from the water body by an outflow stream, and can be represented by:

$$Outflow = Q\rho C_p T \tag{3}$$

Sounding heat exchange is mostly contribution of the free surface heat to warming and cooling. However, in some cases energy exchange with the bedstream can be an important term in rivers and shallow lakes. In this review I neglected the terms related to the heat exchange of river and bed sediment. The net heat exchange across the surface of a river is given by:

$$Sourface\ heat\ exchange = A_s J \tag{4}$$

in which, A_s is the surface area and J is the surface heat flux with a positive flux referring to heat addition into the river. Surface heat exchange is composed of five main processes as it is shown in the Figure 1. We can categorize these processes in two ways. First radiational and nonradiational groups, where the former terms depends on the energy transmitted as electromagnetic waves (shortwave and longwave) while the latter is classical conduction convection and sink source of heat. The second way of categorization is considering the terms which are depending on the temperature of water (state variable here). Processes like atmospheric longwave radiation and solar radiation are independent of the water temperature in the river, whereas, longwave radiation of water, convection-conduction and evaporation and condensation, are direct functions of river temperature. Therefore, the total surface heat flux can be calculated as sum of the five above mentioned heat fluxes:

$$J = J_{sn} + J_{an} - (J_{br} + J_c + J_e) \tag{5}$$

in which the J_{sn} is the solar shortwave radiation, J_{an} is net atmospheric longwave radiation, J_{br} refers to outward longwave radiation from the water body, J_c is conduction and J_e is evaporation. In the rest f this section we briefly review each of these terms.

Solar shortwave radiation "J_{sn}" magnitude depends on several factors: Date, time and angle of radiation on the earth are the main factors. However, scattering and absorption of solar wave in the atmosphere is important too. In turn, reflection and shading effect are important and can greatly decrease solar radiation. Solar shortwave radiation usually measured directly however for numerical models there are some relations which can reproduce these values based on the parameters. Figure 2 shows the daily totals of solar radiation for different latitudes as a function of time of the year.

Although some part of solar shortwave radiation absorbs in the atmosphere of the Earth, a smaller portion of that emits from the atmosphere to the Earth surface in the form of long wave radiation. Long wave radiation of atmosphere follows the general governing equation of long wave radiation from a hot object, the Stefan-Boltzmann law. The modification of this law for atmosphere is:

$$J_{an} = \sigma(T_{air} + 273)^4 \left(A + 0.031\sqrt{e_{air}}\right)(1 - R_l) \tag{6}$$

where σ is Stefan-Boltzmann constant, T_{air} is air temperature, A is a constant of atmospheric attenuation (~0.6), e_{air} is air vapor pressure, and R_l is reflection coefficient which is relatively small for rapid rivers (0.02).

Reverse long wave radiation from river's water is also governed by Stefan-Boltzmann law:

$$J_{br} = \epsilon\sigma(T_w + 273)^4 \tag{7}$$

herein ϵ is emissivity of water and T_w is the water surface temperature.

Conduction and convection (also known as advection and diffusion of heat) can happen at the water-air interface and it is defined by

$$J_c = c_1 F(U_{wind})(T_W - T_{air}) \quad (8)$$

where c_1 is a Bowen's coefficient, and the term $F(U_{wind})$ depicts the effect of wind in heating and cooling of water based on a 10 meter reference wind. One of the commonly used closures for this term is:

$$F(U_{wind}) = 19.0 + 0.95U_{wind}^2 \quad (9)$$

Finally, latent evaporation (and condescension) is the loss (and gain) of heat due to evaporation. This flux is represented by Dalton's law:

$$J_e = F(U_{wind})(e_{s_{vapor}} - e_{air}) \quad (10)$$

Herein, $F(U_{wind})$ is same as equation (10), and $e_{s_{vapor}}$ is the saturation vapor on the top of the free surface, and e_{air} is the vapor pressure of air in the water-air interface and they are calculated as follows:

$$e_{air} = 4.596 \exp(\frac{17.27T_{dry}}{273.3+T_{dry}}) \quad (11)$$

$$e_{s_{vapor}} = 4.596 \exp(\frac{17.27T}{273.3+T}) \quad (12)$$

The surface head budget could be form based on the above equations. In the next section (Section 3) I will review the historic effect of the Glen Canyon Dam construction on the water temperature distribution of Colorado River. Then, in the Section 4 I review a suggested simplified temperature model derived based on the above equations.

3- Effect of Glen Canyon Dam on Temperature Distribution

Glen Canyon Dam was built during a ten year period of 1956-66. It is owned by USBR. It is one-way arch gravity concrete dam with a length of 480 m, height of 220 m, maximum water depth of 178 m, crest width of 7.6 m, and base width of 91 m. The Dam's crest elevation is 1,132 m from the ocean. The dam does not have a fish ladder or an ogee spillway. It has two concrete tunnels with double radial gates and design capacity of 7,800 $\frac{m^3}{s}$. The highest handled discharge happened in 1983 flood which ended up to the failure of the right tunnel (discharge 2,760 $\frac{m^3}{3}$). The Glen Canyon Dam's reservoir, Lake Powell, is the second largest reservoir in the US after Lake Mead, with the capacity of 32.33 km^3 and active capacity of 25.75 km^3. It took 17 years to completely fill the reservoir (1963-80). The dam typically gets water from April to July. The upstream watershed catchment area is 280,590 km^2. The power station of the dam is composed of 8 Francis turbine with installed capacity of 1296 MW total and maximum working hydraulic head of 160 m. 85% of the Glen Canyon Dam water goes for irrigation purposes and the rest for civic usage. In addition, the Dam and it lake have four million tourist visits per year.

The water of hypolimnion of Lake Powell typically released in the tailwater of Colorado River. Therefore, less seasonal and daily variation in downstream temperature happen compared to pre-dam situation. So water temperature is considerably colder in the summer and warmer in the winter. To date, dam operation modification with the goal of reduction of heat pollution and even construction of selective withdrawal facilities has been considered and studied (Garrett, 2003). Figure 3 shows the location of the gaging stations which record water temperature in Colorado River downstream of the Lake Powell. Figure 4 shows time-series of recorded water temperature in USGS Less Ferry gauge (Station ID 09380000). As it can be seen in the pre-dam condition the water temperature used to drop down to near zero in the winter and in the summer it raised to around 25 degree Celsius. The downstream temperature measurements in Colorado River show the released water from Glen Canyon Dam demonstration an upward gradient. The slope of this temperature gain depends on the air-temperature. Thus a correlation between temperature and monthly is suggested (Figure 5). In line with Figure 5, the monthly temperature gradient at each station is drawn in the Figure 6. It shows only in a short period of time in December the released water is warmer than the weather. In general Figures 5 and 6 illustrate that in summer we would see significant increase in the tail-water after release from the Dam. Also some researchers took advantage of the relatively constant gradient of the temperature and suggested simplified heat exchaneg model for Colorado River water temperature (Ferrari, 1987; Walters et al., 2000). In the next section we review one of these simplified and calibration based models.

4- Simplified Model

With simplifying advection-diffusion-reaction equation (ADR) can be written for heat in a river, several simplified model were suggested to date. The assumptions are: steady state condition, complete cross-sectional mixing (cross-sectionally integrated variables), high Peclet number (heat diffusion negligible), and simplified linear expression for surface heat exchange instead of the equation (8). These river temperature models do not consider radiational terms and heat bed exchange. One interesting issue about the mentioned simplification is that: the resulting ADR equation has an exact solution and we do not need to resort to numerical solutions. The following model first suggested by Walters et al., (2000) and later modified by Wright et al., (2009) from direct integration of simplified ADR equation for heat:

$$T(x) = T_0 + \frac{K}{U}x(T_{air} + T_{shift} - T_0) \qquad (13)$$

Here, $T(x)$ denotes temperature as a function of location, $K = 6.51 \times 10^{-7}\ s^{-1}$ is a constant which was found with calibration, T_0 is the temperature right after the dam, $T_{shift} = 7.91\ C^0$ is the second calibration factor, and U is velocity which is given by the relation based on the released water for that certain reach of the Colorado River, $U = 0.021Q^{0.63}$. Wright et al. (2009) find the calibration factors based on an extensive least square linear regression.

The model (eqn 13) was validated versus a separate dataset of river temperature and it shows relatively good agreement with the close downstream measurements. However, as the distance from the Glen Canyon dam gets farther than 200 km the deviation of the model form the measured data increases and the model significantly over-predicts the water temperature in the Colorado River (Figure 8).

5- Final Remarks

The simplified model contains two empirical parameters that were calibrated using the long term available water and air temperature data. I am not considering it as a purely physical process-based model, whereas it is more an empirical model to me. The suggested model has its benefits and limitations. I personally think this model has to be used very carefully and only for the big picture view of the phenomenon. I cannot fully trust this model to incorporate results into the fine engineering or ecological studies. The extra unphysical term in the equation (13) (T_{shift}) is the single representative of all neglected terms such as short and long wave radiations. As the neglected terms are highly nonlinear and widely depending on metrological data, the assumption of a single term instead is a very loose assumption. The other limitation of this model is neglecting the tributaries contribution in the heat balance of the river. Due to the fact that the mythological and water release data are available online, and nowadays computational burden of one dimensional transport equation for heat is very affordable, I strongly suggest that for more detailed studies, researcher resort to the typical 1-D water quality models. Moreover, the Authors explicitly mentioned the limitations and they mentioned their model is a useful tool for "first-order analyses". All in all, as Vito Vanoni said: "*In conclusion, the choice of a model at this time is arbitrary, and the choice of a modeler is probably more important than the choice of a model.*" (Dawdy and Vanoni, 1986).

References

1. Chapra, S.C. 2008. Surface Water-Quality Modeling. Waveland Press.
2. Dawdy, D. R. and Vanoni, V. A. (1986). "Modeling alluvial channels." Water Resour. Res., 22(9), 71-81.

3. Ferrari R. 1987. Colorado River water temperature modeling below Glen Canyon Dam. Glen Canyon Environmental Studies Report GCES/13/87.

4. Garrett D. Science GCDAMP, Advisors. 2003. Evaluating a Glen Canyon Dam temperature control device to enhance native fish habitat in the Colorado River, A risk assessment by adaptive management program science advisors.

5. Ji, Z.G. 2008. Hydrodynamics and Water Quality, Modeling Rivers, Lakes and Estuaries, Wiley.

6. Voichick N, Wright SA. 2007. Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, Northern Arizona, 1988–2005. U.S. Geological Survey Data Series 251, 24 p.

7. Wright, S. A., C. R. Anderson, and N. Voichick. 2009. A simplified water temperature model for the Colorado River below Glen Canyon Dam. River Research and Applications 25:675–686.

Figures:

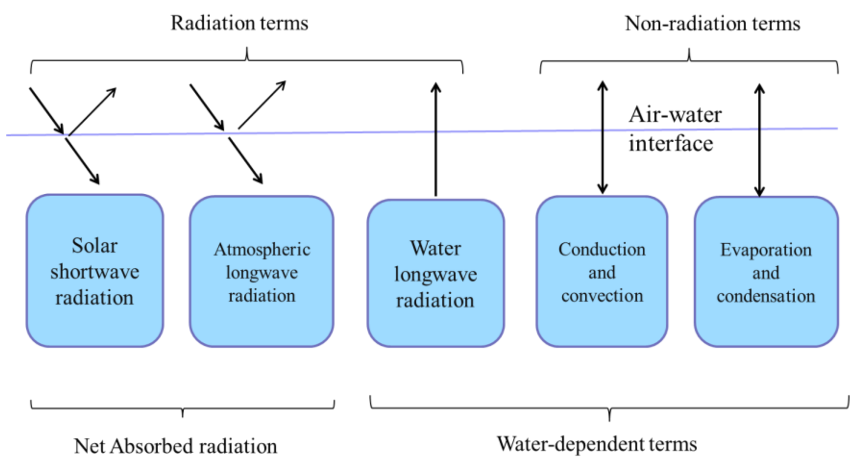

Figure 1: The five main issue contributing to the surface heat flux in a river (After Chapra, 2008)

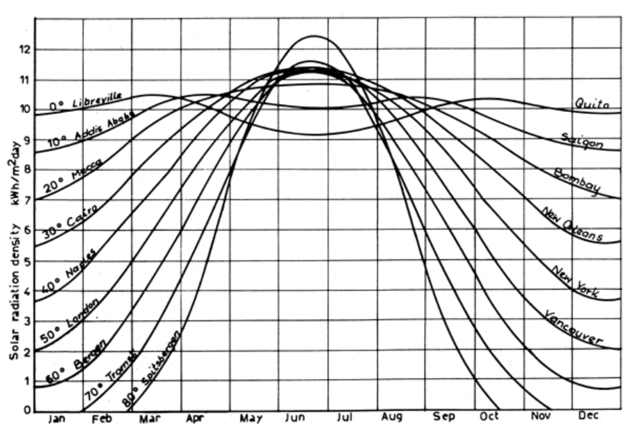

Figure 2: Daily totals of solar radiation for different latitudes as a function of time of year (From wikipedia)

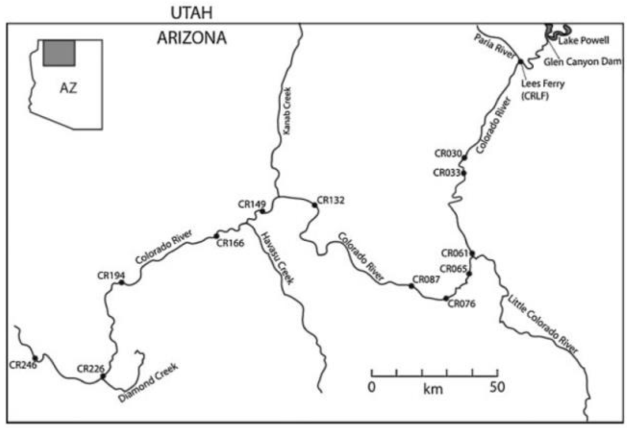

Figure 3: Map of below Glen Canyon and location of water temperature monitoring stations (From Voichick and Wright, 2007).

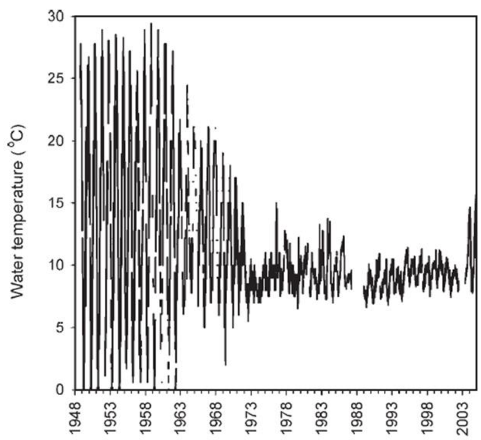

Figure 4: Daily water temperature record at Less Ferry gaging station from 25 July 1949 to 30 September 2005 (From Voichick and Wright, 2007).

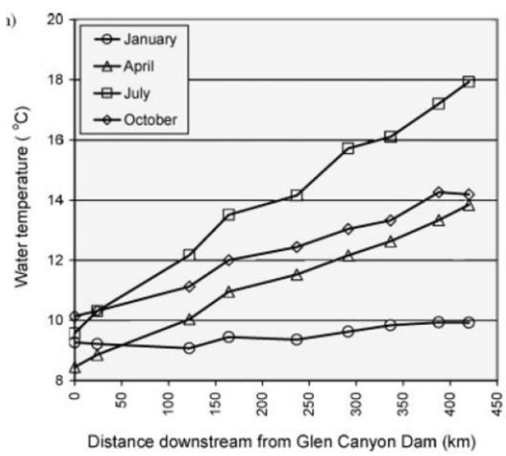

Figure 5: Monthly average water temperature downstream of Glen Canyon Dam

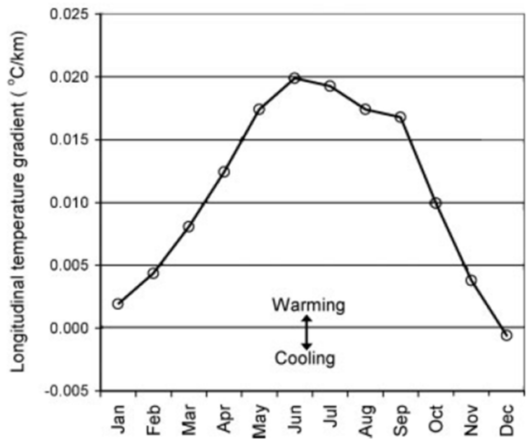

Figure 6: The temperature gradient downstream of Glen Canyon Dam in different months.

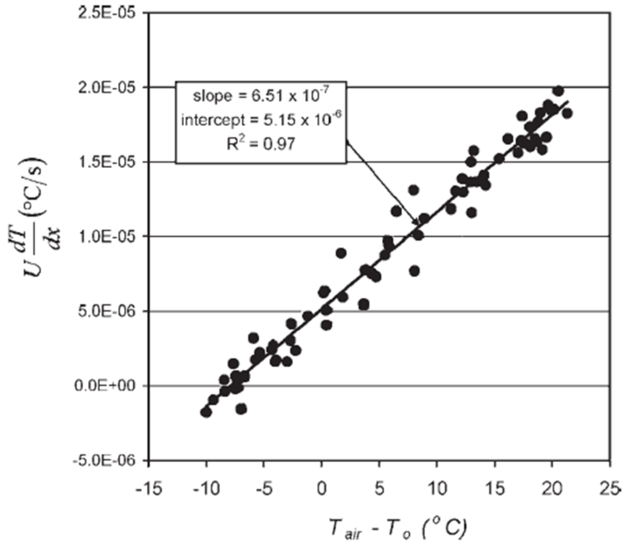

Figure 7: Linear regression of equation (13) for calibration of the parameters

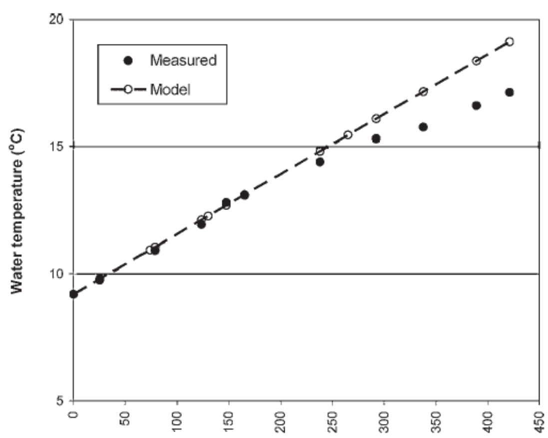

Figure 4: Results of validation of the suggested simplified model versus field measurements of Colorado River water temperature