Effects of the Glen Canyon Dam on Colorado River Temperature Dynamics

GEL 230 – Ecogeomorphology
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Derek Roberts
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Abstract: *At the upstream end of the Grand Canyon, the Glen Canyon Dam has changed the Colorado River from a run-of-the-river flow to a deep, summer-stratified reservoir. This change in flow regime significantly alters the temperature regime of the Colorado River. Seasonal temperature variation, once ranging from near* $0℃$ *to almost* $30℃$, *is now limited to* $7-14℃$. *The lack of warm summer temperatures has prevented spawning of endangered humpback chub in the Colorado River. Implementation of a temperature control device, to allow for warmer summer releases to mitigate negative temperature effects on endangered fish, was considered by the federal government. Ultimately, this proposal was put on indefinite hold by the Bureau of Reclamation and U.S. Fish and Wildlife Service due to concerns of cost and unintended ecological consequences. The low-variability of the current dam-induced Colorado River temperature regime will continue into the foreseeable future. Agencies are reviewing humpback chub conservation efforts outside of temperature control.*

Keywords: Colorado River, Grand Canyon, Glen Canyon Dam, thermal dynamics

1.0 Introduction

Temperature in natural water bodies is a primary driver of both ecological and physical processes. Freshwater plant and animal metabolisms are heavily affected by temperature *(Coulter* 2014). Furthermore, the thermal structure of a water body has significant impacts on the physical processes that drive ecosystem function (*Hodges et al* 2000); fluid dynamics drive transport of nutrients, oxygen, and heat. Human action, often the introduction of dams or industrial cooling systems, can alter the natural thermal regimes of rivers and lakes leading to reverberating impacts throughout associated ecosystems.

This report presents a general background on thermal dynamics in water bodies. These basic principles are used to compare and contrast heat exchange processes in lakes versus rivers. The comparison is specifically extended to the effects of the Glen Canyon Dam (GCD), and resulting Lake Powell formation, on temperature dynamics of the Colorado River in the Grand Canyon (GC). Impacts of the GCD-forced change to Colorado River temperature regime change in the Grand Canyon are discussed. Potential mitigation strategies for these impacts are presented.

2.0 Temperature dynamics in water bodies

Temperature in water bodies represents a balance of energy fluxes into and out of a given system; energy is conserved. Meteorological conditions and inflows/outflows are the primary drivers of heat into and out of water bodies. The inputs of one forcing can affect the outputs of other forcings; heat exchange can be thought of as a dynamic feedback process between a water body and its surrounding environment.

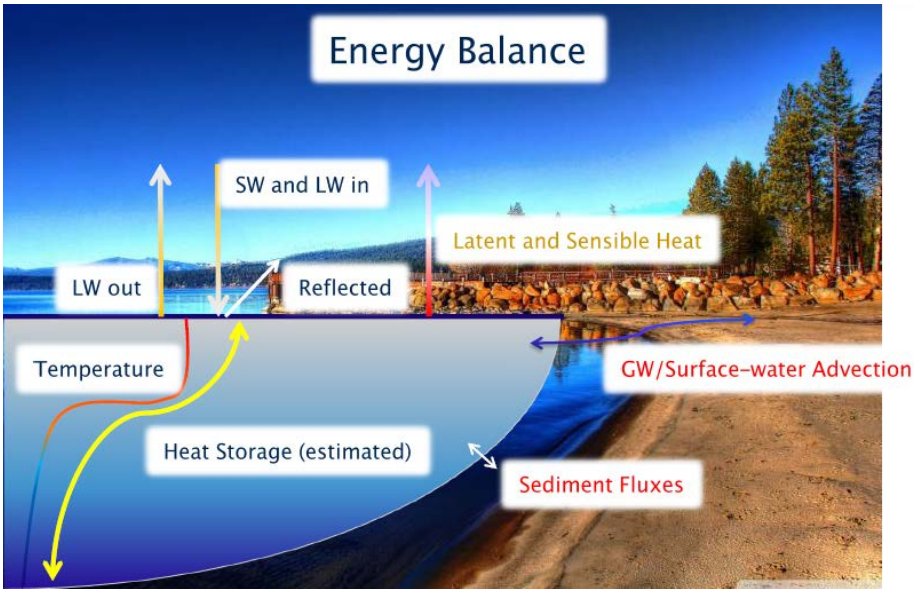

Figure 1 – Energy balance in water bodies (Tom Mathis, UC Davis)

2.1 Meteorological forcing

Shortwave (SW) radiation, sunlight, is a major heat flux into water bodies. SW energy absorption into water is a function of albedo effect (amount of light reflected off of the water's surface), water clarity (affecting how deeply SW penetrates into the water body), and strength and angle of incoming SW radiation. While more wavy water generally has a lower albedo (less reflectance), the "whiteness" in foam caused by white-capping waves increases water-surface reflectance. More turbid, less clear, water will absorb more SW heat near the water's surface, leading to stronger thermal stratification. Clear water will allow light to penetrate deeper, more evenly distributing energy throughout the water column. Cloud cover and time of day also directly affects how much SW energy reaches a water body.

All matter not at absolute zero Kelvin emits longwave electromagnetic radiation (LW). This includes both the atmosphere and the water body itself. Most modelers assume that all atmospheric LW energy that reaches the water's surface and is not reflected via albedo effect is absorbed into the water's surface.

LW emission by the atmosphere is a product of atmospheric moisture content and temperature, generally well approximated by cloud cover estimates. Emission of LW energy from the water body is a product of water surface temperature.

Latent heat is fluxed out of water bodies through evaporative cooling. Rate of heat loss due to evaporation is a product of water temperature, air temperature, relative humidity of air, and wind speed. Warmer water, less moisture-saturated air, and higher winds increase evaporative heat flux out of water body.

Sensible heat is exchanged at the air-water interface, through conduction and convection, as a function of relative temperature, air moisture-saturation, and wind speed.

2.2 Inflows

Inflows to and outflows from a water body are also vectors for heat. Warm or cold inflows can increase or decrease, respectively, water-body temperature. Outflows withdraw heat energy from a system. However, the depth and associated temperature of these outflows are important considerations. If a water body receives all of its inflows from tepid surface flows but all outflows are through bottom-seepage or bottom-reservoir release of cold bottom waters, the net inflow/outflow heat exchange could warm the water body even if the inflows are cooler than the surface waters.

2.3 Mixing processes - heat flux in lakes versus rivers

Heat is not only distributed through a water body by the processes outlined in Sections 2.2 and 2.3; internal mixing processes also play a major role in water body thermal dynamics. As average depth, or the ratio of surface area to volume, increases, many of the meteorological heat fluxes transport less heat as a fraction of total water volume; there is less surface-exposure to meteorological forcings relative to water body volume. In deep lakes and reservoirs, this often leads to thermal stratification during warm seasons.

Lakes or reservoirs stratify when surface heating leads to significant temperature difference through the water column. Warmer surface waters are less dense than cooler bottom waters. Vertical water mixing is buffered by this density gradient, further increasing thermal stratification when surface heat flux is net-positive into the water body. When net surface heat flux is out of a water body (cooling), surface waters can eventually cool to below the temperature of bottom waters. This inverse density gradient drives plunging of surface waters and upwelling of bottom waters. The mixing processes associated with cyclical stratification and de-stratification plays a primary role in lake and reservoir temperature, biochemical, and ecological dynamics.

Rivers are typically less deep than lakes or reservoirs. As a result of having lower average depth (lower surface area to volume ratio), meteorological forcing can generally have direct effects on the *full* water column, as opposed to these effects being comparatively isolated to only surface waters in deep lakes (particularly during the stratified season). This is especially the case with turbulent, rapid-filled rivers like the Colorado River in the Grand Canyon. Turbulent mixing through rapids churns river water, distributing surface heat down to the riverbed.

Lake temperature models are typically run one-dimensionally, on the vertical, with nodes representing depth values (*Chapra* 1997). River temperature models are typically longitudinal (*Anderson et al.* 2007); water temperature is assumed to be uniform through the water column. This difference in typical modelling approach of lakes versus rivers is telling of the differences in thermal dynamics

3.0 Colorado River in the Grand Canyon: Historic temperature regime

Fed by underground springs and Rocky Mountain snowmelt, the Colorado River flows through the 277 miles of the Grand Canyon between Glen Canyon Dam (GCD) and the backwaters of Lake Mead. Prior to the closure of the GCD in 1963, the Colorado River saw very significant seasonal variation in temperature in the Grand Canyon. As the river wound through the heat of southern Utah summer, it warmed significantly. Typical summer temperatures were in the range of $25 - 30\ ℃$. Winter temperatures were in the range of $0 - 7\ ℃$.

3.1 Effects of Glen Canyon Dam on Colorado River temperature regime

The closure of Glen Canyon Dam in 1963 significantly decreased seasonal variation in the Colorado River temperature regime. This change is due to the difference in temperature dynamics between the current water body, Lake Powell, and its predecessor, the historic Colorado River flow through Glen Canyon.

As described in Section 2 of this report, thermal dynamics in deep reservoirs are different than those in comparatively shallow, turbulent rivers. Lake Powell depth, typically greater than 150 meters (but varying with inflows and reservoir release), buffers heat exchange into and out of bottom waters. This is particularly true when summer stratification prevents significant vertical mixing in the reservoir. Even if flows into the reservoir are warm, they will not significantly increase bottom temperature because they will "insert" at a depth of neutral buoyancy; they will mix into the reservoir at a depth where reservoir temperature is the same as inflow temperature. As a result, Lake Powell bottom temperatures remain consistently around 7 ℃.

Glen Canyon Dam is a bottom-release reservoir; the waters feeding the Colorado River into the Grand Canyon are consistently about 7 ℃ year-round (*Bureau* 2004, USGS). This presents a significant decrease in the seasonal temperature variation described in Section 3.0. Post-GCD typical seasonal temperature variation, about 7 – 13 ℃, is illustrated in Figure 2 below.

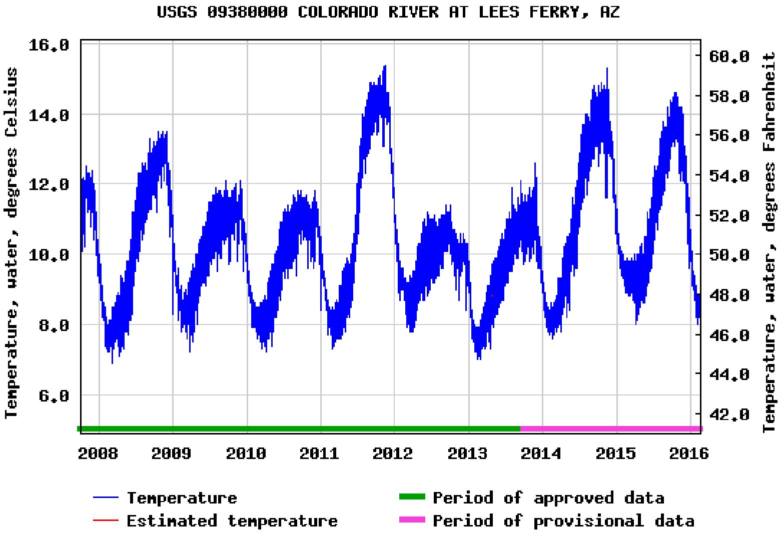

Figure 2 – Recent temperature variation in CO River. (USGS)

4.0 Impacts of GCD-induced temperature regime change on the Colorado River

The humpback chub, officially listed as an Endangered Species since 1967, is native to the Colorado River in the Grand Canyon. It spawns in waters at about 20 ℃. The year-round cold release from the GCD prevents any humpback chub spawning in the main Colorado River. Since the closure of the dam, the humpback chub has only been able to spawn in the warmer Little Colorado River tributary to the Grand Canyon (*Makinster et al.*2010, *Baron et al* 2003, *Bureau* 2004). Additionally, the cold, clear Lake Powell release water has created an ideal salmonid (mainly rainbow trout) habitat. Salmonids prey on juvenile chub, further exacerbating the temperature-related threat to the endangered chub (*Makinster et al.* 2010).

4.1 Proposed mitigation of dam effects on temperature regime

The Bureau of Reclamation has reviewed proposals to mitigate the negative effects of the GCD on the endangered humpback chub. Generally, dam removal has been dismissed as infeasible due to sedimentation effects on downstream Lake Mead and Hoover Dam. A more seriously considered mitigation proposal involves installing selective-withdrawal temperature control devices (TCD) on the GCD intake penstocks (see Figure 3).

A GCD TCD would allow dam operators to withdraw reservoir waters from multiple depths to control release temperature during the stratified season (*Bureau* 2004, *Vermeyen* 2008). In theory, warmer reservoir releases could return humpback chub spawning to the Colorado River below the GCD. The GCD TCD went through a series of review and planning studies from 1997 through 2008 (*Vermeyen* 2008). The final design, estimated to cost on the order of tens-of-millions of dollars, was sent to the US Fish and Wildlife Service (USFWS) for approval in 2008. The manager of the Environmental Resources Division for the Upper Colorado Region office of the Bureau of Reclamation, Beverley Heffernan (personal communication, 2016), indicated that the USFWS does not plan to move forward with the project due to "high cost… coupled with the uncertain effects associated with its use." Heffernan expressed concern for "potential unintended consequences associated with… benefiting non-native species that could lead to higher loss of native fish through predation and competition for habitat and food." Specifically, there is concern that warmer temperatures could cause the proliferation of predatory catfish on juvenile humpback chub.

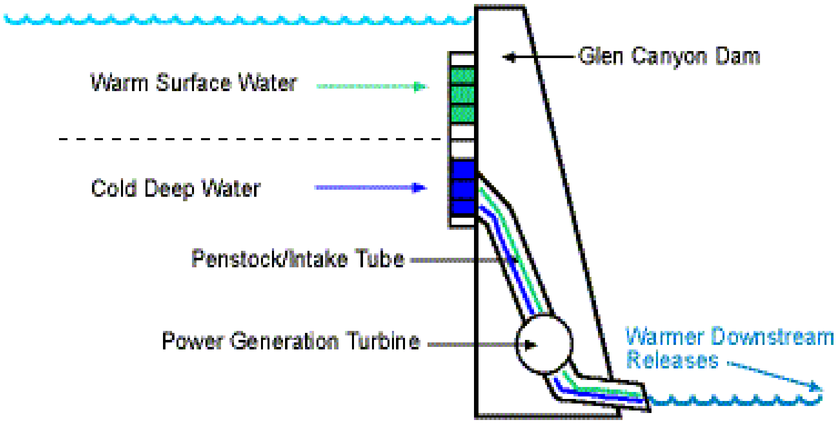

Figure 3 – Glen Canyon Dam Temperature Control Device schematic (US BOR).

A draft environmental impact statement (DEIS) for Glen Canyon Dam management was released by the Bureau of Reclamation in January 2016. Per Heffernan: "It does not contemplate any changes to the dam infrastructure, but proposes an array of operational protocols intended to benefit the many resources in and near the Colorado River, including endangered fish." While still in draft form, these protocols primarily intend to inform occasional high-flow releases to impede non-native fish spawning.

5.0 Conclusions

The Grand Canyon is a natural gem; it is both a unique natural habitat and a prized outdoor recreation area. The introduction of the Glen Canyon Dam significantly affected the natural seasonal temperature variation of the Colorado River through the Grand Canyon. This change in temperature regime adversely affected endangered humpback chub fish habitat. Changes to GCD operation have been proposed to return the Colorado River temperature regime to its natural state. However, there are currently no plans for the Bureau of Reclamation to complete any of the proposed mitigatory infrastructure changes to the dam. Basic procedural changes are hoped to control non-native fish species, but it is likely that the low-variability GCD-controlled temperature regime of the Colorado River in the Grand Canyon will remain unchanged for the foreseeable future.

6.0 References

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