Hydros Consulting

MEMORANDUM

TO: Will Tully, USBR
FROM: Christine Hawley and Jean Marie Boyer, PhD, PE, Hydros Consulting Inc.
SUBJECT: WGFP EIS, Bounding Analysis of Bank Storage Temperature Effects
DATE: June 21, 2011

EPA provided verbal comments in meetings with the USBR expressing concern that that the Windy Gap Firming Project (WGFP) proposed action may result in reductions in Colorado River bank storage, which may, in turn, affect river temperatures. EPA believes this effect should be analyzed in the EIS. The river reach in question is between Windy Gap Reservoir and Kremmling on the Colorado River. This memo presents a bounding analysis, using very conservative assumptions, that evaluates whether additional pumping as a result of the WGFP will affect river temperatures due to reduced bank storage cooling.

Summary

A bounding analysis was completed to assess the potential magnitude of bank storage effects on river temperatures under existing conditions and the proposed action. The years of simulated record with the greatest daily flow rate difference and greatest daily stage difference (1952 and 1969, respectively) were evaluated. A range of conservative assumptions, designed to maximize the estimated potential influence of bank storage on river temperature were applied. The following conclusions can be drawn from this analysis:

- The upper bound calculations of bank storage flow rates produced a maximum bank storage flow rate to the river of 19 cfs for the 14 mile reach of the river for the years evaluated.
- The maximum bank storage cooling effects during July and August are simulated when high hydraulic conductivities are assumed, which corresponds to rapid, short-term responses to stage changes.
- The upper bound calculations of bank storage flow rates showed maximum percent daily contributions to river flow of 5.6% in July and August on the years evaluated.
- The greatest daily cooling effect in July and August was estimated to be 0.077°C for EC and 0.075°C for Alt2.
- The largest estimated decrease in cooling effect from EC to Alt2 was 0.076°C.
- Changes in bank storage associated with the WGFP would have a negligible effect on water temperature in the Colorado River.

Bank Storage Temperature Effects – Defined

This section defines the concept of bank storage cooling effects. Bank storage cooling effects fall into the larger category of groundwater-related cooling effects on rivers. The following three concepts of groundwater-related cooling are described below to fully define bank storage and the extent of this analysis:

- Bank storage,
- Hyporheic flow, and
- Groundwater advection.

Bank storage refers to the river water that flows into the porous material at the margins of a river channel (bank) during high river stages (Figure 1). Bank storage water is typically cooled by the soil matrix in warmer months of the year (and warmed in cooler months, depending on conditions) and subsequently released back to the river as the river stage lowers. In addition to flowing back to the river, it also flows away from the river and releases to shallow groundwater. This is a phenomenon that occurs, to some extent, in all flowing water reaches with varying stage and porous bank material. As such, bank storage cooling effects are expected to occur to some degree under current conditions on this reach of the Colorado River.

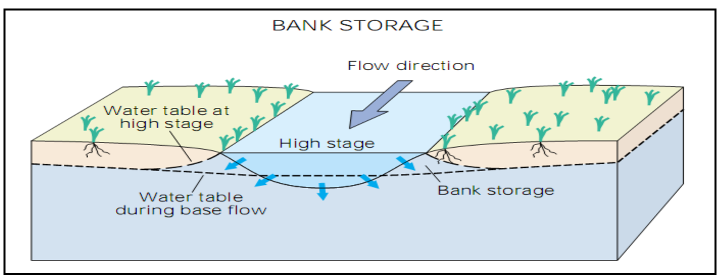

Figure 1. Bank Storage (Image from USGS, 1998)

Hyporheic flow[1] occurs beneath and lateral to the stream bed, where there is mixing of shallow groundwater and surface water. This zone is usually a high conductivity zone (sands and gravels), allowing surface water to enter and flow along subsurface paths before returning to the main channel. This type of flow occurs below the bank storage zone. Hyporheic flow paths leave and return to the stream many times within a single reach, unlike groundwater flow paths which typically enter or leave only once in a given reach. This exchange removes heat from the channel when river temperatures are high by moving water out of direct contact with solar radiation and mixing with cooler groundwater (Figure 2).

Hyporheic flow in alluvial rivers, like sections of the reach of the Colorado River in question, is often associated with flow through small islands, bars, and bends, and is therefore largely a

[1] For this document, we separate bank storage from hyporheic flow. We note that bank storage is sometimes considered to be a portion of a larger category of subsurface hyporheic cooling in the literature.

function of geomorphology. The Windy Gap Firming Project DEIS (as well as additional analyses being completed in response to other EPA comments) indicates that no substantive changes to geomorphology (e.g., channel width, depth, and aggradation/degradation) in this reach are anticipated. As such, hyporheic cooling can be expected to be insignificantly changed by the proposed action.

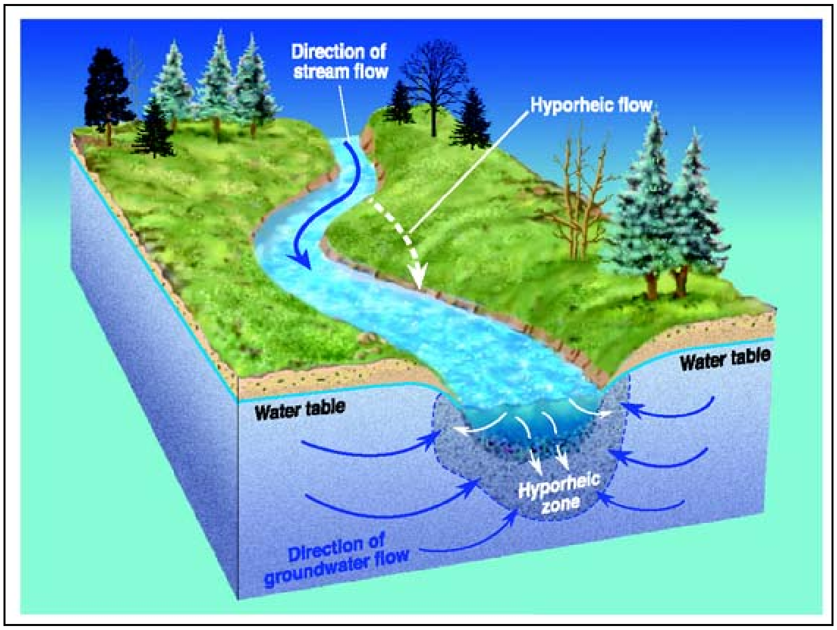

Figure 2. Hyporheic and Shallow Groundwater Flow (Image from Alley et al., 2002)

Another mechanism of subsurface cooling is groundwater advection. Cooling by groundwater advection occurs in flowing surface waters in gaining reaches when groundwater (shallow and/or deeper) is cooler than the surface water, which is often the case, particularly in the warmer months of the year. According to the Water Resources Technical Report prepared for the Windy Gap Firming Project EIS (USBR, 2007; Section 7.2.1), the predicted change in river stage is not expected to change the groundwater conditions in the alluvial aquifer, with the possible exception of water levels immediately adjacent to (up to “tens of feet from”) the river bank. That kind of localized effect is captured in our bounding analysis of bank storage, described in the following section.

Methodology

A bounding analysis was conducted to determine whether the potential decrease in bank storage cooling effects could be a concern requiring more detailed analysis for the Windy Gap

Firming Project EIS. Darcy's Law[2] was applied to generate bank storage flow rates to the river on a daily basis over a range of assumed conditions/parameter settings. The analysis focused on the most sensitive reach of the Colorado River in terms of temperature concerns -- Windy Gap Reservoir to a point just upstream of the Williams Fork confluence. The bounding analysis was based on daily data and the years of most interest included:

- The year with the largest predicted difference in flow between EC and Alt2 (1952)
- The year with the largest predicted stage difference between EC and Alt2 (1969)

The hydrographs for EC and Alt2 for these two years are presented in Figure 3.

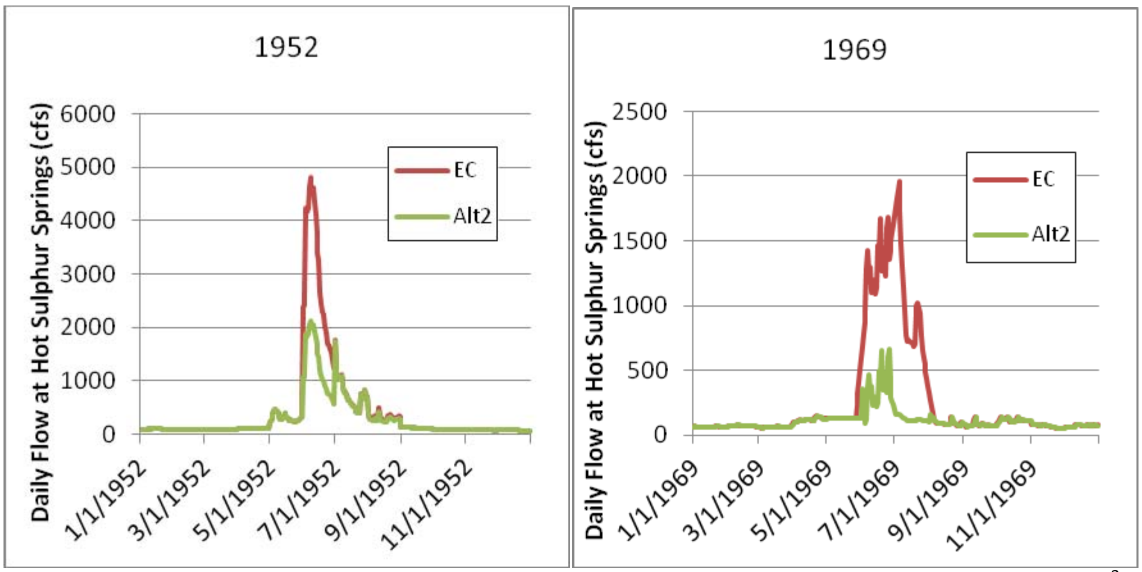

Figure 3. Hydrographs for Existing Conditions and the Proposed Action for 1952 and 1969.[3]

Conservative assumptions were applied to maximize the estimate of the bank storage temperature change effect to provide an upper bound assessment of the potential significance of the effect. The following assumptions and were applied to the calculations:

---

[2] Darcy's Law is an equation often applied to groundwater calculations that relates flow rate through a uniform porous medium to cross-sectional area, saturated hydraulic conductivity, and gradient.

[3] The large differences in flow at Hot Sulphur Springs between Existing Conditions and Alternative 2 in 1952 and 1969 are due to differences in the timing and magnitude of spills from Granby Reservoir as well as differences in the amount of Windy Gap water pumped. In 1952, Granby Reservoir spills in June and July and there is no Windy Gap pumping those months under Existing Conditions, whereas under Alternative 2 there is no Granby Reservoir spill in June and Windy Gap water is pumped that month. Similarly in 1969 Granby Reservoir spills in June and July and there in no Windy Gap pumping in those months under Existing Conditions, however, under Alternative 2 there is no spill in June and July and Windy Gap water is pumped. Differences in the timing and magnitude of spills create differences in flows between the two scenarios that exceed 600 cfs, which is the decreed capacity of the Windy Gap diversion.

- **Initial Conditions** – Daily calculations were initiated at the peak flow rate and stage for each year simulated. This occurs in early June for 1952 and 1969. It was assumed that the bank storage head matched the peak flow rate at this point in time.
- **Water Volume in Bank Storage** – The volume of water stored in the bank at any given time (and therefore available for flow back to the river, in accordance with Darcy's Law) was defined by assumed values for depth, shape, length, and specific yield of the bank.
    - **Depth** – Based on professional judgment, the perpendicular distance of influence of bank storage in this reach is expected to range from several feet to tens of feet. However, to be conservative, bank depth was assumed to be 100 ft from the river's edge on each side. This corresponds to a distance more than twenty times the maximum river stage observed in the years evaluated (1954 and 1969).
    - **Shape** – As shown in Figure 1, the cross-sectional shape of the bank stored volume of water is likely to have sloped sides; however, as another conservative assumption, the bank was allowed to fill in a box shape to the river stage height at the assumed river depth.
    - **Length** – The entire length of the river between Windy Gap Reservoir and the Williams Fork was assumed to exhibit bank storage cooling. This assumption overestimates the extent expected to exhibit bank storage cooling behavior because it includes Byer's Canyon. Byer's Canyon comprises roughly 15% of the length of this reach and is characterized by granitic walls, which could be expected to provide little bank storage.
    - **Specific Yield** – A value of 0.2 was assumed to represent the specific yield (drainable fraction of the bank =porosity minus field capacity). This value is typical of fine sand (Fetter, 1994). Finer material such as silt and clay have lower values.
- **Evapotranspiration Losses** – It was conservatively assumed that the volume of water stored in the bank exhibits no losses to evapotranspiration, though there is extensive vegetation along the river in this reach (with the exception of Byer's Canyon).
- **Loss to Groundwater** – It was conservatively assumed that the volume of water stored in the bank exhibits no losses to alluvial groundwater while it is being "stored" for return to the river.
- **Cooling Effect** – Following estimation of volumetric contribution of bank storage, an estimate of the temperature difference in bank stored water and river water is needed to estimate a cooling effect. There is limited literature quantifying the cooling effects of bank storage; however, one study calculated a theoretical maximum cooling of the water in the streambed matrix of 0.64 °C relative to the stream temperatures (Anderson et al., 2010). Another study found hyporheic cooling to reduce water in the Willamette River passing through the hyporheic zone by up to 2.7°C (Seedang et al., 2008). While hypohreic cooling is expected to be much greater than bank storage (due to depth and contact with cooler groundwater), a temperature difference of 2.7 °C between the water stored in bank storage and the river was assumed.
- **Hydraulic Conductivity** – Hydraulic conductivity values for the bank material were varied over a wide range of possible material types, from 10 ft/day (sand) to 0.01 ft/day (silt/loam). The wide range of values was applied to assess the maximum bank storage effect in light of the fact that we could not locate site-specific hydraulic conductivity data.

Applying these initial conditions and conservative assumptions, upper bounding values of bank storage effects were quantified and assessed on a daily basis for EC and Alt2 for the years with the largest daily flow difference (1952) and the largest stage difference (1969). The following discussion of findings presents upper bounding estimates of bank storage flow rates, response timing, and cooling effects.

Findings

What Flow Rates Could Bank Storage Contribute to the River?

Using the approach and conservative assumptions described above, upper bounding estimates of potential flow rates from bank storage to the river were estimated for EC and Alt2 for 1952 (year with the largest flow difference) and 1969 (year with largest stage difference). These flow rates are combined estimated effects for the reach of the river in focus (Windy Gap to Williams Fork), which is approximately 14 river miles. Results are shown in Figures 4 and 5. Two estimates are presented for each year and scenario, showing the flow rates and patterns associated with a range of assumptions for the uncertain parameter - bank hydraulic conductivity. Figures 4 and 5 show flow rates ranging from zero to 19.3 cfs (Alt2 1952 on August 1, assuming K=10 ft/day) over this roughly 14 mile reach of the river. Flow rates for the K=10 assumption reflect rapid responses to changes in stage on the hydrograph. Flow rates are smoother and lower for the lower hydraulic conductivity (K=0.01 through K=0.5) assumption, reflecting slower responses to changes in river stage.

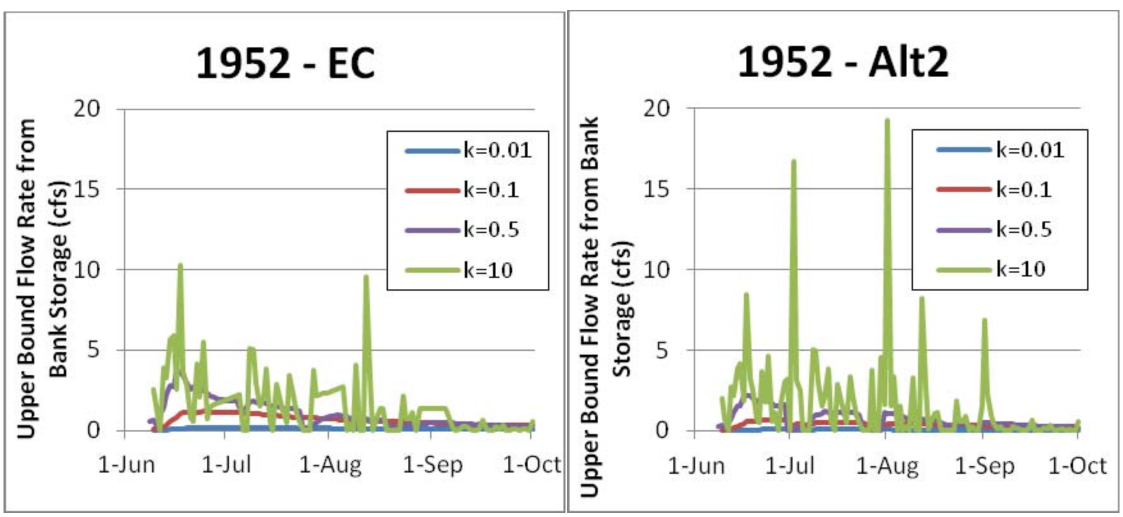

Figure 4. Bounding Calculation Bank Storage Flow Results for High and Low Hydraulic Conductivity Values –Simulated EC Hydrology for 1952 (Largest Flow Rate Differences*).*
K is Hydraulic Conductivity in ft/day.

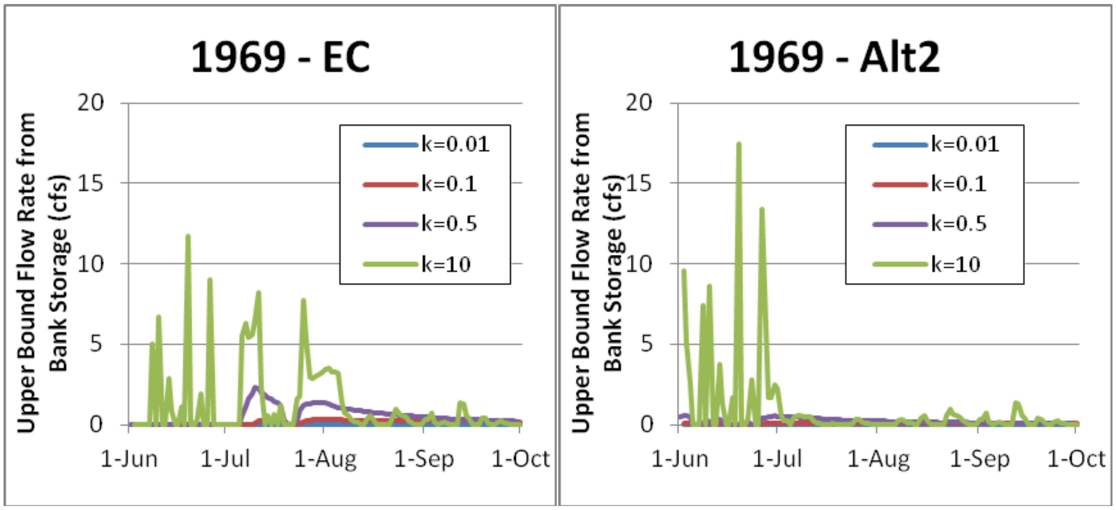

Figure 5. Bounding Calculation Bank Storage Flow Results for High and Low Hydraulic Conductivity Values –Simulated EC Hydrology for 1969 (Largest Stage Differences*).*
K is Hydraulic Conductivity in ft/day.

What is the Timing of Bank Storage Flows Following a Change in River Stage?
As discussed above, bank storage flow to the river occurs following a drop in river stage. The timing/duration of that response is largely controlled by the assumed hydraulic conductivity in the calculation. When a high hydraulic conductivity is applied (10 ft/day), the bank drains faster (at a higher flow rate to the river), and the water level in the bank generally keeps up with the river stage drop on a daily time step. Likewise, at high hydraulic conductivity, a highly variable stage over the time period in question greater bank storage effects. At low hydraulic conductivities (0.5 to 0.01 ft/day evaluated), a lag in response to the change in stage can be simulated; however, the flow rate to the river is much lower.

Figure 6 (EC) and Figure 7 (Alt2) present the range of bank storage responses estimated by these bounding calculations for 1952 and 1969, given hydraulic conductivity values ranging from 10 ft/day to 0.01 ft/day. The calculated bank storage flow rates are presented in these figures as percent contributions to river flow rates. This presentation of results allows for a more direct assessment of the potential effect of bank storage flows on the river, as compared to the presentation of bank storage flow rates in Figures 4 and 5. High hydraulic conductivity values lead to rapid return of bank storage water to the river (within days), as indicated by the spikey pattern of percent contribution to river flow over time. Low hydraulic conductivity values extend the time it takes to return bank storage water to the river; however, the tradeoff is a much lower flow rate of return.

In short, the greatest bank storage effects in June, July, and August occur assuming high hydraulic conductivity, corresponding to short term responses to stage changes. This finding is in agreement with the technical literature that largely focuses on short duration bank storage temperature effects in response to rapid stage changes induced by reservoir operation (e.g., Gerecht et al., 2010) and temperature buffering of urban runoff or low-order streams (e.g., Anderson et al., 2010 and Constanz, 1998).

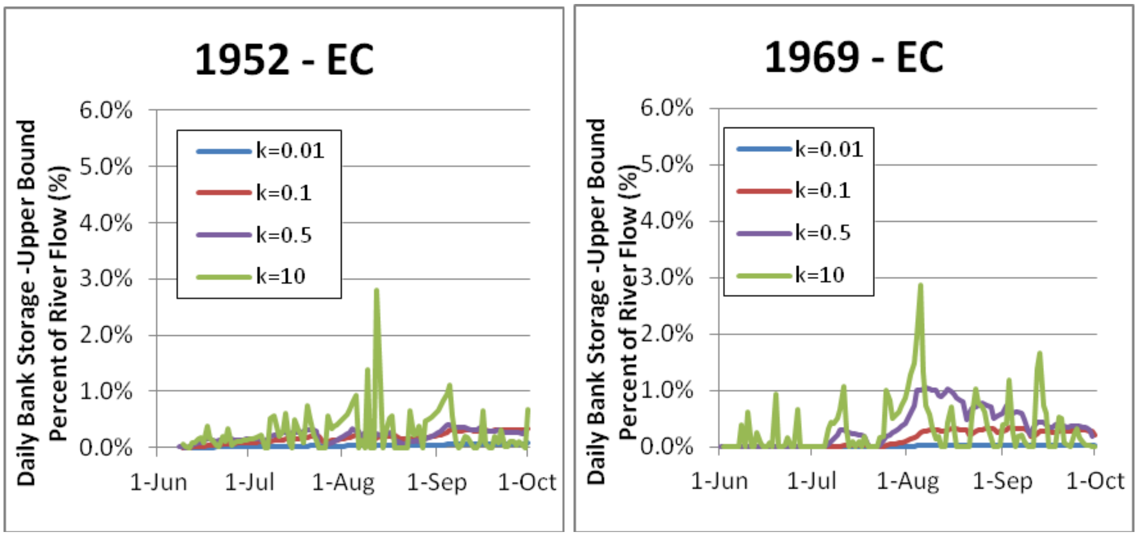

Figure 6. Estimated EC Contribution of Bank Storage to Total Estimated River Flows as Percent of River Flow. *K is Hydraulic Conductivity in ft/day.*

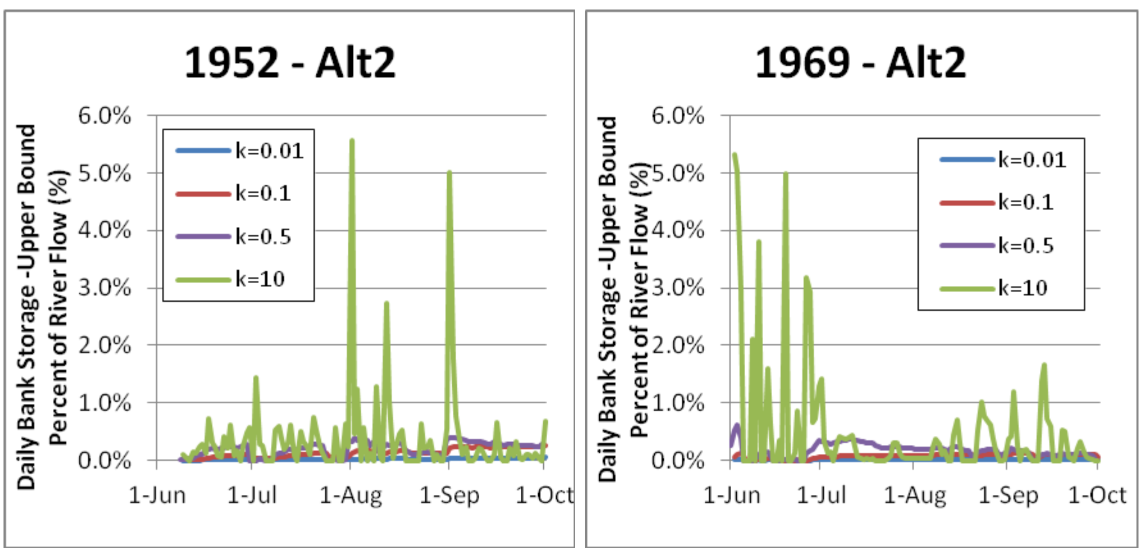

Figure 7. Estimated Alt2 Contribution of Bank Storage to Total Estimated River Flows as Percent of River Flow. *K is Hydraulic Conductivity in ft/day.*

What is the Upper Bound Percent Contribution of Banks Storage Flow Rates to the River for EC and Alt2?

Figures 6 and 7 present the upper bound estimates for daily flow rates from bank storage to the river, expressed in terms of percent of river flow on the given day. The largest estimated percent flow rate contribution of bank storage to the river for EC was estimated as 2.9% on August 5, 1969 (using K=10 ft/day), and the largest percent flow rate contribution of bank storage to the river for Alt2 was estimated as 5.6% on August 1, 1952 (using K=10 ft/day). Focusing on the critical time of the year for river temperatures, typically July and August, we looked for the greatest difference in bank storage effects between EC and Alt 2 (greatest reduction in bank storage percent flow contribution for Alt2 relative to EC). The greatest difference between EC and Alt2 was calculated on August 5, 1969 (using K = 10 ft/day), with a conservatively estimated 2.8% contribution of bank storage for EC and less than 0.03% contribution of bank storage for Alt2. Thus, using very conservative assumptions, the maximum daily difference in bank storage flow between EC and Alt 2 (relative to river flow) is low (<3%). The corresponding potential difference in cooling effects is discussed in the following subsection.

What are the Upper Bound Bank Storage Cooling Effects for EC and Alt2?
Focusing on the assumed hydraulic conductivity that provided the highest flow rate and percent contribution to river flows (K=10 ft/d), estimates of the cooling effect of this process were generated. As described above (Methodology - cooling effect assumptions), bank storage flows were assumed to have been cooled by 2.7°C relative to river water temperatures. The resulting calculated cooling effects for EC and Alt2 for 1952 and 1969 are presented in Figure 8.

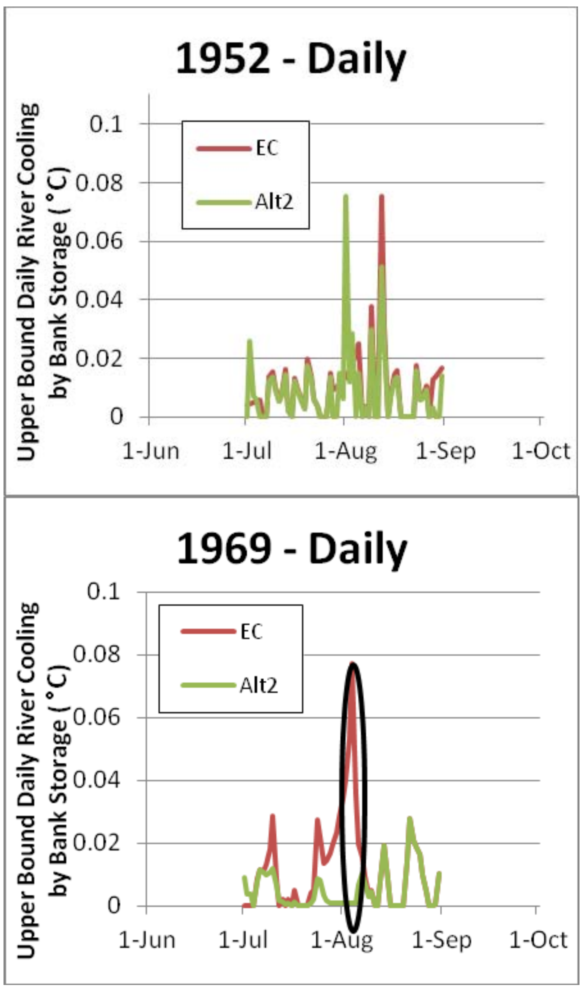

Figure 8. Daily Upper Bound Cooling Estimates for EC and Alt 2 – 1952 and 1969.

The greatest upper bound estimate of river cooling resulting from bank storage effects is less than 0.14°C (in June for Alt2). In July and August, the greatest upper bound cooling effect is estimated to be 0.077°C for EC on August 4, 1969. This date, circled on Figure 8, is also the date of the largest estimated decrease in cooling effects from EC to Alt2 (also 0.076°C). For perspective, the estimated maximum change in potential effect is less than the reported accuracy of the temperature recording devices (±0.2 °C; Personal Communication with Jane Tollett, GCWIN, 2/21/2011).

Conclusion

The projected changes in the cooling effect of bank storage associated with the WGFP would have a negligible effect on water temperature in the Colorado River. The results of this analysis will be included in the final EIS, but the potential effects are of such a small magnitude that bank storage cooling would not be explicitly modeled in the dynamic temperature modeling of the Colorado River.

References

Alley, W.M., Healy, R.M., LaBaugh, J.W., and Reilly, T.E. 2002. Flow and Storage in Groundwater Systems. Science. Vol. 296 no. 5575 pp. 1985-1990.

Anderson, W.P., Evans, D.G., and Storniolo, R.E. 2010. American Geophysical Union, Fall Meeting 2010, Abstract #H31C-1023.

Constanz. W. 1998. Interaction Between Stream Temperature, Streamflow, and Groundwater Exchanges in Alpine Streams Water Resources Research , Vol. 34, no. 7, pp. 1609–1615, July.

Fetter, C. W. 1994. Applied Hydrogeology, 3rd ed. Upper Saddle River, NJ: Prentice Hall, Inc.

Gerecht, K., Cardenas, B., Guswa, A.J., Sawyer, A.J., Swanson, T., and Nowinski, J.D. 2010. Hyporheic Flow and Heat Transport Within a Bed-to-Bank Transect of a Large Regulated River, Colorado River, Austin, TX. American Geophysical Union, Fall Meeting 2010, abstract #H21B-1049.

Seedang, S., Fernald, A.G., and Landers, D.H. 2008. Economic Analysis of Water Temperature Reduction Practices in a Large River Floodplain: An Exploratory Study of the Willamette River, Oregon, River Research and Applications, Wiley Interscience.

USBR. 2007. Windy Gap Firming Project Water Resources Technical Report. Prepared by ERO Resources Corp and Boyle Engineering for the U.S. Department of the Interior Bureau of Reclamation Great Plains Region, December.

USGS. 1998. Groundwater and Surface Water; A Single Resource. USGS Circular 1139. Prepared by: T.C. Winter, J.W. Harvey, O.M. Franke, W.M. Alley.