RECLAMATION

Managing Water in the West

Windy Gap Firming Project

Bounding Analysis of Advective Groundwater Temperature Effects

U.S. Department of the Interior
Bureau of Reclamation
Great Plains Region

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Bounding Analysis of Advective Groundwater Temperature Effects

Windy Gap Firming Project

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Introduction

EPA has expressed concern that the Windy Gap Firming Project (WGFP) proposed action may result in reductions in recharge to the alluvial aquifer along the Upper Colorado River, which may, in turn, reduce advective groundwater flows back to the river, affecting river temperatures. The river reach in question is between Windy Gap Reservoir and Williams Fork on the Colorado River, the critical reach in terms of river temperature issues. 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 recharge of alluvial groundwater. To further support this analysis, this memo also presents a review of 47 years of daily disaggregated hydrologic modeling results, evaluating simulated effects of the proposed WGFP alternative (Alt2) on peak river stages and on the frequency of out-of-bank flow conditions. Photos of recent 2011 high flow conditions along the river are also presented to support the conceptual understanding of the nature of overbank flow in this reach.

Findings

Recent river observations, a review of hydrologic simulation results, and a bounding analysis were compiled to assess the potential magnitude of WGFP effects on advective groundwater cooling of the river during the critical river temperature months of July and August. The year of greatest simulated peak stage difference was evaluated in the bounding analysis; and a range of conservative assumptions, designed to maximize the estimated potential effect of a reduced peak stage on advective cooling, were applied. The following conclusions can be drawn from this analysis:

- The bounding analysis provided an upper bound estimate of < 0.08°C of lost cooling effect for the year with the largest estimated stage difference due to the WGFP proposed alternative.
- While WGFP will reduce peak river stages below Windy Gap reservoir in some years, this bounding analysis shows that the potential effect on advective groundwater cooling later in the season (during the critical temperature months of July and August) would be negligible.
- Of the 47 years of daily disaggregated hydrologic simulation results reviewed, overbank conditions would occur at the Below Windy Gap gage under existing conditions in 22 years. Of those 22 years, overbank conditions would not occur in 4 years due to the WGFP proposed alternative.

Advective Groundwater Temperature Effects – Defined

This section defines the concept of advective groundwater cooling effects. Advective groundwater 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 advective groundwater cooling and the limits of this analysis:

- Groundwater advection,

- Bank storage, and
- Hyporheic flow

Groundwater advection is a widely recognized mechanism of river cooling. Groundwater advection to the river is the mechanism by which groundwater flows into the river, driven by the pressure head of the adjacent water table (Figure 1). 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. River cooling by groundwater advection is expected to be occurring in the focus reach of the Upper Colorado River.

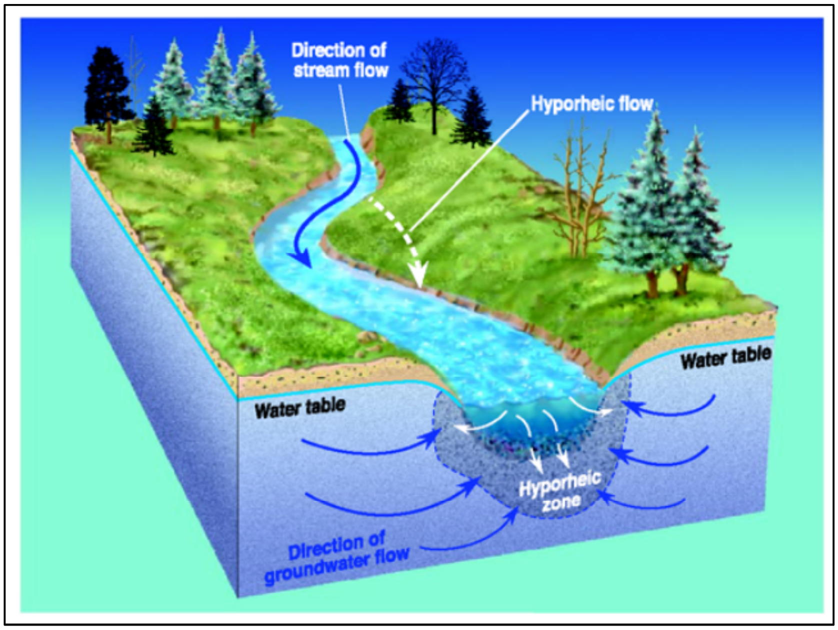

Figure 1. Advective Groundwater and Hyporheic Flow (Image from Alley et al., 2002)

Irrigation return flows can also enter the river through this mechanism of groundwater advection; however, this phenomenon is distinct from the concern identified by EPA. Irrigation return flows are not expected to change as a result of WGFP proposed alternative. Further, irrigation return flows tend to have a warming influence on surface water in hot months of the year, in contrast to the cooling effect of advective groundwater, which is the focus here.

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 2). 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. Potential changes in bank storage cooling effects attributable to WGFP were determined to be insignificant (<0.1 °C) by a bounding analysis (Hydros Bounding Analysis of Bank Storage Temperature Effects Memo to USBR, June 21, 2011).

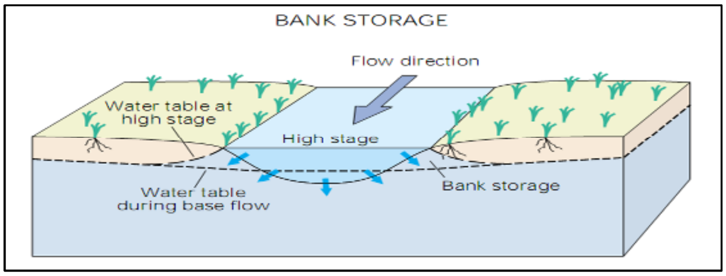

Figure 2. Bank Storage (Image from USGS, 1998)

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 1).

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 function of geomorphology. River cooling by hyporheic flow is expected to be an important mechanism in the focus reach of the Upper Colorado River. No substantive changes to geomorphology (e.g., channel width, depth, and aggradation/degradation) in this reach are anticipated. Streamflow in the Colorado River changed substantially after construction of the C-BT Project and Granby Reservoir began storing water in 1949. However, over the last six decades, the river channel has remained stable despite changes in the timing and quantity of flows. The form and structure of the channel, banks, and floodplain have changed very little. The river has continued to convey sediment without aggradation or degradation of the stream channel. The Upper Colorado River is a morphologically stable stream. The review of aerial photographs as well as an analsysis of the timing and frequency of various channel maintenance flows under the alternatives is presented in the FEIS to further support this. As such, hyporheic cooling can be expected to be insignificantly changed by the proposed action.

Conceptual Understanding of Groundwater–River Interactions

The Upper Colorado River is a high mountain river, serving as a conduit for water to lower elevations. As such, the Colorado River is at the lowest regional elevation, and groundwater systems in connection with the river would be expected to move toward the river. The river is in

[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.

connection with a shallow alluvial aquifer and may be in connection with the deeper bedrock aquifer as well. The WGFP is not expected to have any effect on the deeper groundwater system. Changes in peak flows in the Colorado could affect the shallow alluvial aquifer, though those effects are expected to be small and very localized (on the order of tens of feet from the river (USBR, 2007; Section 7.2.1). Though any effects are expected to be small, effects on the alluvial aquifer are the focus of this analysis, and the remainder of this conceptual groundwater-river interactions discussion focuses on the alluvial aquifer.

The focus river reach runs through an unconfined alluvial aquifer which may be present over nearly 90% of the reach from Windy Gap to Williams Fork (~12 miles of the 14 mile reach) (Topper et al., 2003). The alluvial thickness varies but is relatively thin. Geology reports indicate that it may range in thickness from less than 10ft up to 100ft (Shroeder, 1995), though the maximum thickness is likely no more than 50ft (Izett, 1968). Where present, the alluvial aquifer extends perpendicular to the river (laterally) between 0ft and 2,500ft, with typical lateral distances from the river's edge on the order of 1,000ft to 1,500ft (Topper et al., 2003). There is little hydraulic conductivity data available for the aquifer, but the aquifer material is expected to be typical of high mountain alluvial aquifers, with inter-bedded materials ranging in permeability from coarse gravels to sands to lenses of silts and clays. As such, flows between the aquifer and the river would largely travel through the coarser materials, where continuous, following paths of least resistance.

Simple schematics of the factors driving flow direction between the river and the alluvial aquifer are presented in Figure 3. Looking at the upper portion of Figure 3, when the river stage is greater than that of the adjacent aquifer, river water recharges the alluvial aquifer. This rate of recharge to the aquifer is limited by the hydraulic conductivity of the aquifer material as well as the lateral extent at which the alluvial aquifer head is lower than the river stage.

As shown on the lower portion of Figure 3, when river stage drops and there is a positive gradient from the alluvial aquifer to the river, the flow direction reverses, and advective groundwater flow to the river occurs. This case is expected to define the conditions in the focus reach of the Upper Colorado River most of the year (generally during times other than during the rising limb snowmelt/runoff hydrograph which typically occurs in June).

The rate of flow between the alluvial aquifer and the river is a function of the difference between head in the aquifer and river stage (gradient) and the hydraulic conductivity of the aquifer. At a high hydraulic conductivity, water could recharge from the river to the aquifer at a higher rate during times of peak river stage (usually June). That same high hydraulic conductivity would also make recharged groundwater return to the river at a higher rate. In other words, in the case of highly-conductive aquifer materials, groundwater that entered the aquifer as recharge from the river would return to the river rapidly as opposed to being held in waiting for weeks or months until the river levels drop and air temperature increases in July or August. In contrast, at lower hydraulic conductivities, recharge to the aquifer would be slower during high river stages, and groundwater advection flows to the river would also be slower once the gradient reverses.

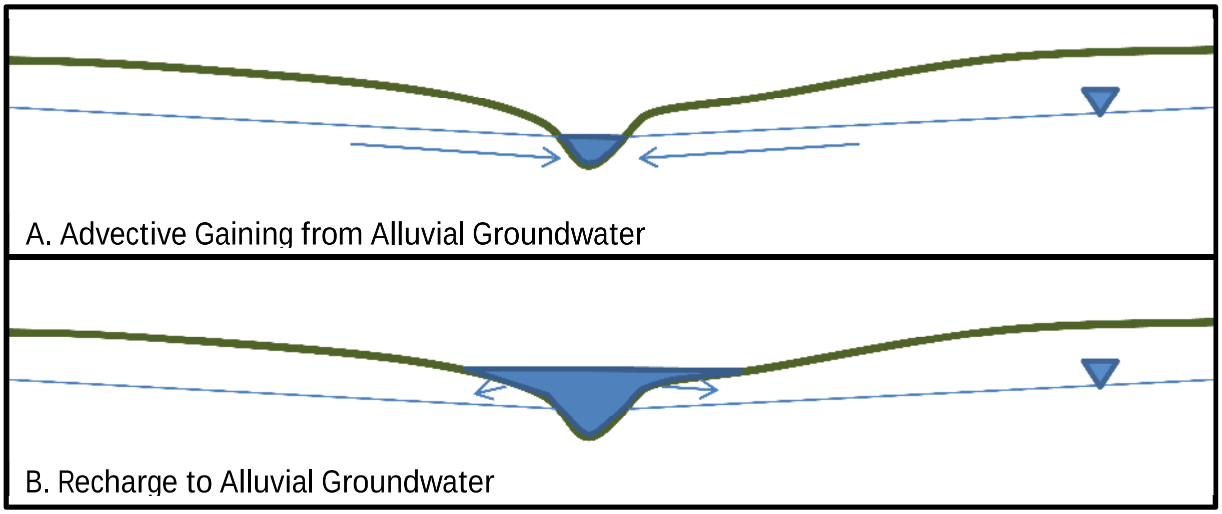

Figure 3. Schematics of Advective Groundwater Loss to River and Recharge from River.

Based on this conceptual picture of the Upper Colorado River, it is expected that if high river stage provides significant amounts of recharge to the alluvial aquifer (typically in June), then the alluvial aquifer will release that water back to the river at comparably high rates, likely lagging only slightly behind receding river stages. As such, the resulting difference in advective groundwater cooling later in the season (July/August) would not be expected to be affected by any WGFP influence on peak stages. Still, a bounding analysis, designed to test the concern, is described below.

Bounding Analysis Methodology

A bounding analysis was conducted to determine whether the potential decrease in advective groundwater cooling effects could be a concern requiring more detailed analysis for the Windy Gap Firming Project EIS or additional data collection. Darcy's Law[2] was applied to generate estimates of the potential <u>difference</u> in advective groundwater flow and cooling to the river between existing conditions and the proposed WGFP alternative (Alt2). A hypothetical scenario was developed to test the EPA-state concern; however, it must be noted that this scenario goes outside of the expected behavior of the system according to the conceptual understanding described above. In this scenario, the groundwater table is assumed to "fill up" to the level of the peak river stage. The groundwater table then holds that level until the low flow/high air temperature period of July/August, receding only locally to establish the gradient between the water table and the lower river stage. This scenario is presented in Figure 4.

[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 hydraulic gradient.

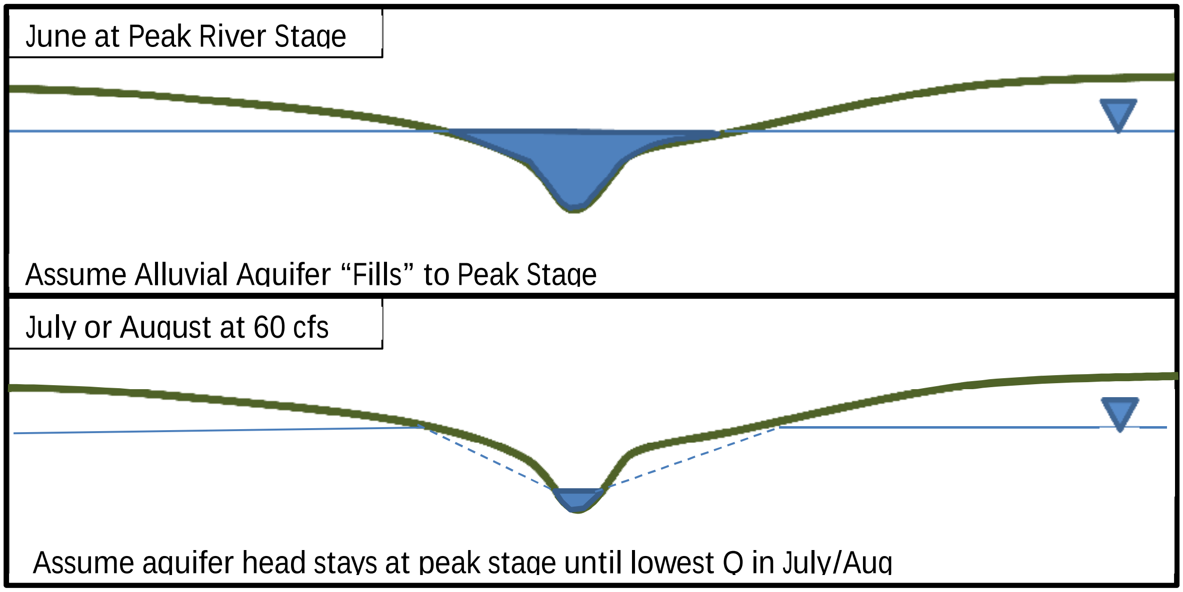

Figure 4. Schematics Describing Hypothetical Hydrologic Scenario of Bounding Analysis

As stated above, this bounding analysis was conducted to evaluate the EPA stated concern; however, this scenario is expected to produce unrealistically large estimates of peak stage influence on advective groundwater flows to the river for several reasons:

1. The lateral extent of influence of the peak river stage on the groundwater table will be limited by the gradient of the groundwater table at the time of peak stage. As such, both volume and extent of recharge would be limited.
2. The recharge rate would be limited by the duration of the peak stage condition and the hydraulic conductivity of the aquifer, resulting in an influence less than that assumed.
3. The recharge from the peak river stage is not expected to continue to have influence on advective groundwater flow to the river weeks or months after the peak stage. With the high hydraulic conductivities needed to get large amounts of recharge from the river to the aquifer, water would return to the river at high rates when the gradient reversed.

The following calculation approach was used:

DARCY’s LAW: $Q = K \cdot \frac{dh}{dx} \cdot Area$, where

Q = Advective groundwater flow rate,
K = Hydraulic conductivity,
dh/dx = the Hydraulic gradient, and
Area = the cross-sectional area of an imaginary vertical face through the bank at the river water line at low river flow

Let Q_{EC} = Groundwater gains for EC at a time of low flow in July/Aug
Let Q_{Alt2} = Groundwater gains for Alt2 at a time of low flow in July/Aug

$$Q_{EC} = K \cdot \frac{dh_{EC}}{dx} \cdot Area$$

$$Q_{Alt2} = K \cdot \frac{dh_{Alt2}}{dx} \cdot Area$$

$$Q_{EC} - Q_{Alt2} = \frac{(K \cdot Area)}{dx} \cdot (dh_{EC} - dh_{Alt2})$$, where

$$(dh_{EC} - dh_{Alt2}) = diff.\, in\ groundwater\ table\ elevation\ between\ EC\ and\ Alt2.$$

To generate the largest estimated difference, the simulated year of daily hydrology with the greatest difference in peak stages between existing conditions and Alt2 (1975) was applied to define the peak stage differences.

To convert the results to a temperature effect, a low flow rate of 60 cfs was assumed in the river at the time of the gains calculation, with a river temperature of 25°C. The groundwater temperature was assumed to be 12°C, based on the best available observations[3].

The calculations will cover the reach from Windy Gap to Williams Fork, assessing a net total difference in cooling effect.

The following assumptions were made to complete this bounding analysis:

- A two order of magnitude range of K values was tested. The low K-value tested was 0.5 ft/d, representing fine sand to silt. This lower K values was tested to evaluate potential effects at lower groundwater advection flow rates to the river. The high K-value tested was 50ft/d, representing coarse sand. Higher K values representing gravels were considered inappropriate as gravels would drain extremely rapidly, contrary to the assumed scenario (coarse sand would also likely drain rapidly; however, it was tested to evaluate the upper end estimate).
- The area through which groundwater can flow to the river was assumed to be 90% of the 14 mile reach of the Upper Colorado River between Windy Gap and Williams Fork x 2 sides x 0.5 ft vertical “seep face” (for July/Aug low flow) [4].
- To establish the hydraulic gradient for the calculation describing gains in July/August, it was assumed that the groundwater table with the receding river stage to a lateral distance of 100 ft from river’s edge at the lower stage. The groundwater head is set to the peak stage elevation (as described in the hypothetical scenario). This value is “dx” in the Darcy’s Law equations and in the schematic in Figure 5. Therefore, dx is set to 100 ft. Smaller dx values give bigger gradients, so a relatively small value was selected, relative

[3] USGS 400456106051801 SB00107802ADB well near river near HSS – 1 temperature measurement at 22ft deep of 12°C.
[4] 0.5 ft at HSS is 77 cfs, which is conservatively larger than the 60 cfs assumption.

to the typical 1,000 to 1,500ft lateral extent of the aquifer. 100 ft was selected because bank storage was evaluated to 100 ft. Given the expected high hydraulic conductivities of alluvial aquifer, the dx value would likely be much higher than 100 ft given the weeks to months of time for the water to drain back to the river between peak stage and July/August.

- dh_2-dh_1= 0.93ft. This corresponds to the largest difference in peak stage elevations at Hot Sulphur Springs (in the middle of the focus reach) predicted by the daily disaggregated hydrology model. The year of the biggest predicted difference is 1975. This parameter is also shown on Figure 5.
- To calculate loss in cooling effect, low flow conditions were assumed in the river to maximize the results and better test the EPA-stated concern. 60cfs was assumed to be the river flow at the time of the groundwater gain calculation (July/August) for both Alt2 and EC.

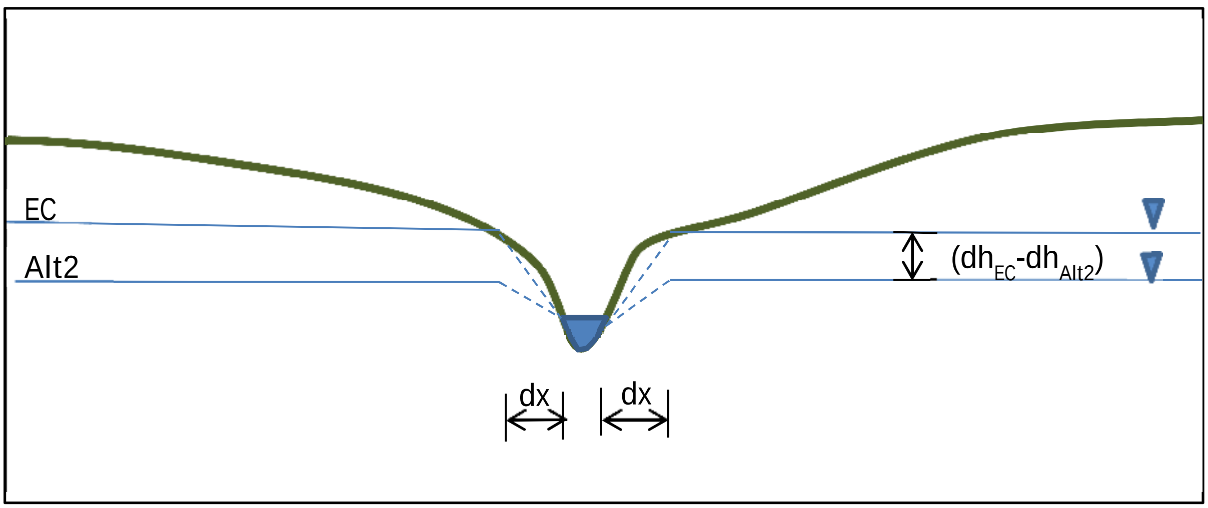

Figure 5. Schematic of Existing Conditions and Alt2 in Hypothetical Scenario.

Bounding Analysis Results

Applying the methodology and assumptions described above, the bounding analysis calculations were completed to evaluate the difference in advective groundwater flow and corresponding cooling effects between existing conditions and Alt2, for the hypotheical scenario described. As stated previously, this scenario does not match the site conceptual model for groundwater, but was tested to evaluate EPA's concern about WGFP effects on peak stages (June) affecting groundwater advective cooling later in the season (July/August).

Calculations indicate that, for the assumed scenario on the year of the greatest peak stage difference, net advective flow rates to the river could decrease by as much as 0.36 cfs over the 14 mile focus reach due to WGFP Alt2. This corresponds to <0.6% of the flow at the 60 cfs condition. The effect for the lower hydraulic conductivity value tested, (0.5 ft/d), provided a difference in advective groundwater flow of only 0.004 cfs over the 14 mile reach.

To evaluate the 0.36 cfs value in terms of reduced cooling effects, this advective groundwater was assigned a temperature of 12°C, based on the best available groundwater observations in the area. The river flow was assumed to be 60 cfs, and the river temperature was assumed to be 25°C, corresponding to observed peak temperatures on hot July/August days with low flow rates in the Upper Colorado River. The resulting difference in cooling effect attributable to the 0.36 cfs value was estimated to be 0.08°C. Even if the peak stage difference were doubled, the net effect would only be 0.16°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).

Peak Stage Differences and Frequency of Overbank Conditions

Daily disaggregated hydrologic simulation results were reviewed to evaluate the effects of the WGFP on peak stages and the frequency of overbank conditions. Daily flow results below Windy Gap were analyzed to determine the number of days flows exceeded 765 cfs during the study period from 1950 through 1996. 765 cfs is identified by the USGS as the bank-full value at the gage below Windy Gap (Craig, 2010). Direct effects data were used for the Existing Conditions and Alt2 scenarios.

Typically, flows below Windy Gap are higher under Existing Conditions than under Alt2 because Windy Gap diversions are higher with firming storage on-line. As shown in the Table 1, flows exceeded 765 cfs for a total of 820 days under Existing Conditions versus 646 days under Alt2. The maximum difference in the number of days flows exceeded 765 cfs was 45 days in 1969. The difference in the number of days flows exceeded 765 cfs was greater than 10 days in 5 years (1957, 1958, 1969, 1988, and 1995). There was no difference in the number of days greater than 765 cfs in 29 years out of the 47-year study period.

Table1. Comparison of Simulated Days of Flow Greater than Bank Full Below Windy Gap.

WATER YEAR	Existing Conditions # Days Flow > 765 cfs	Alt2 # Days Flow > 765 cfs	Difference
1950	0	0	0
1951	0	0	0
1952	41	34	-7
1953	0	0	0
1954	0	0	0
1955	0	0	0
1956	0	0	0
1957	41	28	-13
1958	43	24	-19
1959	0	0	0
1960	2	0	-2
1961	8	8	0

WATER YEAR	Existing Conditions # Days Flow > 765 cfs	Alt2 # Days Flow > 765 cfs	Difference
1962	73	72	-1
1963	0	0	0
1964	0	0	0
1965	1	1	0
1966	0	0	0
1967	0	0	0
1968	0	0	0
1969	45	0	-45
1970	42	40	-2
1971	47	44	-3
1972	8	0	-8
1973	52	52	0
1974	28	26	-2
1975	0	0	0
1976	0	0	0
1977	0	0	0
1978	0	0	0
1979	2	0	-2
1980	40	36	-4
1981	0	0	0
1982	0	0	0
1983	70	65	-5
1984	77	74	-3
1985	31	30	-1
1986	54	54	0
1987	0	0	0
1988	22	0	-22
1989	0	0	0
1990	0	0	0
1991	0	0	0
1992	0	0	0
1993	0	0	0
1994	0	0	0
1995	43	10	-33
1996	50	48	-2

Recent Observations of Overbank Flows

To support conceptual understanding of over bank flows in the Upper Colorado River, observations from a recent site visit are presented here. Observations of the Colorado River from below Granby Reservoir to Kremmling on June 16, 2011 indicate limited lateral surficial extent out of bank flooding at high flows (photos are attached to this memo). The Colorado River at the Windy Gap Gage, which is located downstream of Windy Gap Reservoir, was flowing at a rate of about 3,500 cfs at a stage of about 6.3 feet on the morning of June 16, 2011 (USGS, 2011). Flows of 3,500 cfs have a recurrence interval of about 6 years based on historical data collected at the Hot Sulphur Springs gage located a few miles downstream of the Windy Gap gage. Bank full flow at the Windy Gap gage has been calculated to occur at a stage of 4.15 feet, or about 765 cfs ±10 percent, according to the U.S. Geological Survey (Craig, 2010). Thus, the river was 2.2 feet higher than bank full at the Windy Gap gage on June 16th.

The Colorado River above the Williams Fork on June 16th was observed to be horizontally out of its banks by about 5 to 20 feet at most locations. Greater out-of-bank flooding only occurred where structures constricted river flow, resulting in greater inundation of areas upstream of the constrictions. Examples include Photo 5, an area of broader flooding above a railroad trestle, and Photo 13, where water backed up behind a bridge crossing (photos attached to this memo). Photo 14, near Kremmling, shows broader river flooding of adjacent lands where the topography is flatter, and where bridge constrictions and the narrow Gore Canyon mouth back up the river in the Kremmling area.

These observations indicate that the Colorado River between Windy Gap Reservoir and the Williams Fork experiences very little flooding in terms lateral surficial movement outside of the active channel even at higher flow rates. As such, a conceptual model of frequent floodplain inundation and pooling is not appropriate. In any case, on the aquifer scale, aquifer recharge is expected to be driven by the difference in river stage and alluvial pressure head, as evaluated in the bounding analysis in this memo.

Summary

To evaluate EPA's concern that WGFP effects on peak river stages (typically in June) could affect river cooling by reducing advective groundwater flow in critical temperature months (July/August), a consideration of recent observations, a review of the daily hydrologic modeling results, and a bounding analysis were conducted.

The WGFP is expected to reduce peak river stages is some years. Focusing on over bank conditions, a review of the daily hydrologic model results showed that the WGFP proposed alternative would reduce the number of years with out of bank conditions in less than 10% of the simulated years (from 22 of 47 years for existing conditions to 18 of 47 years for Alt2).

Based on the conceptual understanding of the system, recharge of the alluvial aquifer is expected to occur primarily during the rising limb of the annual hydrograph (peak flows typically occurring in June). If high river stage provides significant amounts of recharge to the alluvial aquifer during peak flows (typically in June), then the alluvial aquifer should release that water back to the river at comparably high rates, likely lagging only slightly behind receding river stages. As such, the resulting difference in advective groundwater cooling later in the season (July/August) would not be expected to be affected by any WGFP influence on peak stages. Still, a bounding analysis, designed to test the EPA concern was performed.

The bounding analysis did not attempt to evaluate the magnitude of gains from the alluvial aquifer or the degree of cooling attributable to groundwater. Instead, this analysis looked at an extreme hypothetical scenario to provide an upper bound for the possible difference in the groundwater advective cooling effect attributable to WGFP pumping. The analysis indicated that, even if the aquifer could hold recharge from river peak stages for one or two months (until July or August) the potential difference in effect on river temperatures is less than 0.08°C in the year of the greatest estimated peak stage differences (existing conditions vs. Alt2).

In further support of the conclusions presented here, the calibrated and validated Dynamic Temperature Model developed for the Upper Colorado River has shown that the strongest controls on river temperature for this reach are not advective groundwater, but instead river flow rate, air temperatures, and solar radiation. Of these, WGFP will affect river flow rate, including flows during the critical temperature months of July and August. The Dynamic Temperature Model was developed and applied to evaluate these effects. Dynamic Temperature Model results are presented in the Upper Colorado Dynamic Temperature Modeling Report (Hydros, 2011) and will be included in EIS.

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Aerial Image: © Copyright 2009 USDA NAIP

P1 Photo point

Photo 1 - Colorado River above Highway 34

Aerial Image: © Copyright 2009 USDA NAIP   P1 Photo point

Photo 2 - Windy Gap Gage looking upstream.

Photo 3 - Windy Gap Gage looking downstream.

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Photo 4 - Colorado River upstream of Hot Sulphur Springs.

Photo 5 - Colorado River upstream of rail road trestle.

Photo 6 - Colorado River upstream of Hot Sulphur Springs.

Photo 7 - Colorado River looking downstream to Byers Canyon.

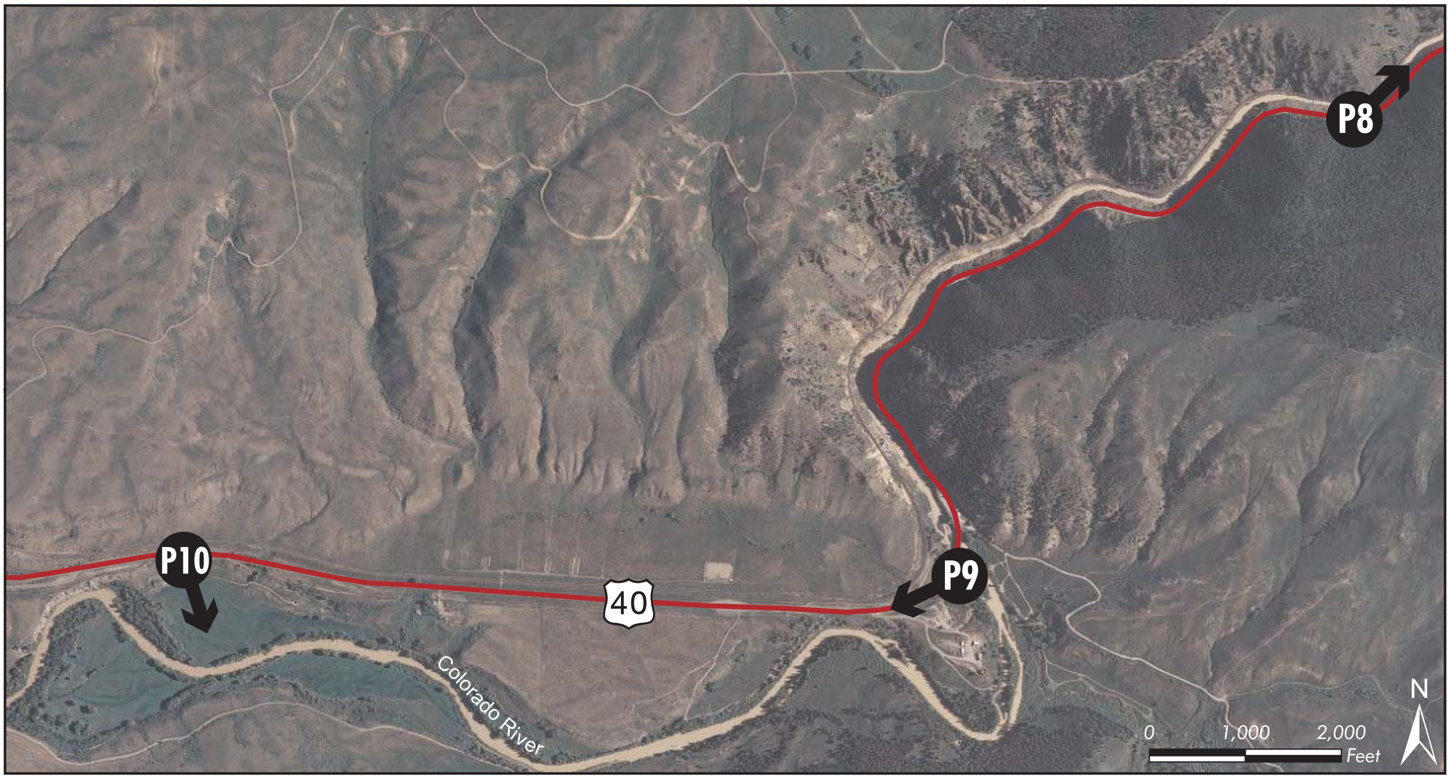

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Photo 8 - Colorado River looking upstream to Byers Canyon.

Photo 9 - Colorado River looking downstream of Byers Canyon.

Photo 10 - Colorado River upstream of Parshall

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P1 Photo point

Photo 11 - Colorado River looking downstream from Breeze

Photo 12 - Colorado River looking downstream below Breeze

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Photo 13 - View of Colorado River flooding upstream of County Road 39 bridge.

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Photo 14 - View of Colorado River flooding upstream of Kremmling.