Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact

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LIST OF ACRONYMS

CBCU	Computed Beneficial Consumptive Use
$CBCU_C$	Computed Beneficial Consumptive Use of Groundwater caused by state-wide Colorado pumping
$CBCU_G$	Computed Beneficial Consumptive Use of Groundwater
$CBCU_K$	Computed Beneficial Consumptive Use of Groundwater caused by state-wide Kansas pumping
$CBCU_N$	Computed Beneficial Consumptive Use of Groundwater caused by state-wide Nebraska pumping
$CBCU_S$	Computed Beneficial Consumptive Use of Surface Water
CWS	Computed Water Supply
CWS_G	Groundwater-related portion of the Computed Water Supply
FSS	Final Settlement Stipulations
IWS	Imported Water Supply Credit
RRCA	Republican River Compact Administration
VWS	Virgin Water Supply
VWS_G	Groundwater-related portion of the Virgin Water Supply

1.0 INTRODUCTION AND OVERVIEW

In 1943 the United States and the States of Kansas, Nebraska, and Colorado entered into the Republican River Compact (the Compact). Among the Compact's stated purposes is "to provide for an equitable division" of the waters of the Republican River Basin. Providing for such equitable division entails determining changes in flow in the River caused by human activities. Since 1943, and especially since the 1970s, a human activity responsible for significant depletions in River flow has been the interception of water by wells that might otherwise have discharged to the River. The primary activity that has caused accretions to flow in the Republican River is the importation of water from the Platte River Basin, which infiltrates into the ground from canals and from irrigation. Determining the magnitude of depletions and accretions to streamflow caused by consumption of groundwater and importation of groundwater entails estimating flow in the River both with and without the activity. The difference between the two estimates is an estimate of the accretions to, or depletions of, streamflow.

Depletions of flow caused by consumption of groundwater used to irrigate crops and for municipal use are collectively called Computed Beneficial Consumptive Use from groundwater ($CBCU_G$). Accretions to streamflow caused by infiltration of surface water imported from the Platte River Basin are collectively called the Imported Water Supply Credit (IWS). The current method[1] for computing $CBCU_G$ and IWS is problematic because the impacts of several individual sets of stresses do not equal the impact of the combination of those sets of stresses (i.e., the sum of the parts does not equal the whole). This phenomenon occurs in many years over several of the sub-basins in the Basin. The problem arises from the assumption that the correct impact of a given stress in a sub-basin can be determined from the difference of a run of the RRCA Groundwater Model in which all stresses are active and one in which the target stress is inactive. This assumption is flawed. This paper explains the nature of the problem, presents a solution to correct it, and evaluates the practical impact on Compact accounting of applying that solution. In summary, application of the solution presented herein will improve the accuracy of Compact accounting and eliminate residual values not currently accounted for under the RRCA Accounting Procedures.

[1] The current method for computing $CBCU_G$ and IWS is explained in Appendix A.

2.0 BACKGROUND

2.1 Overview of the Basin and Hydrologic Interactions

The Main Stem of the Republican River (figure 1) is formed by the confluence of the North Fork of the Republican River and the Arikaree River at Haigler, Nebraska. Both streams rise in eastern Colorado. Four other streams that rise in eastern Colorado also add to the flow of the Republican. The South Fork of the Republican flows through Kansas to join the Main Stem at Benkelman, Nebraska. Frenchman Creek flows directly from Colorado into Nebraska. Beaver Creek flows from Colorado into Kansas and then into Nebraska where it joins Sappa Creek. Sappa Creek and Prairie Dog Creek both rise in Kansas and flow into Nebraska where they join the Republican. Red Willow Creek and Medicine Creek both rise in Nebraska.

The Republican River Basin is underlain by the High Plains Aquifer, a combination of shallow alluvial deposits and bedrock units. The channels of the Republican River and its tributaries are incised into the unconsolidated deposits of the High Plains Aquifer. Water from the aquifer is free to move into the stream channels of the river and vice-versa. Recharge to the aquifer is primarily from infiltration of precipitation, excess irrigation, and seepage from canals.

Pre-development conditions of the hydrologic system were relatively simple. Most of the water that percolated into the ground ultimately discharged to the Republican River or its tributaries; the remainder was discharged to the atmosphere as evapotranspiration by phreatophytes. Flow in river channels consisted of surface runoff and discharge from the ground. Discharge from the ground to river channels is referred to as baseflow. Water that runs off on the surface is expected to have left the basin within a week of falling to the ground. Water moving through the ground probably did not get to the River for many years.[2]

The advent of irrigated agriculture complicated the hydrologic system. Water was diverted from the Republican River and its tributaries for distribution on crops. The diversions reduced flow in the streams, increased discharge to the atmosphere and increased percolation into the ground from excess irrigation (return flow). Percolation into the ground increased water levels in the ground which, in turn, increased evapotranspiration by phreatophytes and discharge

[2] Baseflow can be estimated by observing flow in river channels during fair weather several days after surface runoff has moved downstream.

to rivers. The depletion in streamflow caused by the surface water diversion would occur immediately. The accretion to streamflow caused by return flow would be delayed for years.

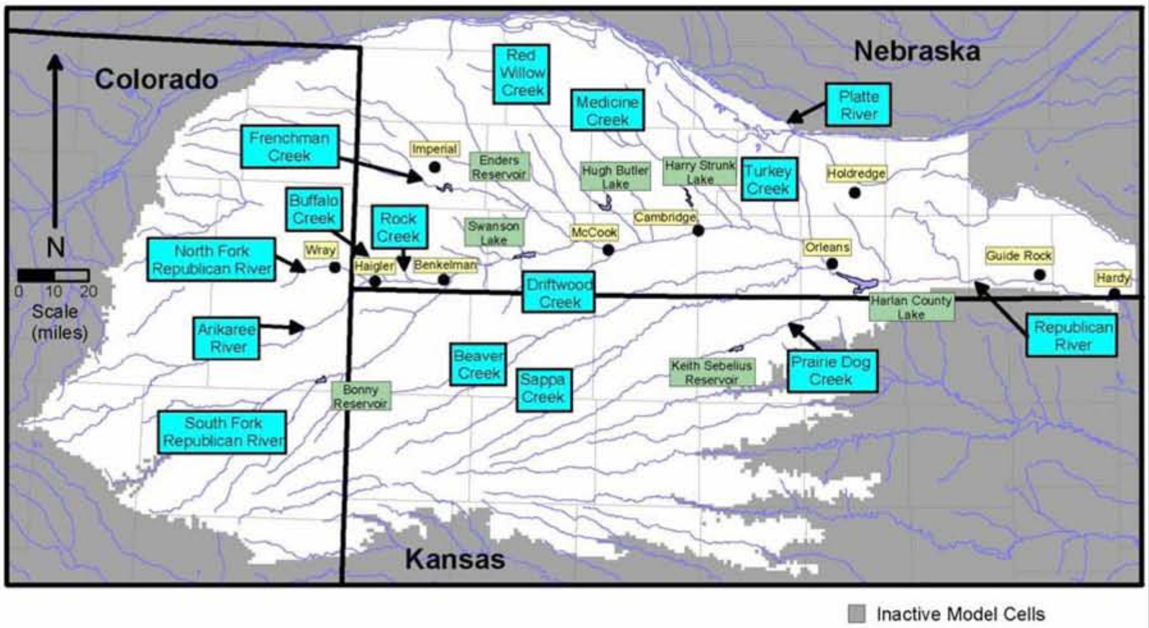

Figure 1. Map showing location of Republican River, tributaries, reservoirs and lakes, and selected towns.

A distinctive feature of the pre-development hydrologic system of the Republican River Basin was movement of groundwater into the basin from the Platte River. There was not a groundwater divide between the Platte Basin and the Republican Basin over a considerable distance. Over that distance, water infiltrated into the ground from the Platte River, moved to the south and discharged to tributaries of the Republican. The northern boundary of the groundwater system associated with the Republican River was the Platte River. Post-development, water diverted from the Platte River and used to irrigate crops south of the Platte River seeped from canals or infiltrated from irrigated fields and percolated into the groundwater system that had been part of the groundwater system that supplied baseflow to the Republican River. That water, imported from the Platte Basin to the Republican Basin, caused a groundwater mound to develop south of the Platte. The crest of the mound then became a groundwater divide between the Platte and the Republican Rivers. Water that percolated south of that divide increased the flow in tributaries to the Republican River especially Medicine Creek and small tributaries to the east of Medicine Creek. It continues to do so. That water, which will be referred to as "mound recharge" is the source of the IWS.

The use of groundwater for irrigation, which became significant in the 1960s, yet further complicated the hydrologic system. Water pumped from the ground for irrigation intercepted flow that would otherwise have discharged to streams, reduced evapotranspiration by phreatophytes, or removed water stored in the ground. Intercepting water that would have otherwise discharged to streams reduced flow in streams. Removing water stored in the ground near a stream may have induced flow from the stream to the ground. Water removed from storage far from streams ultimately reduced flow in the streams but only after a long delay. Although most of the water pumped from the ground for irrigation was consumed, some of it percolated back into the ground as excess irrigation water.

Water enters or exits the saturated groundwater system of the Republican Basin continuously and at an essentially infinite number of points. The mechanism through which it enters may be a result of irrigation application, infiltration of rain or seepage from a canal or river. The mechanism through which it exits may be a result of pumping, removal by plants, or seepage into stream channels. When represented by numerical models, water is treated as if rates are constant over a small time interval and over a small area. Water entering or exiting the groundwater system by a given mechanism over a small time interval and a small area is referred to in this report as a "stress." The time interval is referred to as a "stress period;" the small area is referred to as a "cell."

2.2 Role of the RRCA Groundwater Model and Accounting Procedures

The RRCA Groundwater Model was developed in accordance with the Final Settlement Stipulation (FSS). In his Final Report recommending approval of the FSS, Special Master McKusick reported: "The FFS laid out the parameters for the RRCA Groundwater Model which would, for use in the accounting formulas for administering the Republican River Compact, determine both streamflow depletions caused by groundwater pumping and streamflow accretions resulting from recharge by imported water."[3] The Groundwater Model was developed by representing all major sources and sinks for water in the ground and properties of the subsurface material relating to the transmission and storage of water. It was calibrated so that water levels calculated by the Groundwater Model were consistent with those observed in the ground and net baseflow as calculated at gaging stations was consistent with estimates of baseflow at the gaging stations. The period of record over which such comparisons were made was 1918-2000. It is the baseflow for subsequent years that is calculated by the Groundwater Model and, in accordance with RRCA Accounting Procedures, used to calculate estimates of streamflow depletions caused by pumping and streamflow accretions caused by the importation of water from the Platte River Basin.

3.0 THE PROBLEM AND THE SOLUTION

This section of the report is organized into two parts. In the first part, elements of the current Accounting Procedures are analyzed through examination of several examples. It is shown that, under certain circumstances, the current Accounting Procedures fail to provide the correct values for individual state contributions to streamflow changes that are related to groundwater pumping and water importation. These errors occur when the Groundwater Model predicts that the streams have gone dry. In the second part of this section, Nebraska proposes a corrected procedure that eliminates all of the errors found in the current procedure. The proposed procedure does *not* require modification of the Groundwater Model. Instead, the new procedure uses additional model results, beyond those used in the current procedure, to reduce error and improve the accuracy of the estimates of streamflow accretion and depletion caused by human activity.

3.1 The Problem: Errors in CBCU and IWS

The Compact allocates water in each sub-basin to the states based on fixed percentages of the estimated water supply in a given year. The Accounting Procedures are used to estimate this annual water supply. The annual allocation for a state is determined as a percentage of this estimated annual water supply. The annual allocation for each state is then compared with an

[3] This is somewhat misleading. In fact, the Groundwater Model does not calculate depletions and accretions, but rather net baseflow in stream channels. The Accounting Procedures are used to calculate streamflow depletions and streamflow accretions. The Accounting Procedures use net baseflow as calculated by the Groundwater Model to do so.

estimate of actual water use by that state to determine over or under-utilization of the state's annual allocation for that year. The Accounting Procedures that are at issue in this report do not affect the fixed percentages assigned to each state as defined in the Compact (i.e., do not alter the Compact allocations) but do affect the estimates of water supply and water use. Both the estimated water supply and the estimated annual actual water use are computed using estimates of changes in streamflow that result from groundwater pumping and importation of water. These groundwater-related estimates are derived using the output of the Groundwater Model. The methodology for using this model output is the focus of the analysis in this report.

The current Accounting Procedures divide the Republican River Basin into 12 sub-basins and several segments of the Main Stem. The outlet of each sub-basin or Main Stem segment is defined by an "accounting point." The accounting point is located at a numerical cell in the Groundwater Model. A streamflow is computed at the accounting point at each stress period of a run of the Groundwater Model. This streamflow is more properly called baseflow, since the streamflow reported by the Groundwater Model is the net discharge from the aquifer to the stream. As a result, the Groundwater Model-computed streamflow is not necessarily the actual streamflow at the accounting point, but instead only an estimate of that portion of streamflow attributable to groundwater discharge to the stream. Terminology in the Accounting Procedures (e.g., section III.D.1) is not entirely consistent on the use of streamflow and baseflow. In this report, the net groundwater discharge to the stream will be referred to as "baseflow."

For purposes of the Accounting Procedures, the primary product of the RRCA Groundwater Model is the rate of baseflow at each accounting point at each stress period for the duration of the Groundwater Model run. This direct output of the Groundwater Model is not at issue in this report. Instead, this report provides an analysis of the way in which this model output is used. It is shown that when the Groundwater Model-calculated baseflows drop to zero, assumptions used in the current Accounting Procedures about the characteristics of the Groundwater Model output are incorrect. Under these circumstances the quantities computed using the current procedures detailed in sections III.A.3 and III.D.1 of the RRCA Accounting Procedures and Reporting Requirements do contain significant errors.

Note that the model runs presented here produce slightly different values from those officially adopted by the RRCA.

3.1.1 Accounting for $CBCU_G$

The current Accounting Procedures are described in Appendix C (revised July 27, 2005) of the FSS. An important concept in Compact accounting is Virgin Water Supply (VWS). Definitions and formulas within the FSS and Appendix C make it clear that the working definition of VWS is the water supply or streamflow of the Basin "unaffected" by human activities. To estimate VWS, the Accounting Procedures call for the estimation of Computed Beneficial Consumptive Use (CBCU) and IWS. The CBCU is the streamflow depletion resulting from a specific list of human activities. As noted earlier, IWS is defined as "the accretions to streamflow due to water imports from outside of the Basin as computed by the RRCA Groundwater Model."

The VWS is computed independently for each sub-basin on an annual basis. Considering a sub-basin that does not have any federal reservoirs or imported water supply effects, the VWS is computed as the sum of gage flow, measured at the sub-basin accounting point in the stream and all CBCU in the sub-basin. For purposes of the present analysis, the CBCU is divided into two parts; $CBCU_G$ is the streamflow depletion caused by groundwater pumping and $CBCU_S$ is streamflow depletion caused by surface diversions and other non-groundwater activities identified in the Accounting Procedures.

In the Accounting Procedures the annual gage flows for a given sub-basin are determined by direct measurement at stream gages and the $CBCU_S$ is determined using direct measurements, for example, by tabulation of water actually diverted from streams during the year. The estimation of $CBCU_G$ is complicated by the fact that streamflow depletions in a sub-basin may be affected by groundwater pumping that occurred in earlier years or pumping from wells located in neighboring sub-basins. Hence, direct measurement of $CBCU_G$ is impossible. Instead, $CBCU_G$ is estimated using the results of multiple runs of the Groundwater Model. It is evident from the context of the Accounting Procedures that the intention of the Compact is that this estimated $CBCU_G$ be as close as practical to the true depletion of streamflow in a given year caused by groundwater pumping in all prior years.

In a given sub-basin, $CBCU_G$ may arise as a result of the pumping activity of several states. The current Accounting Procedures call for the separate estimation of the contribution by each state to the $CBCU_G$ for the sub-basin. In this report these quantities will be referred to as state impacts and will be defined using the following notation:

$CBCU_C$ = the contribution to $CBCU_G$ in the sub-basin caused by state-wide Colorado pumping

$CBCU_K$ = the contribution to $CBCU_G$ in the sub-basin caused by state-wide Kansas pumping

$CBCU_N$ = the contribution to $CBCU_G$ in the sub-basin caused by state-wide Nebraska pumping

Using this notation, the Accounting Procedures call for computing the $CBCU_G$ as the sum of individual state impacts, that is, for a given sub-basin and year,

$$CBCU_G = CBCU_C + CBCU_K + CBCU_N . \qquad \textbf{(Equation 1)}$$

If no imported water supply or federal reservoirs are present then the VWS is computed as

$$VWS = Gage + CBCU_S + CBCU_G . \qquad \textbf{(Equation 2)}$$

When federal reservoirs or imported water supply are relevant to the VWS in a sub-basin or Main Stem reach, the computation of VWS is modified, and estimates of change in reservoir storage (ΔS) and IWS are needed. The change in reservoir storage is estimated using reservoir elevation change and is not relevant to the discussion in this report. IWS is estimated using results from the Groundwater Model in a manner similar to that for the $CBCU_C$, $CBCU_K$, and $CBCU_N$. When the IWS is relevant to computation of the VWS, it is included in the computation as

$$VWS = Gage + CBCU_S + CBCU_G - IWS . \qquad \textbf{(Equation 3)}$$

For purposes of the present analysis it is useful to isolate those terms related to groundwater and to define

$$VWS_G = CBCU_G - IWS \qquad \textbf{(Equation 4)}$$

where VWS_G is the groundwater-related portion of the VWS.

Taken together, it is evident that it is the intention of the Compact that, for a given sub-basin and a given year, the $CBCU_G$ be the best estimate of actual streamflow depletion caused by pumping and that $CBCU_C$, $CBCU_K$, and $CBCU_N$ represent the best estimates of each state's contribution to $CBCU_G$. Similarly, it is the intention of the Compact that IWS be computed so that when it is combined with $CBCU_G$ it produces the best estimate of actual VWS_G.

The current Accounting Procedures (see Appendix A) describe computing streamflow depletion for each state (that is, $CBCU_C$, $CBCU_K$ and $CBCU_N$) as the difference in Model-computed baseflow at the accounting point for a "base" condition, with all human activity "on" and a second condition when the target state is "off." Similarly, IWS is computed by taking the difference of baseflows computed for the same "base" condition and baseflows computed when the mound recharge is turned off.

Although not called for by the current Accounting Procedures, a similar procedure can be used to independently compute VWS_G. This is accomplished by subtracting model-computed baseflows when all human activity is active from model-computed baseflows with all human activity absent. This independently-computed value of VWS_G is the best estimate of the impact of all groundwater-related human activity on streamflow and should be viewed as the true value of this property.

Combining equations 1 and 4, the current Accounting Procedures assume that VWS_G can be computed using the individually-computed impacts in a sub-basin ($CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS) as

$$VWS_G = CBCU_C + CBCU_K + CBCU_N - IWS \qquad \textbf{(Equation 5)}$$

Using the independently computed value of VWS_G, it is possible to test the assumption that the individual state impacts have values that combine, according to equation 5, to produce the true value of VWS_G. If the combination of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS on the right side of equation 5 equals (or nearly equals) the independently computed value of VWS_G then the assumption in the current Account Procedures is valid. As will be shown in this report, under some stream drying conditions, the current Accounting Procedures do not produce values that combine to the independently-computed value of VWS_G. This leads to the conclusion that the values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS computed using the current Accounting Procedures are in error.

3.1.2 Hypothetical Example of Flow Components

The issue raised in this report is the way in which the results of the Groundwater Model are used to compute $CBCU_C$, $CBCU_K$, and $CBCU_N$ and IWS, and the failure, under some circumstances, of these computed values to represent accurate estimates of these impacts. To illustrate some of the elements of the current Accounting Procedures, a simple, hypothetical example is presented here. The example includes groundwater recharge from precipitation, discharge of groundwater to a stream, storage of water in the aquifer and streamflow at an accounting point for a hypothetical sub-basin. Groundwater pumping is aggregated to a single well from each of hypothetical states A and B. Streamflow leaves the sub-basin at the accounting point. Flows are presented as volumes (acre-feet) over the course of a year. For illustrative purposes, many of the complicating factors present in the Groundwater Model are removed from the example. The example is presented in figures 2a through 2d, which depict the annual flows in the hypothetical sub-basin under different conditions of human activity.

Figure 2a depicts flows in the absence of human activity. Recharge of 32,000 acre-feet ("ac-ft") reaches the water table, increasing the volume of water stored in the aquifer. At the same time, water discharges from the aquifer to the stream at a rate of 32,000 ac-ft. Under these conditions, the net change in the volume of water in storage is zero. The groundwater that discharges to the stream accumulates along the length of the stream so that the flow that exits the sub-basin at the accounting point is 32,000 ac-ft. The flows in this hypothetical system are balanced with recharge equaling groundwater discharge to the stream. If water is withdrawn by pumping, this balance is disrupted because the pumped water causes a reduction in discharge to the stream, or a decline in aquifer storage, or both.

In figure 2b, it is assumed that state A activates its pumping at a net rate of 60,000 ac-ft. Net pumping is the amount pumped minus return flow. Groundwater pumping by state A reduces the discharge of water to the stream from 32,000 ac-ft to 22,000 ac-ft. The remaining groundwater withdrawal comes from water stored in the aquifer, which is reduced by 50,000 ac-ft. It can be inferred from these values that the impact on streamflow of groundwater pumping by state A is 10,000 ac-ft.

In figure 2c, it is assumed that state A is not operating, but instead state B pumps at a net rate of 40,000 ac-ft. Comparing figure 2a with figure 2c, 15,000 ac-ft of the 40,000 ac-ft of pumping activity by state B causes a decrease in discharge of water to the stream from 32,000 ac-ft to 17,000 ac-ft. The remaining 25,000 ac-ft of groundwater pumping by state B comes from a decrease in the volume of water stored in the aquifer. It can be inferred that 15,000 ac-ft is the appropriate value for the impact on streamflow of the pumping activity of state B.

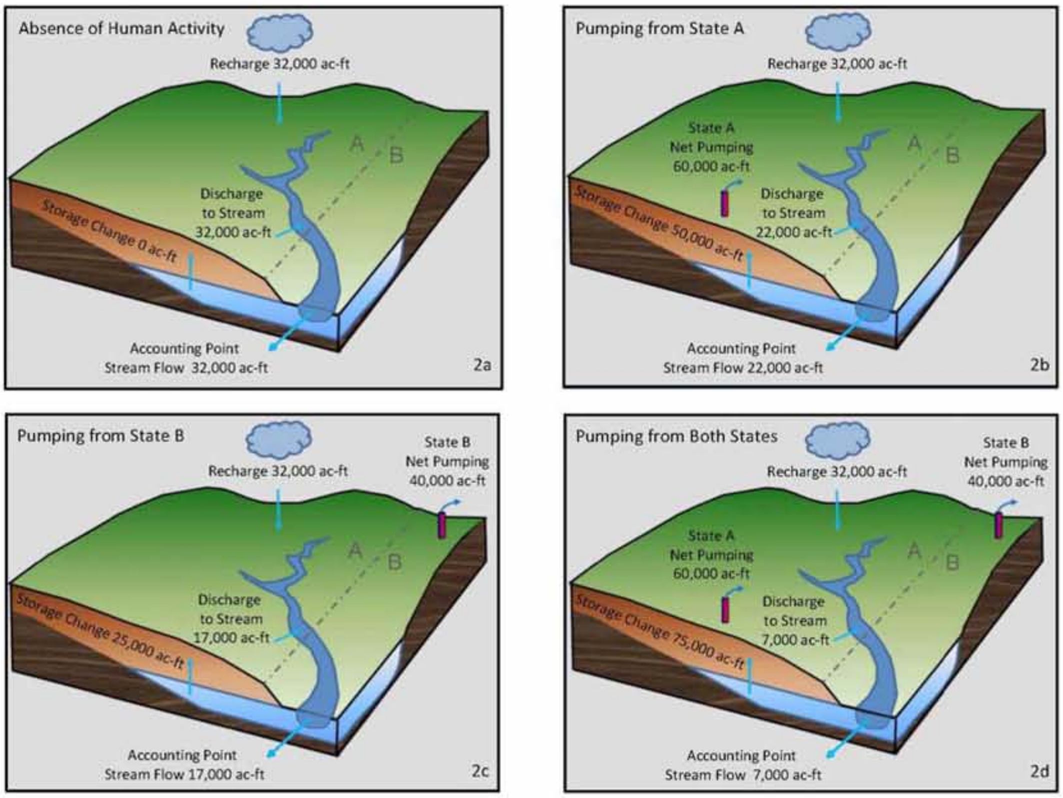

Figure 2. Block diagram showing annual flows in hypothetical sub-basin under different conditions of human activity.

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In figure 2d, it is assumed that both state A and state B are pumping with annual withdrawals of 60,000 ac-ft and 40,000 ac-ft, respectively. When both states pump, their combined impacts produce a reduction in groundwater storage of 75,000 ac-ft and a reduction in discharge to the stream of 25,000 ac-ft. As a result the streamflow at the accounting point is reduced to 7,000 ac-ft when both states are pumping.

Applying the current Accounting Procedures to this example, the impact of state A would be computed as the difference between the streamflow at the accounting point depicted in figure 2d and Figure 2c. That is, the impact of state A would be computed as the streamflow at the accounting point when only state B is pumping and state A is not pumping (17,000 ac-ft) minus the streamflow when both states are pumping (7,000 ac-ft) for an estimated impact of state A of 10,000 ac-ft. Similarly, the current Accounting Procedures would estimate the impact of state B as the streamflow at the accounting point when only state A is pumping (22,000 ac-ft) minus the streamflow at the accounting point when both states are pumping (7,000 ac-ft) to yield a value of 15,000 ac-ft for the impact of groundwater pumping from state B.

The example illustrates an important point. For the hypothetical values used in this example, the impacts of each individual state can be added to produce the total impact of both states (i.e., the sum of the parts equals the whole). The true total impact of both states is computed by comparing the case with no human activity with the case of both states being simultaneously active (figures 2a and 2d). In this example, it is found to be 25,000 ac-ft. The separately-calculated impacts of state A and B (10,000 ac-ft and 15,000 ac-ft) sum to this same value. That these two independent methods for computing total impact yield the same result may seem to be an obvious and intuitive result. However, as will be shown below, this additivity does not always apply for the Republican River Basin. The deviation from additivity can be substantial and is of critical importance since this additivity is assumed to hold under the current Accounting Procedures.

A second point that is illustrated by this example is that the value for impact obtained for both states A and B using the current Accounting Procedures can also be obtained by taking the difference in streamflow at the accounting point when only one state is pumping (e.g., figures 2b or 2c) and the streamflow when no human activity is present (figure 2a). This was the approach taken in the discussion of the figure above and consists of carrying out the calculation from a different "base" condition. As will be shown below, this is a general result under certain conditions. This notion of using different approaches to compute impacts for different human activities will be discussed in the proposed new method presented later in this section.

3.1.3 Beaver Creek: CBCU Estimation Failure from Stream Drying at Accounting Point

The example above utilizes hypothetical values for recharge, pumping, storage change, and streamflow to demonstrate how impacts of individual states are computed under the current Accounting Procedures and to show how individual state impacts can be added to find the total impacts for the sub-basin. As stated above, the current Accounting Procedures can yield poor estimates of $CBCU_C$, $CBCU_K$, and $CBCU_N$. This will be demonstrated using baseflows computed by the Groundwater Model for the Beaver Creek accounting point. Beaver Creek originates in Colorado, flows into Kansas, then to Nebraska where it discharges into Sappa Creek a few miles above the confluence of Sappa Creek and the Republican River. The location of Beaver Creek and the accounting point at its mouth is shown in figure 3. Beaver Creek is a useful demonstration case because there are only two groups of human activities that have, to date, had any significant impact on streamflow at the accounting point. These groups of human activities are Kansas pumping and Nebraska pumping.

The Groundwater Model-computed baseflows for Beaver Creek will be used to compute $CBCU_K$ and $CBCU_N$ and VWS_G for two specific years: 1965 and 2003. It will be shown that computed values of $CBCU_K$ and $CBCU_N$ for 2003 fail to meet the expectation that their sum will equal the VWS_G for the sub-basin and that, therefore, they are inadequate estimates of $CBCU_K$ and $CBCU_N$. In contrast, $CBCU_K$ and $CBCU_N$ for 1965 do appear to meet expectations. To understand why additivity of $CBCU_K$ and $CBCU_N$ fails in 2003, it is useful to begin the analysis with an examination of baseflow behavior and impact results for 1965.

3.1.3.1 Beaver Creek Baseflows and CBCU for 1965

Analysis begins with figure 4, which is a plot of the baseflow in Beaver Creek, computed by the RRCA Groundwater Model, on the vertical axis versus the percentage of Kansas and Nebraska pumping. This and similar plots make it possible to assess the linearity of the response of baseflow to pumping. At the left side of the plot, with zero pumping, streamflow takes a value of 12,226 ac-ft. At the right side of the plot, with both Kansas and Nebraska pumping at 100% of their historical rates for the entire period of record, the Groundwater Model-computed baseflow is 8,822 ac-ft. The plot also includes values of streamflow at intermediate levels of pumping. For example, at the 50% pumping level, the Groundwater Model is run with both Kansas and Nebraska pumping at 50% of their actual rates in every year of the simulation period. The solid line on figure 4 indicates the baseflow in 1965 resulting from the indicated percentage of Kansas and Nebraska pumping. The stream remains wetted over the entire range of pumping.

The baseflow with no human activity (0% pumping) is projected horizontally on figure 4 as the dashed line. The vertical distance between the dashed and solid lines represents the streamflow depletion produced by the indicated level of pumping. At 100% pumping, the decrease in baseflow or streamflow depletion is 3404 ac-ft. At 50% pumping, the stream depletion is 1656 ac-ft.

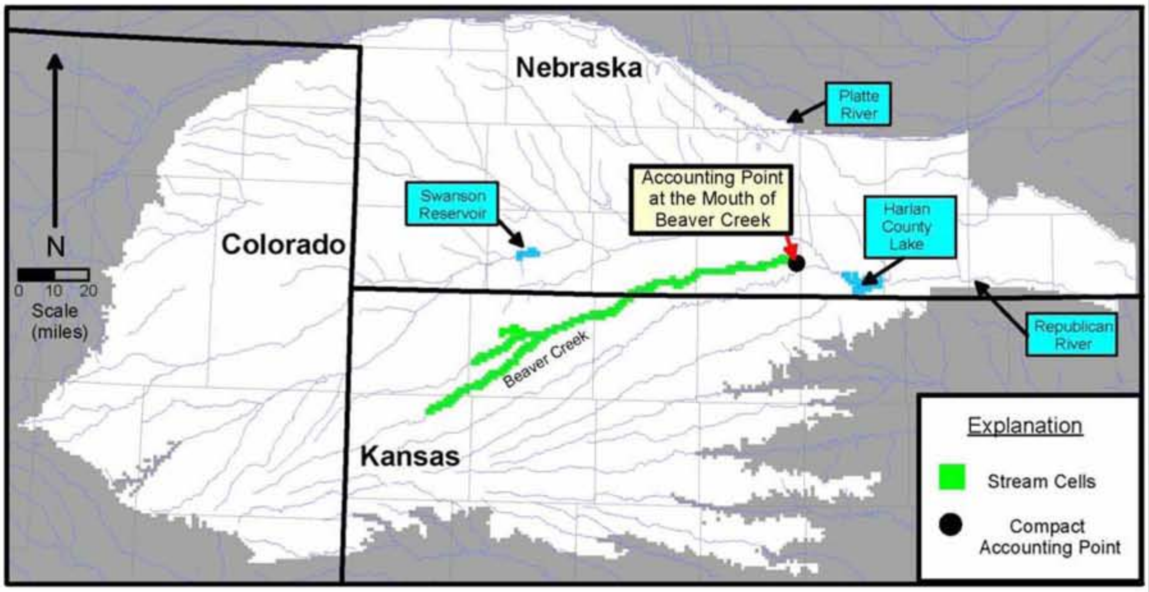

Figure 3. Map showing location of cells with stream boundary condition in Beaver Creek.

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It is important to note the nearly linear (straight-line) response of baseflow to pumping. This causes a near-linear increase of streamflow depletion with percent of pumping. That is, going from 0 to 50% pumping yields a streamflow depletion of 1656 ac-ft. Going from 50% to 100% pumping produces an additional streamflow depletion of about the same magnitude (1748 ac-ft). Doubling pumping causes an approximate doubling of streamflow depletion. Recognizing this nearly linear response is critical for understanding the problems with the current Accounting Procedures.

At this point it is useful to recognize that the response of baseflow to pumping is not precisely linear. When the Groundwater Model and associated Accounting Procedures were devised, minor nonlinearities were anticipated and were deemed negligible for purposes of the Accounting Procedures. One of these minor nonlinearities is the precipitation irrigation recharge "bump" which results from a nonlinear increase in recharge when pumping is activated. This bump can be seen in figure 4 at the left end of the straight-line interval. As soon as pumping exceeds zero percent, the Groundwater Model adds a fixed amount of irrigation recharge which in turn causes a slight increase in computed baseflow. Other minor nonlinearities include the nonlinear response of leakage to stream stage and changes in head-dependent boundary conditions representing phreatophyte evapotranspiration, drains and baseflow before the stream goes dry. In addition, the numerical solution of the MODFLOW problem and the tabulation of results will contain some small numerical roundoff error.

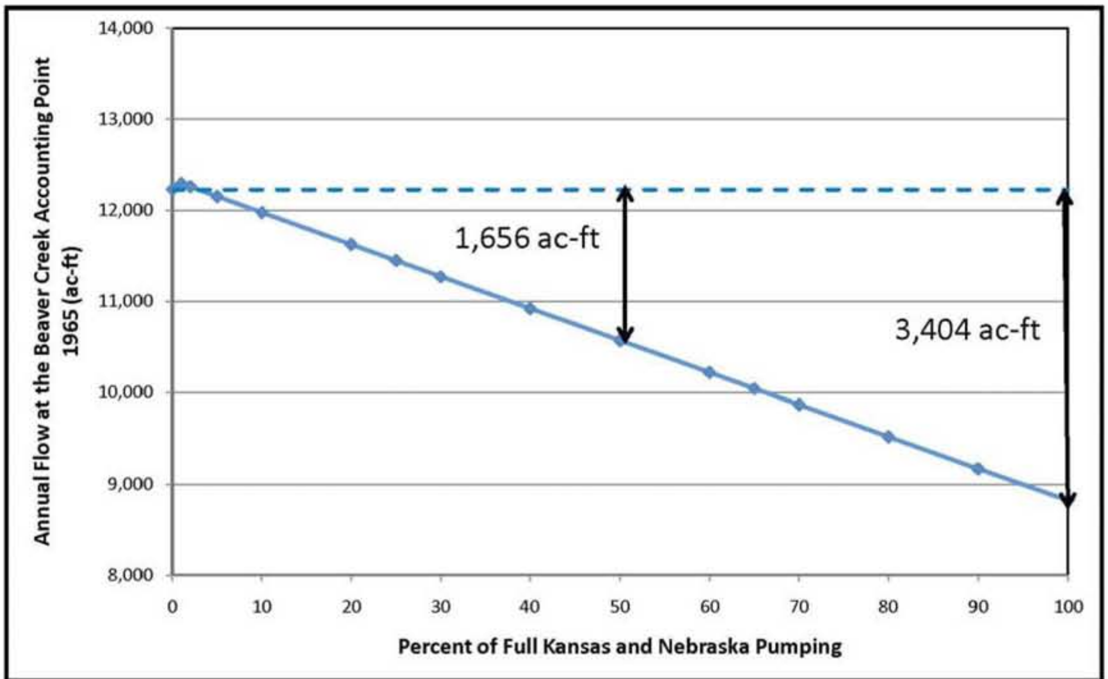

Figure 4. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

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As will be discussed below, there are circumstances where the response is ***severely*** non-linear. This condition arises under stream drying conditions and far exceeds the minor nonlinearity effects described above. The major nonlinearity due to stream drying results in substantial error in the values of VWS_G computed using the current Accounting Procedures. For purposes of this report, references to “linear” response should be interpreted as baseflow response that is nearly linear and only subject to the minor nonlinearities described here. Hence, the response of baseflow at Beaver Creek to pumping shown in figure 4 will be considered a linear response.

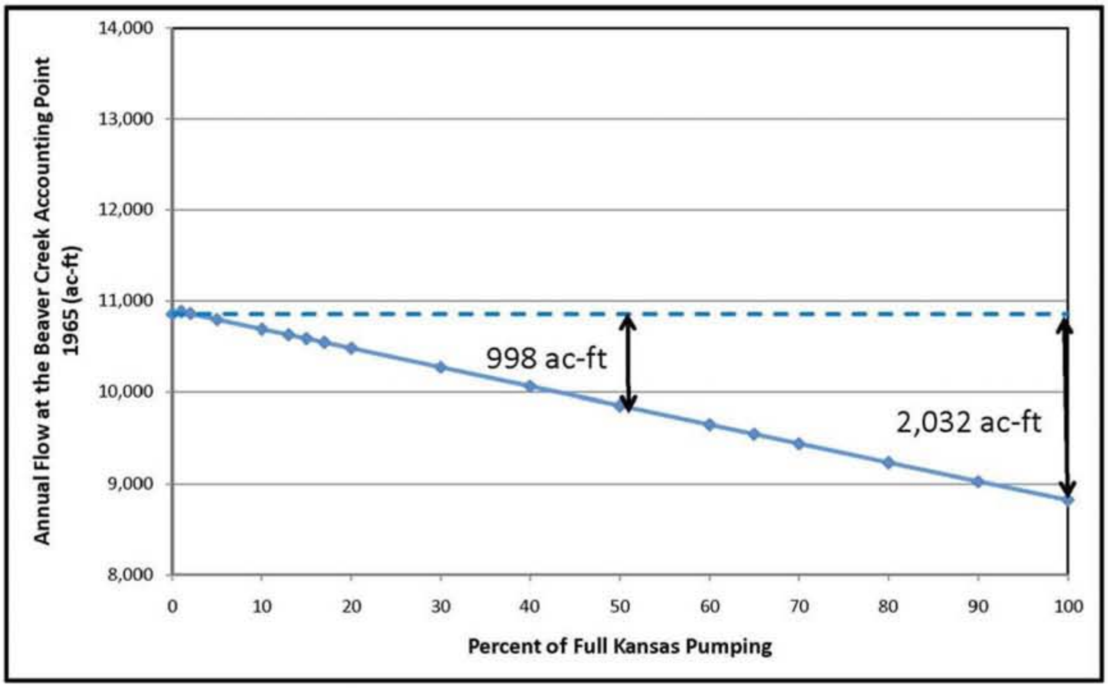

Figure 5. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

The linear response of baseflow to increasing pumping also occurs when each individual state is considered. Figure 5 shows the response of baseflow at the Beaver Creek accounting point when Kansas pumping is varied from 0% to 100% and Nebraska pumping is held at 100% of its historical levels. For this case, when Kansas pumping is at 100%, baseflow is again 8,822 ac-ft. As Kansas pumping is decreased, baseflow increases with a linear response until at 0% pumping baseflow is 10,894 ac-ft. Comparison of the dashed and solid lines in figure 5 again shows a nearly linear response with a stream depletion of 2,032 ac-ft attributable to Kansas pumping. Figure 6 shows the corresponding response of baseflow to Nebraska pumping when Kansas pumping is held at 100%. Response of baseflow is again linear with baseflow of 10,192 ac-ft when Nebraska pumping is fully off dropping to 8,822 ac-ft at 100% pumping corresponding to a streamflow depletion of 1,371 ac-ft.

Under the current Accounting Procedures, one should be able to add $CBCU_K$ and $CBCU_N$ to determine the VWS_G for the entire sub-basin. $CBCU_K$ and $CBCU_N$ are computed as the difference between baseflow when both states are pumping and when the target state is off. The first two rows of table 1 show the results of this calculation for Kansas and Nebraska, respectively. The final row of the table shows the VWS_G computed directly by taking the difference between computed baseflow when both states are pumping and when neither state is pumping. The independently computed $CBCU_K$ and $CBCU_N$ sum to 3,402 ac-ft. As anticipated by the current Accounting Procedures, this is the same as the correct value of VWS_G of 3,404 ac-ft (ignoring minor nonlinearities). As demonstrated above, it is also possible to compute these same VWS_G values (to within round-off error) by taking the difference between computed streamflow when the target state is pumping and when there is no pumping activity. This computational procedure is shown in table 2.

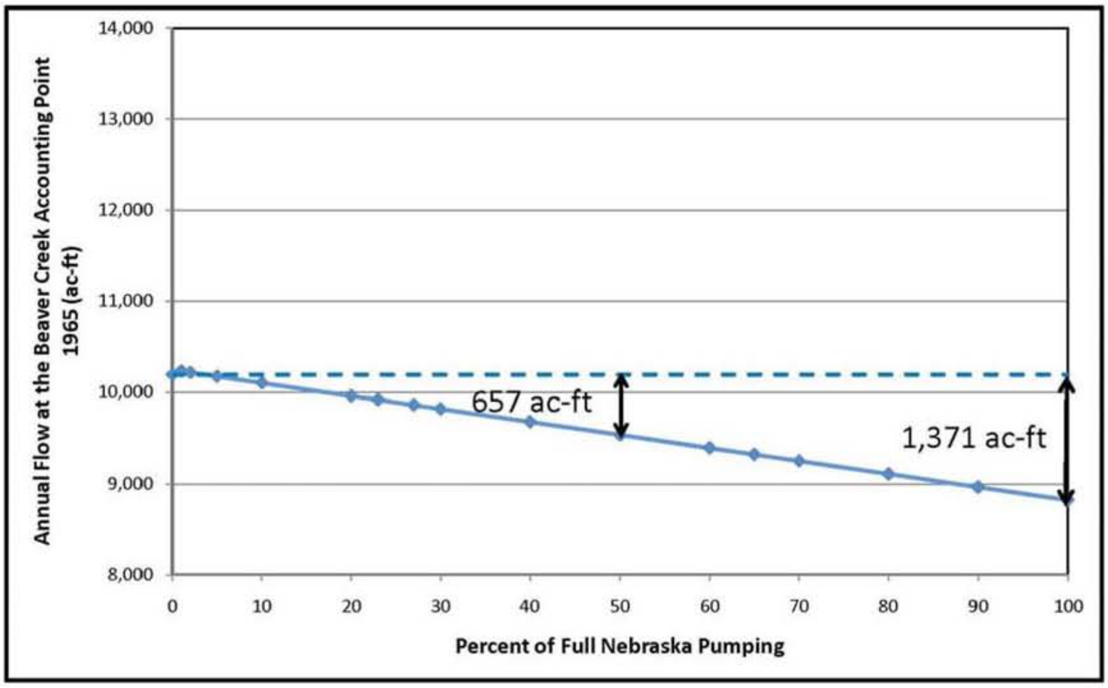

Figure 6. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

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Table 1. Computation of Beaver Creek sub-basin $CBCU_K$, $CBCU_N$ and VWS_G in 1965 using current Accounting Procedures method.

Subtract …	From …	To Obtain …
Baseflow with both States at 100% pumping: 8,822 ac-ft	Baseflow with Kansas at 0% and Nebraska at 100% pumping: 10,854 ac-ft	$CBCU_K$: 2,032 ac-ft
Baseflow with both States at 100% pumping: 8,822 ac-ft	Baseflow with Kansas at 100% and Nebraska at 0% pumping: 10,192 ac-ft	$CBCU_N$: 1,370 ac-ft
Baseflow with both States at 100% pumping: 8,822 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 12,226 ac-ft	VWS_G : 3,404 ac-ft

Table 2. Computation of Beaver Creek sub-basin $CBCU_K$, $CBCU_N$ and VWS_G in 1965 by subtracting from the condition with no human activity.

Subtract …	From …	To Obtain …
Baseflow with Nebraska at 0% and Kansas at 100% pumping: 10,192 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 12,226 ac-ft	$CBCU_K$: 2,034 ac-ft
Baseflow with Kansas at 0% and Nebraska at 100% pumping: 10,854 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 12,226 ac-ft	$CBCU_N$: 1,372 ac-ft
Baseflow with both States at 100% pumping: 8,822 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 12,226 ac-ft	$CBCU_G$: 3,404 ac-ft

The current Accounting Procedures assume that $CBCU_K$ and $CBCU_N$ can be added to determine the correct VWS_G for the sub-basin. This additivity assumption is valid for the flows show in table 1 and table 2. The additivity observed here follows from the mathematical principle of superposition. Applying this principle to the Groundwater Model output, if pumping from each individual state produces a linear baseflow response, the sum of individual state impacts can be added to obtain the true total impact of all states operating simultaneously.

The key test of the validity of the additivity assumption is this: do the baseflows respond linearly to individual state pumping? As shown in figure 5 and 6, they do for 1965. Hence, the ability of $CBCU_K$ and $CBCU_N$ to add to the true VWS_G, as shown in Tables 1 and 2, is entirely predictable based on the linear response of baseflow to pumping and the principle of superposition. In contrast, when the response of baseflow to pumping is substantially non-linear, the principal of superposition no longer applies and additivity can not be expected. The failure of the additivity assumption means that the values of $CBCU_K$ and $CBCU_N$ computed under the current Accounting Procedures are flawed. Such a case occurs for Beaver Creek in 2003.

3.1.3.2 Beaver Creek Baseflows and CBCU for 2003

The Groundwater Model-computed baseflows and impacts for Beaver Creek in 1965 showed linear response of baseflow to increases in pumping and additivity of $CBCU_K$ and $CBCU_N$ to reach VWS_G. The year 2003 is selected as the second period for analysis because its characteristics are much different and provide evidence of failure of the current Accounting Procedures. A similar analysis of baseflow response to pumping and computation of impacts is presented beginning with the tabulated computation of individual and total VWS_G shown in table 3.

Table 3. Computation of Beaver Creek sub-basin $CBCU_K$, $CBCU_N$ and VWS_G in 2003 using current Accounting Procedures method.

Subtract …	**From …**	**To Obtain …**
Baseflow with both States at 100% pumping: 0 ac-ft	Baseflow with Kansas at 0% and Nebraska at 100% pumping: 323 ac-ft	$CBCU_K$: 323 ac-ft
Baseflow with both States at 100% pumping: 0 ac-ft	Baseflow with Nebraska at 0% and Kansas at 100% pumping: 727 ac-ft	$CBCU_N$: 727 ac-ft
Baseflow with both States at 100% pumping: 0 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 6,445 ac-ft	VWS_G : 6,445 ac-ft

As shown in table 3, $CBCU_K$ and $CBCU_N$ are computed as 323 ac-ft for Kansas and 727 ac-ft for Nebraska. The sum of these values is 1,050 ac-ft and would be expected to equal the VWS_G for the sub-basin. However, direct computation of the VWS_G, as indicated in the third row of table 3 indicates that the correct value of VWS_G is 6,445 ac-ft. The difference between the true total impact, 6,445 ac-ft, and the total impact estimated by summing individual impacts is 5,395 ac-ft. This amount of streamflow depletion is occurring but not being accounted for in the current procedure. The failure of $CBCU_K$ and $CBCU_N$ to sum to VWS_G indicates that these values of $CBCU_K$ and $CBCU_N$ are in error.

This failure to properly estimate individual state impacts is not limited to Beaver Creek or to 2003 computed baseflows. These failures are caused by stream drying both at the accounting point and at upstream locations. In the sections that follow, the stream drying phenomenon is examined in detail for three sub-basins: Beaver Creek, Frenchman Creek, and Swanson Reservoir to Harlan County Lake. It will be shown that stream drying occurs in these sub-basins and that results from the current Accounting Procedures, when used under dry stream conditions, produce errors in $CBCU_C$, $CBCU_K$, $CBCU_N$, and *IWS*.

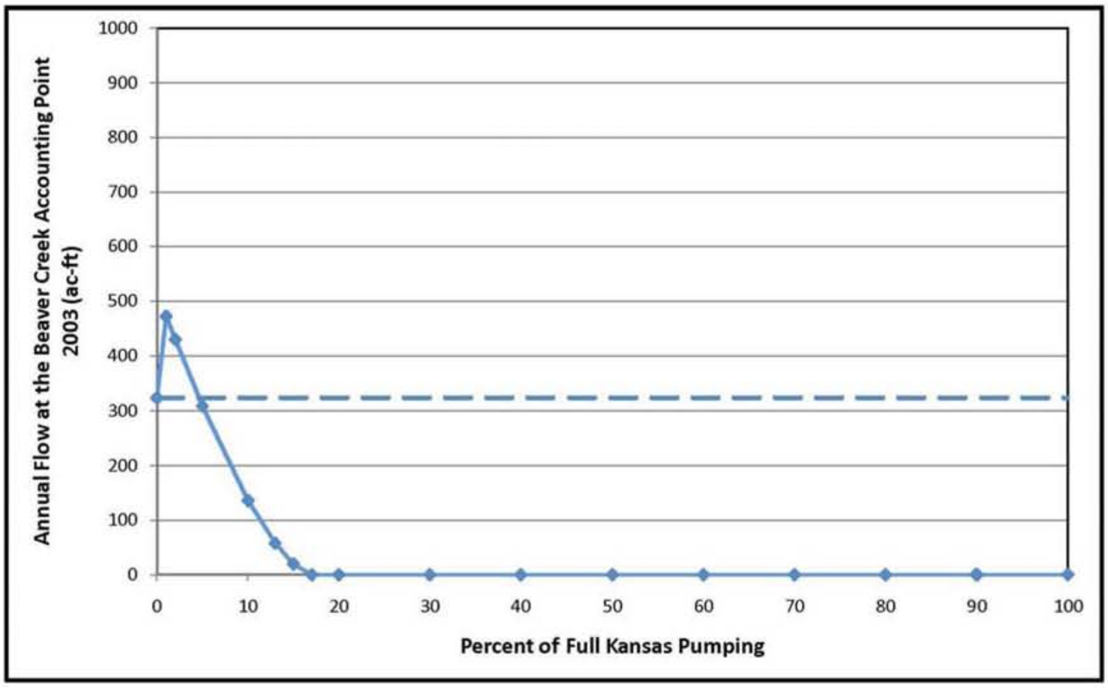

Figure 7. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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Insight into the source of the poor estimates for $CBCU_K$ and $CBCU_N$ can be found by examining plots of baseflow at the Beaver Creek accounting point versus percent of total pumping. In figure 7, Kansas pumping is varied while Nebraska pumping remains at its 100% level. As Kansas pumping increases from 0% pumping, the recharge “bump” causes an increase in streamflow. With further increases in pumping, baseflow decreases until, at a pumping percentage of about 17%, baseflow goes to zero. There is no change in baseflow beyond this point despite continued increases in Kansas pumping simply because there is no more streamflow to deplete. Comparison of the solid line of computed baseflow with the dashed line of baseflow when pumping is at 0% emphasizes that the response of baseflow as pumping varies from 0% to 100% is severely non-linear.

Figure 8 shows similar behavior resulting from incrementally increasing Nebraska pumping from 0% with Kansas at 100% pumping. In the case of Nebraska, after pumping is increased above about 40% baseflow goes to zero.

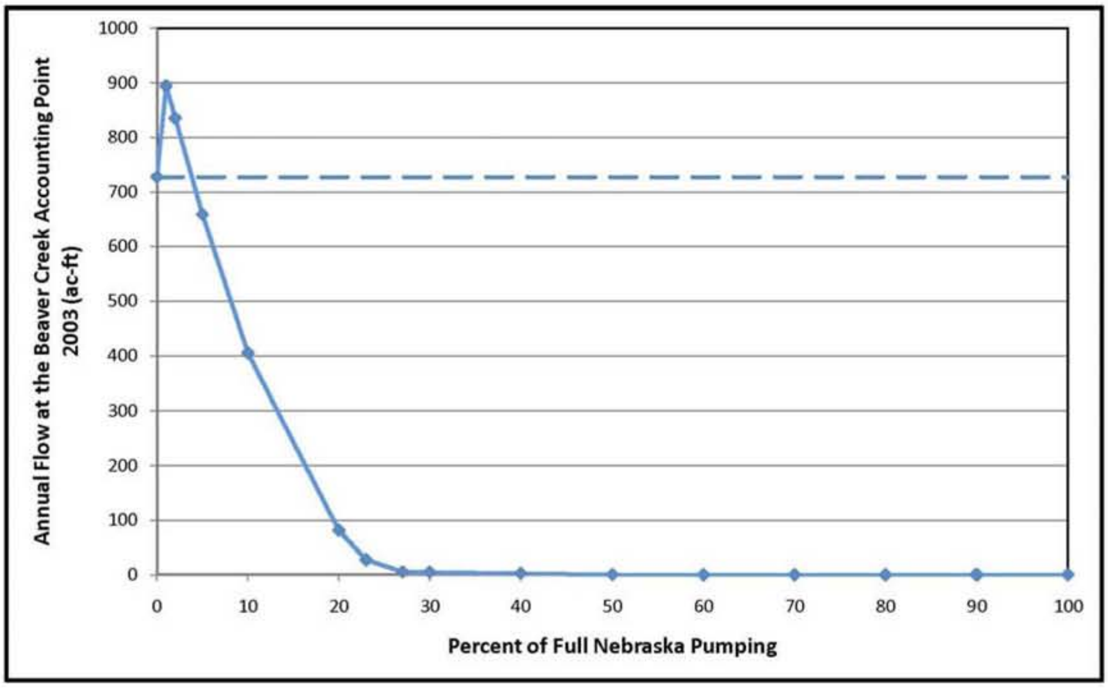

Figure 8. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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A third case is considered, as shown in figure 9, in which both Kansas and Nebraska pumping are increased simultaneously so that, for example, at 50% pumping, Kansas and Nebraska are both active at 50% of their historical rates. Here, baseflow goes to zero after pumping by both States has been increased to slightly less than 60% of full levels. This response is also nonlinear.

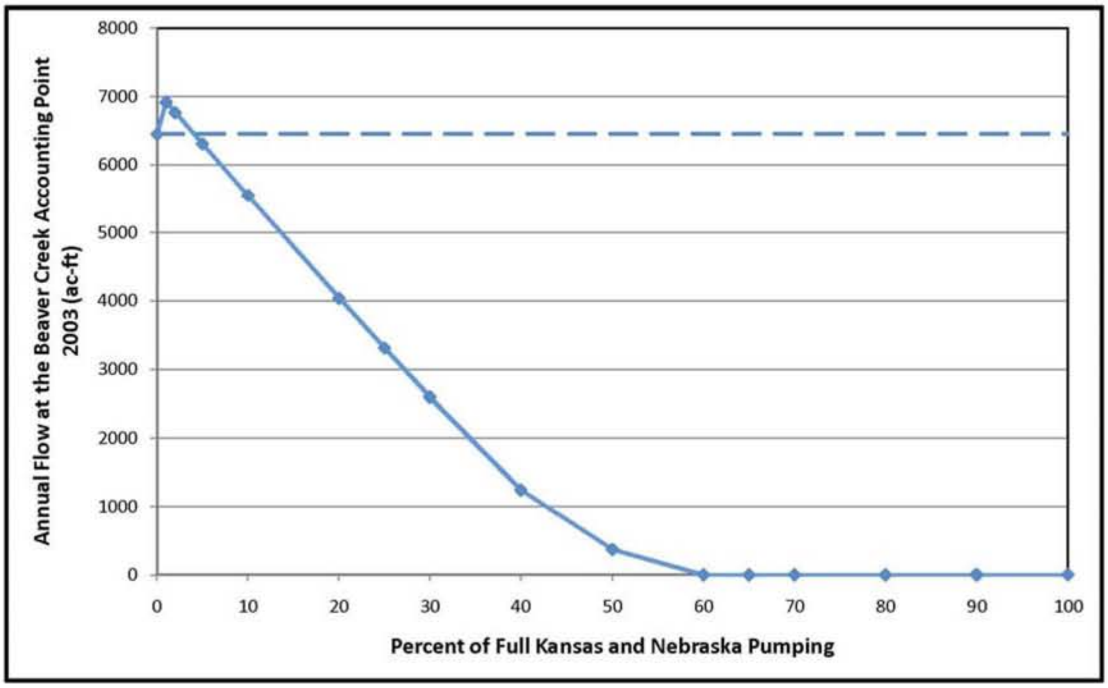

Figure 9. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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3.1.3.3 Model Behavior When Baseflow is Zero

Figures 7 through 9 indicate that increasing pumping by either Kansas or Nebraska alone or both states together causes baseflow at the Beaver Creek accounting point to drop to zero after a threshold is reached. Baseflow remains zero beyond this threshold as pumping is further increased. Clearly, increasing pumping beyond this point by either state must have some impact on the groundwater/stream system. Where in the system is this impact felt? This question can be answered by a close examination of all water-balance components for all the MODFLOW cells that define Beaver Creek. These cells are shown on the location map in figure 3 and constitute all cells that contain a Beaver Creek reach in the MODFLOW Stream Package representation of Beaver Creek. They will be referred to as Beaver Creek cells.

The water-balance components for Beaver Creek, for the case of incrementally increasing Kansas and Nebraska pumping, are shown in table 4. Each row of the table gives the volume of water, in ac-ft that has moved into or out of the Beaver Creek cells during 2003 at a given level of Kansas and Nebraska pumping. For example, the first row of table 4 shows flows at 0% pumping. The water balance components are shown in each column as net water flows into these cells from precipitation and irrigation return recharge, flows out to phreatophyte evapotranspiration, flows in from storage, flows out to the stream, flows out to wells that are represented in Beaver Creek cells, and flows in from cells that are adjacent to the Beaver Creek cells. Flow values across any row will sum to zero indicating full accounting for all flows. As depicted in figure 8, as Kansas and Nebraska pumping increases to just below 60%, baseflow is lost. This is reflected in the "Net Flow Out to Streams" column in table 4. The net streamflow out accumulates as baseflow so that this value is streamflow at the accounting point. At pumping below 60%, baseflow decreases as pumping increases. The "Net Flow in From Storage" column represents storage depletion. As pumping increases, the rate of storage depletion also increases.

Table 4 illustrates how the hydrologic balance is affected as pumping is changed. First, consider the case when flow out to wells increases from 10% to 20% (an increase of 2,127 ac-ft). This increased pumping causes a decrease in baseflow of 1,506 ac-ft and flow from storage increases by 243 ac-ft. However, when pumping is increased from 90% to 100% (again, an increase of 2,127 ac-ft), there is no change in baseflow and flow from storage increases by 1,059 ac-ft. This indicates that when baseflow is zero, each increment of pumping increase is provided, in part, by depleted storage.

When baseflow is adequate (i.e. pumping at 40% or less) and pumping is greater than 0%, each ac-ft of pumping causes a 0.18 ac-ft increase in precipitation and irrigation return, about a 0.70 ac-ft decrease in streamflow, and about a 0.12 ac-ft depletion of storage. However, when baseflow is zero (i.e. pumping at 60% or more), each ac-ft of pumping increase causes a 0.18 ac-ft increase in precipitation and irrigation return, no change in streamflow, and about a 0.50 ac-ft depletion of storage with other flow components adjusting accordingly. When pumping is between 40% and 60% of maximum pumping, a transition zone occurs. This analysis further indicates the role of storage depletion in accounting for the source of water to supply increased pumping.

Table 4. Table showing annual groundwater mass balance terms for cells with a stream boundary condition in the Beaver Creek sub-basin in 2003 for various percentages of full pumping in Kansas and Nebraska. (-): Flow into cells with a Stream Boundary Condition. (+): Flow out of cells with a Stream Boundary Condition. Values represent net mass balance terms for all cells with a stream boundary condition in the Beaver Creek Sub-basin upgradient of the Beaver Creek accounting point.

Percent of Full Kansas and Nebraska Pumping	Flow In from Precipitation and Irrigation Return Recharge (ac-ft)	Flow Out to Phreatophyte Evapotranspiration (ac-ft)	Net Flow In From Storage (ac-ft)	Net Flow Out to Streams (ac-ft)	Flow Out to Wells (ac-ft)	Net Groundwater Flow into Stream Cells (ac-ft)
0	-1,559	31,388	-2,692	6,447	0	-33,583
1	-1,799	31,709	-2,611	6,917	213	-34,428
2	-1,838	31,602	-2,634	6,764	425	-34,319
5	-1,955	31,280	-2,703	6,306	1,064	-33,990
10	-2,150	30,743	-2,821	5,546	2,127	-33,444
20	-2,541	29,661	-3,064	4,040	4,254	-32,350
25	-2,736	29,115	-3,195	3,311	5,318	-31,811
30	-2,931	28,567	-3,334	2,597	6,381	-31,281
40	-3,321	27,453	-3,648	1,239	8,508	-30,230
50	-3,712	26,244	-4,327	371	10,635	-29,212
60	-4,102	24,918	-5,296	0	12,763	-28,280
65	-4,297	24,240	-5,915	0	13,826	-27,852
70	-4,492	23,538	-6,488	0	14,890	-27,444
80	-4,883	22,166	-7,562	0	17,017	-26,737
90	-5,273	20,900	-8,629	0	19,144	-26,141
100	-5,664	19,701	-9,688	0	21,271	-25,619

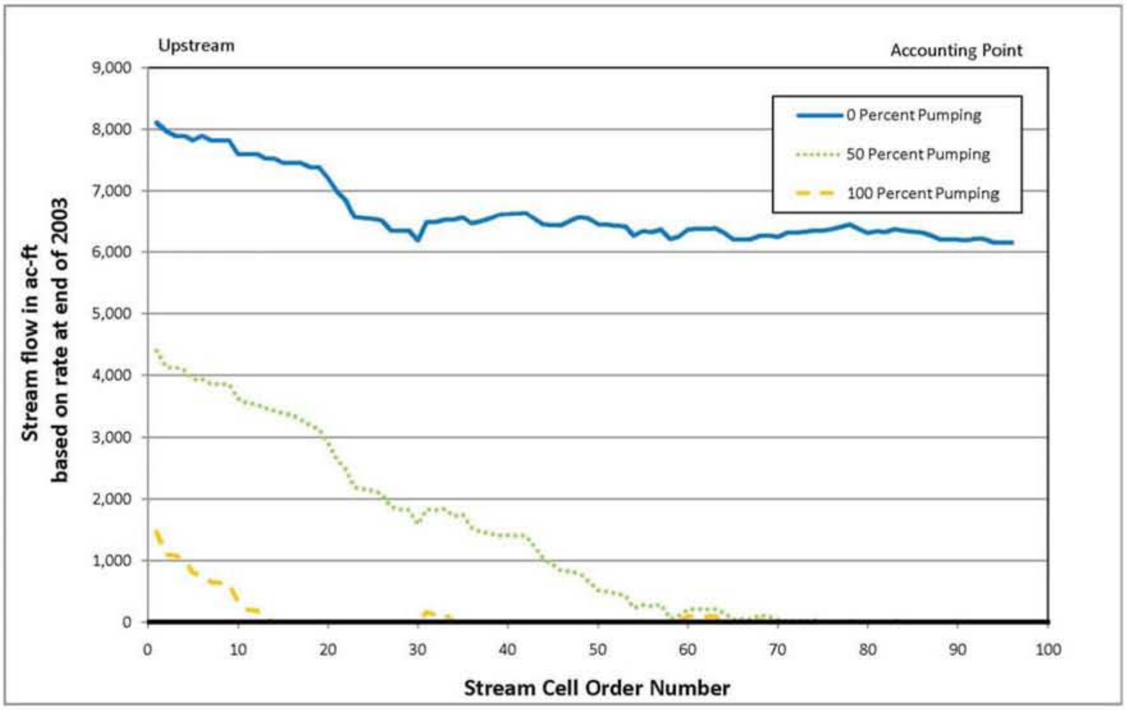

Figure 10. Graph showing stream cell order vs flow for various percents of full pumping for Kansas and Nebraska Pumping, Beaver Creek at the end of 2003.

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The relationship between storage replenishment and baseflow reestablishment has a direct physical basis. As water is taken from storage, the water-table elevation declines. If the water table declines sufficiently far beneath the elevation of the streambed and upstream flows are insufficient, the modeled stream will go dry. To reestablish baseflow, the modeled water table must rise again to an elevation greater than the streambed elevation. This phenomenon can be seen in figures 10 and 11 which depict, respectively, the baseflow computed along the length of the stream and the relative elevations of streambed and head at the end of 2003. The horizontal axis in both figures represents distance along Beaver Creek from the accounting point at the right end of the figure and then extending upstream nearly 100 cells from this point. The figures depict three cases: one case in which all pumping is at 100% of historic levels, a condition in which pumping for both Kansas and Nebraska are reduced by 50%, and a condition where pumping is at 0% for both states. Figure 10 indicates that at 100% pumping, baseflow is zero over nearly the entire stream portion depicted. At 50% pumping, baseflow has been reestablished at many upstream cells but not at the accounting point. At 0% pumping, baseflow is fully established along the entire stream.

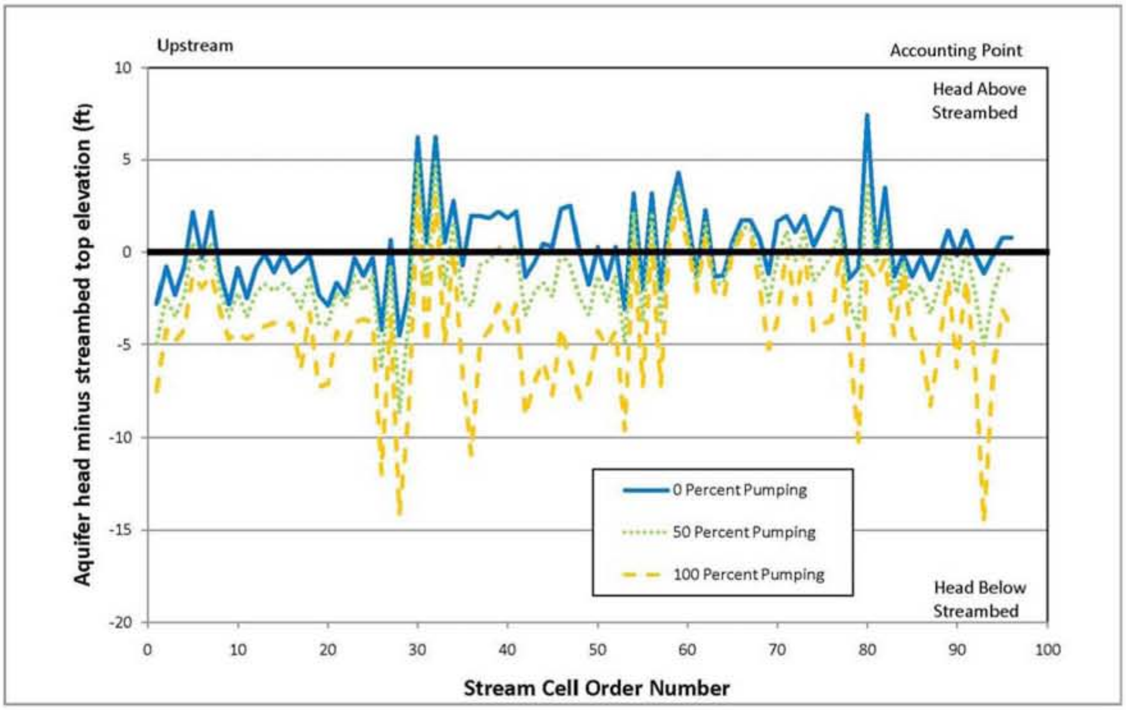

Figure 11. Graph showing stream cell order vs aquifer head minus stream top elevation for various percents of full pumping for Kansas and Nebraska Pumping, Beaver Creek at the end of 2003.

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Figure 11 shows the effect of the various pumping conditions listed above on groundwater levels. The vertical axis of figure 11 represents the distance of the water table from the streambed, as reflected in the computed hydraulic head at each cell along the creek. Positive differences indicate that the water table is above the streambed and negative differences indicate that the water table is below the streambed. At 100% pumping, the water table is largely below the streambed. As pumping decreases, the water table increases in elevation indicating storage replenishment so that at 0% pumping the water table is above the streambed at many cells.

3.1.3.4 Storage Replenishment and Reestablishment of Baseflow

Results above indicate that if model-computed baseflow at the accounting point at the mouth of Beaver Creek begins at a value of zero, then baseflow can only be reestablished if storage is first replenished. Storage replenishment is related to increasing head levels. Storage must be replenished sufficiently to allow modeled heads beneath the stream to recover to levels near the streambed.

Further analysis of the pumping reductions required to reestablish baseflow helps to understand the source of the failure of additivity for VWS_G. When both Kansas and Nebraska pumping are reduced together, as shown in table 4, the combined pumping in Beaver Creek cells must be reduced by about 9,100 ac-ft (43% of the total 21,271 ac-ft of combined pumping) to replenish the storage sufficiently to reestablish baseflow. When only Kansas pumping in Beaver Creek cells is reduced, pumping has to be reduced about 6,500 ac-ft (83% of the 7,829 ac-ft of Kansas pumping) before baseflow is reestablished. When only Nebraska pumping in Beaver Creek cells is reduced, pumping has to be reduced about 8,000 ac-ft (60% of the 13,442 ac-ft of Nebraska pumping) before baseflow is reestablished. It is evident that somewhere between 6,500 and 9,100 ac-ft of pumping reduction in Beaver Creek cells is required to produce sufficient storage replenishment to reestablish baseflow. Differences between the three cases in the pumping reduction necessary to reestablish baseflow are attributable to differences in well locations, pumping changes outside the Beaver Creek cells and other water balance components.

Because pumping must be reduced substantially to replenish storage, reducing Kansas or Nebraska pumping alone leaves little additional pumping reduction available to increase baseflow. For Kansas, the first 83% of its pumping reduction is used to replenish storage leaving only about 1,300 ac-ft of additional pumping reduction for baseflow increase. The computed value of $CBCU_K$ will reflect the fact that Kansas' pumping reduction alone replenishes storage sufficient to reestablish baseflow. For Nebraska, the first 60% of pumping reduction replenishes storage leaving only about 5,400 ac-ft of additional pumping reduction available for baseflow increase. Again, the computed value of $CBCU_N$ will reflect the fact that Nebraska's pumping reduction is the sole cause of storage replenishment. By adding $CBCU_K$ and $CBCU_N$, produced by individually turning off Kansas and Nebraska, respectively, the pumping reduction needed to replenish storage is counted twice. In contrast, if Kansas and Nebraska are reduced simultaneously, their combined pumping reductions replenish storage, leaving about 12,200 ac-ft of combined pumping reduction available for baseflow increase. By adding $CBCU_K$ and $CBCU_N$ produced by individually turning off Kansas and Nebraska, the pumping reduction needed to replenish storage is double-counted and the increase in baseflow is undercounted.

3.1.3.5 Conclusions for Beaver Creek

The expectation that $CBCU_K$ and $CBCU_N$ can be summed to find the VWS_G has been shown to fail for Beaver Creek under conditions present in 2003. Comparison of model-computed baseflow characteristics for 2003 and 1965 emphasizes the importance of the linearity or non-linearity of the response of baseflow to pumping. If this response is linear or nearly linear, then $CBCU_K$ and $CBCU_N$ can be successfully added to find the VWS_G. When the response is nonlinear, this additivity fails. This explanation, based in mathematical theory, has been supplemented by a hydrologic explanation for the observed additivity failure. As pumping is decreased, depleted storage must be replenished before baseflow can be established. The need to replenish storage leads to the nonlinear response and causes a double-counting when $CBCU_K$ and $CBCU_N$ are added.

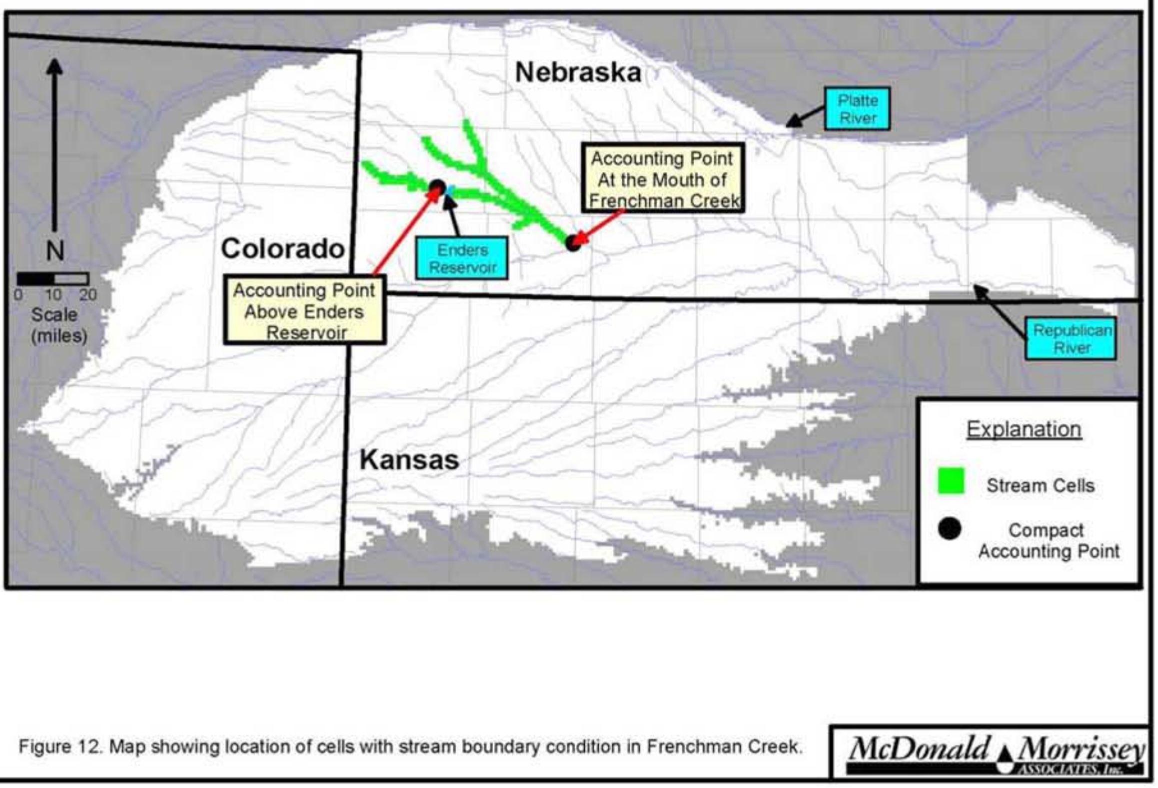

Figure 12. Map showing location of cells with stream boundary condition in Frenchman Creek.

3.1.4 Frenchman Creek: CBCU Estimation Failure from Stream Drying Upstream of Accounting Point

Another failure in computation of individual state impacts occurs in Frenchman Creek. The stream cells associated with the two Frenchman Creek accounting points are shown on figure 12. As will be shown, the source of this violation is again stream drying; however, in this case, the drying occurs upstream of an accounting point. The VWS_G computed for Frenchman Creek is based on the sum of impacts at two points; one accounting point at the mouth of Frenchman Creek and another accounting point above Enders Reservoir. Because the impacts at these two points are summed, it is possible to examine the computed impacts at each point individually. For this analysis, the focus is on the accounting point above Enders Reservoir. As with Beaver Creek, only two states have a significant impact on baseflow. For Frenchman Creek, these are Colorado and Nebraska pumping.

Table 5 shows $CBCU_C$ and $CBCU_N$ computed for Colorado and Nebraska and the independently computed VWS_G. The sum of $CBCU_C$ and $CBCU_N$ is 43,074 ac-ft and does not equal the independently-calculated value of VWS_G of 48,140 ac-ft. This indicates errors in the values of either $CBCU_C$ or $CBCU_N$. The VWS_G estimated using the sum of $CBCU_C$ and $CBCU_N$ underestimates the true VWS_G by 5,066 ac-ft.

Table 5. Computation of sub-basin $CBCU_C$, $CBCU_N$ and VWS_G in 2003 for Frenchman Creek at the Accounting Point Above Enders Reservoir using current Accounting Procedures.

Subtract …	From …	To Obtain …
Baseflow with both States at 100% pumping: 4,523 ac-ft	Baseflow with Colorado at 0% and Nebraska at 100% pumping: 4,555 ac-ft	$CBCU_C$: 32 ac-ft
Baseflow with both States at 100% pumping: 4,523 ac-ft	Baseflow with Nebraska at 0% and Colorado at 100% pumping: 47,565 ac-ft	$CBCU_N$: 43,042 ac-ft
Baseflow with both States at 100% pumping: 4,523 ac-ft	Baseflow with Colorado at 0% and Nebraska at 0% pumping: 52,663 ac-ft	$CBCU_G$: 48,140 ac-ft

In contrast with the Beaver Creek behavior, the baseflow at the accounting point above Enders Reservoir does not go to zero. Instead, the additivity failure occurs because of stream drying upstream of the accounting point. This can be seen in table 6, which shows 2003 baseflows for each segment and reach of Frenchman Creek from the headwaters to the accounting point above Enders Reservoir for four different stress conditions. In the third column of the table, baseflows are shown for the case of no human activity. In segment 68, reach 4, 736 ac-ft discharges from the aquifer to the stream producing 736 ac-ft of modeled baseflow. In segment 68, reach 5, an additional 607 ac-ft discharges from the aquifer to the stream incrementing the baseflow to a value of 1,343 ac-ft. The modeled stream continues to gain water at each reach along its entire length to produce a baseflow of 52,663 ac-ft at the accounting point above Enders Reservoir. In the fourth column of the table, both states are pumping at 100% levels. Here, the stream gains flow at some locations but loses water elsewhere so that baseflow repeatedly goes to zero. There is sufficient gain of water at the downstream reaches so that a baseflow of 4,523 ac-ft is present at the accounting point above Enders Reservoir.

A comparison of the results for the run with no human activity (column 3) and with all activity except Nebraska pumping (column 6) shows that the baseflow is reestablished at nearly all points and the stream once again gains water along its length. This is to be expected since the majority of the Frenchman Basin is in Nebraska and Nebraska pumping can be expected to have the largest influence. However, baseflows do not completely return to the levels that occur when no human activity is present. This must be influenced by Colorado pumping. Comparison of the results in columns 3 and 6 of table 6 shows that the difference in baseflows at the accounting point above Enders Reservoir is 5,098 ac-ft. It is expected from this result that the impact of Colorado pumping at the accounting point above Enders Reservoir should be substantially more than the value of 32 ac-ft determined from the current Accounting Procedures.

Table 6. Annual streamflow in Frenchman Creek from headwaters to Enders Reservoir for various scenarios for 2003.

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft/yr)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft/yr)	Flow into Reach Colorado Pumping Off, Kansas and Nebraska Pumping On, Mound On (ac-ft/yr)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft/yr)	Comments
68	1	0	0	0	0	Headwaters
68	2	0	0	0	0	
68	3	0	0	0	0	
68	4	736	0	0	0	
68	5	1,343	0	0	0	
68	6	3,842	0	0	1,400	
68	7	4,718	0	0	1,611	
68	8	5,261	0	0	1,964	
68	9	7,272	0	0	3,438	
68	10	8,318	0	0	4,296	
68	11	9,907	0	0	5,659	
119	1	11,018	0	0	6,665	Tributary Enters
119	2	12,947	0	0	8,409	
123	1	13,414	95	127	8,847	
123	2	18,900	1,635	2,209	14,186	
123	3	21,170	303	1,208	16,367	
123	4	22,434	522	1,552	17,581	
123	5	24,036	0	293	19,087	
123	6	25,698	231	656	20,723	
126	1	28,049	58	478	23,044	Frenchman at Imperial Gage

Table 6 cont. Annual streamflow in Frenchman Creek from headwaters to Enders Reservoir for various scenarios for 2003.

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft/yr)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft/yr)	Flow into Reach Colorado Pumping Off, Kansas and Nebraska Pumping On, Mound On (ac-ft/yr)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft/yr)	Comments
126	2	28,244	54	472	23,236	
126	3	28,806	132	595	23,789	
126	4	29,816	0	156	24,774	
126	5	31,857	144	388	26,802	
126	6	34,093	0	96	29,022	
126	7	34,587	0	4	29,512	
126	8	36,159	0	0	31,070	
134	1	37,718	304	337	32,625	Tributary Enters
134	2	39,432	619	688	34,333	
147	1	40,878	21	93	35,776	Tributary Enters
147	2	41,225	2	46	36,123	
147	3	41,272	0	0	36,173	
147	4	42,709	129	152	37,608	
147	5	43,319	0	0	38,221	
147	6	46,292	1,326	1,344	41,191	
147	7	47,603	1,537	1,562	42,503	
147	8	49,731	2,822	2,850	44,632	
147	9	51,828	4,026	4,056	46,730	
147	10	52,663	4,523	4,555	47,565	Accounting Point above Enders

The primary source of the apparent failure to properly compute $CBCU_C$ and $CBCU_N$ at the accounting point above Enders Reservoir can be seen by examining the impact of Colorado pumping. The impact of Colorado pumping on baseflows can be seen when comparing baseflows when all human activity is on (column 4 of table 6) and baseflows when all activity except for Colorado is on (column 5 of table 6). Examination of baseflows at upstream reaches such as segment 123, reach 5, shows that turning off Colorado pumping does increase baseflow. However, this baseflow is lost from the stream before it reaches the accounting point above Enders Reservoir. Because the baseflow at segment 147, reach 5, remains at zero under both conditions, any information about change in baseflow upstream of this point does not transfer downstream to the accounting point above Enders Reservoir. Similar zero baseflows occur at segment 126, reach 8, and segment 147, reach 3.

The hydrologic interpretation of this is quite similar to that for Beaver Creek. The combined pumping of Colorado and Nebraska causes a substantial drop in the modeled water table in the vicinity of Frenchman Creek. Nebraska's pumping is by far the dominant factor in this phenomenon. The water table drop depletes storage and dries the stream at multiple locations. Turning off Nebraska pumping allows replenishment of the storage and reestablishes baseflow. However, turning off Colorado when Nebraska is pumping has no such effect. Nebraska pumping is of sufficient magnitude that eliminating Colorado pumping is insufficient alone to replenish storage and significantly change baseflow at the accounting point above Enders Reservoir. With Nebraska pumping active, the impact of Colorado is masked.

3.1.5 Swanson-Harlan: IWS Estimation Failure

In this section, focus is on failure in estimation of *IWS* that occurs along the Main Stem of the Republican River in the section between Swanson Reservoir and Harlan County Lake. For the purposes of Compact accounting, Swanson to Harlan impacts are designated as those impacts associated with the Main Stem and its minor tributaries between Swanson Reservoir and Harlan County Lake. To calculate these impacts, flow at the mouth of a number of major tributaries (Frenchman Creek, Driftwood Creek, Medicine Creek, Red Willow Creek, and Sappa Creek) are subtracted from the Groundwater Model-computed baseflow at the accounting point above Harlan County Lake. This isolates the computed flows to only those associated with the Main Stem and its minor tributaries between Swanson Reservoir and Harlan County Lake. For purposes of the analysis presented here, the actual computed baseflow at the accounting point and other cells is reported. This approach makes it possible to directly view the relationship between stream drying and error in *IWS* estimation. A parallel analysis in which the upstream major tributary flows are subtracted away is presented in Appendix B and reaches the same conclusions as are reached in this section.

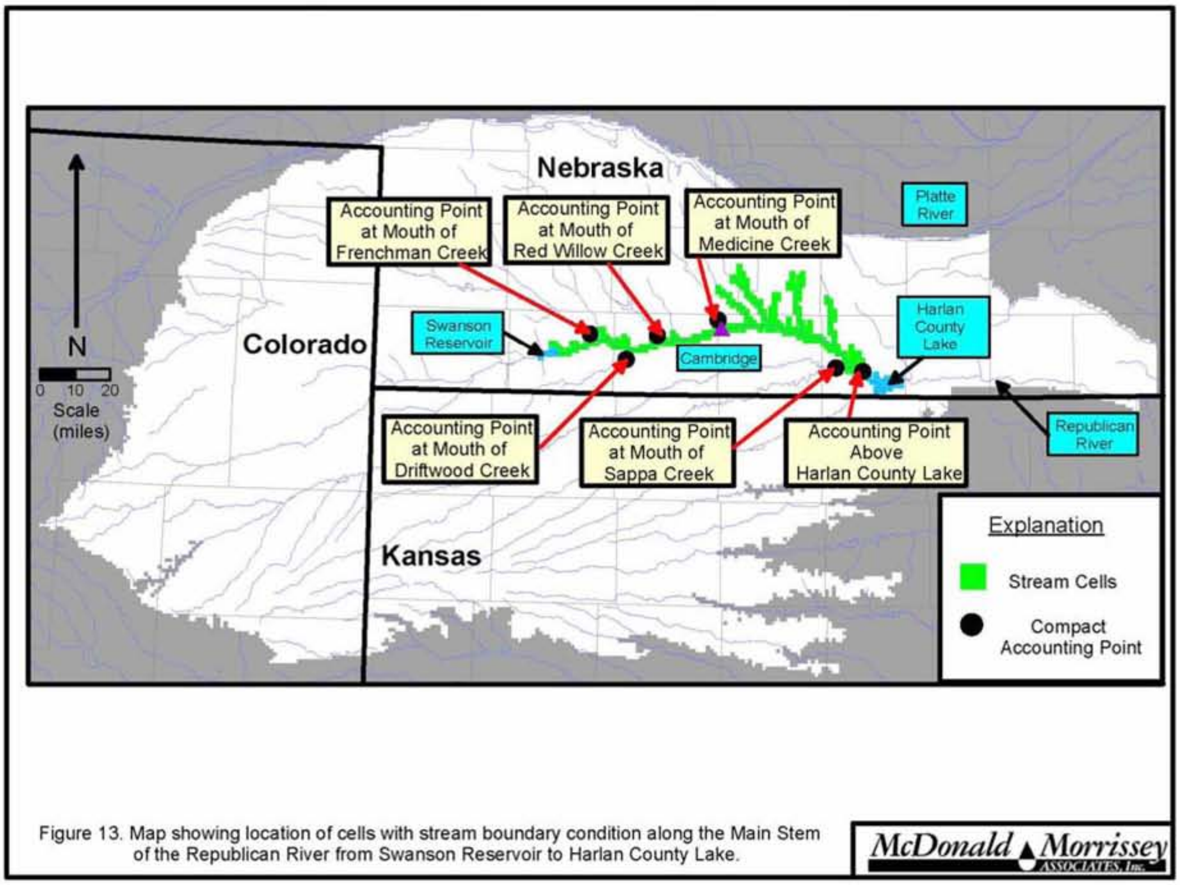

Figure 13. Map showing location of cells with stream boundary condition along the Main Stem of the Republican River from Swanson Reservoir to Harlan County Lake.

McDonald Morrissey Associates, Inc.

Stream cells and accounting points associated with the Swanson to Harlan Main Stem section impact calculation are shown in figure 13. As will be shown, the failure in *IWS* estimation results from stream drying both at the accounting point and upstream of the accounting point above Harlan County Lake. Table 7 shows the computation of the relevant quantities using a modified version of the current Account Procedures for $CBCU_K$ and $CBCU_N$ for Kansas and Nebraska and the *IWS*. For this case, the impact of Colorado pumping is negligible. As described above, the VWS_G, the groundwater-related portion of the VWS, is computed by subtracting the *IWS* from the VWS_G. For the Swanson-Harlan case, this is written as

$$VWS_G = CBCU_K + CBCU_N - IWS \qquad \textbf{(Equation 6)}$$

The quantity VWS_G can be directly computed by comparing the baseflows with all man-made stresses active (all pumping and mound recharge on) and all man-made stresses off. This computation is done in the last row of table 7.

Table 7. Computation of $CBCU_K$, $CBCU_N$, IWS and VWS_G in 2003 for the Main Stem at the Accounting Point Above Harlan County Lake using a version of the current Accounting Procedures in which computations are performed using actual computed baseflows at the accounting point.

Subtract …	From …	To Obtain …
Baseflow with all man-made stresses active: 144 ac-ft	Baseflow with Kansas at 0% and all other man-made stresses active: 197 ac-ft	$CBCU_K$: 53 ac-ft
Baseflow with all man-made stresses active: 144 ac-ft	Baseflow with Nebraska pumping at 0% and all other man-made stresses active: 71,667 ac-ft	$CBCU_N$: 71,523 ac-ft
Baseflow with Mound recharge off and all other man-made stresses active: 0 ac-ft	Baseflow with all man-made stresses active: 144 ac-ft	IWS : 144 ac-ft
Baseflow with all man-made stresses active: 144 ac-ft	Baseflow with all man-made stresses inactive: 59,924 ac-ft	VWS_G : 59,780 ac-ft

If the $CBCU_K$ and $CBCU_N$ and IWS were properly computed, then it would be expected that their combination would equal the independently calculated VWS_G value of 59,780 ac-ft. Instead, these individual values combine to 71,432 ac-ft (53 + 71,523 – 144). The current Accounting Procedures over-estimate the groundwater portion of the VWS by 11,652 ac-ft, indicating an error in either the $CBCU_K$, $CBCU_N$ or IWS. It is noteworthy that this error differs from those at Frenchman and Beaver Creeks where the groundwater portion of the VWS is under-estimated when using the current Accounting Procedures. It is also worth noting that the value of 59,780 ac-ft reported here includes the increased flows from Sappa Creek when pumping is turned off. When all major tributary flows, including Sappa Creek, are subtracted from the baseflow, the difference between the independently calculated VWS_G and the VWS_G calculated by equation 6 grows from 11,652 ac-ft to 17,290 ac-ft. (*See* Appendix B for details).

The cause of this violation can be seen in table 8, which shows baseflows under different pumping conditions for each segment and reach of the Main Stem from Cambridge to the accounting point above Harlan County Lake for 2003. The third column shows baseflows when no human activity is present. Under this condition, the stream is fully wetted along its entire length with a net gain of 17,054 ac-ft from Cambridge to the accounting point above Harlan County Lake. In the fourth column, baseflows are shown for the case when all human activities are present. Here, the stream has many reaches that are dry. Although the baseflow is active at the accounting point, segment 230, reach 5, the stream is dry just six reaches upstream at segment 229, reach 3.

The fifth column shows baseflows for the condition when Nebraska pumping is turned off and all other man-made stresses are active. Turning off Nebraska reestablishes baseflow to again produce a net gain from Cambridge to the accounting point above Harlan County Lake. Notably, the baseflow at the accounting point above Harlan County Lake is higher with Nebraska off than for the case with no human activity (column 3). This increase in baseflow must be a result of mound recharge. The significance of mound recharge is reinforced by examining column 6 of table 8 where mound recharge is the only human activity. Based on comparison of columns 6 and 3, adding mound recharge alone adds approximately 17,363 ac-ft of baseflow at the accounting point.

These results suggest that an *IWS* of only 17,363 ac-ft as computed by the current Accounting Procedures is an erroneous estimate. The mechanism by which this value is obtained can be seen in column 7 where all pumping activity is present, but mound recharge has been turned off. With all other man-made stresses active, turning off the mound recharge should decrease baseflows, and it does. However, since the baseflow in the “base” run is only 144 ac-ft, the baseflow decrease recorded by turning off mound recharge can be no larger than 144 ac-ft. This error arises from the same type of nonlinear response, caused by stream drying, that has been observed in the modeled results from Beaver Creek and Frenchman Creek.

Table 8. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
217	1	42,870	0	42,934	42,915	0	Medicine Cr. Enters, Republican R. at Cambridge
218	1	42,784	0	42,848	42,829	0	
218	2	42,718	0	42,782	42,762	0	
218	3	42,712	0	42,776	42,756	0	
218	4	42,818	0	42,882	42,862	0	
218	5	42,815	0	42,879	42,860	0	
218	6	42,817	0	42,881	42,862	0	
218	7	42,796	0	42,860	42,840	0	
218	8	42,536	0	42,600	42,580	0	
218	9	42,475	0	42,540	42,520	0	
218	10	42,384	0	42,448	42,428	0	
218	11	42,626	133	42,691	42,671	133	
218	12	42,668	77	42,733	42,712	77	
218	13	42,657	51	42,723	42,702	51	
218	14	43,100	0	43,165	43,144	0	
218	15	42,524	0	42,589	42,568	0	
218	16	42,834	135	42,900	42,879	135	
218	17	43,264	486	43,330	43,309	486	

Table 8 cont. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
218	18	43,344	364	43,410	43,388	364	
218	19	43,186	61	43,253	43,230	61	
218	20	43,194	73	43,261	43,238	73	
219	1	44,006	611	44,072	44,050	611	Tributary Enters
219	2	44,128	691	44,195	44,172	691	
219	3	44,189	561	44,256	44,234	561	
219	4	43,985	130	44,052	44,029	130	
219	5	43,365	0	43,433	43,410	0	
219	6	43,321	0	43,388	43,365	0	
219	7	42,861	0	42,929	42,905	0	
219	8	41,847	0	41,916	41,892	0	
219	9	41,421	0	41,491	41,467	0	
219	10	41,377	0	41,447	41,423	0	
219	11	41,146	0	41,218	41,193	0	
219	12	40,988	0	41,061	41,036	0	
220	1	45,526	2,073	46,790	46,763	1,405	Muddy Cr. Enters
220	2	45,195	1,327	46,459	46,433	665	
221	1	46,432	1,830	47,924	47,897	1,151	Tributary Enters

Table 8 cont. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
221	2	46,621	1,796	48,112	48,085	1,118	
221	3	46,992	2,020	48,484	48,456	1,339	
221	4	47,090	1,740	48,582	48,555	1,071	
221	5	46,305	1,054	47,795	47,767	491	
221	6	46,031	539	47,521	47,493	40	
221	7	45,203	0	46,697	46,668	0	
222	1	45,281	38	46,776	46,747	37	Tributary Enters
222	2	45,600	0	47,095	47,066	0	
222	3	45,255	0	46,752	46,722	0	
222	4	45,723	363	47,222	47,192	359	
222	5	46,018	606	47,543	47,513	555	
222	6	45,440	0	46,986	46,956	0	
222	7	45,389	0	46,936	46,906	0	
222	8	45,044	0	46,642	46,611	0	
222	9	44,060	0	45,822	45,791	0	
222	10	44,047	0	45,810	45,778	0	
222	11	43,853	0	45,618	45,586	0	
223	1	49,999	7,161	63,602	63,568	208	Turkey Cr. Enters

Table 8 cont. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
223	2	50,192	7,257	63,778	63,744	353	
224	1	50,288	7,292	63,880	63,846	374	Tributary Enters
224	2	50,158	6,904	63,746	63,711	83	
224	3	50,246	6,931	63,830	63,795	0	
224	4	50,191	6,668	63,776	63,741	0	
224	5	50,794	6,771	64,377	64,342	105	
224	6	51,464	7,029	65,048	65,013	310	
224	7	51,111	6,506	64,691	64,655	0	
224	8	50,858	5,830	64,425	64,388	0	
224	9	50,831	5,283	64,396	64,360	0	
224	10	49,869	4,127	63,410	63,373	0	
224	11	49,706	3,510	63,244	63,206	0	
224	12	48,777	2,395	62,292	62,254	0	
224	13	48,455	1,940	61,969	61,930	0	
224	14	48,341	1,896	61,851	61,812	0	
224	15	47,842	1,673	61,400	61,362	0	
224	16	47,042	963	60,627	60,588	0	
224	17	48,769	1,005	62,849	62,809	0	

Table 8 cont. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
225	1	56,373	4,240	74,423	74,381	681	Tributary Enters
225	2	56,378	4,250	74,425	74,382	693	
226	1	48,434	2,762	64,735	64,692	264	Tributary Enters
226	2	54,142	3,954	71,635	71,588	486	
226	3	53,726	3,230	71,214	71,166	0	
226	4	53,804	2,938	71,289	71,241	0	
226	5	54,956	3,805	72,456	72,407	843	
226	6	54,858	3,374	72,352	72,302	406	
227	1	55,068	3,326	72,579	72,529	321	Tributary Enters
227	2	55,105	3,113	72,614	72,563	147	Republican River nr Orleans
228	1	54,810	2,622	72,308	72,260	0	
228	2	54,753	2,539	72,252	72,204	0	
228	3	54,693	2,368	72,176	72,137	0	
228	4	54,392	2,035	71,860	71,828	0	
228	5	54,576	2,093	72,045	72,013	42	
228	6	54,190	1,747	71,639	71,616	0	
228	7	54,631	1,895	72,079	72,056	101	
228	8	54,534	1,783	71,978	71,957	0	

Table 8 cont. Annual streamflow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On (ac-ft)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound On (ac-ft)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off (ac-ft)	Comments
228	9	54,445	1,477	71,878	71,857	0	
228	10	49,981	287	67,394	67,399	0	
228	11	49,983	284	67,393	67,398	0	
229	1	56,828	272	68,570	74,253	0	Sappa Creek Enters
229	2	56,761	258	68,503	74,183	0	
229	3	56,500	0	68,236	73,912	0	
229	4	61,085	1,302	72,844	78,492	72	
230	1	60,996	1,140	72,765	78,403	294	Tributary Enters
230	2	60,919	957	72,687	78,324	46	
230	3	60,931	882	72,694	78,329	0	
230	4	60,604	449	72,361	77,991	0	
230	5	59,924	144	71,667	77,287	0	Mainstem Above Harlan Accounting Point

When Nebraska is pumping, heads are lowered and storage is depleted. With mound recharge present, some storage is replenished and some baseflow is established. Removing mound recharge while Nebraska pumping is active results in the highest level of stream drying and storage depletion. Turning off mound recharge should produce a large decrease in baseflow because of the large flow associated with this activity. Instead, the impact of mound recharge is masked by the presence of Nebraska pumping. Once again, the assumption of additivity fails.

3.1.6 Conclusions Regarding Errors in Estimation of Individual State CBCU and IWS

It has been shown that stream drying is a cause of significant errors in the calculation of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS when the current Accounting Procedures are used. Error in these values not only affects the annual allocation to each state but also the estimate of actual water use. The errors have been detected by comparing values of VWS_G directly computed with those computed by summing $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS. The current Accounting Procedures assume that this additivity will apply to all model results. In fact, it does not. Errors in Beaver Creek, Frenchman Creek, and the Main Stem of the Republican River between Swanson Reservoir to Harlan County Lake have been examined. Stream drying may also cause errors at other accounting points.

While stream drying is shown to be the source of significant violations, these results are not intended to imply that there is anything inherently wrong with stream drying as computed by the Groundwater Model. Indeed, the total impact defined herein includes stream drying as, for example, at the Beaver Creek accounting point where the baseflow is zero when all human activities are present. These results ***do*** indicate a problem with the method for using the output of the Groundwater Model. The current method for determining $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS can be ineffective when stream drying is present. The current Accounting Procedures must be modified to produce better estimates of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS .

3.1.7 Proposed Method for Determining CBCU and IWS

It was shown in the preceding section that the current Accounting Procedures will produce erroneous values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS under some circumstances. In this section, a new method is proposed for determining these quantities. It only affects the procedures in sections III.A.3 and III.D.1 of the Accounting Procedures and Reporting Requirements for computing $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS. The proposed method does not change the allocation percentages defined in the Compact. However, the proposed method will produce much more accurate estimates of water supply and actual water use when stream drying conditions are significant. When compared with the current method, the proposed method will produce different values of both the annual allocation for each state and the actual water use by that state. When nonlinear responses are not significant, the proposed method will produce the same values of water supply and water use as the current method.

The proposed method requires no modification of the Groundwater Model but instead requires additional output from the Groundwater Model and combines the output in new ways. The current Accounting Procedures compute $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* using a differencing approach. The Groundwater Model is run with all human activity on to produce the "base" condition. The model is run again with the targeted human activity (state-wide pumping or mound recharge) turned off. The difference in Groundwater Model-computed baseflow at the accounting point between the base and off conditions is used to compute the impact of the particular human activity. The key concept of the proposed modification to the current Accounting Procedures is the use of multiple base conditions. The proposed method takes the weighted average of impacts computed from different base conditions to produce improved estimates of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS*. One major advantage of this approach is elimination of the arbitrariness inherent in selecting one base condition over another in a manner that could favor one state over another.

3.2 Importance of Base Condition

$CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* for a sub-basin can be computed by using a base condition in which all human activity is off and comparing that with a run in which only the targeted state activity is on. Such a calculation was performed in table 2 for the Beaver Creek accounting point for 1965. Comparison of the results using a base condition with all human activity on and a base condition with all off (see Tables 1 and 2), shows that the values of $CBCU_K$, and $CBCU_N$ are the same to within round-off error. The ability to compute the same values of $CBCU_K$ and $CBCU_N$ from alternate base conditions is a consequence of the linear response of baseflow to pumping exhibited in figures 4, 5, and 6. If this response is linear, then additivity is a valid assumption and the same impact values will be computed from any base condition. However, this result will not apply if response is nonlinear.

If the response of baseflow to pumping is not linear, then additivity is not valid and different base conditions may produce different computed impacts. In Section 3.1.3.2, it was established that a nonlinear condition is present in the 2003 computed baseflows. In table 3, $CBCU_K$, and $CBCU_N$ were computed using the all-on base condition resulting in impacts values of 323 and 727 ac-ft, respectively. In table 9, the calculation of $CBCU_K$, and $CBCU_N$ is repeated, this time using the all-off base condition. Comparison of results in table 3 with results in table 9 shows that the two different base conditions produce very different estimates of impacts. Results using either base condition alone produce estimates whose sums deviate substantially from the independently computed value of VWS_G, indicating that they are in error.

Table 9. Computation of Beaver Creek sub-basin $CBCU_K$, $CBCU_N$ and VWS_G in 2003 by subtracting from the condition with no human activity.

Subtract …	**From …**	**To Obtain …**
Baseflow with Nebraska at 0% and Kansas at 100% pumping: 727 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 6,445 ac-ft	$CBCU_K$: 5,718 ac-ft
Baseflow with Kansas at 0% and Nebraska at 100% pumping: 323 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 6,445 ac-ft	$CBCU_N$: 6,122 ac-ft
Baseflow with both States at 100% pumping: 0 ac-ft	Baseflow with Kansas at 0% and Nebraska at 0% pumping: 6,445 ac-ft	VWS_G : 6,445 ac-ft

When baseflow response to pumping is linear, the choice of base condition is unimportant. Any base condition will yield the same computed impacts (ignoring minor nonlinearities) as a direct consequence of the principle of superposition. This implies that there is no inherently “correct” choice for the base condition. When baseflow response is nonlinear, the choice of base condition makes a critical difference to the values computed. The proposed method is based on the idea that a non-arbitrary base condition (or conditions) should be chosen to produce the best estimates of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS*.

3.2.1 Criteria for Method to Compute CBCU and IWS Values

In Section 3.1, the impact values determined by the current Accounting Procedures were tested by comparing the sum of individual impacts with an independently-computed measure of total impact. When these two measures were found to be unequal, the individual impact values were deemed to be in error. It was shown that failure was related to nonlinear responses of baseflow to pumping.

The first criterion for any new method should be that it produces impact values that properly sum to the true total impact even when nonlinear responses are present. This criterion can be measured using a residual, *R*, which is the magnitude of the error between the true groundwater-related VWS for a sub-basin and that computed using the individual impacts of human activity. It is computed as:

$$R = VWS_G - (CBCU_C + CBCU_K + CBCU_N - IWS). \qquad \textbf{(Equation 7)}$$

VWS_G will be assumed to be the correct or true value of this quantity computed independently of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* as described in Section 3.1. The residual was computed several times in Section 3.1 and found to be large for the cases demonstrated with the exception of Beaver Creek in 1965 where the residual was zero. The reference to "zero" residual here implies approximately zero. It is expected that numerical round-off and mild nonlinearities will result in small residuals in nearly all cases. Clearly, there are many ways to select values for $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* that will add to the known value of VWS_G and produce a residual of zero. Arbitrary values would not be acceptable. Instead, the method to compute impact values must have a relationship to the current Accounting Procedures.

A second criterion for any new method is then that impacts should be determined using the same concept used in the current Accounting Procedures, namely, that of differencing between model runs with the target activity and other activities either fully on or fully off. Satisfying the second criterion will lead to meeting the third criterion which is that any new method should produce the same results as the current Accounting Procedures when the response of baseflow in a sub-basin is linear.

3.2.2 Proposed Method: Using Multiple Base Conditions

The current method computes $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* for a sub-basin using five runs of the Groundwater Model: a "base" run with all human activity on and four runs with each of the human activities turned-off. In effect, the current method uses only two runs of the Groundwater Model to examine how baseflow responds to a given target human activity. The proposed method relies on sixteen runs of the Groundwater Model. By using multiple model runs, additional information is obtained from the Groundwater Model about baseflow response. Combining this additional information in an appropriate way is the key to increasing the accuracy of estimates of impacts.

Table 10. Definition of RRCA Groundwater Model run names for 16 combinations of human activity on or off.

Run Name	Colorado Pumping	Kansas Pumping	Mound Recharge	Nebraska Pumping
θ	OFF	OFF	OFF	OFF
CKMN	ON	ON	ON	ON
CKM	ON	ON	ON	OFF
CMN	ON	OFF	ON	ON
CKN	ON	ON	OFF	ON
KMN	OFF	ON	ON	ON
CK	ON	ON	OFF	OFF
CM	ON	OFF	ON	OFF
CN	ON	OFF	OFF	ON
KM	OFF	ON	ON	OFF
KN	OFF	ON	OFF	ON
MN	OFF	OFF	ON	ON
C	ON	OFF	OFF	OFF
K	OFF	ON	OFF	OFF
M	OFF	OFF	ON	OFF
N	OFF	OFF	OFF	ON

The selection of the additional model runs to be used is based on the idea that using a base condition with any one human activity either on or off may bias the results for or against one state. This effect was seen in the examples in Section 3.1. As a result, analysis should be performed using all possible base conditions in which human activities are either on or off. Considering all possible combinations of the four activities results in sixteen different configurations[4]. The base cases are selected from among these depending on the target activity to be analyzed. These sixteen cases are summarized in table 10 with each run assigned a name which designates the condition of each of the human activities in that run. The presence of a letter indicates that the activity is on while its absence indicates that it is off. The θ run has all

[4] The possible combinations for any set of target stresses (n) where each stress is either fully on or fully off is given by two to the power of the number of target stresses (2^n).

activity off. For example, the run name *CKMN* indicates that Colorado pumping, Kansas pumping, mound recharge and Nebraska pumping are all on during this run. In each of the sixteen cases, the output of the model is the baseflow at the accounting point of interest.

Considering the entries in table 10, it is apparent that values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* could be computed from any one of 8 possible base conditions. For example, for computing $CBCU_N$, the difference of *CKM* and *CKMN* uses all-on as the base condition (this is the current Accounting Procedures). The difference of θ and *N* is an impact of Nebraska pumping computed from an all-off condition. The difference of *C* and *CN* is the impact of Nebraska pumping computed from a base in which only Colorado pumping is active. The proposed method uses all 8 of the possible base conditions and combines them in a weighted combination.

The proposed method can be summarized as follows. Perform 16 runs of the Groundwater Model according to the definitions in table 10. When a human activity is listed as "on," it means that all activity in the model data base since 1918 is active at the 100% level. When an activity is listed as "off," that activity is absent during the entire modeled period. To compute the values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* for a given sub-basin in a given year, combine these results of the 16 runs using the formulas shown below. In these formulas, the run name represents the value of baseflow at the relevant accounting point when the model is run using the indicated status of human activity. For example, *KM* in these formulas is the value of baseflow in the target year and sub-basin when the Groundwater Model is run with Colorado pumping off, Kansas pumping on, Nebraska pumping off and mound recharge on.

$$CBCU_C = [(\theta-C) + ((K-CK) + (M-CM) + (N-CN))/3 + ((KM-CKM) + (KN-CKN) + (MN-CMN))/3 + (KMN-CKMN)]/4 \quad \textbf{(Equation 8)}$$

$$CBCU_K = [(\theta-K) + ((C-CK) + (M-KM) + (N-KN))/3 + ((CM-CKM) + (CN-CKN) + (MN-KMN))/3 + (CMN-CKMN)]/4 \quad \textbf{(Equation 9)}$$

$$CBCU_N = [(\theta-N) + ((C-CN) + (M-MN) + (K-KN))/3 + ((CM-CMN) + (CK-CKN) + (KM-KMN))/3 + (CKM-CKMN)]/4 \quad \textbf{(Equation 10)}$$

$$IWS = [(M-\theta) + ((CM-C) + (KM-K) + (MN-N))/3 + ((CKM-CK) + (CMN-CN) + (KMN-KN))/3 + (CKMN-CKN)]/4 \quad \textbf{(Equation 11)}$$

3.2.3 Characteristics of Proposed Method

The proposed method meets the criteria set forth above. It is based on the differencing concept of the current method wherein it compares runs with the target set fully on or off. When the response of baseflow to pumping is linear, the proposed method produces the same values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* as the current method. This can be seen by noting that for a linearly responding sub-basin, each of the 8 differences in any one of the impact equations will have the same value. For example, for the Nebraska impact, $CBCU_N$, *CKM-CKMN* takes the same value as *θ-N* and *C-CN* and the remaining five baseflow differences in equation 10. Combining these 8 values in the manner dictated by equation 10 simply returns the computed impact. These same results apply to any of the other impacts.

The residual will always be zero for impacts computed using the proposed method. This is a direct result of the use of the 16 combinations in table 10 and the use of the particular weights selected here. Constructing a new method that has zero residual requires that the terms in $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* include baseflows computed from both the *θ* and the *CKMN* runs in the computation of individual impacts. This is necessary to cancel the appearance of these terms in the VWS_G expression. Using the differencing approach of the current method and given that the *θ* run is included, it is necessary to also include the baseflows determined from the single-activity runs (*C, K, M* and *N*). To eliminate these single-activity runs from the equation, it is necessary to include baseflows from two-activity runs in the computation. The baseflows from three-activity runs must also be included by similar reasoning so that the computation of a single impact involves use of baseflows from all 16 runs in table 10. In short, in order to devise a method that is guaranteed to have zero residual and that is true to the run-differencing concept in the current Accounting Procedures, it is necessary to include baseflows computed by all of the 16 runs listed in table 10. These 16 baseflows produce eight differences for a given impact. The weightings proposed here on these eight differences are guaranteed to always produce a zero residual.

3.2.4 Application to Beaver Creek

For many sub-basins, there are only two significant stresses. This applies to Beaver Creek, where only Kansas and Nebraska pumping are significant. Using Beaver Creek again as an example, $CBCU_K$ and $CBCU_N$ can be computed from equations 9 and 10.

For this case, the following observations can be made:

1) $C = M = CM = \theta$ (turning on Colorado pumping or mound recharge produces the same baseflow at the accounting point as a run in which there is no human activity.

2) $N = CN = MN = CMN$ (adding Colorado pumping and mound recharge does not change the impact of Nebraska pumping)

3) $K = CK = KM = CKM$ (adding Colorado pumping and mound recharge does not change the impact of Kansas pumping)

4) $KN = CKN = KMN = CKMN$ (adding Colorado pumping or mound recharge does not change the impact of Kansas pumping, Nebraska pumping.)

The proposed impact equations can be simplified using these observations:

$$CBCU_K = (\theta - K + CMN - CKMN)/2 \qquad \textbf{(Equation 12)}$$

$$CBCU_N = (\theta - N + CKM - CKMN)/2 \qquad \textbf{(Equation 13)}$$

Table 11 shows the calculation of $CBCU_K$ and $CBCU_N$ for the Beaver Creek accounting point in 2003 using the proposed method in the form of equations 12 and 13. The sum of the values computed is 6,446 ac-ft (3,021+3,425). This is nearly identical to 6,445, the value of VWS_G directly computed as reported in table 9. These results indicate that the proposed method meets the criteria of producing $CBCU_K$ and $CBCU_N$ values that sum to the independently calculated VWS_G, producing a residual of zero. This will always be the case as can be shown by examining the equation for the residual in detail.

Table 11. Computation of Beaver Creek sub-basin $CBCU_K$ and $CBCU_N$ in 2003 using the proposed method with Mound recharge and Colorado pumping assumed negligible.

Terms in the Calculation of the Proposed Method (ac-ft)				**Impacts Computed by Proposed Method**
θ = 6,445	K = 726	CMN = 323	$CKMN$ = 0	$CBCU_K$ = 3,021 ac-ft
θ = 6,445	N = 323	CKM = 727	$CKMN$ = 0	$CBCU_N$ = 3,425 ac-ft

For the Beaver Creek accounting point in 2003, the residual calculation shown in equation 7 is simplified because $CBCU_C$ and IWS can both be assumed to be zero. As a result, the residual is calculated as:

$$R = VWS_G - (CBCU_K + CBCU_N) \qquad \textbf{(Equation 14)}$$

Using the notation in table 10, the value of VWS_G is independently computed as the difference between the all-on and all-off conditions or $\theta\text{-}CKMN$. Substituting this and the equations above, the residual produced by the proposed method is:

$$R = \theta\text{-}CKMN - (\theta\text{-}K + CMN\text{-}CKMN)/2 + (\theta\text{-}N + CKM\text{-}CKMN)/2 \qquad \textbf{(Equation 15)}$$

Recognizing that runs *K* and *CKM* will yield the same computed baseflow, since Colorado pumping and mound recharge have no impact on Beaver Creek, these terms cancel each other in equation 15. Similarly, the terms *N* and *CMN* will take the same value and cancel from the equation. Evaluating the remainder of the equation, it can be seen that the residual will be zero. In fact, the proposed method will produce impact values that always yield a zero residual.

3.2.5 Conclusion

A new method for computing the $CBCU_C$, $CBCU_K$, $CBCU_N$ and *IWS* for a sub-basin in the Accounting Procedures has been proposed here. This method requires computation of baseflow in a given sub-basin using 16 different combinations of human activity. The results of these 16 runs are combined to produce values of impacts for each stress activity that address major errors in the current method for computing impacts. The proposed method provides values for impact that satisfy the expectation that individual impacts will sum to the total impact of human activity for a given sub-basin. The proposed method could be extended to address the calculation of impacts for any sets of stresses including those that occur within individual states.

4.0 APPLICATION OF THE PROPOSED METHOD FOR DETERMINATION OF $CBCU_G$, IWS, COMPUTED WATER SUPPLY, AND STATE ALLOCATIONS

As discussed above, the Accounting Procedures are used to determine the annual amount of water available to each state under the Compact's allocation formulae. These "annual allocations" are combined with the *IWS* and *CBCU* that occurred in each state. These balances are used to compute the five-year (and two-year during water short year administration) running average that serves as a test of Compact compliance for each state. As discussed in Section II above, the current Accounting Procedures are flawed and Nebraska has proposed a new method for determining $CBCU_C$, $CBCU_K$, and $CBCU_N$, and the *IWS*. These four groundwater components are combined in the RRCA accounting (along with surface water components) to produce an estimate of the computed water supply (CWS), which is used to determine the state allocations.

In this section, we demonstrate that Nebraska's proposed method produces a substantially better estimate of the *CWS* than that produced by the current method for 2003 accounting. In all sub-basins, the difference between the estimated *CWS* produced by the proposed method and the actual *CWS* are zero. The proposed method provides a far superior estimate of the states' annual allocations, as well as better estimates of the $CBCU_C$, $CBCU_K$, $CBCU_N$, and the *IWS*, resulting in a significant change to the final state balance in the Compact accounting.

4.1 Computed Water Supply

The allocation for each state from each sub-basin and the Main Stem is based on the CWS, which is defined in the Accounting Procedures as:

$$CWS = VWS - \Delta S - FF, \qquad \textbf{(Equation 16)}$$

where *FF* refers to flood flows. By substituting equation 2 for the *VWS*, including the addition of the change in federal reservoir storage in the *VWS* calculation, and neglecting the flood flows term (to help simplify this example), equation 16 reduces to:

$$CWS = Gage + CBCU_S + CBCU_G - IWS. \qquad \textbf{(Equation 17)}$$

or,

$$CWS = Gage + CBCU_S + CWS_G \qquad \textbf{(Equation 18)}$$

where,

$$CWS_G = CBCU_G - IWS. \qquad \textbf{(Equation 19)}$$

And because VWS_G is also equal to $CBCU_G$-*IWS* (equation 4), then,

$$VWS_G = CWS_G. \qquad \textbf{(Equation 20)}$$

In the same manner for VWS_G discussed above, CWS_G can be computed by taking the difference between modeled stream baseflow when pumping in all states and mound recharge is on and modeled stream baseflow when pumping in all states and mound recharge is off. Ultimately, it is necessary to determine a separate value for each component of the CWS_G (the $CBCU_C$, $CBCU_K$, $CBCU_N$, and the *IWS*) in order to compare each state's allocation plus *IWS* to the corresponding *CBCU*. Current Accounting Procedures compute the CWS_G by applying a method (discussed above) for the determination of these components and summing the results.

Table 12. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ computed using the current accounting with the actual CWS_G for 2003 in ac-ft. Values from current accounting are slightly different from the final adopted accounting from 2003 due to small differences in the groundwater model output presented in this report.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	125	226	502	0	853	1,012	159
Beaver	0	323	727	0	1,050	6,445	5,395
Buffalo	268	0	3,332	0	3,600	3,683	83
Driftwood	0	0	1,391	0	1,391	1,391	0
Frenchman	19	0	85,624	0	85,643	90,671	5,028
North Fork	14,155	33	1,257	0	15,445	15,426	-19
Medicine	0	0	20,221	9,439	10,782	10,304	-478
Prairie Dog	0	1,678	0	0	1,678	1,679	1
Red Willow	0	0	7,813	20	7,793	7,753	-40
Rock	58	0	3,419	0	3,477	3,500	23
Sappa	0	-323	500	0	177	472	295
South Fork	12,168	5,284	1,331	0	18,783	20,046	1,263
Main Stem	148	390	76,572	334	76,776	57,840	-18,936

Table 12 documents the difference between the CWS_G and the combination of these components determined using the current accounting methodology for 2003. The combination of $CBCU_C + CBCU_K + CBCU_N - IWS$ determined using the current Accounting Procedures yields a poor estimate of the CWS_G in many sub-basins. Clearly, the failure of these terms to sum to the CWS_G indicates there is substantial error in some or all of the values for $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS in many of the sub-basins. This error ripples through the accounting, resulting in errors in the CWS and the computed allocations.

4.2 State Allocations and the Compact

Under the Compact, the CWS for each sub-basin is allocated to each state based on the percentages in table 13. Each sub-basin is split between one or more states, with some percentage of the sub-basin CWS that is unallocated. The sum of the unallocated supply is added to the Main Stem CWS and this total is allocated according to table 13. The components of the CWS along with the CWS and the resulting state allocations for 2003 are shown in table 14.

Table 13. Compact Allocations. The unallocated CWS is added to the Main Stem CWS.

Basin	CO % of Basin Supply	KS % of Basin Supply	NE % of Basin Supply	% Unallocated
Arikaree	78.5%	5.1%	16.8%	-0.4%
Beaver	20.0%	38.8%	40.6%	0.6%
Buffalo			33.0%	67.0%
Driftwood		6.9%	16.4%	76.7%
Frenchman			53.6%	46.4%
North Fork	22.4%		24.6%	53.0%
Medicine			9.1%	90.9%
Prairie Dog		45.7%	7.6%	46.7%
Red Willow			19.2%	80.8%
Rock			40.0%	60.0%
Sappa		41.1%	41.1%	17.8%
South Fork	44.4%	40.2%	1.4%	14.0%
Main Stem + Unallocated		51.1%	48.9%	

Table 14. CWS (with surface water and groundwater components) and the resulting state allocations for 2003 in ac-ft.

	Gage + $CBCU_S$	CWS_G	CWS	Allocations			Unallocated
				CO	KS	NE	
Arikaree	1,060	1,012	2,072	1,627	106	348	-8
Beaver	239	6,445	6,684	1,337	2,593	2,714	40
Buffalo	2,497	3,683	6,180	0	0	2,039	4,141
Driftwood	1,099	1,391	2,490	0	172	408	1,910
Frenchman	20,236	90,671	110,907	0	0	59,446	51,461
North Fork	25,288	15,426	40,714	9,120	0	10,016	21,578
Medicine	23,834	10,304	34,138	0	0	3,107	31,031
Prairie Dog	6,011	1,679	7,690	0	3,514	584	3,591
Red Willow	6,605	7,753	14,358	0	0	2,757	11,601
Rock	4,712	3,500	8,212	0	0	3,285	4,927
Sappa	-36	472	436	0	179	179	78
South Fork	4,917	20,046	24,963	11,084	10,035	349	3,495
Main Stem	91,803	57,840	149,643	0	144,862	138,626	N/A
Total	188,265	220,223	408,488	23,167	161,462	223,858	

As seen in table 14, the total basin-wide *CWS* for 2003 is 408,488 ac-ft, obtained by combining the sum of the gage + $CBCU_S$ with the CWS_G, from equation 18. Table 15 presents the same information, except the CWS_G is estimated by summing the $CBCU_C$, $CBCU_K$, $CBCU_N$, and the *IWS*, which are computed using the current Accounting Procedures. Table 16 presents a comparison of the total *CWS* and state allocation computed from the actual CWS_G with the *CWS* and state allocations obtained using the estimate of CWS_G from current Accounting Procedures.

Table 15. CWS (with surface water and groundwater components) and the resulting state allocations for 2003 in ac-ft. Here, the $CBCU_C + CBCU_K + CBCU_N$ - IWS computed using the current accounting methodology is used to estimate the CWS_G in equation 18.

	Gage + $CBCU_S$	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS	Allocations			Unallocated
				CO	KS	NE	
Arikaree	1,060	853	1,913	1,502	98	321	-8
Beaver	239	1,050	1,289	258	500	523	8
Buffalo	2,497	3,600	6,097	0	0	2,012	4,085
Driftwood	1,099	1,391	2,490	0	172	408	1,910
Frenchman	20,236	85,643	105,879	0	0	56,751	49,128
North Fork	25,288	15,445	40,733	9,124	0	10,020	21,588
Medicine	23,834	10,782	34,616	0	0	3,150	31,466
Prairie Dog	6,011	1,678	7,689	0	3,514	584	3,591
Red Willow	6,605	7,793	14,398	0	0	2,764	11,634
Rock	4,712	3,477	8,189	0	0	3,276	4,913
Sappa	-36	177	141	0	58	58	25
South Fork	4,917	18,783	23,700	10,523	9,527	332	3,318
Main Stem	91,803	76,776	168,579	0	153,421	146,816	N/A
Total	188,265	227,448	415,713	21,406	167,290	227,017	

The current Accounting Procedures resulted in an overestimation of the *CWS* by 7,225 ac-ft. The 2003 allocation was underestimated for Colorado by 1,761 ac-ft. Conversely, the 2003 Compact allocation was overestimated for Kansas and Nebraska by 5,828 and 3,159 ac-ft, respectively. The current Accounting Procedures thus produced a poor estimate of the CWS_G, resulting in the incorrect calculation of the CWS and the state allocations.

Table 16. Comparison of CWS and state allocations (in ac-ft).

	CWS	CO	KS	NE
Computed from CWS_G	408,488	23,167	161,462	223,858
Computed using current accounting estimate of CWS_G	415,713	21,406	167,290	227,017
Difference	7,225	-1,761	5,828	3,159

4.3 State Impacts and IWS

The Accounting Procedures require individual estimates of the $CBCU_C$, $CBCU_K$, $CBCU_N$, and *IWS*. Simply correcting the *CWS* and allocations, while continuing to use the current methodology for computing $CBCU_C$, $CBCU_K$, $CBCU_N$, and *IWS* is not acceptable, because the CWS_G would not be equal to $CBCU_C + CBCU_K + CBCU_N + IWS$. The Compact compliance tests that compare allocations to *CBCU-IWS* would no longer be valid. Nebraska proposes an accounting method that produces estimates of $CBCU_C$, $CBCU_K$, $CBCU_N$, and *IWS* that, when summed, equal the CWS_G for all sub-basins. The resulting groundwater pumping impacts by sub-basin and target stress for 2003 are presented in table 17. For each sub-basin, table 17 shows the impact of each of the four major stress sets ($CBCU_C$, $CBCU_K$, $CBCU_N$, and *IWS*), the CWS_G as estimated by combining the four impacts ($CBCU_C + CBCU_K + CBCU_N - IWS$), the actual CWS_G, and the difference between the estimated CWS_G and the actual CWS_G. ***The proposed method exactly reproduces the*** $\boldsymbol{CWS_G}$**.** Appendix C presents a comparison of the current method and proposed method for 2001-2006.

Table 17. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2003 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	159	284	568	0	1,012	1,012	0
Beaver	-1	3,021	3,425	0	6,445	6,445	0
Buffalo	309	0	3,374	0	3,683	3,683	0
Driftwood	0	0	1,391	0	1,391	1,391	0
Frenchman	2,565	-9	88,141	26	90,671	90,671	0
North Fork	14,149	29	1,248	0	15,426	15,426	0
Medicine	-2	-1	19,987	9,680	10,304	10,304	0
Prairie Dog	0	1,679	1	0	1,679	1,679	0
Red Willow	-1	0	7,793	39	7,753	7,753	0
Rock	69	0	3,430	0	3,500	3,500	0
Sappa	0	-173	648	2	472	472	0
South Fork	12,535	5,837	1,672	-2	20,045	20,046	0
Main Stem	-627	446	67,066	9,044	57,840	57,840	0

4.4 Compliance Test

The final step in the RRCA annual accounting is a comparison between the total annual Compact allocation for each state and that state's total *CBCU – IWS*. These comparisons are used to calculate each state's success regarding two- and/or five-year running average compliance tests. The calculated state allocations using the newly-proposed methodology are shown in table 18. In other words, the allocations shown in table 18 represent the estimated CWS_G from the proposed methodology for groundwater accounting, as opposed to the actual value of CWS_G, as calculated by comparing the model run with all state pumping and mound recharge on and modeled stream baseflow with all states' pumping and mound recharge off. Note that these values are identical to those in table 14 (which uses the actual CWS_G).

Table 18. CWS (with surface water and groundwater components) and the resulting state allocations for 2003 in ac-ft. Here, the $CBCU_C + CBCU_K + CBCU_N$ - IWS computed using the proposed accounting methodology is used to estimate the CWS_G in equation 5.

	Gage + $CBCU_S$	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS	Allocations			Unallocated
				CO	KS	NE	
Arikaree	1,060	1,012	2,072	1,627	106	348	-8
Beaver	239	6,445	6,684	1,337	2,593	2,714	40
Buffalo	2,497	3,683	6,180	0	0	2,039	4,141
Driftwood	1,099	1,391	2,490	0	172	408	1,910
Frenchman	20,236	90,671	110,907	0	0	59,446	51,461
North Fork	25,288	15,426	40,714	9,120	0	10,016	21,578
Medicine	23,834	10,304	34,138	0	0	3,107	31,031
Prairie Dog	6,011	1,679	7,690	0	3,514	584	3,591
Red Willow	6,605	7,753	14,358	0	0	2,757	11,601
Rock	4,712	3,500	8,212	0	0	3,285	4,927
Sappa	-36	472	436	0	179	179	78
South Fork	4,917	20,045	24,963	11,084	10,035	349	3,495
Main Stem	91,803	57,840	149,643	0	144,862	138,626	N/A
Total	188,265	220,223	408,488	23,167	161,462	223,858	

Table 19 presents a comparison of the total *CWS* and state allocation computed from the actual CWS_G with the *CWS* and state allocations obtained using the estimate of CWS_G from the proposed change to the Accounting Procedures. The proposed Accounting Procedures produce an exact estimate of the CWS_G, resulting in a highly accurate calculation of the *CWS* and the state allocations.

Table 19. Comparison of CWS and state allocations (in ac-ft).

	CWS	CO	KS	NE
Computed from CWS_G	408,488	23,167	161,462	223,858
Computed using proposed accounting estimate of CWS_G	408,488	23,167	161,462	223,858
Difference	0	0	0	0

Table 20 presents a comparison of the final results of the current accounting method and the final results for the proposed accounting method. As previously discussed, the allocation for Colorado is greater, while the allocations for Kansas and Nebraska are less. It is important to understand that these are not changes to the Compact allocations, they are corrections to the estimated annual volume of water available and consumed under those allocations. In addition, the proposed methodology results in a *CBCU – IWS* for Colorado and Kansas that is greater than the values determined under the current method, while the *CBCU – IWS* for Nebraska is nearly 13,000 ac-ft less than that determined under the current method (primarily due to a substantial increase in the *IWS* for Nebraska). This results in a small decrease in Colorado's balance, a large decrease in Kansas' balance, and a large increase in Nebraska's balance.

Table 20. Comparison of the current accounting results with the corrected accounting results for 2003. The CBCU – IWS term includes both the $CBCU_G$ and $CBCU_S$. Units are in ac-ft.

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	21,406	33,538	-12,132	23,167	35,753	-12,586
Kansas	167,290	49,264	118,026	161,462	52,766	108,696
Nebraska	227,017	251,511	-24,494	223,858	238,569	-14,711

4.5 Conclusion

As shown above, the current Accounting Procedures produce a poor estimate of the CWS_G in many sub-basins (table 12). In contrast, the proposed method produces an exact estimate of CWS_G (table 17), resulting in the correct computation of the total *CWS* and the state allocations (table 19). The final balance for each state is further affected by the differences in the state-wide impacts (table 20). The net result for 2003 is substantial. The results are similar for all the years 2001-2006 (Appendix C).

APPENDIX A: Current Calculations of $CBCU_g$ and IWS

A.1 Current Calculation of $CBCU_g$

$CBCU_G$ is not specifically defined in the list of definitions that is part of the Accounting Procedures but rules for its determination are given in the RRCA Accounting Procedures (section III.D.1) as set forth below:

> Computed Beneficial Consumptive Use of groundwater shall be determined by use of the RRCA Groundwater Model. The Computed Beneficial Consumptive Use of groundwater for each State shall be determined as the difference in streamflows using two runs of the model:
>
> The "base" run shall be the run with all groundwater pumping, groundwater pumping recharge, and surface water recharge within the model study boundary for the current accounting year "on."
>
> The "no State pumping" run shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge of that State shall be turned "off."
>
> An output of the Groundwater Model is baseflow at selected stream cells. Changes in the baseflow predicted by the Groundwater Model between the "base" run and the "no-State-pumping" model run is assumed to be the depletions to streamflows. i.e., groundwater computed beneficial consumptive use, due to State groundwater pumping at that location. The values for each sub-basin will include all depletions and accretions upstream of the confluence with the Main Stem. The values for the Main Stem will include all depletions and accretions in stream reaches not otherwise accounted for in a sub-basin. The values for the Main Stem will be computed separately for the reach above Guide Rock, and the reach below Guide Rock.

The notation and wording are confusing. The typical practice among the states has been as follows:

- The "base" run has been made such that those stresses are represented for **<u>all</u>** years during the simulation period.
- The term "pumping recharge" has been applied to mean "that water pumped from the ground for irrigation which, after it is applied to crops, infiltrates back into the ground".
- The term "surface water recharge" has been applied to mean "water diverted from a river or creek for irrigation which either infiltrates into the ground from a canal or, after it is applied to crops, infiltrates into the ground." It does not include recharge of surface water directly from rivers.

- The term "groundwater computed beneficial consumptive use" has been applied to be the same as $CBCU_G$.
- The term "depletion" in the first sentence of the last paragraph quoted above is equivalent to the term "depletions and accretions" used in third and fourth sentences of the same paragraph. Both terms are applied to mean "net depletions."

A.2 Current Calculation of IWS

The current rules for calculation of the IWS also are given in the RRCA Accounting Procedures (section III.A.3), as set forth below:

> The amount of Imported Water Supply Credit shall be determined by the RRCA Groundwater Model. The Imported Water Supply Credits shall be determined using two runs of the RRCA Model:
>
> The "base" run shall be the run with all groundwater pumping, groundwater pumping recharge, and surface water recharge within the model study boundary for the current accounting year turned "on." This will be the same "base" run used to determine groundwater Computed Beneficial Consumptive Uses.
>
> The "no NE import" run shall be the run with the same model inputs as the base run with the exception that surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."
>
> The Imported Water Supply Credit shall be the difference in streamflows between these two model runs.

Again, the notation and wording are confusing. The typical practice among the states has been as follows:

- The term "pumping recharge" has been applied to mean "that water pumped from the ground for irrigation which, after it is applied to crops, infiltrates back into the ground";
- The term "surface water recharge" has been applied to mean "water diverted from a river or creek for irrigation which either infiltrates into the ground from a canal or, after it is applied to crops, infiltrates into the ground." It does not include recharge of surface water directly from rivers.

Terms used in this report reflect the states' actual practices.

APPENDIX B: Alternate Calculation of Swanson Harlan Impacts

In this appendix, portions of the analysis for the Swanson-Harlan reach of the Main Stem are repeated using the current Accounting Procedures without modification. The current procedure calls for computing the baseflow by subtracting the computed flows at the mouth of a number of major tributaries (Frenchman Creek, Driftwood Creek, Medicine Creek, Red Willow Creek, and Sappa Creek) from the baseflow at the accounting point above Harlan County Lake. This subtraction was not done in section 3.1.5 where the actual computed baseflows at the accounting point were reported instead. Table 7 is repeated here as table B.1 with all values now including the subtraction of major tributary flows. For many baseflow values, this produces a negative flow. The values of $CBCU_K$ and IWS are nearly identical as those shown in table 7 because the flows in the major tributaries are also nearly identical. The values of $CBCU_N$ and the independently calculated VWS_G value of 59,780 ac-ft both result from turning off Nebraska pumping for one of the baseflow conditions. This results in a substantial change in the flows in the subtracted major tributaries translating into a major change in these computed values.

Table B.1: Computation of $CBCU_K$, $CBCU_N$, IWS and VWS_G in 2003 for the Main Stem at the Accounting Point Above Harlan County Lake using the current Accounting Procedures in which computations include subtraction of major tributary flow from computed baseflows at the accounting point.

Subtract …	From …	To Obtain …
Baseflow with all man-made stresses active: -3394 ac-ft	Baseflow with Kansas at 0% and all other man-made stresses active: -3341 ac-ft	$CBCU_K$: 53 ac-ft
Baseflow with all man-made stresses active: -3394 ac-ft	Baseflow with Nebraska pumping at 0% and all other man-made stresses active: 23,859 ac-ft	$CBCU_N$: 27,253 ac-ft
Baseflow with mound recharge off and all other man-made stresses active: -3534 ac-ft	Baseflow with all man-made stresses active: -3394 ac-ft	IWS : 140 ac-ft
Baseflow with all man-made stresses active: -3394 ac-ft	Baseflow with all man-made stresses inactive: 6482 ac-ft	VWS_G : 9,876 ac-ft

The main point of section 3.1.5 is that combination of $CBCU_K$, $CBCU_N$ and *IWS* does not equal the independently-calculated VWS_G value of 59,780 ac-ft. This same general conclusion holds. Using the values from table B.1, the individual values combine to 27,166 ac-ft (53 + 27,253 – 140). Comparing this value with the independently calculated VWS_G value of 9,876 ac-ft, it is evident that the current Accounting Procedures over-estimates the groundwater portion of the VWS by 17,290 ac-ft, further confirming that an error exists in $CBCU_K$, $CBCU_N$ or *IWS*.

APPENDIX C: Results of Current and Proposed Method for 2001-2006

Table C.1. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS computed using the current accounting with the actual CWS_G for 2001 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N$ - IWS	CWS_G	Difference
Arikaree	1,098	320	340	0	1,758	1,900	142
Beaver	0	3,645	2,988	0	6,633	9,502	2,869
Buffalo	250	0	3,094	0	3,344	3,496	152
Driftwood	0	0	1,221	0	1,221	1,221	0
Frenchman	559	0	82,267	0	82,826	87,147	4,321
North Fork	13,656	23	1,548	0	15,227	15,235	8
Medicine	0	0	17,592	9,303	8,289	7,898	-391
Prairie Dog	0	3,406	0	0	3,406	3,402	-4
Red Willow	0	0	7,766	29	7,737	7,714	-23
Rock	46	0	3,216	0	3,262	3,284	22
Sappa	0	-939	873	0	-66	2,180	2,246
South Fork	10,986	7,398	637	0	19,021	21,017	1,996
Main Stem	-4,181	283	80,207	9,009	67,300	61,972	-5,328

Table C.2. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2001 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N$ - IWS	CWS_G	Difference
Arikaree	1,148	370	382	0	1,900	1,900	0
Beaver	-1	5,081	4,423	1	9,502	9,502	0
Buffalo	326	1	3,170	0	3,496	3,496	0
Driftwood	0	0	1,221	0	1,221	1,221	0
Frenchman	2,736	0	84,433	23	87,147	87,147	0
North Fork	13,654	29	1,552	-1	15,235	15,235	0
Medicine	-1	-2	17,401	9,500	7,898	7,898	0
Prairie Dog	-1	3,405	-1	1	3,402	3,402	0
Red Willow	0	-1	7,755	41	7,713	7,713	0
Rock	57	0	3,227	0	3,284	3,284	0
Sappa	-1	182	2,007	8	2,180	2,180	0
South Fork	11,602	8,299	1,114	-2	21,017	21,017	0
Main Stem	-2,784	323	77,698	13,266	61,971	61,971	0

Table C.3. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ computed using the current accounting with the actual CWS_G for 2002 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	261	226	349	0	836	910	74
Beaver	0	1,739	1,791	0	3,530	7,587	4,057
Buffalo	247	0	3,221	0	3,468	3,594	126
Driftwood	0	0	1,272	0	1,272	1,272	0
Frenchman	603	0	78,254	0	78,857	83,200	4,343
North Fork	13,691	25	1,801	0	15,517	15,503	-14
Medicine	0	0	18,676	8,373	10,303	9,201	-1,102
Prairie Dog	0	2,804	0	0	2,804	2,805	1
Red Willow	0	0	6,938	24	6,914	6,890	-24
Rock	53	0	3,297	0	3,350	3,371	21
Sappa	0	-422	695	0	273	1,287	1,014
South Fork	10,831	4,854	1,259	0	16,944	17,099	155
Main Stem	-6,193	871	60,875	5,608	49,945	42,130	-7,815

Table C.4. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2002 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	280	257	374	0	910	910	0
Beaver	-1	3,768	3,820	1	7,587	7,587	0
Buffalo	310	0	3,284	0	3,594	3,594	0
Driftwood	0	0	1,272	0	1,272	1,272	0
Frenchman	2,797	-5	80,431	24	83,200	83,200	0
North Fork	13,685	22	1,796	0	15,503	15,503	0
Medicine	-2	-1	18,130	8,925	9,201	9,201	0
Prairie Dog	0	2,806	0	0	2,805	2,805	0
Red Willow	-1	0	6,926	36	6,889	6,889	0
Rock	63	0	3,307	0	3,371	3,371	0
Sappa	0	85	1,206	5	1,287	1,287	0
South Fork	10,822	4,814	1,463	-2	17,099	17,099	0
Main Stem	-4,421	546	57,167	11,162	42,130	42,130	0

Table C.5. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS computed using the current accounting with the actual CWS_G for 2003 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	125	226	502	0	853	1,012	159
Beaver	0	323	727	0	1,050	6,445	5,395
Buffalo	268	0	3,332	0	3,600	3,683	83
Driftwood	0	0	1,391	0	1,391	1,391	0
Frenchman	19	0	85,624	0	85,643	90,671	5,028
North Fork	14,155	33	1,257	0	15,445	15,426	-19
Medicine	0	0	20,221	9,439	10,782	10,304	-478
Prairie Dog	0	1,678	0	0	1,678	1,679	1
Red Willow	0	0	7,813	20	7,793	7,753	-40
Rock	58	0	3,419	0	3,477	3,500	23
Sappa	0	-323	500	0	177	472	295
South Fork	12,168	5,284	1,331	0	18,783	20,046	1,263
Main Stem	148	390	76,572	334	76,776	57,840	-18,936

Table C.6. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2003 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	159	284	568	0	1,012	1,012	0
Beaver	-1	3,021	3,425	0	6,445	6,445	0
Buffalo	309	0	3,374	0	3,683	3,683	0
Driftwood	0	0	1,391	0	1,391	1,391	0
Frenchman	2,565	-9	88,141	26	90,671	90,671	0
North Fork	14,149	29	1,248	0	15,426	15,426	0
Medicine	-2	-1	19,987	9,680	10,304	10,304	0
Prairie Dog	0	1,679	1	0	1,679	1,679	0
Red Willow	-1	0	7,793	39	7,753	7,753	0
Rock	69	0	3,430	0	3,500	3,500	0
Sappa	0	-173	648	2	472	472	0
South Fork	12,535	5,837	1,672	-2	20,045	20,045	0
Main Stem	-627	446	67,066	9,044	57,840	57,840	0

Table C.7. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS computed using the current accounting with the actual CWS_G for 2004 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	161	311	427	0	899	861	-38
Beaver	0	272	1,182	0	1,454	7,375	5,921
Buffalo	294	0	3,327	0	3,621	3,717	96
Driftwood	0	0	1,479	0	1,479	1,479	0
Frenchman	39	0	89,706	0	89,745	94,980	5,235
North Fork	14,501	31	1,302	0	15,834	15,832	-2
Medicine	0	0	20,602	9,533	11,069	10,548	-521
Prairie Dog	0	1,823	0	0	1,823	1,823	0
Red Willow	0	0	8,218	25	8,193	8,159	-34
Rock	57	0	3,581	0	3,638	3,669	31
Sappa	0	-272	558	0	286	558	272
South Fork	12,929	5,723	1,188	0	19,840	20,476	636
Main Stem	-1,233	473	80,403	826	78,817	61,364	-17,453

Table C.8. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N$ - IWS where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2004 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	166	291	405	0	861	861	0
Beaver	-1	3,233	4,143	0	7,375	7,375	0
Buffalo	341	0	3,375	0	3,717	3,717	0
Driftwood	0	0	1,479	0	1,479	1,479	0
Frenchman	2,685	-7	92,330	28	94,980	94,980	0
North Fork	14,499	33	1,300	0	15,832	15,832	0
Medicine	-2	-1	20,347	9,795	10,548	10,548	0
Prairie Dog	-1	1,823	0	0	1,822	1,822	0
Red Willow	-1	0	8,202	42	8,158	8,158	0
Rock	72	0	3,597	0	3,669	3,669	0
Sappa	0	-133	694	2	558	558	0
South Fork	13,181	5,977	1,316	-2	20,476	20,476	0
Main Stem	-1,295	375	71,738	9,453	61,364	61,364	0

Table C.9. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ computed using the current accounting with the actual CWS_G for 2005 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	632	250	245	0	1,127	1,158	31
Beaver	0	1,633	2,588	0	4,221	8,855	4,634
Buffalo	309	0	3,351	0	3,660	3,810	150
Driftwood	0	0	1,481	0	1,481	1,481	0
Frenchman	52	0	82,705	0	82,757	88,147	5,390
North Fork	14,485	30	1,303	0	15,818	15,815	-3
Medicine	0	0	20,200	9,644	10,556	10,031	-525
Prairie Dog	0	5,773	0	0	5,773	5,774	1
Red Willow	0	0	8,303	34	8,269	8,241	-28
Rock	60	0	3,745	0	3,805	3,839	34
Sappa	0	-1,540	703	0	-837	1,866	2,703
South Fork	15,029	7,162	1,348	0	23,539	23,374	-165
Main Stem	-1,962	397	83,899	2,288	80,046	64,686	-15,360

Table C.10. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2005 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C + CBCU_K + CBCU_N - IWS$	CWS_G	Difference
Arikaree	658	266	234	0	1,158	1,158	0
Beaver	-1	3,950	4,906	0	8,855	8,855	0
Buffalo	384	0	3,426	0	3,810	3,810	0
Driftwood	0	0	1,481	0	1,481	1,481	0
Frenchman	2,773	-9	85,411	28	88,147	88,147	0
North Fork	14,479	33	1,302	0	15,815	15,815	0
Medicine	-1	-1	19,941	9,908	10,031	10,031	0
Prairie Dog	-1	5,775	1	0	5,775	5,775	0
Red Willow	0	0	8,289	48	8,241	8,241	0
Rock	77	0	3,762	0	3,839	3,839	0
Sappa	0	-193	2,069	10	1,866	1,866	0
South Fork	14,985	7,096	1,289	-4	23,374	23,374	0
Main Stem	-1,653	365	76,233	10,258	64,686	64,686	0

Table C.11. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ computed using the current accounting with the actual CWS_G for 2006 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	1,018	141	122	0	1,281	1,332	51
Beaver	0	3,127	3,431	0	6,558	9,561	3,003
Buffalo	323	0	3,329	0	3,652	3,804	152
Driftwood	0	0	1,422	0	1,422	1,422	0
Frenchman	35	0	78,291	0	78,326	83,875	5,549
North Fork	14,427	19	1,233	0	15,679	15,671	-8
Medicine	0	0	19,409	9,405	10,004	9,299	-705
Prairie Dog	0	5,509	0	0	5,509	5,511	2
Red Willow	0	0	7,745	25	7,720	7,684	-36
Rock	63	0	3,845	0	3,908	3,947	39
Sappa	0	-1,828	1,028	0	-800	2,784	3,584
South Fork	11,823	4,340	1,023	0	17,186	17,230	44
Main Stem	-3,028	250	76,660	2,752	71,130	56,571	-14,559

Table C.12. Comparison of the estimate of $CWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$ where these individual impacts are estimated using the proposed methodology with the actual CWS_G for 2006 in ac-ft.

	$CBCU_C$	$CBCU_K$	$CBCU_N$	IWS	$CBCU_C$ + $CBCU_K$ + $CBCU_N$ - IWS	CWS_G	Difference
Arikaree	1,047	164	120	-1	1,332	1,332	0
Beaver	-1	4,629	4,933	0	9,561	9,561	0
Buffalo	399	0	3,405	0	3,804	3,804	0
Driftwood	0	0	1,422	0	1,422	1,422	0
Frenchman	2,842	-2	81,065	31	83,875	83,875	0
North Fork	14,424	17	1,230	0	15,671	15,671	0
Medicine	-1	0	19,061	9,759	9,300	9,300	0
Prairie Dog	-1	5,511	1	0	5,511	5,511	0
Red Willow	0	0	7,727	43	7,684	7,684	0
Rock	82	0	3,864	0	3,947	3,947	0
Sappa	-1	-59	2,871	28	2,784	2,784	0
South Fork	11,847	4,355	1,028	1	17,230	17,230	0
Main Stem	-2,466	96	69,736	10,794	56,572	56,572	0