Analysis of Current Methods Used to Calculate Groundwater Impacts for the Republican River Compact

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LIST OF ABREVIATIONS

CBCU	Computed Beneficial Consumptive Use
$CBCU_G$	Computed Beneficial Consumptive Use of Groundwater
$CBCU_S$	Computed Beneficial Consumptive Use of Surface Water
CWS	Computed Water Supply
FSS	Final Settlement Stipulations
IWS	Imported Water Supply Credit
RRCA	Republican River Compact Administration
VWS	Virgin Water Supply

ABSTRACT

The Republican River Compact (Compact) apportions certain waters within the Republican River Basin among the states of Kansas, Colorado, and Nebraska. To do so requires the determination of depletions to stream-flow caused by groundwater pumping ($CBCU_G$) and accretions to stream-flow caused by infiltration of surface water imported from the Platte basin (IWS). The Republican River Compact Administration (RRCA) uses certain "accounting" procedures to quantify the water subject to the Compact. To do so it uses a groundwater model to calculate base-flow at accounting points distributed throughout the basin.

The Accounting Procedures state that "An output of the model is baseflows(sic) at selected stream cells. Changes in the baseflows (sic) predicted by the model between the "base" run and the "no-State-pumping" model run is assumed to be the depletions to stream-flow, i.e., groundwater computed beneficial consumptive use due to the State groundwater pumping at that location."[1]. The "Changes in baseflow" as calculated by the accounting procedures should **not** have been "assumed to be the depletions to stream-flow" due to groundwater pumping. Rather than "determining" depletions and accretions they grossly mis-estimate depletions and accretions. The errors in determining depletions and accretions are substantial. The impact of these errors propagates through all disputes related to the Compact including those related to management of irrigation within states.

The current method for computing $CBCU_G$ and IWS produces substantial violations of the Impact Summation Requirement; the requirement that the sum of impacts of individual stresses in a sub-basin be equal to the total impact of all stresses applied simultaneously. Violations of the Impact Summation Requirement occur in many years over many of the Sub-basins in the Republican River Basin. The violations arise from the assumption that the 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. The assumption is flawed.

A method for computing $CBCU_G$ and IWS is proposed that substantially reduces the discrepancy between the combination of impacts of several sets of stresses and the impact of the combination of those sets of stresses. It adheres more closely to the Impact Summation Requirement and provides a more equitable allocation of water among the states. The proposed method produces results that are superior to the current method and produces a final allocation that is substantially different than that computed by the current method.

Notes:

[1]Republican River Compact Administration, Accounting Procedures and Reporting Requirements, Revised July 27, 2005, Section IIID1.

1.0 INTRODUCTION

The State of Nebraska has established that the accounting procedures currently used by the RRCA substantially misrepresents Virgin Water Supply (VWS), Computed Beneficial Consumptive Use (CBCU), and IWS and are not in accord with the Compact. This document provides Nebraska's understanding of the problem and describes a proposed solution that "would equitably determine both stream flow depletions caused by groundwater pumping and streamflow accretions resulting from recharge by imported water." The introduction outlines the problem, and, as background, provides a general description of the Republican River Basin, and relevant RRCA accounting concepts. The description is complicated by poorly chosen terminology and notation in the Accounting Procedure. Subsequent sections describe where and to what extent the Sub-basin accounting calculations are affected, why the problem occurs and identify a reasonable and equitable solution.

1.1 Description of Physical Setting

The Republican River rises in the high plains of northeastern Colorado and western Kansas and Nebraska (Figure 1.1). The main stem, which is formed by the confluence of the North Fork of the Republican River and the Arikaree River near Haigler, Nebraska, flows generally to the east through Nebraska until it enters into Kansas near Hardy, Nebraska. Other major tributaries are the South Fork of the Republican River, Frenchman Creek, Red Willow Creek and Medicine Creek which rise in Nebraska and are tributaries to the main stem, Sappa and Prairie Dog Creeks which rise in Kansas and are tributaries to the main stem and Beaver Creek which rises in Colorado and is a tributary to Sappa Creek.

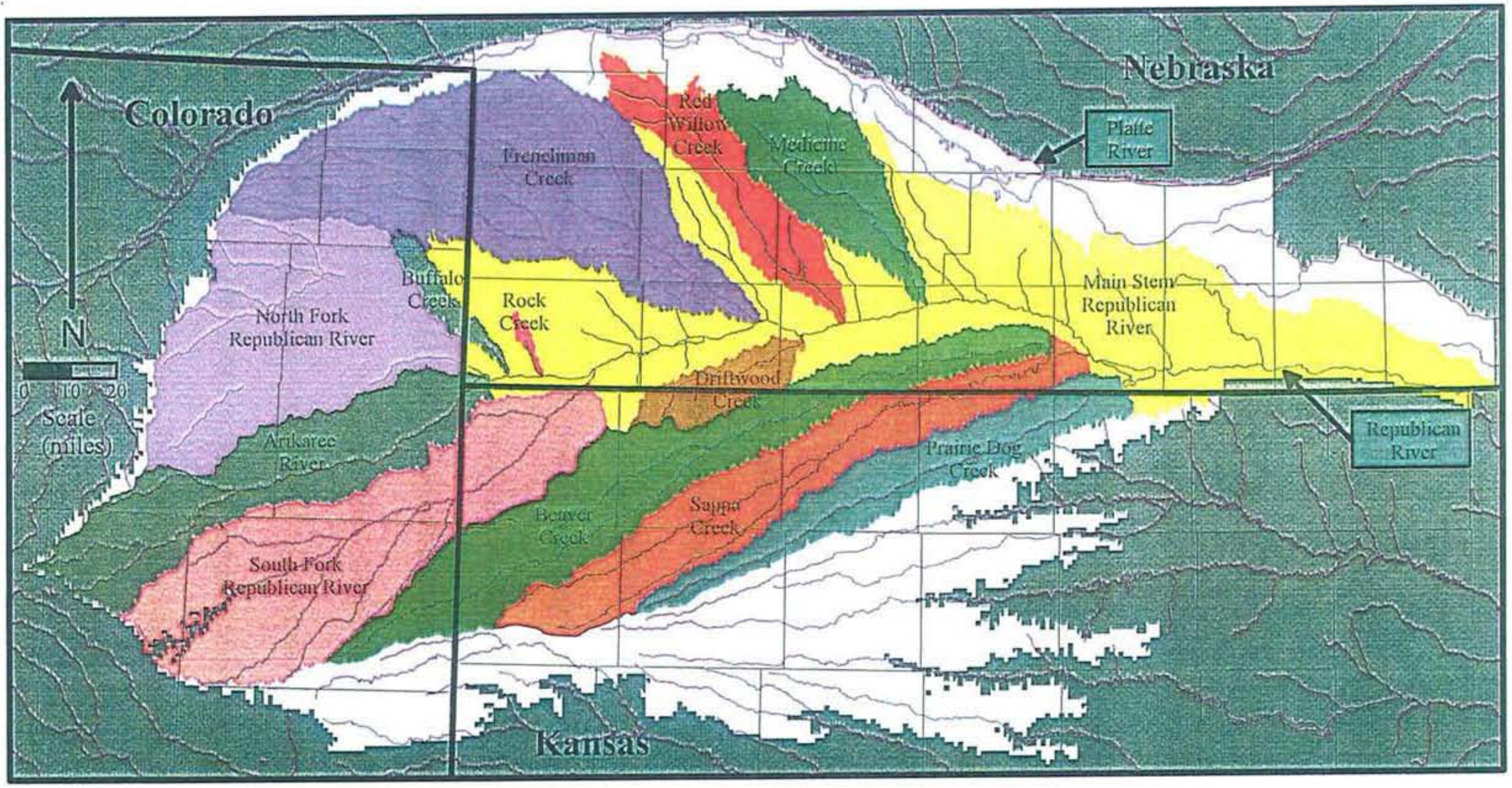

Figure 1.1. Map showing location of Republican River and the Republican River Compact sub-basins.

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: precipitation averaged about 16 inches/year in the western part of the basin and ranged as high as about 26 inches/year in the eastern part of the basin. Precipitation ran off on the surface to streams, percolated deep into the ground or returned to the atmosphere as evapotranspiration. Roughly 75-85% returned to the atmosphere, 10-15% ran off on the surface and less than 5% percolated deep into the ground.

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 base-flow or fair weather flow. Surface runoff probably gets to the river channels within several days. Most base-flow gets to the river channels after tens of years. Base-flow can be estimated by observing flows during fair weather several days after surface runoff has moved downstream.

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 Basin. There was not a groundwater divide between the Platte Basin and the Republican Basin over a considerable distance. The northern boundary of the groundwater system associated with the Republican River was the Platte River.

The advent of irrigated agriculture complicated the hydrologic system. Diversions of waters from stream channels for irrigation reduced flow in the streams, increased discharge to the atmosphere and increased percolation deep into the ground from excess irrigation and increased infiltration of precipitation. Percolation deep into the ground would have somewhat increased evapotranspiration by phreatophytes and discharge to rivers. The increase in stream-flow caused by discharge from the ground to rivers would have been considerably less than the decrease in stream-flow caused by diversions for irrigation.

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 base-flow 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 the Republican River. It continues to do so. Most of the water diverted from the Platte Basin was transmitted to the atmosphere as evapotranspiration.

Construction of dams in the early 1950's further complicated flow in the Republican River and its tributaries. Dams interfered with the flow regime. Flow down-stream from dams cannot be readily identified as base-flow or surface runoff.

The use of groundwater for irrigation, which became significant in the 1960's, yet further complicated the hydrologic system. Water pumped from the ground for irrigation intercepted flow that would otherwise have discharged to streams or it intercepted water that would have been transferred to the atmosphere by evapotranspiration by phreatophytes or it 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 may induce flow from the streams to the ground.

Some of the water pumped from the ground for irrigation will percolate back into the ground as excess irrigation water thereby partially mitigating the impacts of pumping. Most of the water pumped for irrigation will be taken up by crops and transferred to the atmosphere by evaporation and transpiration from the crops. Water, transferred to the atmosphere, because it is no longer available is referred to as having been consumed.

Consumption of water that would otherwise have been in the channels of the Republican River is the subject of this report. Such consumption cannot be readily measured. It can, however, be estimated. This report, when discussing pumping water from the ground, the associated percolation of part of that water back into the ground, and increased recharge from precipitation will use the "shorthand terms" in Table 1.1. Likewise, it will use terms from the same table when discussing percolation of water imported from the Platte Basin at the mound.

The net amount of water that discharges to stream channels from groundwater systems, "base-flow", is a significant part of the flow in the Republican River and its tributaries. Depletions to base-flow caused by pumping groundwater for irrigation and municipal water supply, accretions to base-flow caused by excess irrigation and accretions to base-flow caused by recharge of imported water are, therefore, like depletions and accretions to stream flow caused by diversions, dams and irrigation with surface water, of concern in allocating the total flow of the Republican River.

Stress Set	Term	Meaning
Kansas	Kansas pumping stresses or simply Kansas pumping	Groundwater pumping for irrigation less associated percolation of excess irrigation and the associated increase of infiltration from precipitation on irrigated lands and municipal groundwater pumping less associated return flow.
Colorado	Colorado pumping stresses or simply Colorado pumping	Groundwater pumping for irrigation less associated percolation of excess irrigation and the associated increase of infiltration from precipitation on irrigated lands and municipal groundwater pumping less associated return flow.
Nebraska	Nebraska pumping stresses or simply Nebraska pumping	Groundwater pumping for irrigation and groundwater pumping for municipal supply and independently return flow of irrigation water and municipal water and the associated increase of infiltration from precipitation on irrigated lands.
Mound	Mound recharge stresses or simply Mound recharge	Percolation of imported water from canals and excess surface water irrigation and the associated increase of infiltration from precipitation on irrigated lands.

Table 1.1. "Shorthand" terms used in this report when discussing the pumping of water from the ground and the associated percolation of some of that water back into the ground and the percolation of water from canals and irrigated fields that has been imported from the Platte Basin.

1.2 Description of RRCA Compact Objectives

The Republican River Compact is an agreement among the three states through which the river and its tributaries flow. The first paragraph of Article I of the Compact is reproduced below:

> The major purposes of this compact are to provide for the most efficient use of the waters of the Republican River Basin (hereinafter referred to as the "Basin") for multiple purposes; to provide for an equitable division of such waters; to remove all causes, present and future, which might lead to controversies; to promote interstate comity; to recognize that the most efficient utilization of the waters within the Basin is for beneficial consumptive use; and to promote joint action by the states and the United States in the efficient use of water and the control of destructive floods.

To provide for "...an equitable division of such waters," the RRCA applies accounting procedures to determine the amount of water that would have been in the river channel if there had been no depletions or accretions caused by the activities of man. The accounting procedures refer to "the Water Supply within the basin undepleted by the activities of man" as the "Virgin Water Supply."

The VWS is calculated at various "accounting points" throughout the basin. This is in part to facilitate another objective of the Compact, to balance state specific consumption of water with state-by-state allocations for individual drainage basins within the Republican River Basin as identified in Articles III and IV. The accounting points are generally at or immediately above the confluence of streams or immediately downstream of major reservoirs.

1.3 Current RRCA Accounting Procedures

The current RRCA Accounting Procedures are described in Appendix C (revised July 27, 2005) of the Final Settlement Stipulation (FSS) dated December 15, 2002.

1.3.1 Definitions of Virgin Water Supply and Imported Water Supply

The RRCA applies accounting procedures to determine the amount of water that would have been in the river channel if there had been no depletions or accretions caused by the activities of man. The Compact, in Article II as well as the FSS define the "Virgin Water Supply," to be "the water supply of the Basin undepleted by the activities of man. The FSS defines the "Imported Water Supply" to be "the water supply imported by a State from outside the Basin resulting from the activities of man."

Other definitions and formulas within the FSS and Appendix C of the FSS make it clear that the working definition of VWS is the water supply or stream flow of the Basin "unaffected" by the activities of man.

1.3.2 Definition of Computed Beneficial Consumptive Use and Imported Water Supply Credit

The accounting procedures, to estimate the VWS call for the estimation of two terms: the "Computed Beneficial Consumptive Use" (CBCU) and the "Imported Water Supply Credit" (IWS). The CBCU is the stream flow depletion resulting from a specific list of activities of man. The IWS is defined in the accounting procedures as: "the accretions to stream flow due to water imports from outside of the Basin as computed by the RRCA Groundwater Model." The definition is faulty because, as discussed below, the model does not calculate "accretions." It calculates base-flow which is, in turn, used according to accounting procedures to calculate accretions. The distinction is important because the issues discussed in this document are related to the accounting procedures rather than the groundwater model.

1.3.3 Current Calculation of Computed Beneficial Consumptive Use of Groundwater

"Computed Beneficial Consumptive use of groundwater" ($CBCU_G$) 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, Revised July 27, 2005 Section IIID1 and presented 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 model is base-flow at selected stream cells. Changes in the base-flow predicted by the 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. It seems to indicate that for the "base"-run only the current year's groundwater pumping, groundwater pumping recharge, and surface water recharge are represented. Nebraska's interpretation of the "base" run is that those stresses are represented for <u>all</u> years during the simulation period. Nebraska's interpretation of the term "pumping recharge" is "that water pumped from the ground for irrigation which, after it is applied to crops, infiltrates back into the ground"; Nebraska interprets "surface water recharge" 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.

Nebraska interprets the term "groundwater computed beneficial consumptive use" to be the same as "Computed Beneficial Consumptive Use of groundwater" ($CBCU_G$). Nebraska interprets the term "depletion" in the first sentence of the last paragraph quoted above to be equivalent to the term "depletions and accretions" used in third and fourth sentences of the same paragraph. Both terms are assumed to mean "net depletions." In this report, therefore, the terms "net depletion of base-flow", "impact" and "$CBCU_G$" will be regarded as interchangeable with respect to Nebraska pumping stresses, Kansas pumping stresses and Colorado pumping stresses. Similarly the term "accretion to base-flow", "impact" and "IWS" will be regarded as interchangeable with respect to Mound recharge stresses.

The sentence cited above: "Changes in the base-flow predicted by the 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" is interpreted to mean: "For any location on a river the base-flow calculated at that location by the 'no-State-pumping' run minus the base-flow calculated at that location by the 'base' run is assumed to be the net depletions to stream flow. i.e., groundwater computed beneficial consumptive use, due to State groundwater pumping at that location."

The sentence, as it is written in the accounting procedures, suggests that the model "predicts" changes in base-flow. In fact, the model does not calculate changes in base-flow nor does it calculate depletions or accretions. It calculates "base-flow", under specific conditions. In this case the conditions are related to stresses --- either pumping, seepage or infiltration. The user specifies a set of stresses; the model calculates the base-flow.

1.3.4 Current Calculation of Imported Water Supply Credit (IWS)

The current rules for calculation of the IWS are given in the RRCA Accounting Procedures, Revised July 27, 2005 Section IIIA3 and presented 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 stream flows between these two model runs.

As with the $CBCU_{G}$, the notation and wording for the IWS are confusing. It seems to indicate that for the "base"-run only the current year's groundwater pumping, groundwater pumping recharge, and surface water recharge is represented. Nebraska's interpretation of the "base" run is that those stresses are represented for **all** years during the simulation period. Nebraska's interpretation of the term "pumping recharge" is "that water pumped from the ground for irrigation which, after it is applied to crops, infiltrates back into the ground"; "surface water recharge" means "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.

1.4 Example of the Use of the Model and Misrepresentation of Model Results

The stated objective of the Republican River Compact to equitably divide waters within the Republican River Basin requires a methodology to evaluate the impact of stresses, e.g., pumping, excess irrigation recharge, and influx of imported water, on stream flow. A conventional way to estimate the impact of a set of stresses (a target set of stresses) is to test a system or in this case a numerical groundwater flow model with the target set and then without the target set. The difference of output is assumed to be a reasonable estimate of the impact of the target set of stresses. The concept is the same as weighing first an empty cup then the same cup full of milk and concluding that the weight of the milk is the difference between the two. For the method of determining impacts to be useful the combined impacts of two sets of stresses should equal the impact of the combination of the two sets of stresses.

The accounting procedures had been expected to provide reasonable estimates of impacts to base-flow caused by changes in stresses. Within the RRCA model there are millions of specifications of stresses including those representing irrigation pumping, irrigation return flow, canal seepage, infiltration of precipitation, and evapotranspiration by phreatophytes. Changes in individual stresses, generally, have negligible impacts on base-flow. Individual stresses or small sets of individual stresses, therefore, would not be expected to be target sets. The set of stresses representing all groundwater irrigation pumping in Colorado or in Kansas or in Nebraska are expected to have a large impact on base-flow in many streams; they are target sets for Compact compliance. The set of stresses related to seepage of imported water from canals and infiltration of imported water used for irrigation is a target set. Although they do not use the term "target sets", the accounting procedures were geared toward the target sets of stresses described above.

It is apparent that the parties to the Compact expected to represent other target sets as well. Nebraska has specified target sets representing all wells in a specific natural resources district. In its December 19, 2007 letter, Kansas reported results for what this report would term a target set consisting of all stresses related to groundwater irrigation in Nebraska within 2.5 of the Republican River and its tributaries. Kansas also specified as a target set "all irrigation wells and municipal wells in Nebraska added after the year 2000." Clearly Kansas assumed that applying the model to calculate base-flow for any target set would be reasonable.

The RRCA Accounting Procedures, again though they do not use the term, addressed the issue of what this document will call the "background set" of stresses. The background set of stresses is that set of stresses which is represented in both the run with the target stresses and the run without the target stresses. The accounting procedures, in effect, specify that the background set of stresses shall be all man-made stresses other than the target set. For example: when the target set is the irrigation wells and municipal wells in Nebraska, the background set is all of the irrigation wells and municipal wells in Colorado and all of the irrigation wells and municipal wells in Kansas and all of the sites for infiltration of water imported from the Platte Basin.

Beaver Creek is an example for which the choice of the set of background stresses is critical. It rises in Colorado, flows into Kansas, then to Nebraska where is 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 where it discharges into Sappa Creek is shown in Figure 1.2. The choice of Beaver Creek and the year 2003 were chosen to highlight the failure of the accounting procedures to adequately determine $CBCU_G$ during a very dry year when seepage from the stream is constrained by the availability of base-flow in the stream

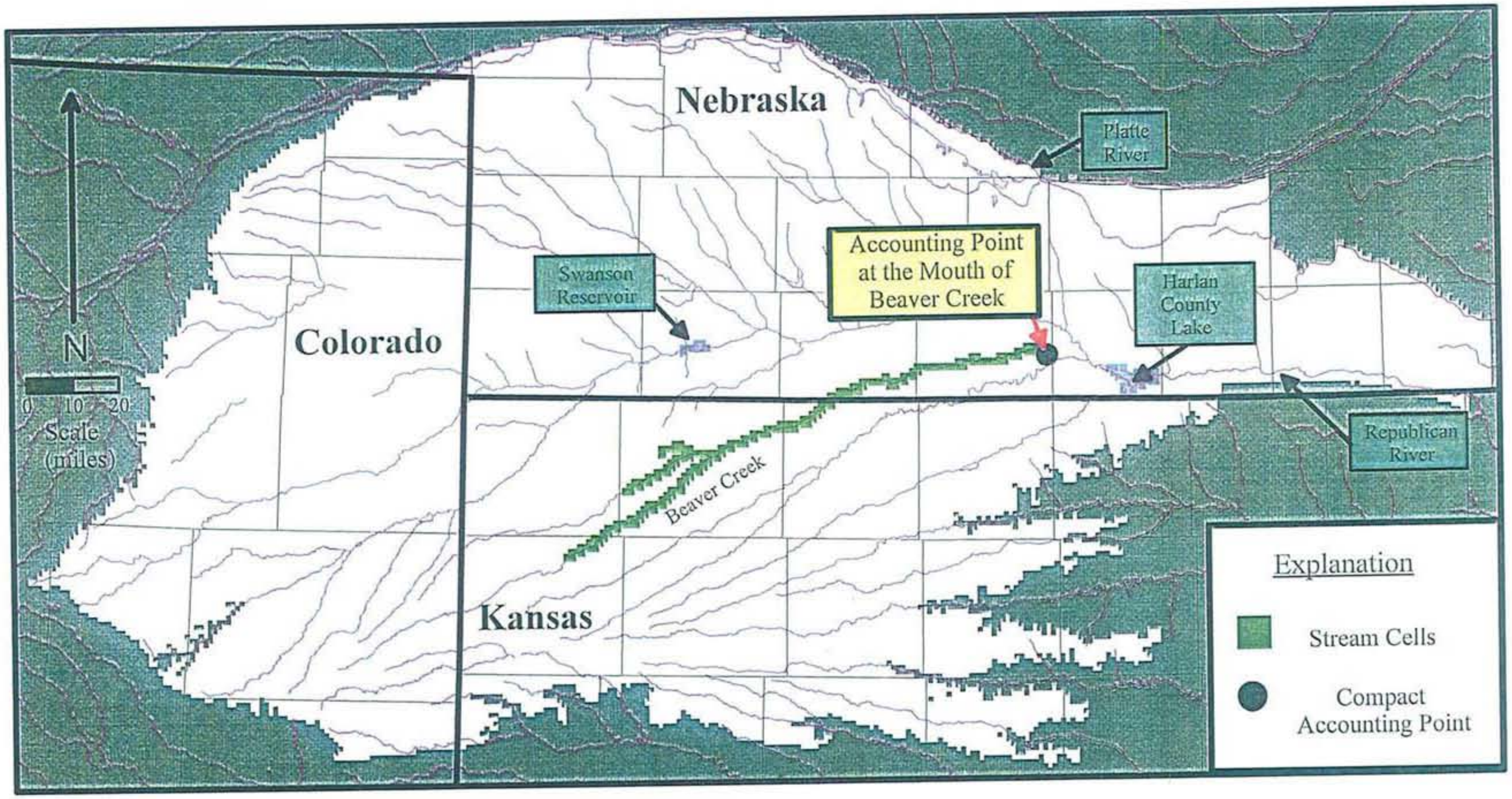

Figure 1.2. Map showing location of cells with stream boundary condition in Beaver Creek.

channel. In this context, "base-flow" refers to water in the stream channel that originated in the ground.

Table 1.2 shows base-flow at the mouth of Beaver Creek as calculated by the model for all of the possible combinations of the four major man-made stresses. When all four target sets of man-made stresses were represented (Run CKMN) there was no base-flow (i.e. base-flow was 0 ac-ft/yr). When none of the state-wide man-made stresses were represented (Run θ) base-flow was 6,445 ac-ft/yr. When all stresses were represented except Kansas irrigation and municipal well pumping (Run CMN), then base-flow was 323 ac-ft/yr. When all stresses were represented except Nebraska irrigation and municipal well pumping (Run CKM) base-flow was 727 ac-ft/yr. When all stresses were represented except combined Kansas and Nebraska irrigation and municipal well pumping (Run CM) base-flow was 6,447 ac-ft/yr.

Note that base-flow for runs CKM, KM, CK and K is about the same in spite of the fact that imported water and pumping by Colorado is represented in some but not in others; clearly importation of water in Nebraska and pumping by Colorado have no influence on base-flow at the mouth of Beaver Creek. Similar results can be noted for runs CMN, MN, CN, N.

Several examples of the application of the current accounting rules, using base-flow shown in Table 1.2 to determine $CBCU_G$ are shown in Table 1.3. These include the impact of:

- the Nebraska pumping stresses,
- the Kansas pumping stresses,
- the combined Kansas and Nebraska pumping stresses, and
- the combined Kansas, Nebraska and Colorado pumping stresses and Mound recharge stresses.

Run Name[3]	Colorado Pumping[1]	Kansas Pumping[1]	Mound Recharge[2]	Nebraska Pumping[1]	Base-flow at Mouth of Beaver Creek (ac-ft/yr)
0	OFF	OFF	OFF	OFF	6,445
CKMN	ON	ON	ON	ON	0
CKM	ON	ON	ON	OFF	727
CMN	ON	OFF	ON	ON	323
CKN	ON	ON	OFF	ON	0
KMN	OFF	ON	ON	ON	0
CK	ON	ON	OFF	OFF	727
CM	ON	OFF	ON	OFF	6,447
CN	ON	OFF	OFF	ON	323
KM	OFF	ON	ON	OFF	727
KN	OFF	ON	OFF	ON	0
MN	OFF	OFF	ON	ON	323
C	ON	OFF	OFF	OFF	6,447
K	OFF	ON	OFF	OFF	726
M	OFF	OFF	ON	OFF	6,446
N	OFF	OFF	OFF	ON	323

Table 1.2. Sum of monthly base-flows for the accounting point at the mouth of Beaver Creek as calculated by the model for the year 2003.

Notes:

[1]Represents modeled net irrigation and municipal pumping (groundwater withdrawals – groundwater return flow) as well as supplemental precipitation recharge for land irrigated by groundwater.

[2]Represents modeled groundwater recharge from water imported from the Platte River infiltrating from canal seepage and surface-water return flow and supplemental precipitation recharge for land irrigated by surface water.

[3]The run name designates the sets of stresses included in the target set. For example CKMN indicates that Colorado pumping stresses, Kansas pumping stresses, Mound recharge stresses and Nebraska pumping stresses constitute the target set.

In each case the depletions caused by a target stress set is determined by subtracting base-flow for all stresses (Run CKMN) from base-flow for all stresses except for the target stresses (Runs θ, CKM, CMN and CM).

Target Set	Runs use to calculate impacts of stresses on base-flow.	Impacts (CBCU$_G$) (ac-ft/yr)
Nebraska pumping stresses	Run CKM – Run CKMN	727 – 0 = 727
Kansas pumping stresses	Run CMN – Run CKMN	323 – 0 = 323
CombinedKansas pumping stresses and Nebraska pumping stresses	Run CM – Run CKMN	6,447 – 0 = 6,447
Combined Kansas, Nebraska and Colorado pumping stresses and Mound recharge stresses	Run θ – Run CKMN	6,445 – 0 = 6,445

Table 1.3. Impacts to base-flow at the mouth of Beaver Creek caused by pumping for irrigation and municipal supply in Kansas and Nebraska.

Notice that the impact for the combined pumping in Nebraska and Kansas, 6,447 ac-ft/yr is nearly identical to the impact of the combined irrigation and municipal well pumping of Kansas, Nebraska and Colorado and importation of water from the Platte: 6,445 ac-ft/yr The difference of 2 ac-ft/yr is negligible and may be attributed to rounding errors and minor non-linearity of the relationship. More importantly notice that the combination of impacts for Kansas (323 ac-ft/yr) and Nebraska (727 ac-ft/yr) is only 1,050 ac-ft/yr.

Common sense suggests that the combination (summation) of the impact of Kansas pumping stresses and the impact of Nebraska pumping stresses should equal (or nearly equal) the impact of the combination of Kansas pumping stresses and Nebraska pumping stresses. That concept we refer to in this document as the "Impact Summation Requirement."

The failure to meet the Impact Summation Requirement indicates that the assumptions on which the current accounting procedures were based are faulty. Clearly at least one of the determinations of impact, and possibly many of the determinations of impact, are wrong. The under-estimation of the $CBCU_G$ leads to an under-estimation of the VWS.

Similarly the faulty assumptions on which the accounting procedures were based would cause the under-estimation of IWS, and the over-estimation of the VWS. The accounting procedures must be changed to permit a more equitable allocation of water supply and responsibility for depletions and accretions.

In his final report the Special Master refers to the FSS as having:

> laid out the parameters for the RRCA Groundwater Model which would, for use in the accounting formulas for administering the Republican River Compact, **determine** *(emphasis added)* both stream flow depletions caused by groundwater pumping and streamflow accretions from recharge by imported water."

The word "determine" used by the Special Master requires that the accounting procedures are to be more than just black-box calculations; that the result of the calculations would somehow approximate stream flow depletions. In the example shown above for the accounting point on Beaver Creek, the impact of the combination Kansas and Nebraska pumping stresses exceeds the amount of base-flow in the stream and that, in fact, each state alone uses nearly all of the base-flow (6,445 ac-ft/yr) in the stream, yet the accounting procedures yield impacts of 727 ac-ft/yr and 323 ac-ft/yr which when combined (1,050 ac-ft/yr) are far smaller than the 6,445 ac-ft/yr. It is clear that the current accounting procedures are not **determining** anything useful for the Beaver Creek accounting point.

1.5 Response to Kansas' Review of Nebraska's Request for Change in Accounting Procedure September 18, 2007

Nebraska had brought this situation to the attention of Kansas and Colorado orally, at a meeting, in September 2007. Kansas, in its written response, dated September 18, 2007, dismissed Nebraska's concern with the reply:

> The states recognized that the sum of the impacts of these individual activities would not necessarily *exactly* (italics added) equal the model-computed impact of all of the activities considered simultaneously. If the groundwater were mathematically linear, it would, in fact, be the case that the sum of the individual affects (sic) would equal the affect (sic) **determined** (bold added) by considering all activities simultaneously. However, because the groundwater model is mildly non-linear, this mathematical equality does not occur.

Nebraska understands that with a "mildly non-linear model", some difference might be expected between the impact of the combined pumping for Kansas and Nebraska and the combination of the impacts for the two states. The difference between 6,447 and 1,050 ac-ft/yr indicates that the accounting procedures as they are currently described are unable to **determine** CBCU. Nebraska does not contend that the errors are a function of a faulty model but are instead related to the misapplication of model results to determine impacts.

Nebraska contends that it is the misinterpretation of model results in the accounting procedures that is at issue. The accounting procedures are expected to and required to **determine** impacts at accounting points in all Sub-basins for each year, they do not do so.

1.6 Significance of the Failure to Determine Impacts

The impacts at the accounting point on Beaver Creek for 2003 was cited as an example in the presentation given here. The issue is not restricted to Beaver Creek. Table 1.4 shows that, for most Sub-basins, the Impact Summation Requirement is not met. It shows for each Sub-basin, the impacts of groundwater irrigation and importation for each target set, the combination of those impacts (Sum), the impact of the combined stresses (Total), as calculated using the current accounting procedures and the discrepancy between the combination of the impacts of the sets of stresses and the impact of the combination of the sets of stresses. Appendix A shows similar tables for other years between 2001 and 2006.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 1.4. Comparison of the sum of individual impacts with the total impacts for 2003 in ac-ft.]

1.7 Summary

The changes in base-flow as calculated by the accounting procedures should not have been assumed to be the depletions to stream-flow due to groundwater pumping. The accounting procedures do not "determine both stream depletions caused by groundwater pumping and stream flow accretions resulting from recharge by imported water" as is claimed in the Final Report of the Special Master. Rather than "determining" depletions and accretions they grossly mis-estimate depletions and accretions. The errors in determining depletions and accretions are substantial. The impact of these errors propagates through all disputes related to the Compact including those related to management of irrigation within states.

2.0 ANALYSIS OF VIOLATION OF IMPACT SUMMATION REQUIREMENT

In this section, the causes of observed violations of the Impact Summation Requirement are analyzed. These violations have a demonstrable mathematical basis that results from the structure of the RRCA Groundwater Model. These violations do not represent errors in the model and their correction does not require modification of the model. Instead, the violations of the Impact Summation Requirement result from the way in which model results are used. The method for calculating impacts using RRCA Groundwater Model output (herein called the "current method"), assumes linear behavior of the RRCA Groundwater Model. Experience has shown that model response is not linear. This nonlinearity is a reflection of modeled hydrologic complexity not model error. Therefore, the method for calculating impacts needs to be modified to account for these nonlinearities.

Under certain simplifying assumptions, a groundwater simulation model will respond linearly to stresses. For example, if a pumping stress increases from zero to 1,000 ac-ft/yr and a reduction in base-flow is computed to be 200 ac-ft/yr, then a linear response would imply that increasing pumping stress from zero to 2,000 ac-ft/yr would reduce base-flow by 400 ac-ft/yr. Such linear response of base-flow to stresses implies that individual impacts can be added by the principle of superposition. The current methodology makes use of this presumed linearity when individual Sub-basin CBCU terms are added to compute the total impact (Section III of RRCA Accounting Procedures and Reporting Requirements, July 27, 2005).

It has long been recognized that the RRCA Groundwater Model does not provide perfectly linear responses. Minor nonlinearities are present in the RRCA Groundwater Model. These include the nonlinear response of leakage to stream stage, the precipitation irrigation recharge "bump" where irrigated lands receive an identical added precipitation recharge at any level of irrigation pumping, and changes in head dependent boundary conditions representing phreatophyte evapotranspiration, drains and base-flow before the stream goes dry. In addition, any numerical solution of a system of equations will contain some numerical roundoff error.

When the RRCA Groundwater Model and associated accounting procedures were devised, numerical round off and other minor nonlinearities were anticipated and were assumed to produce only minor violations of the Impact Summation Requirement. These violations were deemed negligible for purposes of the accounting procedures. However, recent experience, driven in part by modeling of dry conditions over the last several years, has shown that other nonlinear responses are present that cannot be classified as minor. These major nonlinearities are caused by stream drying both at the accounting point and at upstream locations, for some of the runs made to calculate the $CBCU_G$. 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 result in substantial violation of the Impact Summation Requirement.

2.1 Analysis of Beaver Creek Stream Drying

In Section 1 of this report, the significant violation of the Impact Summation Requirement at the Beaver Creek accounting point has been introduced. As shown there, the individual $CBCU_G$ for 2003 are computed as 323 ac-ft/yr for Kansas pumping and 727 ac-ft/yr for Nebraska pumping with Colorado pumping and mound recharge stresses having negligible impact (Table 1.2). The sum of individual impacts would then be 1,050 ac-ft/yr but the computed total impact is 6,445 ac-ft/yr. The difference between the true total impact, 6,445 ac-ft/yr, and the total impact estimated by summing individual impacts is 5,395 ac-ft/yr. This amount of stream depletion is occurring but not being accounted for in the current procedure. Why are the computed impacts of Kansas and Nebraska, 323 and 727 ac-ft/yr, respectively, so small relative to the actual total impact? As shown below, this is a result of stream drying and the resulting nonlinear behavior that occurs in several of the simulated conditions.

2.1.1 Presence of Nonlinear Response

The response of base-flow to stresses contains major nonlinearities that are caused by stream drying. This can be seen by examining the change in base-flow at the accounting point at the mouth of Beaver Creek as pumping by Kansas and Nebraska are incrementally decreased from fully on to fully off. The resulting base-flow changes for 2003 are shown for each state in Figures 2.1 and 2.2. For these runs, all other stresses remain at full activity, so that as, for example, Kansas pumping is decreased, Nebraska and Colorado pumping remains fully on and the mound recharge remains fully active. Considering Figure 2.1, as Kansas pumping decreases from 100% to about 17% there is no change in base-flow. Only after Kansas pumping has decreased to less than 17% of its full rate does base-flow begin to respond. Figure 2.2 shows similar behavior resulting from incrementally decreasing Nebraska pumping. In the case of Nebraska, pumping must be decreased to about 40% of its initial value before base-flow is established. For both figures, after base-flow is established, further decreases in pumping produce a near-linear response, however, the overall response of base-flow to stresses is strongly nonlinear. An unusual feature appears in all cases at pumping just above 0%. This results from increased precipitation recharge on irrigated lands, also known as the recharge "bump."

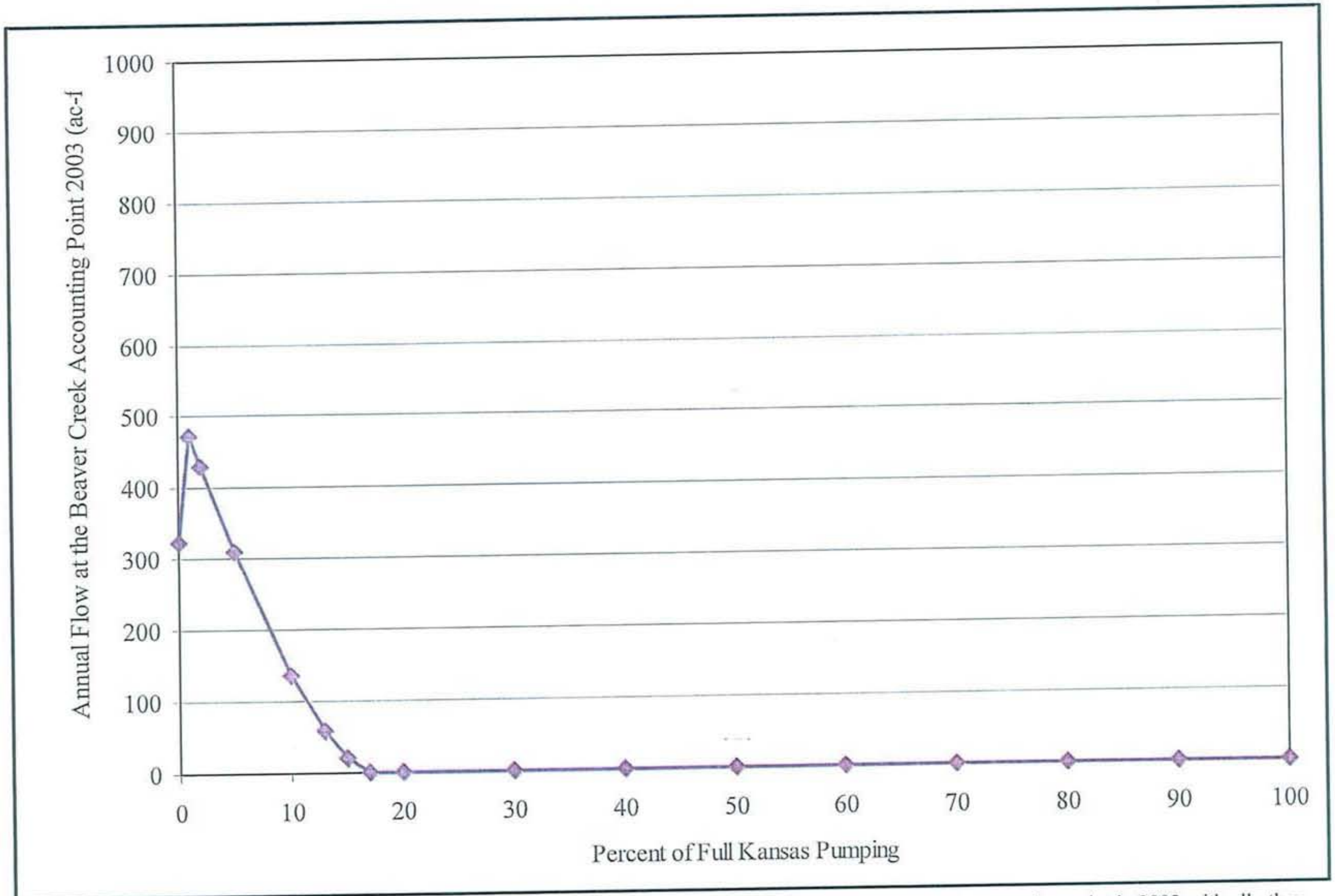

Figure 2.1. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

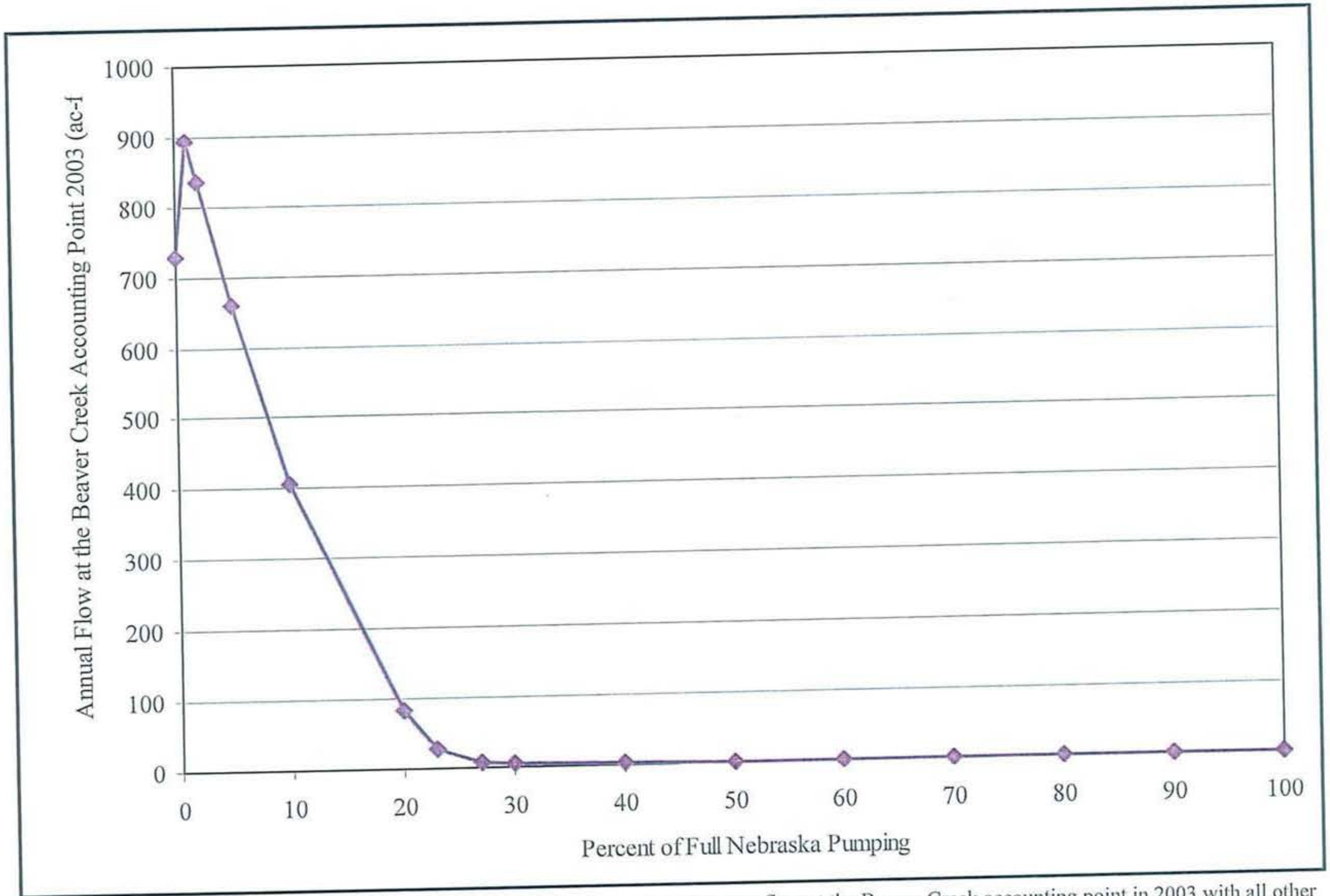

Figure 2.2. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

A third case is considered, as shown in Figure 2.3, in which both Kansas and Nebraska pumping are decreased simultaneously so that, for example, at 50% of full on pumping, Kansas and Nebraska are both active at 50% of their respective full rates. Here, base-flow is established after pumping has been reduced to less than 60% of full levels. This response is also nonlinear.

2.1.2 Physical Basis of Nonlinear Response

Figures 2.1 through 2.3 indicate that decreasing pumping by either Kansas or Nebraska alone or both states together has no impact on base-flow at Beaver Creek accounting point until a threshold is reached. Base-flow remains zero until that threshold is reached. Clearly, decreasing pumping in 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 cells containing Beaver Creek. These cells are shown on the location map in Figure 1.2 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. It is necessary to examine all the Beaver Creek cells upstream of the accounting point because the base-flow value reported at the accounting point accumulates the impact of inflow and outflow from groundwater at all cells upstream of the accounting point. The net flow into the stream from the aquifer is the base-flow computed at the accounting point.

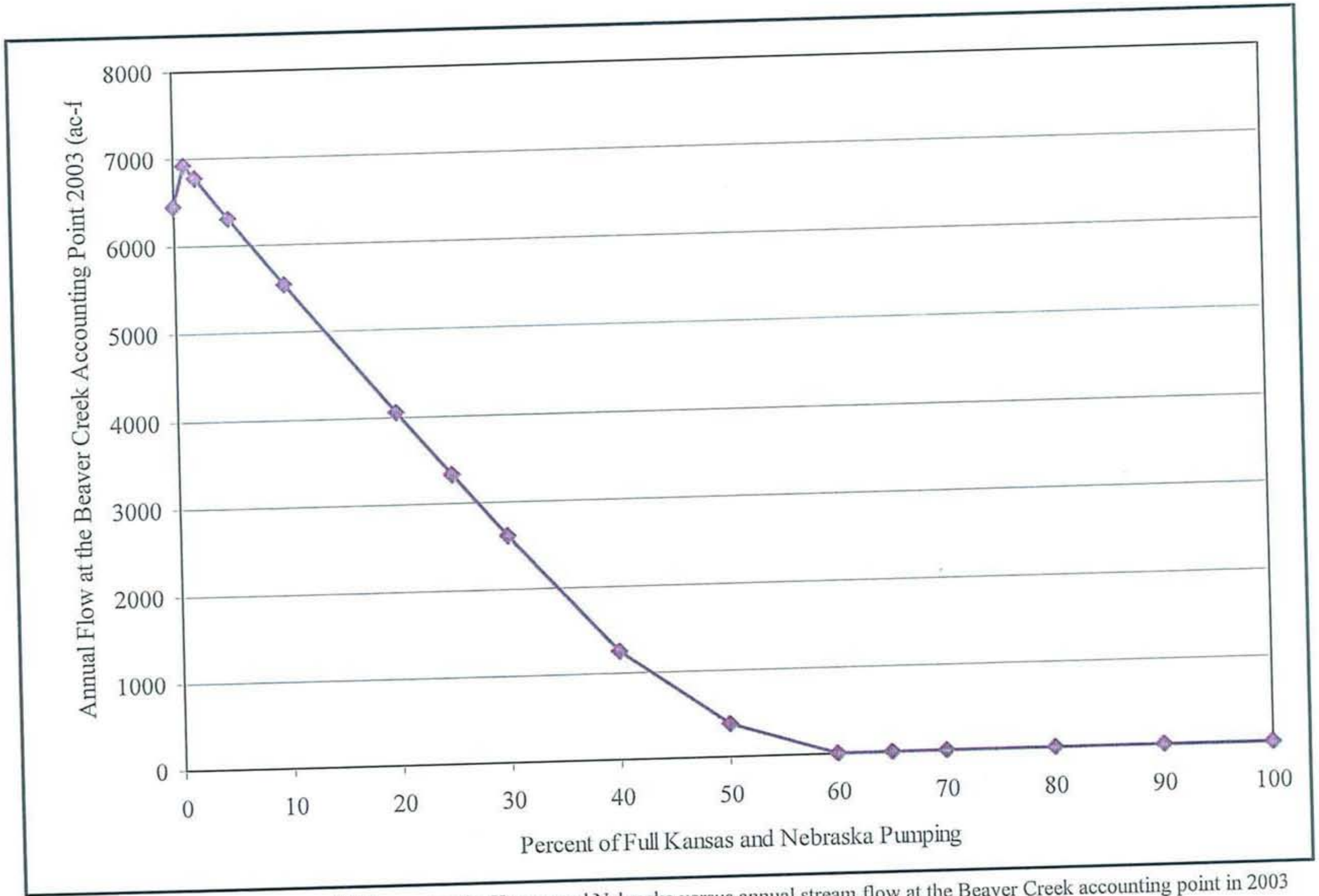

Figure 2.3. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

The water-balance components for Beaver Creek for the case of incrementally decreasing Kansas and Nebraska pumping are shown in Table 2.1. 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. At 0% pumping (the first row) on, 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 2.3, as Kansas and Nebraska pumping decline to below 60%, base-flow is re-established (data not shown here indicates re-establishment at 57% pumping). This is reflected in the "Net Flow Out to Streams" column in Table 2.1. From the perspective of the aquifer, the net stream flow is out, but, this is the same water that supplies base-flow so that the net stream flow out is the same as the base-flow calculated at the accounting point. As pumping decreases further, base-flow increases. The "Net Flow in From Storage" column represents storage depletion. As pumping decreases, the rate of storage depletion decreases.

Table 2.1 illustrates how the hydrologic balance is affected as pumping is decreased. First, consider the case when flow out to wells decreases from 20% to 10% (a drop of 2,127 ac-ft/yr). This reduced pumping causes an increase in base-flow of 1,506 ac-ft/yr and flow from storage decreases by 243 ac-ft/yr. However, when pumping is decreased from 100% to 90% (again, a drop of 2,127 ac-ft/yr), there is no change in base-flow and flow from storage decreases by 1,059 ac-ft/yr. This indicates that when base-flow is zero, the reduction in pumping provides, in part, replenishment of depleted storage.

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

Table 2.1. 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.

When base-flow is adequate (i.e. pumping at 40% or less of fully on) and pumping is greater than 0%, each ac-ft of pumping decrease causes a 0.18 ac-ft decrease in precipitation and irrigation return, about a 0.70 ac-ft increase in stream flow and about a 0.12 ac-ft replenishment of depleted storage. However, when base-flow is zero (i.e. pumping at 60% or more) each ac-ft of pumping decrease causes a 0.18 ac-ft decrease in precipitation and irrigation return, no increase in stream flow and about a 0.50 ac-ft replenishment of depleted 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 replenishment in accounting for the water gained by reducing pumping.

The relationship between storage replenishment and base-flow re-establishment 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 stream will go dry. To re-establish base-flow the water table must rise again to an elevation greater than the streambed elevation. This phenomenon can be seen in Figure 2.4 and 2.5 which depict, respectively, the base-flow observed along the length of the stream and the relative elevations of streambed and head and 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, the Run CKMN condition (all stresses fully on), a condition in which pumping for both Kansas and Nebraska are reduced by 50%, and a condition where pumping is at 0% for these two states. Figure 2.4 indicates that at 100% pumping, base-flow is zero over nearly the entire stream portion depicted. At 50% pumping, base-flow has been re-established at many upstream cells but not at the accounting point. At 0% pumping, base-flow is fully established along the entire stream.

Figure 2.5 shows the effect of the various pumping conditions listed above on groundwater levels. The vertical axis of Figure 2.5 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. Note that, because of the way the MODFLOW Stream Package accumulates base-flow from upstream reaches, base-flow can exist in a given cell even when the head associated with that cell is below the streambed as suggested by comparing Figures 2.4 and 2.6 at various cells.

2.1.3 Cause of Violation of Impact Summation Requirement

Results above indicate that if base-flow at the accounting point at the mouth of Beaver Creek begins at a value of zero (e.g. the Run CKMN condition), then base-flow can only be re-established if storage is first replenished. Storage replenishment is related to increasing head levels. Storage must be replenished sufficiently to allow heads beneath the stream to recover to levels near the streambed.

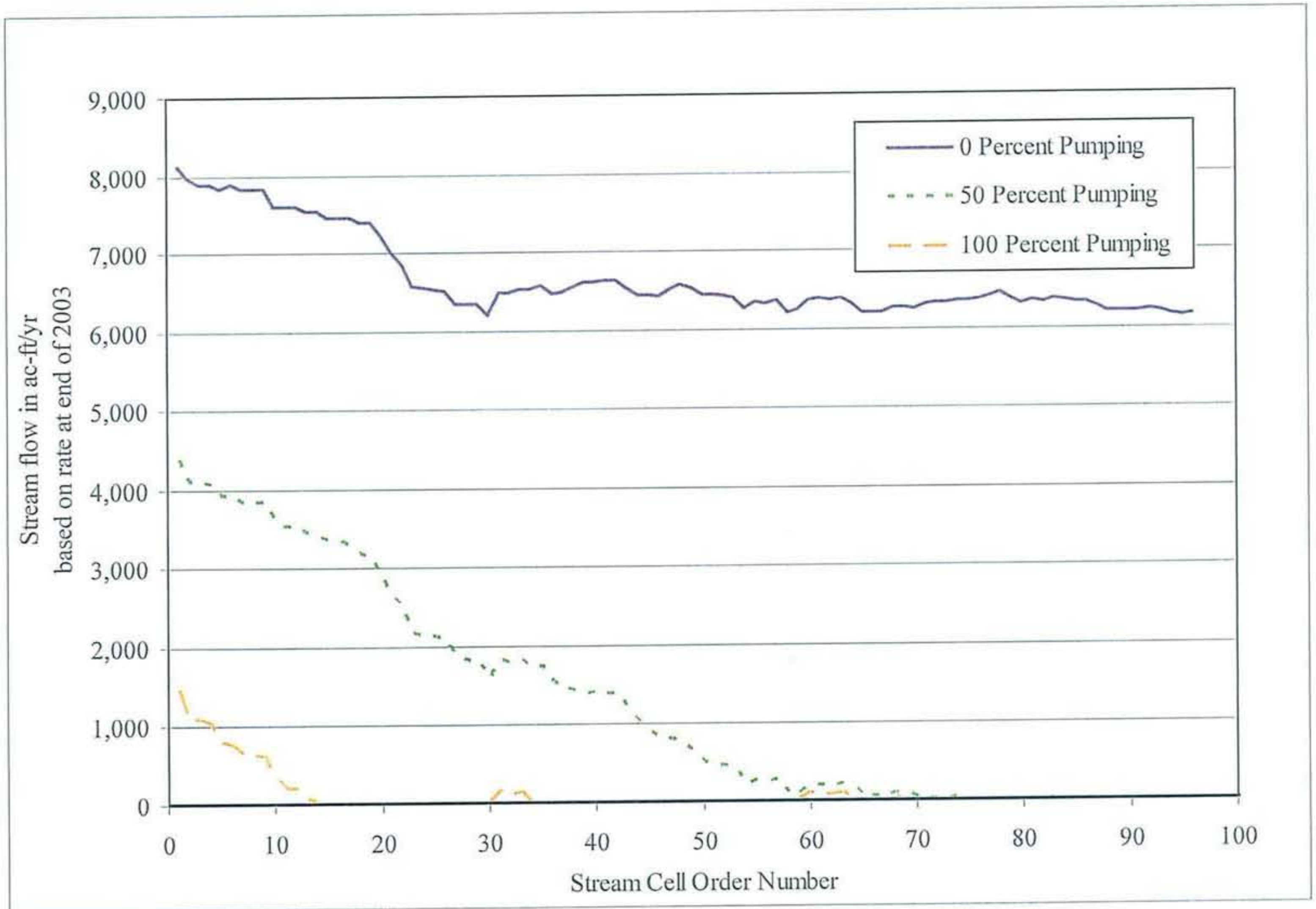

Figure 2.4. Graph showing stream cell order vs flow for various percents of full pumping for Kansas and Nebraska pumping, Beaver Creek at the end of 2003.

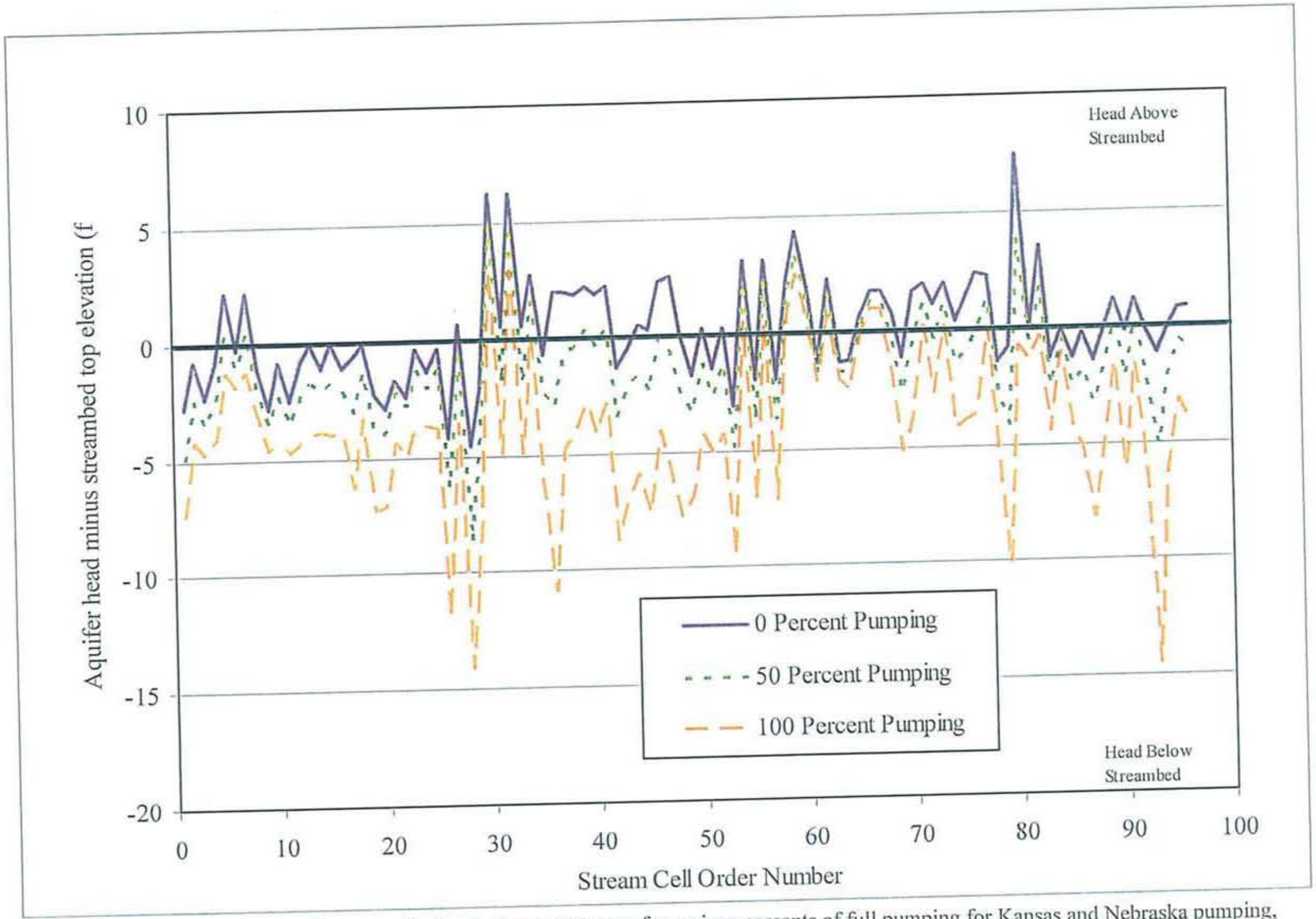

Figure 2.5. Graph showing stream cell order vs aquifer head minus stream top for various percents of full pumping for Kansas and Nebraska pumping, Beaver Creek at end of 2003

Further analysis of the pumping reductions required to re-establish base-flow helps to understand the source of the violation of the Impact Summation Requirement. When both state-wide Kansas and Nebraska pumping are reduced together (essentially, comparison of Runs CKMN and θ) the combined pumping in Beaver Creek cells must be reduced by about 9,100 ac-ft/yr (43% of 21,271 ac-ft/yr of combined pumping) to replenish the storage sufficiently to re-establish base-flow. When only Kansas pumping in Beaver Creek cells is reduced, pumping has to be reduced about 6,500 ac-ft/yr (83% of the 7,829 ac-ft/yr of Kansas pumping) before base-flow is re-established. When only Nebraska pumping in Beaver Creek cells is reduced, pumping has to be reduced about 8,000 ac-ft/yr (60% of the 13,442 ac-ft of Nebraska pumping) before base-flow is re-established. It is evident that somewhere between 6,500 and 9,100 ac-ft/yr of pumping reduction in Beaver Creek cells is required to produce sufficient storage replenishment to re-establish base-flow. Differences between the three cases in the pumping reduction necessary to re-establish base-flow are attributable to differences in well locations, pumping changes outside the Beaver Creek cells and other water balance components.

When comparing the Run CKMN to Run θ conditions, storage is replenished with about 9,100 ac-ft/yr of pumping reduction and base-flow is restored to a level of 6,447 ac-ft/yr by the remaining 12,200 ac-ft/yr of pumping reduction in Beaver Creek cells. When comparing Run CKMN to Run CKM, storage is replenished with about 8,000 ac-ft/yr of pumping reduction and base-flow is restored to a level of only 727 ac-ft/yr by the remaining 5,400 ac-ft/yr of pumping reduction in Beaver Creek cells. Finally, when comparing Run CKMN to Run CMN, storage is replenished with about 6,500 ac-ft/yr of pumping reduction and base-flow is restored to a level of only 323 ac-ft/yr by the remaining 1,300 ac-ft/yr of pumping reduction in Beaver Creek cells. By adding the impacts produced by successively turning Kansas and Nebraska off, the pumping reduction needed to replenish storage is double-counted and the increase in base-flow is undercounted.

2.1.4 Conclusions

The response of base-flow to pumping contains a major nonlinearity. This is obvious in Figures 2.1 to 2.3. The nonlinearity has a clear physical and mathematical basis: as pumping is increased, depleted storage must be replenished before base-flow can be established. This nonlinearity is the source of the violation of the Impact Summation Requirement.

2.2 Analysis of Frenchman Creek Stream Drying

Another major violation of the Impact Summation Requirement occurs in Frenchman Creek. The stream cells associated with the two Frenchman Creek accounting points are shown on Figure 2.6. From Appendix A, this violation ranges from about 4,000 to nearly 6,000 ac-ft/yr during the years 2001-2006. The source of this violation is again stream drying, however, in this case, the drying occurs upstream of an accounting point.

The $CBCU_G$ 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 violations at each point individually. Table 2.2 shows the computed base-flows, again for 2003, at the accounting point above Enders Reservoir, at the accounting point at the mouth of Frenchman Creek and the sum of the two base-flows for six different stress conditions defined in Table 1.2.

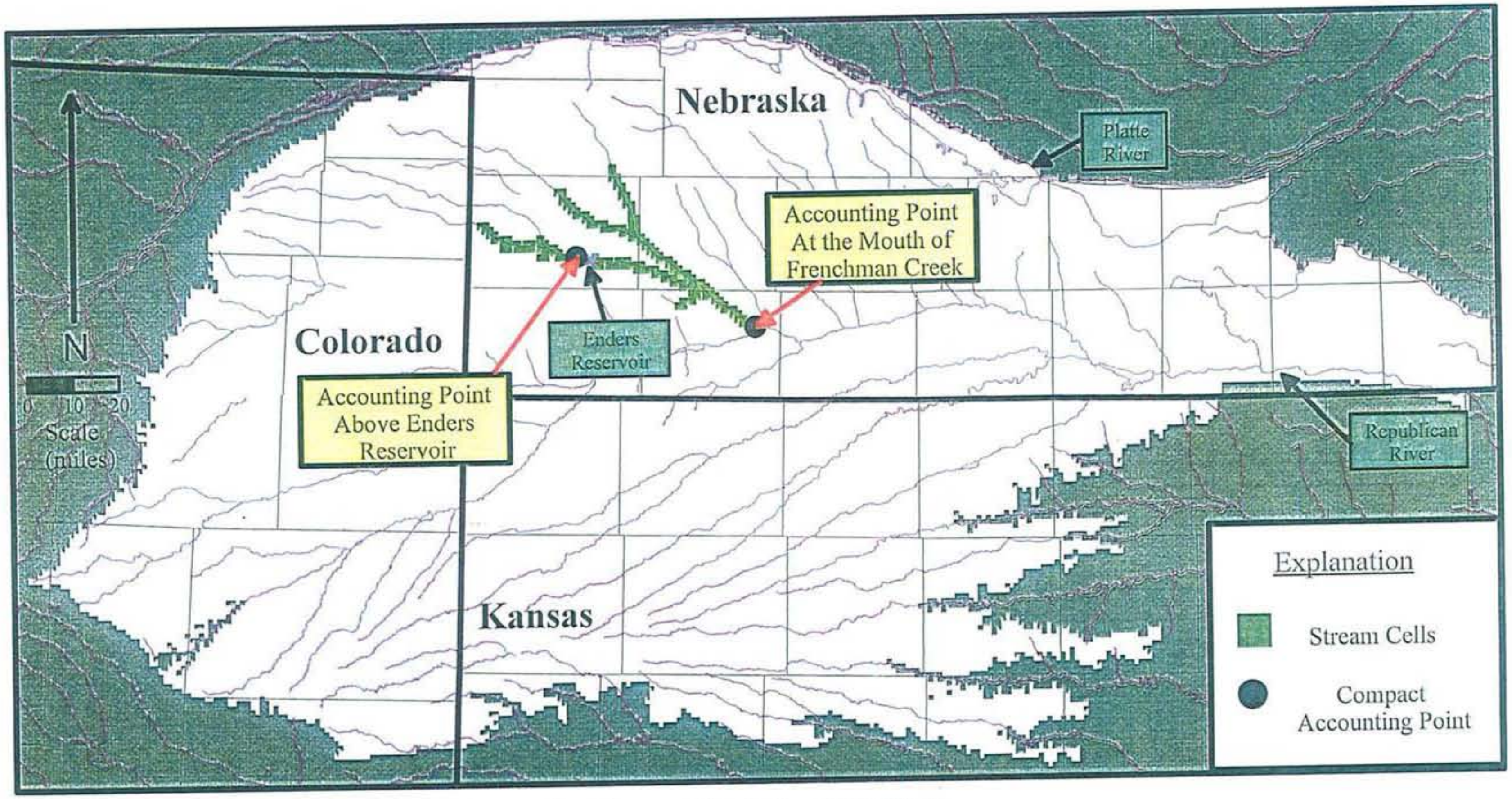

Figure 2.6. Map showing location of cells with stream boundary condition in Frenchman Creek.

Run Name	Computed Base-flow at the Accounting Point Above Enders Reservoir (ac-ft/yr)	Computed Base-flow at the Accounting Point at the Mouth of Frenchman Creek (ac-ft/yr)	Sum of Computed Base-flows (ac-ft/yr)
θ	52,663	40,442	93,105
CKMN	4,523	2,352	6,875
CMN	4,523	2,352	6,875
CKM	47,565	40,497	88,062
KMN	4,555	2,339	6,894
CKN	4,523	2,348	6,871

Table 2.2. Results of RRCA Model Runs for 2003 used to analyze violations of Impact Summation Requirement for Frenchman Creek Sub-basin.

At the accounting point at the mouth of Frenchman Creek, the total impact is 38,090 ac-ft/yr (40,442 ac-ft/yr - 2,352 ac-ft/yr) while the sum of individual impacts is 38,128 ac-ft/yr (2,352 ac-ft/yr - 2,352 ac-ft/yr + 40,497 ac-ft/yr - 2,352 ac-ft/yr + 2,339 ac-ft/yr - 2,352 ac-ft/yr + 2,348 ac-ft/yr - 2,352 ac-ft/yr). At the accounting point above Enders Reservoir the total impact is 48,140 ac-ft/yr (52,663 ac-ft/yr – 4,525 ac-ft/yr) while the sum of individual impacts is 43,074 ac-ft/yr. Most of the violation of the Impact Summation Requirement occurs at the accounting point above Enders Reservoir. Comparing Run CKMN with Runs CMN and CKN for the accounting point above Enders Reservoir, it is seen that Kansas and Mound have virtually no impact on this point so that Colorado and Nebraska pumping are the only significant sources of impact.

In contrast with the Beaver Creek behavior, the stream at the accounting point above Enders Reservoir and at the accounting point at the mouth of Frenchman Creek does not go dry. Instead, the violations occur because of stream drying upstream of the accounting points. This can be seen in Table 2.3 which shows base-flows under different stress conditions for 2003 for each segment and reach of Frenchman Creek from the headwaters to the accounting point above Enders Reservoir. In the Run θ condition, the Creek gains water along its entire length to produce a base-flow of 52,663 ac-ft/yr at the accounting point above Enders Reservoir. In the Run CKMN condition, the stream gains flow at some locations (e.g. 1,635 ac-ft/yr at segment 123, reach 2) but loses water elsewhere so that base-flow repeatedly goes to zero. There is sufficient gain of water at the downstream reaches so that a base-flow of 4,523 ac-ft/yr is present at the accounting point above Enders Reservoir.

By comparing results for Run CKMN and CKM, it can be seen that the base-flow is re-established at nearly all points and the stream once again becomes a gaining stream along its length similar to the Run θ condition. 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, base-flows do not completely return to the levels seen in the Run θ condition. This must be a result of the Colorado pumping. By comparing Run θ and CKM it is seen that the difference in base-flows at the accounting point above Enders Reservoir is 5,098 ac-ft/yr. It is expected that this would be the impact of Colorado pumping at the accounting point above Enders Reservoir. However, when using the current method, this is not the impact of Colorado that is computed.

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off [0] (ac-ft/yr)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN] (ac-ft/yr)	Flow into Reach Colorado Pumping Off, Kansas and Nebraska Pumping On, Mound On [KMN] (ac-ft/yr)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM] (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 2.3. Annual stream flow 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 [0] (ac-ft/yr)	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN] (ac-ft/yr)	Flow into Reach Colorado Pumping Off, Kansas and Nebraska Pumping On, Mound On [KMN] (ac-ft/yr)	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM] (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

Table 2.3 cont. Annual stream flow in Frenchman Creek from headwaters to Enders Reservoir for various scenarios for 2003.

A comparison of Run CKMN and Run KMN, which is done for the current accounting method to calculate Colorado pumping impacts, yields a change in base-flow at the accounting point above Enders Reservoir of only 32 ac-ft/yr. However, this does not mean that Colorado has a small impact on the stream. Examining base-flows at upstream reaches such as segment 123, reach 5, it is noted that turning off Colorado pumping does increase base-flow. However, this base-flow is lost from the stream before it reaches the accounting point above Enders Reservoir. Because the base-flow at segment 147, reach 5 remains zero under both conditions, any information about change in base-flow upstream of this point does not transfer downstream to the accounting point above Enders Reservoir. Similar zero base-flows occur at segment 126, reach 8 and segment 147, reach 3.

The primary source of the violation of the Impact Summation Requirement at the accounting point above Enders Reservoir is the inability of the calculation to capture the impact of Colorado pumping. That Colorado pumping has an impact can be seen when comparing Run θ and Run CKM (Table 2.3) where the only significant activity is Colorado pumping. The same conclusion can be reached by comparing Run θ and Run C (only Colorado pumping active). Base-flows along the entire Creek above Enders for Run C are essentially the same as those shown in the Run CKM column of Table 2.3.

The hydrologic interpretation of this is quite similar to that for Beaver Creek. The combined pumping of Colorado and Nebraska cause a substantial drop in the 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 re-establishes base-flow. 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 base-flow at the accounting point above Enders Reservoir. With Nebraska pumping active in the Run KMN case, the impact of Colorado is masked.

In conclusion, stream drying is again the cause of the observed violation of the Impact Summation Requirement. In the case of Frenchman Creek, it is stream drying at the above Enders Reservoir accounting point that is the source of the problem, even though the stream cell at this accounting point does not go dry.

2.3 Analysis of Swanson-Harlan Stream Drying

An additional major violation of the Impact Summation Requirement occurs along the Main Stem of the Republican River (Main Stem), in particular 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 accounting point above Harlan County Lake. This isolates the calculated impact to only those impacts associated with the Main Stem and its minor tributaries between Swanson Reservoir and Harlan County Lake.

Stream cells and accounting points associated with the Swanson to Harlan Main Stem section impact calculation are shown in Figure 2.7. The violation of the Impact Summation Requirement for the Main Stem has ranged from approximately 5,300 ac-ft/yr to nearly 19,000 ac-ft/yr during 2001-2006 (Appendix A). This violation results from stream drying both at the accounting point and upstream of the accounting point above Harlan County Lake. This violation differs from those at Frenchman and Beaver Creeks where the sum of individual impacts was less than the total impact (under prediction). For the Swanson to Harlan Main Stem section, the sum of individual impacts is larger than the total impact.

To illustrate the causes of the violation of Impact Summation Requirement, the analysis presented focuses on base-flows at the accounting point above Harlan County Lake. Table 2.4 shows the computed base-flows at the accounting point above Harlan County Lake under several of the stress conditions shown in Table 1.2 for 2003.

The total impact at the accounting point above Harlan County Lake for 2003 is 59,780 ac-ft/yr (59,924 ac-ft/yr -144 ac-ft/yr). The individual impact of Nebraska computed using the current method (CKM minus CKMN) is 71,523 ac-ft/yr. Comparing Runs CKMN and CKN produces an impact of –144 ac-ft/yr (0 ac-ft/yr – 144 ac-ft/yr). This can be viewed as a benefit of 144 ac-ft/yr resulting from Mound recharge. Comparing Run CKMN with Runs CMN and KMN shows that Colorado has virtually no impact and Kansas has a very small impact on the accounting point above Harlan County Lake. Therefore, for purposes of this analysis, the Nebraska pumping and Mound recharge will be considered the only significant sources of impact. Adding the Nebraska and Mound impacts yields an impact summation of 71,379 ac-ft/yr, producing a violation of the Impact Summation Requirement of 11,599 ac-ft/yr.

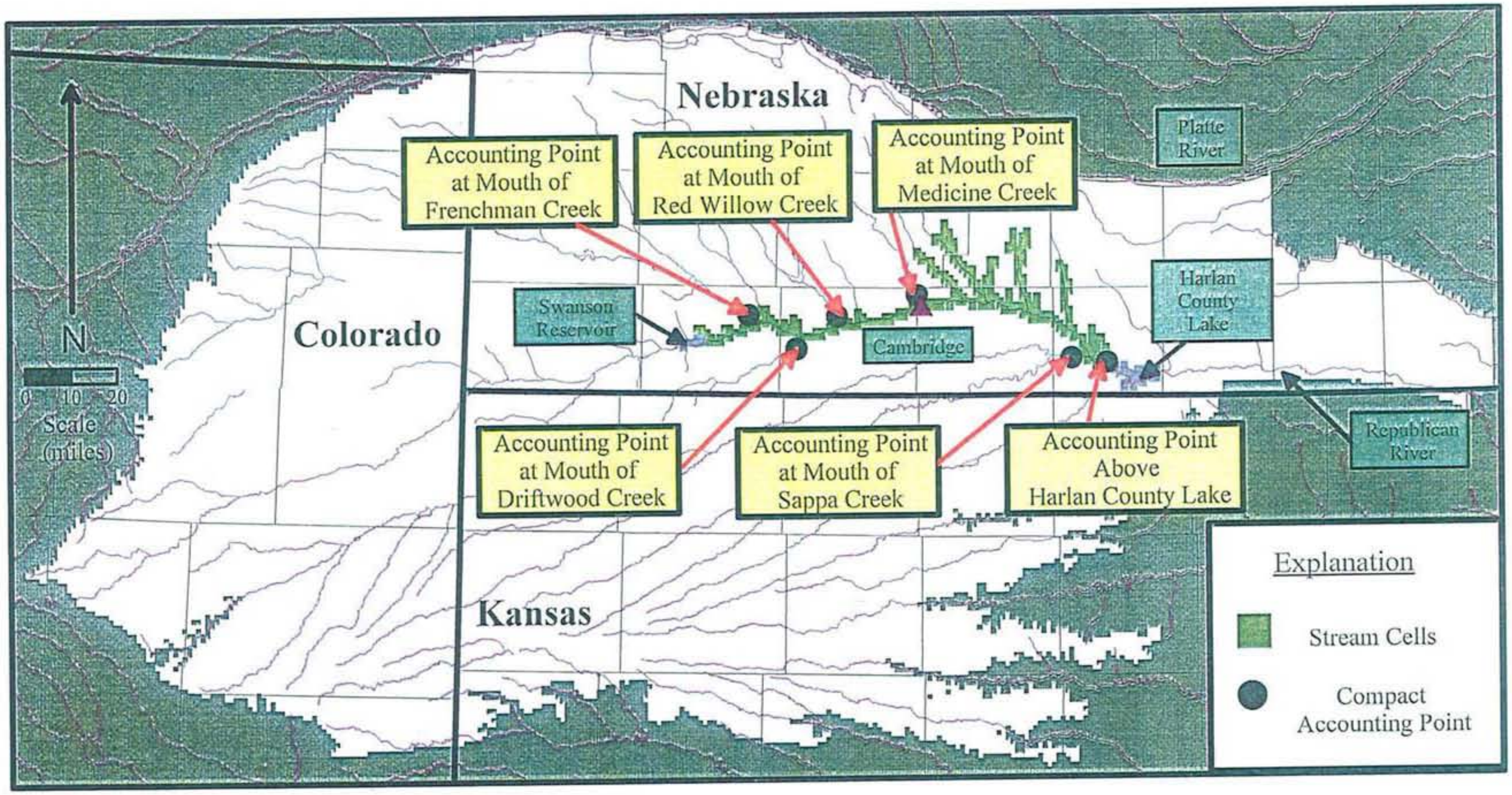

Figure 2.7. Map showing location of cells with stream boundary condition along the Main Stem of the Republican River from Swanson Reservoir to Harlan County Lake.

Run Name	Computed Base-flow at the accounting point above Harlan County Lake (ac-ft/yr)
Θ	59,924
CKMN	144
CMN	197
CKM	71,667
KMN	143
CKN	0

Table 2.4. Results of RRCA Model Runs for 2003 used to analyze violations of Impact Summation Requirement for the accounting point above Harlan County Lake.

The cause of this violation can be seen in Table 2.5 which shows base-flows 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 base-flows in the Run θ condition show that the stream is fully wetted along its entire length with a net gain of 17,054 ac-ft/yr from Cambridge to the accounting point above Harlan County Lake. In the Run CKMN condition, the stream has many reaches that are dry. Although the base-flow is active at the accounting point, segment 230, reach 5, the stream is dry just six reaches upstream at segment 229, reach 3.

Segment	Reach	Flow into Reach Colorado, Kansas, and Nebraska Pumping Off, Mound Off [0]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off [CKN]	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM]	Comments
217	1	42,870	0	0	42,934	Medicine Cr. Enters, Republican R. at Cambridge
218	1	42,784	0	0	42,848	
218	2	42,718	0	0	42,782	
218	3	42,712	0	0	42,776	
218	4	42,818	0	0	42,882	
218	5	42,815	0	0	42,879	
218	6	42,817	0	0	42,881	
218	7	42,796	0	0	42,860	
218	8	42,536	0	0	42,600	
218	9	42,475	0	0	42,540	
218	10	42,384	0	0	42,448	
218	11	42,626	133	133	42,691	
218	12	42,668	77	77	42,733	
218	13	42,657	51	51	42,723	
218	14	43,100	0	0	43,165	
218	15	42,524	0	0	42,589	
218	16	42,834	135	135	42,900	
218	17	43,264	486	486	43,330	
218	18	43,344	364	364	43,410	
218	19	43,186	61	61	43,253	

Table 2.5. Annual stream flow 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 [0]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off [CKN]	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM]	Comments
218	20	43,194	73	73	43,261	
219	1	44,006	611	611	44,072	Tributary Enters
219	2	44,128	691	691	44,195	
219	3	44,189	561	561	44,256	
219	4	43,985	130	130	44,052	
219	5	43,365	0	0	43,433	
219	6	43,321	0	0	43,388	
219	7	42,861	0	0	42,929	
219	8	41,847	0	0	41,916	
219	9	41,421	0	0	41,491	
219	10	41,377	0	0	41,447	
219	11	41,146	0	0	41,218	
219	12	40,988	0	0	41,061	
220	1	45,526	2,073	1,405	46,790	Muddy Cr. Enters
220	2	45,195	1,327	665	46,459	
221	1	46,432	1,830	1,151	47,924	Tributary Enters
221	2	46,621	1,796	1,118	48,112	
221	3	46,992	2,020	1,339	48,484	
221	4	47,090	1,740	1,071	48,582	
221	5	46,305	1,054	491	47,795	
221	6	46,031	539	40	47,521	
221	7	45,203	0	0	46,697	
222	1	45,281	38	37	46,776	Tributary Enters

Table 2.5 cont. Annual stream flow 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 [θ]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off [CKN]	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM]	Comments
222	2	45,600	0	0	47,095	
222	3	45,255	0	0	46,752	
222	4	45,723	363	359	47,222	
222	5	46,018	606	555	47,543	
222	6	45,440	0	0	46,986	
222	7	45,389	0	0	46,936	
222	8	45,044	0	0	46,642	
222	9	44,060	0	0	45,822	
222	10	44,047	0	0	45,810	
222	11	43,853	0	0	45,618	
223	1	49,999	7,161	208	63,602	Turkey Cr. Enters
223	2	50,192	7,257	353	63,778	
224	1	50,288	7,292	374	63,880	Tributary Enters
224	2	50,158	6,904	83	63,746	
224	3	50,246	6,931	0	63,830	
224	4	50,191	6,668	0	63,776	
224	5	50,794	6,771	105	64,377	
224	6	51,464	7,029	310	65,048	
224	7	51,111	6,506	0	64,691	
224	8	50,858	5,830	0	64,425	
224	9	50,831	5,283	0	64,396	

Table 2.5 cont.. Annual stream flow 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 [0]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off [CKN]	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM]	Comments
224	10	49,869	4,127	0	63,410	
224	11	49,706	3,510	0	63,244	
224	12	48,777	2,395	0	62,292	
224	13	48,455	1,940	0	61,969	
224	14	48,341	1,896	0	61,851	
224	15	47,842	1,673	0	61,400	
224	16	47,042	963	0	60,627	
224	17	48,769	1,005	0	62,849	
225	1	56,373	4,240	681	74,423	Tributary Enters
225	2	56,378	4,250	693	74,425	
226	1	48,434	2,762	264	64,735	Tributary Enters
226	2	54,142	3,954	486	71,635	
226	3	53,726	3,230	0	71,214	
226	4	53,804	2,938	0	71,289	
226	5	54,956	3,805	843	72,456	
226	6	54,858	3,374	406	72,352	
227	1	55,068	3,326	321	72,579	Tributary Enters
227	2	55,105	3,113	147	72,614	Republican River nr Orleans
228	1	54,810	2,622	0	72,308	
228	2	54,753	2,539	0	72,252	
228	3	54,693	2,368	0	72,176	
228	4	54,392	2,035	0	71,860	

Table 2.5 cont.. Annual stream flow 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 [0]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound On [CKMN]	Flow into Reach Colorado, Kansas, and Nebraska Pumping On, Mound Off [CKN]	Flow into Reach Nebraska Pumping Off, Kansas and Colorado Pumping On, Mound On [CKM]	Comments
228	5	54,576	2,093	42	72,045	
228	6	54,190	1,747	0	71,639	
228	7	54,631	1,895	101	72,079	
228	8	54,534	1,783	0	71,978	
228	9	54,445	1,477	0	71,878	
228	10	49,981	287	0	67,394	
228	11	49,983	284	0	67,393	
229	1	56,828	272	0	68,570	Tributary Enters
229	2	56,761	258	0	68,503	
229	3	56,500	0	0	68,236	
229	4	61,085	1	72	72,844	
230	1	60,996	1,140	294	72,765	Tributary Enters
230	2	60,919	957	46	72,687	
230	3	60,931	882	0	72,694	
230	4	60,604	449	0	72,361	
230	5	59,924	144	0	71,667	Main Stem Above Harlan Accounting Point

Table 2.5 cont. Annual stream flow along the Main Stem of the Republican River from Cambridge, Nebraska to Harlan County Lake for various scenarios for 2003 (ac-ft/yr).

As with Frenchman Creek, Nebraska pumping has a dominant impact on the Main Stem and the accounting point above Harlan County Lake. By comparing Run CKMN and Run CKM it can be seen that turning off Nebraska re-establishes base-flow to again produce a net gain from Cambridge to the accounting point above Harlan County Lake. The base-flow at the accounting point above Harlan County Lake is higher in the Run CKM condition than the Run θ condition. This increase in base-flow must be a result of Mound recharge. By comparing the Run θ and Run CKM conditions, and assuming that Kansas and Colorado have negligible impact, it can be estimated that the Mound recharge adds approximately 11,743 ac-ft/yr of flow to the stream. The small impacts of Colorado and Kansas would tend to decrease base-flow so that, if they are considered, then the additional flow created by the Mound would be even greater.

While a Mound recharge benefit of about 11,700 ac-ft/yr is expected, the current method computes a value of only 144 ac-ft/yr. This is the primary source of the violation of the Impact Summation Requirement. The current method of estimating the imported water supply impact is to compare the Runs CKMN and CKN in Table 2.4. With all other stresses active, turning off the Mound recharge should decrease base-flows, and it does. However, since the Run CKMN base-flow is only 144 ac-ft/yr, the base-flow decrease recorded by turning off Mound recharge can be no larger than 144 ac-ft/yr.

When Nebraska is pumping, heads are lowered and storage is depleted. With Mound recharge present, some storage is replenished and some base-flow 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 base-flow because of the large flow associated with this activity. Instead, the impact of Mound recharge is masked by the presence of Nebraska pumping.

Stream drying has again been demonstrated to be the source of the violation of the Impact Summation Requirement. In the case of the Harlan County Lake accounting point, the sum of individual impacts computed with the current method is larger than the computed total impact. This results from the inability of the current method to properly calculate the impact of Mound recharge.

2.4 Conclusion

It has been shown that stream drying is a cause of significant violations of the Impact Summation Requirement. These violations result from underestimating or overestimating individual impacts. Violations 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 violations of the Impact Summation Requirement 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 RRCA Model. Indeed, the total impact defined herein includes stream drying as, for example, at Beaver Creek accounting point where the base-flow is zero for the Run CKMN condition.

These results *do* indicate a problem with the method for using the output of the RRCA Groundwater Model. The current method for determining individual $CBCU_G$ is ineffective when stream drying is present. The current method, which assumes a linear response of base-flow to changes in stress fails to satisfy the Impact Summation Requirement when the major nonlinearities of stream drying are present.

3.0 PROPOSED METHOD FOR DETERMINING $CBCU_G$ and IWS

Nebraska proposes a new method for determining $CBCU_G$ for each state and the IWS for the mound. The proposed method computes impacts for each stress in a Sub-basin. For convenience, the following variables for impacts for a given Sub-basin are defined as:

I_C = Impact of Colorado pumping on base-flow (the Colorado $CBCU_G$)

I_K = Impact of Kansas pumping on base-flow (the Kansas $CBCU_G$)

I_N = Impact of Nebraska pumping on base-flow (the Nebraska $CBCU_G$)

I_M = Impact of Mound recharge on base-flow (the Nebraska IWS)

$\boldsymbol{T}$ = Total impact of all stresses computed as the difference between the base-flow at an accounting point with all stresses off and the base-flow at the accounting point with all stresses active.

It will be shown that the proposed method will satisfy, to reasonable accuracy, the requirement that the summation of the impacts of stresses equal the impact of the combination of stresses, that is, the Impact Summation Requirement. Mathematically, this can be stated as a requirement that, for a given Sub-basin,

$$I_C + I_K + I_N + I_M = T \tag{1}$$

As has been noted in previous sections, the current method for computing $CBCU_G$ and IWS deviates substantially from the requirement in Equation 1 for at least some of the Sub-basins. The challenge then is to devise a method that properly computes the four impacts so that they satisfy Equation 1 to reasonable accuracy. Our proposed method achieves this. The current method relies on five runs of the RRCA Groundwater Model; a "base" run and four off-condition runs to arrive at $CBCU_G$. The proposed method relies on sixteen different runs of the RRCA Groundwater Model. These sixteen different configurations consist of all the possible combinations in which each of the four stresses is either on or off. In each of the sixteen cases the output of the model is the base-flow at the accounting point of interest. These sixteen cases are summarized in Table 1.2 with the notation introduced there used in the equations below.

For the proposed method, computing the impact of an activity is accomplished by taking the difference between the off condition for that activity and the on condition. The off and on conditions are computed as the average of all possible off and on conditions from the 16 runs of the RRCA Model listed in Table 1.2. For any given stress, there exist 8 configurations in which the stress is off and 8 configurations in which the stress is on or active. Taking the average of these two sets of configurations and then taking the difference of these averaged values and rearranging the resulting 16 terms yields the impacts for the four stresses, computed as follows:

$$I_C = (\theta - C + K - CK + M - CM + N - CN + KM - CKM + KN - CKN + MN - CMN + KMN - CKMN)/8 \quad (2a)$$

$$I_K = (\theta - K + C - CK + M - KM + N - KN + CM - CKM + CN - CKN + MN - KMN + CMN - CKMN)/8 \quad (2b)$$

$$I_M = (\theta - M + C - CM + K - KM + N - MN + CK - CKM + CN - CMN + KN - KMN + CKN - CKMN)/8 \quad (2c)$$

$$I_N = (\theta - N + C - CN + K - KN + M - MN + CK - CKN + CM - CMN + KM - KMN + CKM - CKMN)/8 \quad (2d)$$

In the sections that follow, a detailed explanation of the proposed method is provided. Also presented is analysis of the deviation of the method from the Impact Summation Requirement in Equation 1.

When there are no major nonlinearities present (e.g. no stream drying), it is shown that the proposed method produces the same values of $CBCU_G$ and IWS as the current method. It is also shown that under these conditions the requirement in Equation 1 will be satisfied except for the effects of numerical roundoff and minor nonlinearities.

The analysis in the following sections also shows that if two of the four stresses have negligible impact on base-flow at a particular accounting point, then the proposed method will produce computed impacts that satisfy requirement in Equation 1 even when major nonlinearities are present. This feature of the proposed method is a significant improvement over the current method. Analysis in Section 4 shows that for many Sub-basins, such as Beaver Creek, there are only two significant stresses. There are only a few Sub-basins where major nonlinear responses are present and more than two stresses produce significant impacts. For these few cases, the proposed method satisfies the requirement in Equation 1 with reasonable accuracy. A supplemental method for residual allocation is proposed for these cases.

3.1 Background of Proposed Method

The proposed method for computing $CBCU_G$ and IWS is based on a conceptualization of the base-flow at an accounting point as a continuous function or response surface. The impacts of individual stresses can then be seen as derivatives on this surface. The proposed method utilizes a central difference concept for representing this derivative based on the use of the 16 corner points of the function domain. Exposition of the method is aided by placing the calculation of impacts in the framework of the Taylor Series. To provide an example, this explanation will examine the impact calculation for Nebraska pumping. The analysis would be the same for any of the other three stresses (Kansas pumping, Colorado pumping and Mound recharge).

Define the base-flow predicted by the RRCA model at a given accounting point as a function of two variables

$$S = S(A, N) \tag{3}$$

where N represents the stress activity of Nebraska pumping, A represents the stress activity of all three other stresses and S is the base-flow at a specified stream cell and time which depends on both A and N. Several levels of stress activity will be considered for A and N. First, define the following terms:

N_{off} = Nebraska pumping activity is off

N_{on} = Nebraska pumping activity is on

A_{off} = All other stress activity is off

A_{on} = All other stress activity is on

Using this notation and considering the current method, the impact of Nebraska is currently computed as

$$I_{N,Current} = S(A_{on}, N_{off}) - S(A_{on}, N_{on}). \tag{4}$$

To understand the mathematical basis for the impact estimate under the current method it is useful to view the impact estimation calculation as a Taylor Series approximation. Using a first-order Taylor Series, the base-flow, when only the Nebraska stress level is changed, can be written as:

$$S(A, N_{on}) = S(A, N_{off}) + \frac{\partial S}{\partial N}(N_{on} - N_{off}) \tag{5}$$

The first-order Taylor Series can be used with stress activity of A in Equation 5 at any level (i.e. on, off or in between) as long as the derivative in Equation 5 is evaluated at this same level of A and with N_{off}.

In the current method, Equation 5 is evaluated with activity A in the on condition. Hence, combining Equation 4 and Equation 5, with the on condition applied to activity A, yields this expression for the impact using the current method

$$I_{N,Current} = -\frac{\partial S}{\partial N}\left(N_{on} - N_{off}\right). \tag{6}$$

The current method estimates the derivative in Equation 5 from the on condition and can be referred to as a backward difference;

$$\frac{\partial S}{\partial N}\bigg|_{backward} = \frac{S(A_{on}, N_{on}) - S(A_{on}, N_{off})}{\left(N_{on} - N_{off}\right)} \tag{7}$$

Substituting this definition of the derivative into Equation 6 produces the definition of impact in Equation 4.

The approximation of the derivative given in Equation 7 is only one way that the derivative can be approximated. One alternative would be to calculate the derivative from the off condition. This alternative was introduced by Nebraska in a memo in March 2008. This can be referred to as a forward difference approximation and results in a derivative approximation of

$$\frac{\partial S}{\partial N}\bigg|_{forward} = \frac{S(A_{off}, N_{on}) - S(A_{off}, N_{off})}{\left(N_{on} - N_{off}\right)} \tag{8}$$

If the modeled system were linear, both the forward and backward approximations of the derivative would produce the same value, however, in the non-linear case, different derivative approximations yield different values for the derivative.

The proposed method approximates the derivative at the mid-point of the domain of A stresses. This approximation shall be referred to as the central difference approximation. In this case, the derivative is approximated as follows

$$\frac{\partial S}{\partial N}\Big|_{central} = \frac{S(A_{midpoint}, N_{on}) - S(A_{midpoint}, N_{off})}{(N_{on} - N_{off})} \tag{9}$$

The proposed method yields an impact calculation for Nebraska given by

$$I_{N,Proposed} = -\frac{\partial S}{\partial N}\Big|_{central}(N_{on} - N_{off}) \tag{10}$$

Substituting Equation 9 into Equation 10 yields

$$I_{N,Proposed} = S(A_{midpoint}, N_{off}) - S(A_{midpoint}, N_{on}) \tag{11}$$

It remains to evaluate the base-flow at the midpoint of the domain. It is proposed that the midpoint evaluation be conducted as the average of the on and off conditions for A. As shown below, the use of this averaging produces desirable properties for the residual produced by the proposed method. The use of this averaging also means that runs of the RRCA Groundwater Model are limited to the 16 cases listed in Table 1.2 with individual stresses either on or off.

Using the notation defined in Table 1.2 the base-flow at the midpoint of the domain of A is defined as

$$S(A_{midpoint}, N_{off}) = \frac{1}{8}(\theta + C + K + M + CK + CM + KM + CKM) \tag{12}$$

$$S(A_{midpoint}, N_{on}) = \frac{1}{8}(N + CN + KN + MN + CKN + CMN + KMN + CKMN) \tag{13}$$

The proposed impact of Nebraska would then be calculated as the difference of Equation 12 and Equation 13 to yield:

$$I_N = (\theta\text{-}N + C\text{-}CN + K\text{-}KN + M\text{-}MN + CK\text{-}CKN + CM\text{-}CMN + KM\text{-}KMN + CKM\text{-}CKMN)/8 \tag{2d}$$

Organized as a sum of differences the impact in Equation 2d can be viewed as the average of 8 different computations of impact. The difference θ-N is an impact of Nebraska pumping computed from a no-stress base. The difference C-CN is the impact of Nebraska pumping computed from a base in which only Colorado pumping is active, etc. The difference of *CKM* and *CKMN* is the current method of impact computation.

Expressions similar to Equation 2d can be derived for the impacts of Kansas and Colorado pumping and Mound recharge and are given as Equations 2a-c above.

3.2 Residual of Proposed Method

As stated in Equation 1, the sum of individual impacts should equal the total impact. Deviations from this requirement can be measured as a residual, R, defined as:

$$R = T - (I_C + I_K + I_N + I_M) \qquad (14)$$

For the proposed method the residual can be computed as follows:

$$\begin{aligned} R = {} & (\theta\text{-}CKMN) - \\ & (\theta\text{-}C + K\text{-}CK + M\text{-}CM + N\text{-}CN + KM\text{-}CKM + KN\text{-}CKN + MN\text{-}CMN + KMN\text{-}CKMN + \\ & \theta\text{-}K + C\text{-}CK + M\text{-}KM + N\text{-}KN + CM\text{-}CKM + CN\text{-}CKN + MN\text{-}KMN + CMN\text{-}CKMN + \\ & \theta\text{-}M + C\text{-}CM + K\text{-}KM + N\text{-}MN + CK\text{-}CKM + CN\text{-}CMN + KN\text{-}KMN + CKN\text{-}CKMN + \\ & \theta\text{-}N + C\text{-}CN + K\text{-}KN + M\text{-}MN + CK\text{-}CKN + CM\text{-}CMN + KM\text{-}KMN + CKM\text{-}CKMN)/8 \end{aligned} \qquad (15)$$

Canceling common terms the residual is given by

$$R = \tfrac{1}{2}(\theta - CKMN) - \tfrac{1}{4}(C + K + M + N - CKM - CKN - CMN - KMN) \qquad (16)$$

3.3 Properties of the Residual

Analysis of the residual under various conditions indicate the benefits of the proposed method. Three cases are considered: 1) when a sub-basin is affected by only two of the four major stress, 2) when the response to stress set in a sub-basin is linear, and 3) when a sub-basin is affected by more than two major stress sets and the response in non-linear. In the first two cases, as is demonstrated in Sections 3.3.1 and 3.3.2, the residual is 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. In the third case the residual may be expected to be non-zero. Section 3.3.3 describes a possible method for allocating non-zero residuals. Section 4, however, shows that the magnitude of the residual in such cases is much smaller than it is using the current method.

3.3.1 Case of Sub-basin Affected by only Two Major Stress Sets

For many Sub-basins there are only two major stress sets that have impacts. In these cases the residual, when using the proposed method, will be zero. For example, in the case of Beaver Creek, Kansas and Nebraska pumping are the only stresses that cause significant change in base-flow at the accounting point.

For this case, the following observations can be made:

1) $C = \theta$ (turning on Colorado pumping produces no change from the all-off condition)
2) $M = \theta$ (turning on the Mound recharge produces no change from the all-off condition)
3) $CMN = N$ (adding Colorado pumping and Mound recharge does not change the impact of Nebraska pumping)
4) $CKM = K$ (adding Colorado pumping and Mound recharge does not change the impact of Kansas pumping)
5) $KMN = CKMN$ (adding Colorado pumping does not change the impact of Kansas pumping, Nebraska pumping and Mound recharge
6) $CKN = CKMN$ (adding Mound recharge does not change the impact of Kansas, Nebraska and Colorado pumping)

Substituting these 6 statements into Equation 16 causes the residual to go to zero. A similar analysis could be conducted for any combination of two stresses. When only two stresses are present, adding one of the stresses to the no-stress base condition produces the same run as subtracting the other stress from the all-on base condition. The results of these two runs cancel each other in the residual calculation. Whenever a Sub-basin is only substantially affected by two stresses the residual will be zero.

3.3.2 Case of Linear Responses

Impacts calculated with the proposed method are identical to those determined with the current method when the computed base-flow response is linear. Again using Nebraska as an example and repeating Equation 2d,

$$I_N = (\theta\text{-}N + C\text{-}CN + K\text{-}KN + M\text{-}MN + CK\text{-}CKN + CM\text{-}CMN + KM\text{-}KMN + CKM\text{-}CKMN)/8 \qquad (2d)$$

As noted above, each of the difference pairs in Equation 2d can be viewed as a different calculation of the impact. For example, the difference θ-N is the impact of Nebraska pumping from the no-stress base condition. This can also be viewed as the product of a derivative times a difference,

$$I_{N,Base\theta} = \theta - N = -\frac{\partial S}{\partial N}\Big|_{base\theta}\left(N_{on} - N_{off}\right) \qquad (17)$$

Similar statements could be written for each of the 8 difference pairs in Equation 2d, each using a derivative of base-flow evaluated at a different point in the A domain. When the base-flow is a linear function of Nebraska pumping the derivative of base-flow with respect to Nebraska pumping will take the same value everywhere in the domain. As a result, each of 8 impacts will have the same value and each of the 8 difference pairs will have the same value. Finally, the current method uses the difference *CKM-CKMN* to compute impacts. Since all other impacts in Equation 2d take this value, it follows that the proposed method will yield the same impact value as the current method when the base-flow response is linear.

When the response is linear it also follows that the residual of the proposed method will be zero. This can be shown by substituting selected differences into Equation 15. For example, the difference *K-CK* can be replaced with its equivalent θ-*C* since they both reflect a change in Colorado stress and take the same value when the response is linear. Making this and similar substitutions, as shown below,

$$R = (\theta\text{-}CKMN) -$$
$$(\theta\text{-}C + \theta\text{-}C + M\text{-}CM + N\text{-}CN + KM\text{-}CKM + KN\text{-}CKN + KMN\text{-}CKMN + KMN\text{-}CKMN +$$
$$\theta\text{-}K + \theta\text{-}K + M\text{-}KM + N\text{-}KN + CM\text{-}CKM + CN\text{-}CKN + CMN\text{-}CKMN + CMN\text{-}CKMN +$$
$$\theta\text{-}M + C\text{-}CM + K\text{-}KM + \theta\text{-}M + CKN\text{-}CKMN + CN\text{-}CMN + KN\text{-}KMN + CKN\text{-}CKMN +$$
$$\theta\text{-}N + C\text{-}CN + K\text{-}KN + \theta\text{-}N + CKM\text{-}CKMN + CM\text{-}CMN + KM\text{-}KMN + CKM\text{-}CKMN)/8, \quad (18)$$

yields a residual that goes to zero.

3.3.3 Case of a Sub-basin impacted by more than two major stress sets with non-linear responses

Some Sub-basins may be affected by more than 2 major stress sets with non-linear responses. For such a case the residual of the proposed method will not necessarily be zero. A supplemental modification to the residual may be considered for these cases. This modification consists of changing all impacts such that the modified impacts exactly meet the Impact Summation Requirement in Equation 1. This is accomplished by dividing any residual that exists among the four stress activities in proportion to the size of impact as computed using Equation 2 a-d. The supplemental modification is given in the following equations where the *Mod* subscript indicates the modified impact for each of the four activities.

$$I_{C,Mod} = I_C + \left[\frac{I_C}{I_C + I_K + I_M + I_N}\right]R \quad (19a)$$

$$I_{K,Mod} = I_K + \left[\frac{I_K}{I_C + I_K + I_M + I_N}\right]R \quad (19b)$$

$$I_{M,Mod} = I_M + \left[\frac{I_M}{I_C + I_K + I_M + I_N}\right]R \quad (19c)$$

$$I_{N,Mod} = I_N + \left[\frac{I_N}{I_C + I_K + I_M + I_N}\right]R \quad (19d)$$

By adding together these four modified impacts it can be confirmed that the modified impacts will always satisfy the Impact Summation Requirement. These modified impact values may be useful in those cases when more than two stress activities are present and residuals are larger than those normally associated with roundoff error and minor nonlinearities.

3.4 Conclusion

An alternate method for computing the $CBCU_G$ and IWS in the RRCA Accounting Procedure has been offered for consideration. This proposed method requires computation of base-flow in a given Sub-basin using 16 different combinations of stress activity. These 16 runs are combined to produce values of impacts for each stress activity that are superior to the current method for computing impacts. The proposed method provides values for impact that satisfy the Impact Summation Requirement to reasonable accuracy in most cases. When required, a modification can be applied to the impacts computed by the proposed method to values of $CBCU_G$ and IWS that exactly meet the Impact Summation Requirement. 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 COMPACT ACCOUNTING USING PROPOSED METHOD

In Section 3, a new method for computing $CBUC_G$ and IWS is proposed. In this section, the results of applying the proposed method to 2003 Compact accounting are described. Similar Tables for all years between 2001 and 2006 are presented in Appendix C. It is shown that the proposed method produces residuals that are much smaller than those produced by the current method. In nearly all Sub-basins the residuals produced by the proposed method are zero or near-zero. The proposed method produces significant changes to the final state balances in the Compact accounting.

4.1 Computed Water Supply

There are substantial discrepancies between sum of individual impacts and the total impact produced by the current accounting methodology (see Section 1). These discrepancies transfer directly to errors in the VWS, and therefore, errors in the state allocations. The VWS is defined in the FSS as "the Water Supply within the Basin undepleted by the activities of man." The Water Supply within the Basin is defined as "the streamflows within the Basin, excluding Imported Water Supply." Therefore, the formula for the VWS for each Sub-basin is defined in the Accounting Procedures as:

$$\textit{Sub-basin VWS} = \textit{Gage} + \textit{All CBCU} + \Delta S - \textit{IWS}, \qquad (20)$$

where Gage represents the measured flow at the Compact gage for that Sub-basin and ΔS is the change in federal reservoir storage (if any). For the Main Stem VWS, the "Gage" term is further defined as the measured flow at the Republican River at Hardy gage minus the sum of the measured flow at every Sub-basin gage.

The allocation for each state from each Sub-basin and the Main Stem is actually based on the Computed Water Supply (CWS), which is defined in the Accounting procedures as:

$$CWS = VWS - \Delta S - FF, \tag{21}$$

where FF refers to flood flows. By substituting the Equation 20 for the VWS, and neglecting the flood flows term (to help simplify this example), the Equation 21 reduces to:

$$CWS = Gage + All\ CBCU - IWS \tag{22}$$

From a practical standpoint, "All CBCU" can be broken into two terms, the CBCU of surface water ($CBCU_S$), and the $CBCU_G$. Substituting these terms into Equation 22 gives:

$$CWS = Gage + CBCU_S + CBCU_G - IWS. \tag{23}$$

This paper is concerned with the accuracy of the last two components of this equation. Current accounting procedures compute the $CBCU_G$ by applying a method (see Section 1) for the determination of the $CBCU_G$ for each state and summing the results. The IWS component is computed using a similar methodology. This is actually not necessary for the computation of the CWS, however, as it is a fairly straightforward exercise to directly compute the $CBCU_G$ – IWS by taking the difference between modeled stream baseflow when all states pumping and mound recharge is on (CKMN) and modeled stream baseflow when all states pumping and mound recharge is off (θ). Table 4.1 documents the difference between the CWS directly computed from this difference and the CWS computed using the current accounting methodology for 2003 (See also Section C.1). **Discrepancies in the sum of $CBCU_G$ – IWS directly translate into errors in the CWS.**

	Gage + $CBCU_S$	Current Accounting		Directly Computed		Difference
		$CBCU_G$ — IWS	CWS	$CBCU_G$ - IWS	CWS	
Arikaree	1,060	853	1,913	1,012	2,072	159
Beaver	239	1,050	1,289	6,445	6,684	5,395
Buffalo	2,497	3,600	6,097	3,683	6,180	83
Driftwood	1,099	1,391	2,490	1,391	2,490	0
Frenchman	20,236	85,643	105,879	90,671	110,907	5,028
North Fork	25,288	15,445	40,733	15,426	40,714	-19
Medicine	23,834	10,782	34,616	10,304	34,138	-478
Prairie Dog	6,011	1,678	7,689	1,679	7,690	1
Red Willow	6,605	7,793	14,398	7,753	14,358	-40
Rock	4,712	3,477	8,189	3,500	8,212	23
Sappa	-36	177	141	472	436	295
South Fork	4,917	18,783	23,700	20,046	24,963	1,263
Main Stem	91,803	76,776	168,579	57,840	149,643	-18,936

Table 4.1. Comparison of the CWS from the current accounting with the directly computed CWS for 2003 in ac-ft. Current CWS is slightly different from the final adopted accounting from 2003 due to small differences in the groundwater model output presented in this report, as documented herein.

4.2 State Allocations

Table 4.2 details the allocation of the CWS between the three states. 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 4.2. Using the results of current compact accounting methodology for determining the $CBCU_G$-IWS (See Table 4.1), the three states' allocation of each Sub-basin CWS for 2003 is shown in Table 4.3 (See also Section C.2).

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 4.2. Compact Allocations. The unallocated CWS is added to the main stem CWS.

	CO	KS	NE	Unallocated
Arikaree	1,502	98	321	-8
Beaver	258	500	523	8
Buffalo	0	0	2,012	4,085
Driftwood	0	172	408	1,910
Frenchman	0	0	56,751	49,128
North Fork	9,124	0	10,020	21,588
Medicine	0	0	3,150	31,466
Prairie Dog	0	3,514	584	3,591
Red Willow	0	0	2,764	11,634
Rock	0	0	3,276	4,913
Sappa	0	58	58	25
South Fork	10,523	9,527	332	3,318
Main Stem	0	153,421	146,816	N/A
Total	21,406	167,290	227,017	

Table 4.3. Compact allocations for 2003 using the current accounting procedures in ac-ft. Note that these allocations do not match the official 2003 Compact allocations due to small differences in the groundwater model output presented in this report, as documented herein.

These allocations can easily be corrected to reflect the true value of $CBCU_G$-IWS as calculated by comparing the model run with all state pumping and mound recharge on (CKMN) and modeled stream baseflow when all states pumping and mound recharge is off (θ). The 2003 Compact allocations that reflect the directly computed value of $CBCU_G$-IWS are shown in Table 4.4 (See also Section C.3).

	CO	KS	NE	Unallocated
Arikaree	1,627	106	348	-8
Beaver	1,337	2,593	2,714	40
Buffalo	0	0	2,039	4,141
Driftwood	0	172	408	1,910
Frenchman	0	0	59,446	51,461
North Fork	9,120	0	10,016	21,578
Medicine	0	0	3,107	31,031
Prairie Dog	0	3,514	584	3,591
Red Willow	0	0	2,757	11,601
Rock	0	0	3,285	4,927
Sappa	0	179	179	78
South Fork	11,084	10,035	349	3,495
Main Stem	0	144,862	138,626	N/A
Total	23,167	161,462	223,858	

Table 4.4. Compact allocations for 2003 using the directly computed value for $CBCU_G$-IWS in ac-ft.

As can be seen from Tables 4.3 and 4.4, the 2003 allocation was underestimated for Colorado by 1,760 ac-ft. Conversely, the 2003 Compact allocation was overestimated for Kansas and Nebraska by 5,828 and 3,185 ac-ft, respectively. Note that this only corrects the allocations for each state. Compact compliance measures also require a related value for each state's CBCU and the IWS.

4.3 State Impacts and Imported Water Supply Credit

Section 3 proposes an accounting method which more closely satisfies the Impact Summation Requirement. The resulting groundwater pumping impacts by Sub-basin and target stress for 2003, computed using equations 2a through 2d in Section 3, are presented in Table 4.5 (See also Section C.4). For each sub-basin Table 4.5 shows the impact of each of the 4 major stress sets, the combination (sum) of those impacts, the impact of the combination of all 4 stress sets (total), and the difference between the combination of the impacts and the impact of the combinations (residual). The residual is a measure of the adherence of the proposed accounting method to the Impact Summation Requirement. Table 4.6 compares the 2003 residuals using the current accounting method to the residuals using the proposed accounting methodology. The residuals using the proposed method are much smaller than those for the current method; most of them are zero. Although the proposed method does not exactly adhere to the Impact Summation Requirement it does far better than the current method. The proposed method can be made to adhere to the Impact Summation Requirement by allocating the residual as shown in Section 3.3.3 of this report.

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	163	288	572	0	1,023	1,012	-11
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	2,566	-8	88,143	26	90,676	90,671	-5
North Fork	14,149	28	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	7,794	39	7,753	7,753	0
Rock	69	0	3,430	0	3,500	3,500	0
Sappa	0	-173	648	2	473	472	-1
South Fork	12,579	5,881	1,716	-1	20,178	20,046	-132
Main Stem	-612	458	67,078	9,050	57,874	57,840	-34

Table 4.5. Comparison of the sum of individual impacts with the total impacts for 2003 in ac-ft using the methodology proposed in Section 3.

	Residual Using Current Method	Residual Using Proposed Method
Arikaree	159	-11
Beaver	5,395	0
Buffalo	83	0
Driftwood	0	0
Frenchman	5,028	-5
North Fork	-19	0
Medicine	-478	0
Prairie Dog	1	0
Red Willow	-40	0
Rock	23	0
Sappa	295	-1
South Fork	1,263	-132
Main Stem	-18,936	-34

Table 4.6. Comparison of the sum of individual impacts with the total impacts for 2003 using the current method and the methodology proposed in Section 3, units are in ac-ft.

4.4 Compliance Test

The final step in the RRCA annual accounting is a comparison between the total Compact allocation for each state and that state's total CBCU – IWS. These comparisons are used to calculate each states success regarding two- and/or five-year running average compliance tests. The calculated state allocations using the newly-proposed methodology are shown in Table 4.7 (See also Section C.5). In other words, the allocations shown in Table 4.7 represent the results of the proposed methodology from Section 3, as opposed to the result obtained from the value for $CBCU_G$-IWS as calculated by comparing the model run with all state pumping and mound recharge is on (CKMN) and modeled stream baseflow when all states pumping and mound recharge is off (θ). Note that these values are almost identical to those in Table 4.4; the only difference is due to the residuals resulting from the proposed methodology, as listed in Table 4.6.

Table 4.8 compares the final results of the current accounting method with the final results for the proposed accounting method (See also Section C.6). As previously discussed, the allocation for Colorado goes up, while the allocations for Kansas and Nebraska go down. 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. This results in a small decrease in Colorado's balance, a large decrease in Kansas' balance, and a large increase in Nebraska's balance.

	CO	**KS**	**NE**	**Unallocated**
Arikaree	1,635	106	350	-8
Beaver	1,337	2,593	2,714	40
Buffalo	0	0	2,039	4,141
Driftwood	0	172	408	1,910
Frenchman	0	0	59,449	51,463
North Fork	9,120	0	10,016	21,578
Medicine	0	0	3,107	31,031
Prairie Dog	0	3,514	584	3,591
Red Willow	0	0	2,757	11,601
Rock	0	0	3,285	4,927
Sappa	0	180	180	78
South Fork	11,142	10,088	351	3,513
Main Stem	0	144,890	138,653	N/A
Total	23,234	161,544	223,892	

Table 4.7. Compact allocations in ac-ft using the values for 2003 for $CBCU_G$-IWS computed for each state using the proposed methodology.

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	21,406	33,538	-12,132	23,234	35,818	-12,584
Kansas	167,290	49,264	118,026	161,545	52,828	108,716
Nebraska	227,017	251,511	-24,494	223,892	238,625	-14,732

Table 4.8. 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.

4.5 Conclusion

As shown above, the current accounting method produces estimates of CWS that contain significant errors when compared with the CWS computed using impacts that are directly computed from the difference of all on and all off conditions. In contrast, the proposed method produces values of CWS that, for most Sub-basins, are identical to those determined by direct computation. The residuals produced by the proposed method are substantially less than those produced by the current method (Table 4.6). The differences in CWS for each Sub-basin produce significant changes in state allocations as shown by comparing Table 4.3 and Table 4.7. The final balance for each state is further affected by the differences in the state-wide impacts (Table 4.8). The net result for 2001-2006 is substantial (Section C.6).

In summary, it has been shown in this section that the violations of the Impact Summation Requirement produce errors in two places in the Compact accounting. The current accounting method results in incorrect estimates of the state-wide impacts (CBCU – IWS) and incorrect estimates of the CWS. Taken together, these two errors produce significant deviations of the final state balance from values that are equitable.

5.0 SUMMARY AND CONCLUSION

Nebraska seeks a modification of the method for computing the $CBCU_G$ and the IWS in the RRCA Accounting Procedures. In this report it has been shown that serious errors arise from the use of the current method for computing $CBCU_G$ and IWS. These errors have significant impact on the final allocations and the equitable division of water in the Republican River Basin. Nebraska has proposed a new method that alleviates these errors.

The current method for computing $CBCU_G$ and IWS is flawed because it produces substantial violations of the Impact Summation Requirement; the requirement that the sum of impacts of individual stresses in a Sub-basin be equal to the total impact of all stresses applied simultaneously. The need to meet this requirement is evident in the Accounting Procedures where the Virgin Water Supply is computed using the sum of impacts of individual stresses. Inherent in this calculation of the VWS is the assumption that the sum of individual impacts is equal to the total impact of all stresses.

Violations of the Impact Summation Requirement occur in many years over many of the Sub-basins in the Republican River Basin. They, in turn, cause substantial errors in the computed VWS and CWS for many individual Sub-basins.

Violations of the Impact Summation Requirement do not arise from errors in the RRCA Groundwater Model but rather from the assumption in the Accounting Procedures that the impact of a given stress in a Sub-basin can be determined from the difference of a run of the RRCA Model in which all stresses are active and one in which the target stress is inactive. This assumption is flawed when severe nonlinearities, such as stream drying, occur in the results of the RRCA Model. Detailed analyses of the effects of stream drying on $CBCU_G$ and IWS computed using the current method have been performed for the Beaver Creek, Frenchman

Creek and Swanson-Harlan Sub-basins. When stream drying is present, the impacts for some stresses are significantly under-estimated or over-estimated.

A new method for computing $CBCU_G$ and IWS has been proposed. It relies on a more complete set of runs of the RRCA Model that span a greater range of possible conditions than are covered in the current method. It has been shown that the proposed method will produce negligible violations of the Impact Summation Requirement for the common condition in which only two stresses in a Sub-basin produce significant impacts. It is shown that, when applied to 2003 data, the proposed method produces results that are superior to the current method and produces a final allocation that is substantially different than that computed by the current method.

Appendix A

Comparison of the Sum of Individual Impacts with the Total Impacts Using Current Method for Compact Sub-basins

(2001-2006)

	CO	KS	NE	IWS	Sum	Total	Discrepancy
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	87,146	4,320
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 A.1. Comparison of the sum of individual impacts with the total impacts for 2001 in ac-ft.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 A.2. Comparison of the sum of individual impacts with the total impacts for 2002 in ac-ft.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 A.3. Comparison of the sum of individual impacts with the total impacts for 2003 in ac-ft.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 A.4. Comparison of the sum of individual impacts with the total impacts for 2004 in ac-ft.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 A.5. Comparison of the sum of individual impacts with the total impacts for 2005 in ac-ft.

	CO	KS	NE	MD	Sum	Total	Discrepancy
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 A.6. Comparison of the sum of individual impacts with the total impacts for 2006 in ac-ft.

Appendix B

Description of Methods Used to Develop Project Data Sets for Analysis of Newly-Proposed RRCA Accounting Procedure

B.1 INTRODUCTION

This appendix summarizes the steps taken in developing data sets for the analysis of the newly-proposed Republican River Compact Administration (RRCA) accounting procedure. The goal of this appendix was to provide sufficient detail such that a knowledgeable independent reviewer could recreate each of the steps followed.

B.2 SELECTION OF MODEL INPUT DATA SETS

The RRCA model as completed July 1, 2003 simulates monthly groundwater flow for the period 1918 to 2000. For each year subsequent to 2000, Kansas, Colorado, and Nebraska provide data sets of pumping, canal losses, and irrigation return to the RRCA on an annual basis. These data are combined with basin-wide information on precipitation and evapotranspiration parameters and an annual simulation update is completed. Initial groundwater levels specified for each annual simulation were based on the previous year's final simulated groundwater levels.

For this investigation, groundwater flow model input data sets for the period 1918 to 2000 were combined with annual model input data sets for the period January 1, 2001 to December 31, 2006. All input data for analyses presented in this document were obtained from the website http:// www.republicanrivercompact. org, the official Republican River Compact website. All downloaded data are provided in original format in the external hard drive provided with this memorandum in the directory "Original RRCA Data Sets 1918 to 2006." Model specification and preprocessor data sets were then modified as needed as described below.

The official data sets were downloaded on May 28-29, 2008 as follows:

1) From http://www.republicanrivercompact.org/v12p/html/ch00.html (MODFLOW input data files), MODFLOW-2000 model input data sets for 1918 to 2000→data0.zip.

2) From http://www.republicanrivercompact.org/v12p/html/ch00.html (MODFLOW input files generated from programs), MODFLOW-2000 model input data sets for 1918 to 2000→data1.zip.

3) From http://www.republicanrivercompact.org/v12p/html/ch00.html (Colorado RRPP input data) Republican River Project Preprocessor (RRPP) input data sets for 1918 to 2000,→ co12b.zip.

4) From http://www.republicanrivercompact.org/v12p/html/ch00.html (Nebraska RRPP input data) Republican River Project Preprocessor (RRPP) input data sets for 1918 to 2000,→ ne12b.zip.

5) From http://www.republicanrivercompact.org/v12p/html/ch00.html (Kansas RRPP input data) Republican River Project Preprocessor (RRPP) input data sets for 1918 to 2000,→ ks12b.zip.

6) From http://www.republicanrivercompact.org/v12p/html/ch00.html (Precipitation source data) Republican River Project Preprocessor (RRPP) precipitation input data sets for 1918 to 2000,→ ppt-data.zip.

7) From http://www.republicanrivercompact.org/v12p/html/ch00.html (Parameter and flag files) Republican River Project Preprocessor (RRPP) parameter and flag file input data files for → par.zip.

8) From http://www.republicanrivercompact.org/2001/html/index.html (2001 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2001→ 2001.zip.

9) From http://www.republicanrivercompact.org/2002/html/index.html (2002 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2002 → 2002.zip.

10) From http://www.republicanrivercompact.org/2003/html/index.html (2003 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2003 → 2003.zip.

11) From http://www.republicanrivercompact.org/2004/html/zip/index.html (2004 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2004 → 2004.zip.

12) From http://www.republicanrivercompact.org/2005/html/zip/index.html (2005 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2005 → 2005.zip.

13) From http://www.republicanrivercompact.org/2006/html/zip/index.html (2006 Simulation) Republican River Project Preprocessor (RRPP) parameter, flag file, and MODFLOW-2000 input data files for 2006 → 2006.zip.

14) From http://www.republicanrivercompact.org/2006/html/zip/index.html (Static MODFLOW Files) MODFLOW-2000 input files for annual updates that do not change over time for 2001 to 2006-->static.zip

15) From http://www.republicanrivercompact.org/2006/html/zip/index.html (Fixed Data Files) Republican River Project Preprocessor (RRPP) and MODFLOW-2000 files for annual updates that do not change over time input files for 2001 to 2006-->data0.zip.

16) From http://www.republicanrivercompact.org/2006/html/zip/index.html (Variable Data Files) Raw annual state data files, raw annual evaportranspiration files, raw reservoir elevation files, and raw and precipitation files for 2006 (Note that ppt.dat has data for 1918 to 2006) -->data.zip.

17) From http://www.republicanrivercompact.org/2003/html/v12s/z12s.html (Stream Package Input Files) Contains corrected version of stream package for the period 1918 to 2000, 12s.str→str.zip

B.3 MODFLOW-2000 SOURCE CODE AND EXECUTABLE

Computer simulations were completed using MODFLOW-2000 version 1.xx.01 as downloaded from the RRCA Website→ http://www.republicanrivercompact.org/2006/html/zip/index.html (Source Code). MODFLOW-2000 is a publicly available computer code that simulates groundwater flow. The 'Openspec.inc' file was set such that unformatted output data would be in data form "Unformatted" and data access format as "Transparent:"

```
C
C  Non-standard Fortran that causes code compiled by Lahey or Absoft
C  Fortran on personal computers to use unstructured non-formatted
C  files. This may make it possible for the non-formatted files used
C  by MODFLOW to be used with programs that are compiled by other
C  compilers.
   DATA ACCESS/'TRANSPARENT'/
C
```

```
C FORM specifier --
C
C  Standard Fortran, which results in vender dependent (non-portable)
C  files. Use unless there is a reason to do otherwise.
  DATA FORM/'UNFORMATTED'/
```

The source code was then compiled with Lahey-Fujitsu Fortran Professional Compiler v5.7 in double precision. The executable version of this code was named mf2k_1_10_RRCA_dbl.exe. The make file used to create this version is provided in the External Hard Drive provided with this report.

B.4 RRPP SOURCE CODE AND EXECUTABLE

The Republican River Pre-Processor (RRPP) program is used to construct MODFLOW recharge and well pumping input files from cell-by-cell specification files. The specification files for each state are kept in a separate directory. The RRPP program reads the monthly and annual specification files for all three states, calculates recharge from precipitation and outputs the resulting recharge and well pumping data sets as input to the MODFLOW program.

To facilitate management simulation calculations, a modified version of RRPP (RRPP1_3CBCMI_CPS) was developed. This version has the capability to eliminate or reduce pumping and associated recharge within multiple model sub-regions defined by an array. Municipal and industrial wells within the sub-region are affected by the specified multiplier. In addition, to facilitate the simulation of the scenarios presented in this report, the code was modified to accurately turn off mound recharge and pumping at the same time. To achieve this, the modified code reclassified the groundwater comingled (GWCO) acreage as "non-irrigated" acreage if both the mound and Nebraska pumping are off. In this way, precipitation recharge for non-irrigated lands is specified for GWCO lands when pumping and mound recharge are turned off.

Source code for RRPP1_3CBCMI_CPS is provided the External Hard-Drive provided with this report. The code was compiled with Compaq Visual FORTRAN Version 6.1. The executable version of this code was named RRPP1_3CBCMI_CPS.exe.

B.5 CREATION OF RRPP DATA SET INPUT

RRPP requires pumping and recharge specifications from each state as well as precipitation specifications for stations within the study area. Specification data files for each state were downloaded from the RRCA Compact Website (Downloads 3 to 5 and 8 to 13 described above). Specifications for 1918 to 2006 were collated into state specific directories. Precipitation data specification files ppt.dat and loc.dat were extracted from Website download #16. The ppt.dat file contained all annual precipitation data available from 1918 to 2006. The file, loc.dat, contained precipitation station location data. Additional files required by RRPP were obtained as follows:

File Name	Description	Source
02.ibound	File containing boundary condition identifiers (IBOUND) in MODFLOW-2000 format.	RRCA Website Download #7
soil.12o	File contain array of soil types. One value for each model cell.	RRCA Website Download #7
terrain.flg	File contain array of terrain type. One value for each model cell. [Note the terrain flag file allows terrain multipliers to be calculated in uplands and overridden in areas assigned as alluvial soil types].	RRCA Website Download #7
terrain.12p	File containing terrain multipliers at the centroid of counties.	RRCA Website Download #7
states.flg	File containing array of RRCA designation of state by model cell. One value for each model cell.	RRCA Website Download #7
moundarea.flg	File containing array that identifies which cells are included in the "mound" area. This is used in the current procedure for calculating the "mound credit."	RRCA Website Download #7

Table B.1. Additional files required by RRPP.

To utilize the sub-region management abilities within RRPP1_3CBCMI_CPS, states.flg was modified and saved as Generic.flg. This file contained an array identifying cells by state with Nebraska equal to 100, Colorado equal to 200, and Kansas equal to 300. This array, along with Input.par and InputM.par was used in batch files to create recharge and well packages for 1918 to 2006 with differing fractions of reported pumping for each of the three states. Input.par and InputM.par were modified from 12p.par, the original parameter input file for RRPP contained in RRCA Website Download #7.

B.6 CREATION OF MODEL INPUT DATA SETS

MODFLOW-2000 input data sets for the entire 1918 to 2006 simulation period were required for each stress package; recharge, well, stream, drain, and evapotranspiration. In addition, updates of MODFLOW-2000 output control and time discretization input files were also required. Recharge and well package input files for 1918 to 2006 were generated using RRPP1_3CBCMI_CPS.

A stream package for the entire 1918 to 2006, 12s_1918_2006.str, was created by appending input specifications from the following files:

File Name	Description	Source
12s.str	MODFLOW-2000 stream package file with corrected stream cell locations for the period 1918 to 2000.	RRCA Website Download #17
2001.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2001.	RRCA Website Download #8
2002.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2002.	RRCA Website Download #9
2003.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2003.	RRCA Website Download #10
2004.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2004.	RRCA Website Download #11
2005.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2005.	RRCA Website Download #12
2006.str	MODFLOW-2000 stream package file with corrected stream cell locations for 2006.	RRCA Website Download #13

Table B.2.. Stream package for the entire 1918 to 2006, 12s_1918_2006.str

The MODFLOW-2000 drain package annual.drn obtained from RRCA Website Download #14 was used as the default drain package. This package repeats specifications sufficiently for 1918 to 2006 and beyond.

A MODFLOW-2000 Evapotranspiration package for the entire 1918 to 2006, 12p_1918_2006.evt, was created by appending input specifications from the following files:

File Name	Description	Source
12p.evt	MODFLOW-2000 evapotranspiration package file for the period 1918 to 2000.	RRCA Website Download #2
2001.evt	MODFLOW-2000 evapotranspiration package file for 2001.	RRCA Website Download #8
2002.evt	MODFLOW-2000 evapotranspiration package file for 2002.	RRCA Website Download #9
2003.evt	MODFLOW-2000 evapotranspiration package file for 2003.	RRCA Website Download #10
2004.evt	MODFLOW-2000 evapotranspiration package file for 2004.	RRCA Website Download #11
2005.evt	MODFLOW-2000 evapotranspiration package file for 2005.	RRCA Website Download #12
2006.evt	MODFLOW-2000 evapotranspiration package for 2006.	RRCA Website Download #13

Table B.3. MODFLOW-2000 evapotranspiration package for the entire 1918 to 2006, 12p_1918_2006.evt

The MODFLOW-2000 discretization package, 12p.dis, from RRCA Website Download#1 was modified to include monthly stress period length specifications for the period 1918 to 2006. This file was renamed to 12p_1918_2006.dis. A new MODFLOW-2000 output control file 1980_2006_CBC.oc was created to save budget terms for 1980 to 2006. A separate MODFLOW-2000 output control file 1980_2006_HDS.oc was created to save heads and budget terms for the end of 2003.

The following files were obtained to complete the files necessary for MODFLOW simulations:

File Name	Description	Source
12p.bas	MODFLOW-2000 basic package file. Contains calls to 02.ibound and 12p.shead	RRCA Website Download #1
02.ibound	File containing boundary condition identifiers (IBOUND) in MODFLOW-2000 format.	RRCA Website Download #1
12p.shead	File containing initial estimates of hydraulic head for the 1918 to 2006 simulation.	RRCA Website Download #1
12p.lpf	MODFLOW-2000 layer property flow package file. Contains calls to 12p.k and 12.ss	RRCA Website Download #1
12p.k	File containing hydraulic conductivity values.	RRCA Website Download #2
12.ss	File containing array of storage values assigned in the RRCA model. [Note that these values must be multiplied by aquifer thickness to obtain specific yield values].	RRCA Website Download #1
12.top	File containing array of aquifer top elevations [Called out by the discretization package,12p_1918_2006.dis]	RRCA Website Download #1
12.bot	File containing array of aquifer bottom elevations [Called out by the discretization package,12p_1918_2006.dis]	RRCA Website Download #1
11.etsurf	File containing array of evapotranspiration surface [Called out by the evapotranspiration package, 12p_1918_2006.evt].	RRCA Website Download #2
12s.hyd	MODFLOW-2000 hydmod package file. Identifies stream segments and reaches for which model-calculated base-flow is to be stored in an unformatted file.	RRCA Website Download #14

Table B.4. Files obtained to complete the files necessary for MODFLOW simulations

A MODFLOW-2000 name file Generic.nam was created to incorporate the new input specification files with imported water supply on. A MODFLOW-2000 name file GenericM.nam was created to incorporate the new input specification files with imported water supply off.

B.7 ANALYSIS OF MODEL CALCULATED STREAMFLOW

Simulated base-flows were stored during the simulation using the HYDMOD package of MODFLOW-2000. The HYDMOD package allows the storage of simulated base-flows at specified locations in an unformatted file for later processing. The original MODFLOW-2000 HYDMOD package file, 12s.hyd was modified to include all stream cells. The resulting file name was 12s_All.hyd.

B.8 BATCH PROCESSING OF SIMULATIONS

To facilitate processing of model simulations, a series of DOS batch files and FORTRAN programs were created. These files include:

File Name	Function	Type
SurfaceDriver.bat	Loops through commands in a user specified sequence, e.g., step 1 will process Nebraska at 100 percent, Colorado at 100 percent, and Kansas at 10 percent of observed pumping; step 2 will process Nebraska at 100 percent, Colorado at 100 percent, and Kansas at 20 percent and so on. SurfaceDriver.bat passes information to other DOS Batch files, SurfaceWorker.bat, SurfaceWorkerM.bat and StreamWorker.bat. These batch files specify the exact tasks required for each step.	DOS Batch File
SurfaceWorker.bat	SurfaceWorker.bat specifies the exact tasks required for each step for the imported water supply (Mound) On, including changing file names based on information from SurfaceDriver.bat, executing ParMult, executing RRPP, executing MODFLOW-2000 and deleting temporary files. The name file used by MODFLOW-2000 is Generic.nam	DOS Batch File
SurfaceWorkerM.bat	SurfaceWorkerM.bat specifies the exact tasks required for each step for the imported water supply (Mound) Off, including changing file names based on information from SurfaceDriver.bat, executing ParMultM, executing RRPP, executing MODFLOW-2000 and deleting scratch files. The name file used by MODFLOW-2000 is GenericM.nam	DOS Batch File
ParMult.exe	Program that preprocesses specific terms in a RRPP par file for the imported water supply (Mound) On, Input.par. The specific terms are passed via command-line variables received from the DOS batch file	FORTRAN program [compiled using Compaq Visual Fortran Version 6.1, see External Hard-Drive provided with this

	SurfaceWorker.bat	report for source code].
ParMultM.exe	Program that preprocess specific terms in a RRPP par file for the imported water supply (Mound) Off, InputM.par. The specific terms are passed via command-line variables received from the DOS batch file SurfaceWorker.bat	FORTRAN program [compiled using Compaq Visual Fortran Version 6.1, see External Hard-Drive provided with this report for source code].

Table B.5. Series of DOS batch files and FORTRAN programs

B.9 SIMULATION NAMING CONVENTION

MODFLOW-2000 and related output files were assigned names based on the following convention. All files were assigned a prefix of "Surface" followed by 3 sets of numbers and no suffix or a suffix of "M." The first number referred to the percent of full pumping in Nebraska (0 to 100), the second number referred to the percent of full pumping in Colorado (0 to 100), the third number referred to the percent of full pumping in Kansas (0 to 100). The absence of the "M" suffix means that the imported water supply is on. The presence of the "M" suffix means that the imported water supply is off.

B.10 POST-PROCESSING OF SIMULATIONS

Simulations results were post-processed in a number of formats. To facilitate post-processing of model simulations, a series of FORTRAN programs were created. Certain data were also futher processed using EXCEL spreadsheets. The FORTRAN programs include:

Program Name	Function	Input	Output
acct_v2_Lahey_dbl	acct_v2_Lahey_dbl is a FORTRAN program used to calculate impacts based on a number of MODFLOW runs. It was compiled using the Lahey compiler in double precision.	Unformatted hydmod output files (.sfi), and a definition file "acct.12s", which specifies how streamflow data are to be processed.	Stream depletion summary files in HTML format
zoncsv3_Lahey_dbl	zoncsv3_Lahey_dbl is a FORTRAN program used to calculate mass balance for specific zones in the model domain. It is based on the USGS Code ZONEBUDGET Version 2.1. It differs from ZONEBUDGET in that it provides output in a record by record comma-separated ASCII format. It was compiled using the Lahey compiler in double precision.	Unformatted cell-by-cell output files (.cbc), and a zone file that specifies which model cells represent which zones.	Mass balance terms for each model time step specified in the MODFLOW-2000 output control file for the zones of interest in comma separated format
Hyd_Extract_dbl	Hyd_Extract_dbl is a FORTRAN program used to extract stream flow from MODFLOW-2000 HYDMOD package output. Output is comma-separated file in ASCII format. It was compiled using the Lahey compiler in double precision.	Unformatted hydmod output files (.sfi), and a definition file (.def) which specifies which stream segments and reaches to process.	Streamflow for each model time step in comma separated format for each stream segment and reach requested.
Head_Process_dbl	Head_Process_dbl is a FORTRAN program used to extract head data from MODFLOW-2000 Headsave output. Output is comma-separated file in ASCII format. It was compiled using the Lahey compiler in double precision.	Unformatted Headsave output files (.hds), and a definition file (.dat) which specifies which model cells to process.	Heads for each model time step specified in the MODFLOW-2000 output control file for the cells of interest in comma separated format

Table B-6. FORTRAN program.

Appendix C

Compact Accounting Comparisons for 2001-2006.

C. 1 COMPUTED WATER SUPPLY

The following tables compare the CWS from the current accounting with the directly computed CWS for 2001-2006 in ac-ft. Current CWS is slightly different from the final adopted accounting due to small differences in the groundwater model output presented in this report, as documented herein.

	Gage + $CBCU_S$	Current Accounting $CBCU_G$ - IWS	Current Accounting CWS	Directly Computed $CBCU_G$ - IWS	Directly Computed CWS	Difference
Arikaree	551	1,758	2,309	1,900	2,451	142
Beaver	852	6,633	7,485	9,502	10,354	2,869
Buffalo	3,314	3,344	6,658	3,496	6,810	152
Driftwood	509	1,221	1,730	1,221	1,730	0
Frenchman	34,838	82,826	117,664	87,146	121,984	4,320
North Fork	27,572	15,227	42,799	15,235	42,807	8
Medicine	34,739	8,289	43,028	7,898	42,637	-391
Prairie Dog	15,704	3,406	19,110	3,402	19,106	-4
Red Willow	19,700	7,737	27,437	7,714	27,414	-23
Rock	5,668	3,262	8,930	3,284	8,952	22
Sappa	6,817	-66	6,751	2,180	8,997	2,246
South Fork	8,105	19,021	27,126	21,017	29,122	1,996
Main Stem	171,252	67,300	238,552	61,972	233,224	-5,328

Table C.1. Computed Water Supply for 2001 (ac-ft/yr)

		Current Accounting		Directly Computed		
	Gage + $CBCU_S$	$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	CWS	Difference
Arikaree	224	836	1,060	910	1,134	74
Beaver	344	3,530	3,874	7,587	7,931	4,057
Buffalo	2,440	3,468	5,908	3,594	6,034	126
Driftwood	848	1,272	2,120	1,272	2,120	0
Frenchman	19,128	78,857	97,985	83,200	102,328	4,343
North Fork	24,708	15,517	40,225	15,503	40,211	-14
Medicine	29,710	10,303	40,013	9,201	38,911	-1,102
Prairie Dog	11,114	2,804	13,918	2,805	13,919	1
Red Willow	15,373	6,914	22,287	6,890	22,263	-24
Rock	6,320	3,350	9,670	3,371	9,691	21
Sappa	2,736	273	3,009	1,287	4,023	1,014
South Fork	9,641	16,944	26,585	17,099	26,740	155
Main Stem	123,228	49,945	173,173	42,130	165,358	-7,815

Table C.2. Computed Water Supply for 2002 (ac-ft/yr)

		Current Accounting		Directly Computed		
	Gage + $CBCU_S$	$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	CWS	Difference
Arikaree	1,060	853	1,913	1,012	2,072	159
Beaver	239	1,050	1,289	6,445	6,684	5,395
Buffalo	2,497	3,600	6,097	3,683	6,180	83
Driftwood	1,099	1,391	2,490	1,391	2,490	0
Frenchman	20,236	85,643	105,879	90,671	110,907	5,028
North Fork	25,288	15,445	40,733	15,426	40,714	-19
Medicine	23,834	10,782	34,616	10,304	34,138	-478
Prairie Dog	6,011	1,678	7,689	1,679	7,690	1
Red Willow	6,605	7,793	14,398	7,753	14,358	-40
Rock	4,712	3,477	8,189	3,500	8,212	23
Sappa	-36	177	141	472	436	295
South Fork	4,917	18,783	23,700	20,046	24,963	1,263
Main Stem	91,803	76,776	168,579	57,840	149,643	-18,936

Table C.3. Computed Water Supply for 2003 (ac-ft/yr)

	Gage + $CBCU_S$	Current Accounting		Directly Computed		Difference
		$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	CWS	
Arikaree	380	899	1,279	861	1,241	-38
Beaver	337	1,454	1,791	7,375	7,712	5,921
Buffalo	2,547	3,621	6,168	3,717	6,264	96
Driftwood	1,231	1,479	2,710	1,479	2,710	0
Frenchman	25,954	89,745	115,699	94,980	120,934	5,235
North Fork	26,525	15,834	42,359	15,832	42,357	-2
Medicine	25,786	11,069	36,855	10,548	36,334	-521
Prairie Dog	2,926	1,823	4,749	1,823	4,749	0
Red Willow	5,854	8,193	14,047	8,159	14,013	-34
Rock	5,491	3,638	9,129	3,669	9,160	31
Sappa	239	286	525	558	797	272
South Fork	4,223	19,840	24,063	20,476	24,699	636
Main Stem	25,539	78,817	104,356	61,364	86,903	-17,453

Table C.4. Computed Water Supply for 2004 (ac-ft/yr)

	Gage + $CBCU_S$	Current Accounting		Directly Computed		Difference
		$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	CWS	
Arikaree	1,187	1,127	2,314	1,158	2,345	31
Beaver	357	4,221	4,578	8,855	9,212	4,634
Buffalo	2,387	3,660	6,047	3,810	6,197	150
Driftwood	1,919	1,481	3,400	1,481	3,400	0
Frenchman	28,189	82,757	110,946	88,147	116,336	5,390
North Fork	28,981	15,818	44,799	15,815	44,796	-3
Medicine	23,257	10,556	33,813	10,031	33,288	-525
Prairie Dog	5,845	5,773	11,618	5,774	11,619	1
Red Willow	6,290	8,269	14,559	8,241	14,531	-28
Rock	5,555	3,805	9,360	3,839	9,394	34
Sappa	450	-837	-387	1,866	2,316	2,703
South Fork	3,999	23,539	27,538	23,374	27,373	-165
Main Stem	10,884	80,046	90,930	64,686	75,570	-15,360

Table C.5. Computed Water Supply for 2005 (ac-ft/yr)

	Gage + $CBCU_S$	Current Accounting		Directly Computed		Difference
		$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	CWS	
Arikaree	455	1,281	1,736	1,332	1,787	51
Beaver	565	6,558	7,123	9,561	10,126	3,003
Buffalo	1,836	3,652	5,488	3,804	5,640	152
Driftwood	1,718	1,422	3,140	1,422	3,140	0
Frenchman	23,993	78,326	102,319	83,875	107,868	5,549
North Fork	25,171	15,679	40,850	15,671	40,842	-8
Medicine	26,048	10,004	36,052	9,299	35,347	-705
Prairie Dog	2,570	5,509	8,079	5,511	8,081	2
Red Willow	12,629	7,720	20,349	7,684	20,313	-36
Rock	5,431	3,908	9,339	3,947	9,378	39
Sappa	222	-800	-578	2,784	3,006	3,584
South Fork	3,356	17,186	20,542	17,230	20,586	44
Main Stem	10,771	71,130	81,901	56,571	67,342	-14,559

Table C.6. Computed Water Supply for 2006 (ac-ft/yr)

C.2 COMPACT ALLOCATIONS FROM CURRENT METHOD

The following tables show the Compact allocations using the current accounting procedures. Note that these allocations do not match the official Compact allocations due to small differences in the groundwater model output presented in this report, as documented herein.

	CO	KS	NE	Unallocated
Arikaree	1,813	118	388	-9
Beaver	1,497	2,904	3,039	45
Buffalo	0	0	2,197	4,461
Driftwood	0	119	284	1,327
Frenchman	0	0	63,068	54,596
North Fork	9,587	0	10,529	22,683
Medicine	0	0	3,916	39,112
Prairie Dog	0	8,733	1,452	8,924
Red Willow	0	0	5,268	22,169
Rock	0	0	3,572	5,358
Sappa	0	2,775	2,775	1,202
South Fork	12,044	10,905	380	3,798
Main Stem	0	205,534	196,685	N/A
Total	24,940	231,087	293,551	

Table C.7. Compact Allocations from current accounting methods for 2001 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	832	54	178	-4
Beaver	775	1,503	1,573	23
Buffalo	0	0	1,950	3,958
Driftwood	0	146	348	1,626
Frenchman	0	0	52,520	45,465
North Fork	9,010	0	9,895	21,319
Medicine	0	0	3,641	36,372
Prairie Dog	0	6,361	1,058	6,500
Red Willow	0	0	4,279	18,008
Rock	0	0	3,868	5,802
Sappa	0	1,237	1,237	536
South Fork	11,804	10,687	372	3,722
Main Stem	0	161,731	154,768	N/A
Total	22,421	181,719	235,687	

Table C.8. Compact Allocations from current accounting methods for 2002 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,502	98	321	-8
Beaver	258	500	523	8
Buffalo	0	0	2,012	4,085
Driftwood	0	172	408	1,910
Frenchman	0	0	56,751	49,128
North Fork	9,124	0	10,020	21,588
Medicine	0	0	3,150	31,466
Prairie Dog	0	3,514	584	3,591
Red Willow	0	0	2,764	11,634
Rock	0	0	3,276	4,913
Sappa	0	58	58	25
South Fork	10,523	9,527	332	3,318
Main Stem	0	153,421	146,816	N/A
Total	21,406	167,290	227,017	

Table C.9. Compact Allocations from current accounting methods for 2003 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,004	65	215	-5
Beaver	358	695	727	11
Buffalo	0	0	2,035	4,133
Driftwood	0	187	444	2,079
Frenchman	0	0	62,015	53,684
North Fork	9,488	0	10,420	22,450
Medicine	0	0	3,354	33,501
Prairie Dog	0	2,170	361	2,218
Red Willow	0	0	2,697	11,350
Rock	0	0	3,652	5,477
Sappa	0	216	216	93
South Fork	10,684	9,673	337	3,369
Main Stem	0	124,028	118,688	N/A
Total	21,535	137,034	205,161	

Table C.10. Compact Allocations from current accounting methods for 2004 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,816	118	389	-9
Beaver	916	1,776	1,859	27
Buffalo	0	0	1,996	4,051
Driftwood	0	235	558	2,608
Frenchman	0	0	59,467	51,479
North Fork	10,035	0	11,021	23,743
Medicine	0	0	3,077	30,736
Prairie Dog	0	5,309	883	5,426
Red Willow	0	0	2,795	11,764
Rock	0	0	3,744	5,616
Sappa	0	-159	-159	-69
South Fork	12,227	11,070	386	3,855
Main Stem	0	117,611	112,547	N/A
Total	24,994	135,960	198,561	

Table C.11. Compact Allocations from current accounting methods for 2005 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,363	89	292	-7
Beaver	1,425	2,764	2,892	43
Buffalo	0	0	1,811	3,677
Driftwood	0	217	515	2,408
Frenchman	0	0	54,843	47,476
North Fork	9,150	0	10,049	21,651
Medicine	0	0	3,281	32,771
Prairie Dog	0	3,692	614	3,773
Red Willow	0	0	3,907	16,442
Rock	0	0	3,736	5,603
Sappa	0	-238	-238	-103
South Fork	9,121	8,258	288	2,876
Main Stem	0	111,659	106,852	N/A
Total	21,058	126,441	188,841	

Table C.12. Compact Allocations from current accounting methods for 2006 (ac-ft/yr).

C.3 DIRECTLY COMPUTED COMPACT ALLOCATIONS

The following tables show the Compact allocations calculated from the CWS using the directly computed value for $CBCU_G$-IWS.

	CO	KS	NE	Unallocated
Arikaree	1,924	125	412	-10
Beaver	2,071	4,017	4,204	62
Buffalo	0	0	2,247	4,563
Driftwood	0	119	284	1,327
Frenchman	0	0	65,383	56,601
North Fork	9,589	0	10,531	22,688
Medicine	0	0	3,880	38,757
Prairie Dog	0	8,731	1,452	8,923
Red Willow	0	0	5,263	22,151
Rock	0	0	3,581	5,371
Sappa	0	3,698	3,698	1,601
South Fork	12,930	11,707	408	4,077
Main Stem	0	204,060	195,274	N/A
Total	26,514	232,458	296,617	166,110

Table C.13. Compact Allocations from directly computed $CBCU_G$-IWS for 2001 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	890	58	191	-5
Beaver	1,586	3,077	3,220	48
Buffalo	0	0	1,991	4,043
Driftwood	0	146	348	1,626
Frenchman	0	0	54,848	47,480
North Fork	9,007	0	9,892	21,312
Medicine	0	0	3,541	35,370
Prairie Dog	0	6,361	1,058	6,500
Red Willow	0	0	4,274	17,989
Rock	0	0	3,876	5,815
Sappa	0	1,653	1,653	716
South Fork	11,873	10,749	374	3,744
Main Stem	0	158,407	151,588	N/A
Total	23,356	180,453	236,854	144,637

Table C.14. Compact Allocations from directly computed $CBCU_G$-IWS for 2002 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,627	106	348	-8
Beaver	1,337	2,593	2,714	40
Buffalo	0	0	2,039	4,141
Driftwood	0	172	408	1,910
Frenchman	0	0	59,446	51,461
North Fork	9,120	0	10,016	21,578
Medicine	0	0	3,107	31,031
Prairie Dog	0	3,514	584	3,591
Red Willow	0	0	2,757	11,601
Rock	0	0	3,285	4,927
Sappa	0	179	179	78
South Fork	11,084	10,035	349	3,495
Main Stem	0	144,862	138,626	N/A
Total	23,167	161,462	223,858	133,845

Table C.15. Compact Allocations from directly computed $CBCU_G$-IWS for 2003 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	974	63	208	-5
Beaver	1,542	2,992	3,131	46
Buffalo	0	0	2,067	4,197
Driftwood	0	187	444	2,079
Frenchman	0	0	64,821	56,113
North Fork	9,488	0	10,420	22,449
Medicine	0	0	3,306	33,028
Prairie Dog	0	2,170	361	2,218
Red Willow	0	0	2,690	11,323
Rock	0	0	3,664	5,496
Sappa	0	328	328	142
South Fork	10,966	9,929	346	3,458
Main Stem	0	116,225	111,221	N/A
Total	22,971	131,894	203,008	140,543

Table C.16. Compact Allocations from directly computed $CBCU_G$-IWS for 2004 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,841	120	394	-9
Beaver	1,842	3,574	3,740	55
Buffalo	0	0	2,045	4,152
Driftwood	0	235	558	2,608
Frenchman	0	0	62,356	53,980
North Fork	10,034	0	11,020	23,742
Medicine	0	0	3,029	30,259
Prairie Dog	0	5,310	883	5,426
Red Willow	0	0	2,790	11,741
Rock	0	0	3,758	5,636
Sappa	0	952	952	412
South Fork	12,154	11,004	383	3,832
Main Stem	0	111,094	106,311	N/A
Total	25,871	132,288	198,218	141,834

Table C.17. Compact Allocations from directly computed $CBCU_G$-IWS for 2005 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,403	91	300	-7
Beaver	2,025	3,929	4,111	61
Buffalo	0	0	1,861	3,779
Driftwood	0	217	515	2,408
Frenchman	0	0	57,817	50,051
North Fork	9,149	0	10,047	21,646
Medicine	0	0	3,217	32,130
Prairie Dog	0	3,693	614	3,774
Red Willow	0	0	3,900	16,413
Rock	0	0	3,751	5,627
Sappa	0	1,235	1,235	535
South Fork	9,140	8,276	288	2,882
Main Stem	0	105,593	101,047	N/A
Total	21,717	123,034	188,705	139,299

Table C.18. Compact Allocations from directly computed $CBCU_G$-IWS for 2006 (ac-ft/yr).

C.4 RESULTS OF PROPOSED METHODOLOGY

The following tables show the groundwater impacts by Sub-basin for the proposed accounting methodology (Section 3). The sum of individual impacts is compared with the total impacts (as calculated by comparing the all on and all off conditions), and the remaining residual is computed.

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	1,149	371	383	0	1,903	1,900	-3
Beaver	-1	5,082	4,423	1	9,503	9,502	-1
Buffalo	326	1	3,170	0	3,496	3,496	0
Driftwood	0	0	1,221	0	1,221	1,221	0
Frenchman	2,735	-1	84,430	25	87,139	87,146	7
North Fork	13,653	28	1,551	-1	15,233	15,235	2
Medicine	-1	-2	17,400	9,500	7,896	7,898	2
Prairie Dog	-1	3,405	-1	1	3,403	3,402	-1
Red Willow	-1	-1	7,755	41	7,713	7,714	1
Rock	57	0	3,227	0	3,284	3,284	0
Sappa	0	180	2,005	10	2,174	2,180	6
South Fork	11,624	8,321	1,135	-1	21,080	21,017	-63
Main Stem	-2,758	281	77,656	13,337	61,842	61,972	130

Table C.19. Results of proposed accounting for 2001 (ac-ft/yr).

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	278	255	372	0	905	910	5
Beaver	-1	3,768	3,820	0	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	2,796	-6	80,430	24	83,196	83,200	4
North Fork	13,685	22	1,796	0	15,503	15,503	0
Medicine	-3	-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	6,890	1
Rock	63	0	3,307	0	3,371	3,371	0
Sappa	0	84	1,205	6	1,284	1,287	3
South Fork	10,832	4,824	1,473	-1	17,131	17,099	-32
Main Stem	-4,442	492	57,113	11,196	41,966	42,130	164

Table C.20. Results of proposed accounting for 2002 (ac-ft/yr).

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	163	288	572	0	1,023	1,012	-11
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	2,566	-8	88,143	26	90,676	90,671	-5
North Fork	14,149	28	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	7,794	39	7,753	7,753	0
Rock	69	0	3,430	0	3,500	3,500	0
Sappa	0	-173	648	2	473	472	-1
South Fork	12,579	5,881	1,716	-1	20,178	20,046	-132
Main Stem	-612	458	67,078	9,050	57,874	57,840	-34

Table C.21. Results of proposed accounting for 2003 (ac-ft/yr).

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	167	291	405	0	863	861	-2
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	2,686	-7	92,330	28	94,980	94,980	0
North Fork	14,499	33	1,300	0	15,832	15,832	0
Medicine	-3	-2	20,346	9,795	10,547	10,548	1
Prairie Dog	-1	1,823	0	0	1,823	1,823	0
Red Willow	-1	0	8,202	42	8,158	8,159	1
Rock	72	0	3,597	0	3,669	3,669	0
Sappa	0	-133	694	2	558	558	0
South Fork	13,195	5,992	1,330	-1	20,519	20,476	-43
Main Stem	-1,297	366	71,728	9,463	61,335	61,364	29

Table C.22. Results of proposed accounting for 2004 (ac-ft/yr).

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	657	264	232	0	1,153	1,158	5
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	2,771	-9	85,411	29	88,143	88,147	4
North Fork	14,481	35	1,304	0	15,820	15,815	-5
Medicine	-1	-1	19,941	9,908	10,030	10,031	1
Prairie Dog	-1	5,775	1	0	5,775	5,774	-1
Red Willow	0	0	8,290	48	8,241	8,241	0
Rock	77	0	3,762	0	3,839	3,839	0
Sappa	0	-196	2,065	13	1,856	1,866	10
South Fork	14,974	7,086	1,278	-4	23,342	23,374	32
Main Stem	-1,644	370	76,235	10,268	64,693	64,686	-7

Table C.23. Results of proposed accounting for 2005 (ac-ft/yr).

	CO	KS	NE	MD	Sum	Total	Residual
Arikaree	1,047	164	120	-1	1,332	1,332	0
Beaver	-1	4,629	4,933	0	9,562	9,561	-1
Buffalo	399	0	3,405	0	3,804	3,804	0
Driftwood	0	0	1,422	0	1,422	1,422	0
Frenchman	2,843	-1	81,065	32	83,876	83,875	-1
North Fork	14,424	17	1,230	0	15,671	15,671	0
Medicine	-1	-1	19,060	9,760	9,299	9,299	0
Prairie Dog	0	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	-71	2,858	40	2,746	2,784	38
South Fork	11,843	4,353	1,024	1	17,219	17,230	11
Main Stem	-2,471	11	69,643	10,888	56,294	56,571	277

Table C.24. Results of proposed accounting for 2006 (ac-ft/yr).

C.5 COMPACT ALLOCATIONS FROM PROPOSED METHOD

The following tables detail the Compact allocation calculated using the values for $CBCU_G$-IWS computed for each state using the proposed methodology.

	CO	KS	NE	Unallocated
Arikaree	1,926	125	412	-10
Beaver	2,071	4,018	4,204	62
Buffalo	0	0	2,247	4,563
Driftwood	0	119	284	1,327
Frenchman	0	0	65,380	56,597
North Fork	9,588	0	10,530	22,687
Medicine	0	0	3,880	38,755
Prairie Dog	0	8,732	1,452	8,923
Red Willow	0	0	5,263	22,149
Rock	0	0	3,581	5,371
Sappa	0	3,695	3,695	1,600
South Fork	12,958	11,732	409	4,086
Main Stem	0	203,994	195,212	N/A
Total	26,544	232,416	296,549	166,112

Table C.25. Compact allocations from proposed methodology for 2001 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	886	58	190	-5
Beaver	1,586	3,077	3,220	48
Buffalo	0	0	1,991	4,043
Driftwood	0	146	348	1,626
Frenchman	0	0	54,846	47,478
North Fork	9,007	0	9,892	21,312
Medicine	0	0	3,541	35,370
Prairie Dog	0	6,361	1,058	6,500
Red Willow	0	0	4,274	17,988
Rock	0	0	3,876	5,814
Sappa	0	1,652	1,652	715
South Fork	11,887	10,762	375	3,748
Main Stem	0	158,324	151,508	N/A
Total	23,366	180,381	236,771	144,638

Table C.26. Compact allocations from proposed methodology for 2002 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,635	106	350	-8
Beaver	1,337	2,593	2,714	40
Buffalo	0	0	2,040	4,141
Driftwood	0	172	408	1,910
Frenchman	0	0	59,449	51,463
North Fork	9,120	0	10,016	21,578
Medicine	0	0	3,107	31,032
Prairie Dog	0	3,515	584	3,591
Red Willow	0	0	2,757	11,601
Rock	0	0	3,285	4,927
Sappa	0	180	180	78
South Fork	11,142	10,088	351	3,513
Main Stem	0	144,891	138,653	N/A
Total	23,234	161,545	223,892	133,867

Table C.27. Compact allocations from proposed methodology for 2003 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	976	63	209	-5
Beaver	1,542	2,992	3,131	46
Buffalo	0	0	2,067	4,197
Driftwood	0	187	444	2,079
Frenchman	0	0	64,821	56,113
North Fork	9,488	0	10,420	22,449
Medicine	0	0	3,306	33,026
Prairie Dog	0	2,170	361	2,218
Red Willow	0	0	2,690	11,322
Rock	0	0	3,664	5,496
Sappa	0	328	328	142
South Fork	10,985	9,946	346	3,464
Main Stem	0	116,212	111,209	N/A
Total	22,992	131,898	202,996	140,547

Table C.28. Compact allocations from proposed methodology for 2004 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,837	119	393	-9
Beaver	1,842	3,574	3,740	55
Buffalo	0	0	2,045	4,152
Driftwood	0	235	558	2,608
Frenchman	0	0	62,354	53,978
North Fork	10,035	0	11,021	23,745
Medicine	0	0	3,029	30,258
Prairie Dog	0	5,311	883	5,427
Red Willow	0	0	2,790	11,741
Rock	0	0	3,758	5,637
Sappa	0	948	948	410
South Fork	12,139	10,991	383	3,828
Main Stem	0	111,094	106,311	N/A
Total	25,854	132,272	198,213	141,829

Table C.29. Compact allocations from proposed methodology for 2005 (ac-ft/yr).

	CO	KS	NE	Unallocated
Arikaree	1,403	91	300	-7
Beaver	2,025	3,929	4,111	61
Buffalo	0	0	1,861	3,779
Driftwood	0	217	515	2,408
Frenchman	0	0	57,818	50,051
North Fork	9,149	0	10,047	21,646
Medicine	0	0	3,217	32,130
Prairie Dog	0	3,693	614	3,774
Red Willow	0	0	3,900	16,413
Rock	0	0	3,751	5,627
Sappa	0	1,220	1,220	528
South Fork	9,135	8,271	288	2,881
Main Stem	0	105,448	100,908	N/A
Total	21,712	122,869	188,551	139,291

Table C.30. Compact allocations from proposed methodology for 2006 (ac-ft/yr).

C.6 COMPARISON OF ACCOUNTING RESULTS

The following tables provide a comparison of the current accounting results with the corrected accounting results for 2001-2006. The CBCU – IWS term includes both the $CBCU_G$ and $CBCU_S$.

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	24,940	30,182	-5,242	26,544	34,550	-8,006
Kansas	231,087	54,968	176,119	232,416	58,497	173,919
Nebraska	293,551	262,857	30,694	296,549	260,890	35,659

Table C.31. Accounting results for 2001 (ac-ft/yr).

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	22,421	30,683	-8,262	23,366	34,708	-11,342
Kansas	181,719	69,923	111,796	180,381	72,071	108,310
Nebraska	235,687	249,895	-14,208	236,771	244,413	-7,642

Table C.32. Accounting results for 2002 (ac-ft/yr).

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	21,406	33,538	-12,132	23,234	35,818	-12,584
Kansas	167,290	49,264	118,026	161,545	52,828	108,716
Nebraska	227,017	251,511	-24,494	223,892	238,625	-14,732

Table C.33. Accounting results for 2003 (ac-ft/yr).

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	21,535	33,700	-12,165	22,992	36,610	-13,619
Kansas	137,034	38,345	98,689	131,898	41,581	90,317
Nebraska	205,161	241,124	-35,963	202,996	229,134	-26,138

Table C.34. Accounting results for 2004 (ac-ft/yr).

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	24,994	35,488	-10,494	25,854	38,579	-12,725
Kansas	135,960	44,546	91,414	132,272	48,116	84,156
Nebraska	198,561	239,716	-41,155	198,213	229,879	-31,666

Table C.35. Accounting results for 2005 (ac-ft/yr).

	Current Accounting Method			Proposed Accounting Method		
	State Allocation	CBCU – IWS	Balance	State Allocation	CBCU – IWS	Balance
Colorado	21,058	30,831	-9,773	21,712	34,333	-12,621
Kansas	126,441	54,961	71,480	122,869	58,015	64,854
Nebraska	188,841	219,954	-31,113	188,551	210,189	-21,638

Table C.36. Accounting results for 2006 (ac-ft/yr).

Donna Ormerod

From: Barfield, David [DBARFIELD@KDA.STATE.KS.US]

Sent: Wednesday, August 06, 2008 1:03 PM

To: Billinger, Mark; Dale Book; Barfield, David; david.pope@mo-rast.org; George Austin; Graves, Paul; JOHN CASSIDY (john.cassidy@ksag.org); John B. Draper; Lee Rolfs; Perkins, Sam; Ross, Scott; Steve Larson

Subject: FW: Paper from Nebraska

Attached is the promised paper.

Please take a quick look and let's discuss our plan for responding on Friday.

David

From: jschneider@dnr.ne.gov [mailto:jschneider@dnr.ne.gov]
Sent: Wednesday, August 06, 2008 1:57 PM
To: Barfield, David; Dick.Wolfe@state.co.us
Cc: Dunnigan, Brian
Subject: Paper from Nebraska

Attached is a letter and document I am sending on behalf of Brian Dunnigan.

James C. Schneider, Ph.D.
Senior Groundwater Modeler
Head - Research and Technical Studies Division
Nebraska Department of Natural Resources
301 Centennial Mall South
4th Floor State Office Building
Lincoln, NE 68509-4676
(402) 471-3141 (office)
(402) 471-2900 (fax)
jschneider@dnr.ne.gov

STATE OF NEBRASKA

Dave Heineman
Governor

DEPARTMENT OF NATURAL RESOURCES
Brian P. Dunnigan, P.E. [redacted]
Acting Director

IN REPLY TO:

August 6, 2008

Mr. Dick Wolfe, P.E.
Colorado Commission, Republican River Compact Administration
Director, State Engineer
Office of the State Engineer
1313 Sherman Street, Suite 818
Denver, CO 80203

Mr. David Barfield, P.E.
Kansas Commissioner, Republican River Compact Administration
Kansas Chief Engineer\Kansas Department of Agriculture
109 SW 9th Street
Topeka, KS 66612

Subject: **Analysis of Current Methods Used to Calculate Groundwater Impacts for the Republican River Compact**

Dear Commissioners Barfield and Wolfe:

The attached document is a report describing Nebraska's proposed method of calculating impacts to stream flow (including the imported water supply credit) due to the consumption of ground water.

As we have discussed at a number of meetings over the past year, current Republican River accounting procedures incorrectly calculate man-made impacts to stream base-flow in the Basin. The purpose of this document is to demonstrate the manner in which accretions and depletions to stream flow are incorrectly calculated, and to provide the primary physical and mathematical reason behind the errors. The proposed alternative provides a more equitable allocation of water among the states.

If you have any questions that I may answer, please call me at (402) 471 – 2366. I look forward to discussing this issue with you in the future.

Sincerely,

Brian P. Dunnigan

Brian P. Dunnigan, P.E.
Nebraska Commissioner
Acting Director, Nebraska Department of Natural Resources

Attachment

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Dr. David P. Ahlfeld, P.E.

Professor

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Links

Groundwater Management Group
"Remediation of acid mine drainage sites"

Research Interests

- Groundwater flow and contaminant transport
- Adaptation of water resource systems to a changing climate
- Water resources engineering
- Systems analysis, mathematical modeling and numerical methods

Education

Ph.D. Civil Engineering, Princeton University, 1987.
M.A. Civil Engineering, Princeton University, 1985.
B.S. Environmental Resources Engineering, Humboldt State University - Arcata, CA, 1983.

Experience

- *Professor*, Department of Civil and Environmental Engineering, University of Massachusetts, September 2004 to present
- *Director*, Environmental Engineering Program, Department of Civil and Environmental Engineering, University of Massachusetts, June 2000 to July 2004
- *Associate Professor*, Department of Civil and Environmental Engineering, University of Massachusetts, January 1998 to August 2004
- *Associate Professor*, Department of Civil and Environmental Engineering, University of Connecticut, September 1994 to January 1998
- *Assistant Professor*, Department of Civil Engineering, University of Connecticut, January 1988 to August 1994
- *Lecturer*, Department of Civil Engineering and Operations Research, Princeton University, Spring semester 1987 and Spring semester 1988
- *Research Associate*, Department of Civil Engineering and Operations Research, Princeton University, September 1986 to June 1988
- *Research Assistant*, Department of Civil Engineering, Princeton University, Sept. 1983 to Aug. 1986

Recent Papers Published

David Pulido-Velazquez, David Ahlfeld, Joaquin Andreu, Andres Sahuquillo, "Reducing the computational cost of unconfined groundwater flow in conjunctive-use models at basin scale assuming linear behaviour: The

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D. P. Ahlfeld, A. Joaquin, J.E. Tobiason and D. Mas, "Case Study: Impact of Reservoir Stratification on Interflow Travel Time", Journal of Hydraulic Engineering, December 2003, Vol 129, No. 12, pp. 966-975.

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Recent Conference Proceedings

D.P. Ahlfeld and G. Baro-Montes, "Alternative Groundwater Management Algorithms for a Large-Scale Transient Problem", Proc. of the World Environmental and Water Resources Congress, American Society of Civil Engineers, Tampa, FL, May 15-19, 2007.

Ahlfeld, D.P. (2006), Comparison of Climate Model Precipitation Forecasts with North American Observations, in Proceedings of the XVI International Conference on Computational Methods in Water Resources, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006.

P.M. Barlow, D.P. Ahlfeld and G.E. Granato, "A Simulation-Optimization Model for Evaluation of Ground-Water Development Options Constrained by Minimum Streamflow Requirements and Water-Supply Demands", Proc. of MODFLOW and More 2006: Managing Ground Water Systems, May 2006, Golden, Colorado.

D.R. Buttrick, J.E. Tobiason and D.P. Ahlfeld, "Modeling as an Operational Tool for an Unfiltered Surface Water Supply", Proc. Of Amer. Water Works Assoc. ACE, June 2005, San Francisco, CA.

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D.P. Ahlfeld, "Solving Mixed-Binary Optimization Problems for Groundwater Management", Proc. of the World Water and Environmental Resources Congress, American Society of Civil Engineers, Philadelphia, PA, June

23-26, 2003.

Recent Research Contracts Funded

D. Ahlfeld, "Expansion of GWM Capabilities to Include State Variables", US Geological Survey, Office of Groundwater, January 30, 2008-January 30, 2009, $30,000.

D. Reckhow, J. Tobiason, P. Rees, D. Ahlfeld, "Water Quality in Massachusetts Reservoirs: 2006-2008", MA Dept. of Conservation and Recreation, July 1, 2006 – June 30, 2008, $422,464.

D. Ahlfeld, "Integration of the Ground Water Management (GWM) Process into MODFLOW-2005 and Expansion of GWM Capabilities", US Geological Survey, Office of Groundwater, January 30, 2007-January 30, 2008, $15,000.

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D. Ahlfeld, "Groundwater-Surface Water Interface", U.S. Environmental Protection Agency (subcontract through the University of Connecticut), July 1, 2002 - June 30, 2007, $300,000.

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D. Ahlfeld, J. Tobiason, S. Long, P. Rees, D. Reckhow, "Water Quality in Massachusetts Reservoirs: FY 2004", Metropolitan District Commission, July 1, 2003 - June 30, 2004, $153,017.

D. Ahlfeld, J. Tobiason, S. Long, P. Rees, D. Reckhow, "Water Quality in Massachusetts Reservoirs: FY 2004", Metropolitan District Commission, July 1, 2003 - June 30, 2004, $153,017.

S. Long, J. Tobiason, P. Rees, D. Reckhow, D. Ahlfeld, "Water Quality in Massachusetts Reservoirs: 2004-2006", MA Dept. of Conservation and Recreation, July 1, 2004 – June 30, 2006, $464,378.

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