Nebraska Expert Report in Support of Counterclaim and Crossclaim

Nebraska's Proposed Changes to the RRCA Accounting Procedures

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QUALIFICATIONS AND COMPENSATION

I have prepared this expert report on behalf of the State of Nebraska. A true and accurate copy of my curriculum vitae is attached hereto as Appendix A. The opinions contained in this report are made to a reasonable degree of scientific certainty. In preparing this report, I utilized theories and methodologies that are accepted within the scientific community and which have been subject to peer reviewed analysis and publication.

I have prepared this report as a part of my regular duties as an employee of the State of Nebraska and have received no compensation outside of my normal salary and benefits.

James C. Schneider, Ph.D.

EXECUTIVE SUMMARY

The Republican River Compact Administration (RRCA) administers the Republican River Compact (Compact) through the RRCA Accounting Procedures and Reporting Requirements (Current Accounting Procedures). This involves the use of the RRCA Groundwater Model (Model) to estimate the impact of groundwater pumping by Colorado, Kansas, and Nebraska and to estimate the impact of water imported, by Nebraska, from outside the Republican River Basin (Basin). The Republican River Compact specifies how much water each state is allowed to use, and the Model and the Current Accounting Procedures are used to determine whether a State is in compliance with the Compact. When the Current Accounting Procedures do not represent impacts to the water supply correctly, this determination will fail to properly distribute water supplies as required by the Compact. In other words, an accounting failure results in an unintended redistribution of water supply between the states.

Nebraska's implementation of the Final Settlement Stipulations of 2002 (FSS) resulted in the identification of a significant failure with the Current Accounting Procedures. This failure does not allow for the proper quantification of impacts from groundwater pumping and imported water. These conditions become amplified during years when water supplies are low and Compact compliance is most challenging. If left uncorrected, this problem (i.e., the failure of the Current Accounting Procedures) could deprive Nebraska of up to 800,000 acre feet of water over the next 50 years (roughly twice the annual virgin water supply of the Republican River). It is important to note the problem is not inherent in the Model, but arises from the way in which the Model results are used, through application of the Current Accounting Procedures, to determine the impact of each state's groundwater pumping or importation of water on streamflows.

This report 1) identifies the nature of the problem presented, 2) shows how the failure of the Current Accounting Procedures results in redistribution of water supply, 3) explains Nebraska's proposed solution (Nebraska's Proposed Procedures), and 4) concludes with a discussion of the anticipated impact of the problem on Compact accounting in the future unless the problem is corrected.

The Problem

As discussed in Section 3.3.3, the Model and Current Accounting Procedures are used to estimate impacts of four Target Sets, discussed further below, by calculating the change in baseflow caused by 1) groundwater pumping in Nebraska; 2) groundwater pumping in Colorado; 3) groundwater pumping in Kansas; and 4) Nebraska's mound recharge (the mechanism for importation of water from the Platte River, Figure ES-1. The total impact of groundwater pumping and mound recharge (Total Impact) should be determined by completing a Model run with groundwater pumping and mound recharge present (or "On") and a Model run with these activities not present (or "Off"). The difference between these two Model runs (first conceptualized by Kansas and termed the Virgin Water Supply Metric) is the only direct estimate of the Total Impact. This is a widely accepted scientific practice (e.g., Zume and Tarhule, 2008; Feinstein et al., 2010; Leake and Pool, 2010; Bent et al., 2011; Ely et al., 2011). The Total Impacts are not computed in this manner under the Current Accounting Procedures. The individual impact estimates of the four Target Sets can only be verified by comparing their sum to these Total Impacts.

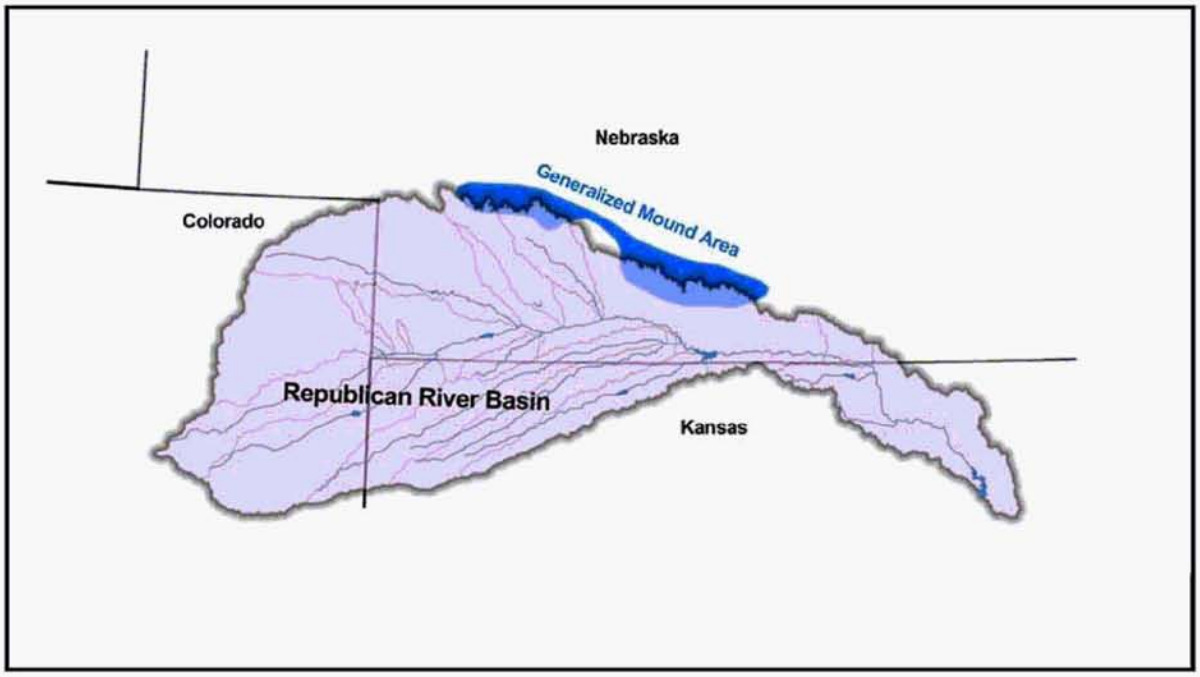

Figure ES-1. The groundwater mound recharge as contribution to the Republican River basin water supply.

The sum of the individual impacts (e.g. Colorado groundwater pumping, Kansas groundwater pumping, etc), as calculated under the Current Accounting Procedures, does not add to the Total Impact and thus fails to meet the Virgin Water Supply Metric. In other words, the sum of the parts does not equal the whole. For the purposes of determining Compact compliance, these "Unaccounted Impacts" are lost in the calculus. It is as if to say that the Current Accounting Procedures would calculate two plus two equals three. This is an unreasonable result that should not exist in any accounting exercise.

The difficulties generated by this problem manifest themselves in multiple ways, but a glaring example is presented in Section 4.4.2. In a hydrologic system, higher groundwater levels increase discharge to streams. This is the practical effect of the mound recharge in the Republican River Basin. Therefore, mound recharge can have only a positive impact to stream baseflow; no negative impact is associated with it. The mound recharge is supplied in Nebraska by water imported from the Platte River. Thus, any positive impact to stream baseflow in the Republican River Basin should accrue as a benefit to Nebraska in the accounting. The Kansas projected future scenario (Kansas Petition, C20) is analyzed as an example for this report, using the Current Accounting Procedures, to determine the positive impact to stream baseflow that should result from the mound recharge over the long term. The Current Accounting Procedures produce the results shown in figure ES-2. These results indicate that continuation of mound recharge will ***reduce*** stream baseflows over the long term. This result makes no sense and demonstrates the absurdity inherent in the Current Accounting Procedures. It is rather difficult from a scientific perspective to reconcile the paradoxical notion that adding imported water to the system, which should be a "credit" to the importer state, results in just the opposite, a "debit".

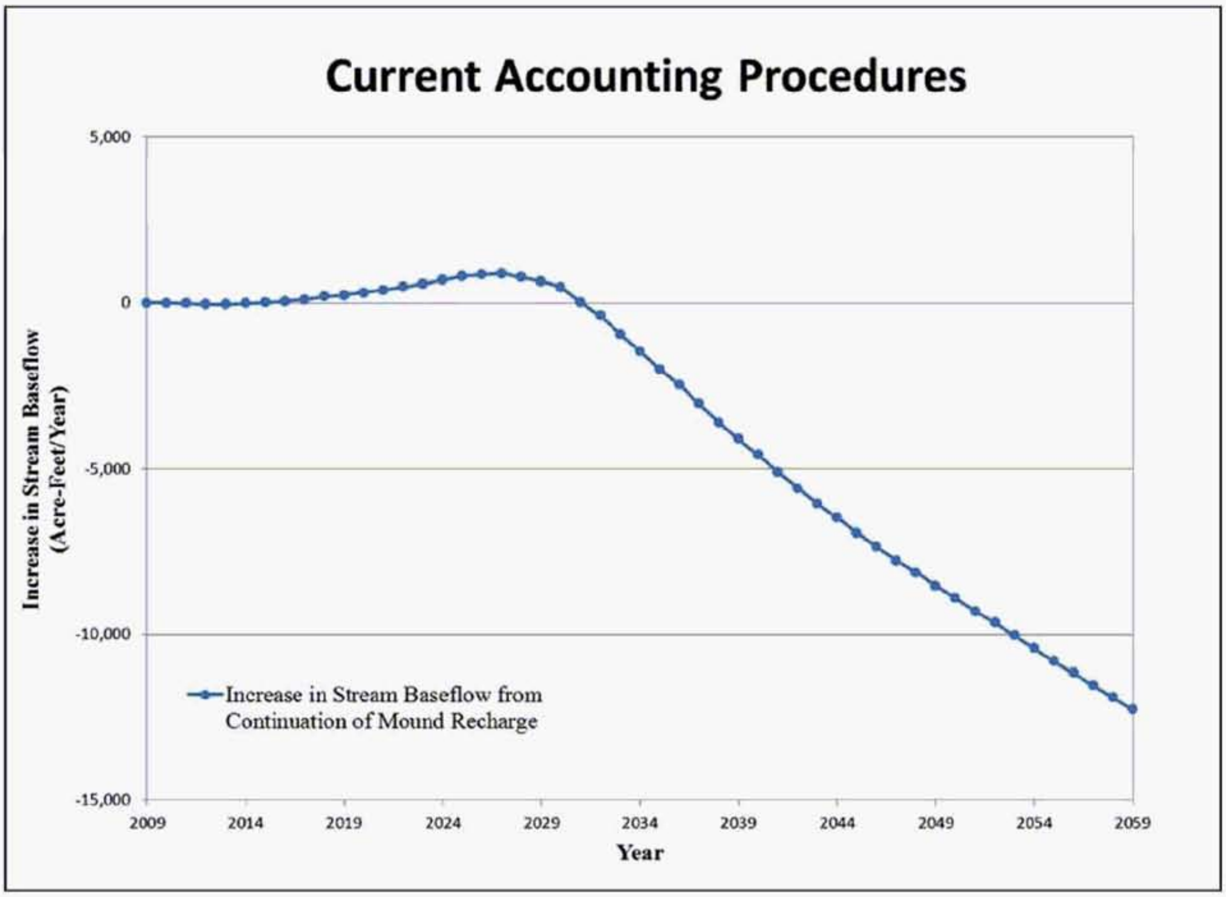

Figure ES-2. The increase in stream baseflow that results from the continuation of mound recharge as determined by the Current Accounting Procedures. These results indicate that continuation of mound recharge will ***reduce*** stream baseflows over the long term.

Section 4 presents an analogy to the Model using a scale and two people whose combined weight exceeds the capacity of the scale. Under the Current Accounting Procedures there are Unaccounted Impacts, and this analogy serves as a simple demonstration of how these Unaccounted Impacts occur. The Current Accounting Procedures do not address these Unaccounted Impacts. These Unaccounted Impacts are eliminated using the existing Model and Nebraska's Proposed Procedures.

Nebraska raised this problem with the RRCA in 2007, but it was not resolved at that time. Nebraska, therefore, presented the problem and Nebraska's Proposed Procedures to an arbitrator in 2009 pursuant to the dispute resolution procedures outlined in the FSS. In acknowledging the problem presented by the Current Accounting Procedures, the arbitrator concluded that Nebraska's approach to estimate the Total Impacts of pumping and mound recharge was more consistent with the Compact and admonished the States to work toward a thorough solution. Kansas and Colorado, however, currently benefit from this failure of the Current Accounting Procedures.

The Solution

To rectify this failure of the Current Accounting Procedures (the problem), Nebraska proposes a solution that complies with the following criteria:

1) The sum of the individually derived impacts equals the Total Impacts.

2) The results obtained from Nebraska's Proposed Procedures are identical to those obtained with the Current Accounting Procedures in the cases in which the latter already satisfy the principle in number (1) above.

3) The Unaccounted Impacts are not distributed among the states arbitrarily, but rather they are applied in a manner related to each state's ability to cause Unaccounted Impacts.

As shown in figure ES-3, Nebraska's Proposed Procedures solve the problem previously illustrated in figure ES-2. The results from the Current Accounting Procedures indicate that continuation of mound recharge will reduce stream baseflows. The results from Nebraska's Proposed Procedures indicate that continuation of mound recharge will increase stream baseflows. Recharging water into the ground cannot by itself ***reduce*** stream baseflow, but it can ***increase*** stream baseflow. Therefore, ***Nebraska's Proposed Procedures produce realistic results, whereas the Current Accounting Procedures do not.***

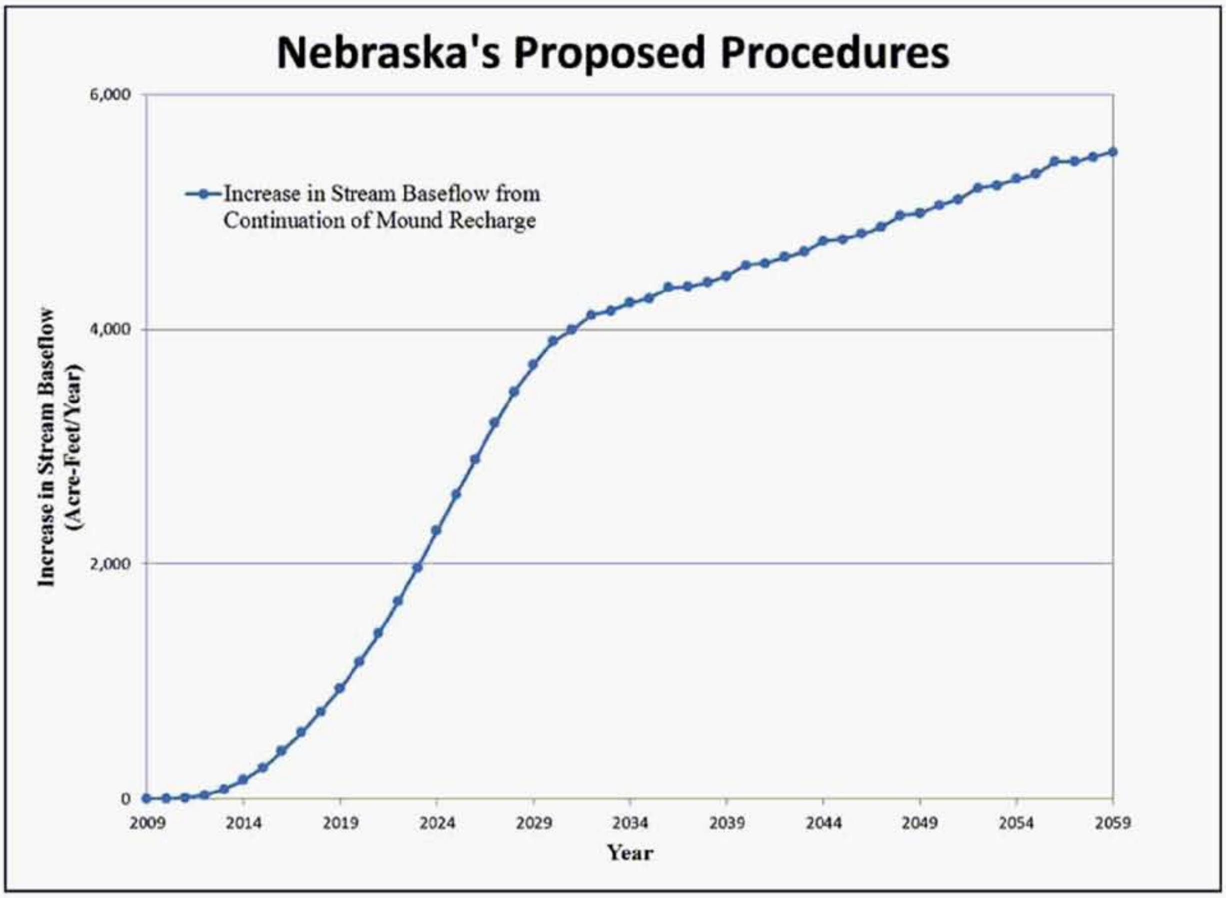

Figure ES-3. The increase in stream baseflow that results from the continuation of mound recharge as determined by Nebraska's Proposed Procedures. These results indicate that continuation of mound recharge will ***increase*** stream baseflows over the long term.

Effect of Problem if Left Unresolved

The Basin wide effect of the failure of the Current Accounting Procedures on Nebraska's annual Compact accounting balances was approximately 10,000 acre-feet per year in 2005 and 2006 (the years subject to the Kansas Complaint). These are example years in which Nebraska's water supply was relatively small. The effect on Nebraska's annual Compact accounting balances may exceed 20,000 acre-feet per year in the future (or approximately 10% of an average Nebraska allocation). The effect, moreover, is cumulative, and unless corrected, will continue to grow into the future depriving Nebraska of a substantial portion of its Compact entitlement (a cumulative total of as much as 800,000 acre-feet over 50 years).

If the problem remains uncorrected, Nebraska will be required to consume less water than it is entitled to under the Compact. This is tantamount to a redistribution of the states' Allocations specified in the Compact.

1.0 INTRODUCTION

In 1943 the United States and the States of Kansas, Nebraska, and Colorado entered into the Republican River Compact (Compact). A primary purpose of the Compact was "to provide for the equitable division" (Compact, 1943) of the streamflow of the Republican River Basin (Basin). Streamflow originates in all three states under the physical processes described in Section 2. The streamflow has been altered by activities of man over time; some of these activities reduce streamflow, some of these activities increase streamflow. In order to provide for the equitable division of water as envisioned in the Compact, a proper quantification of the impacts of man's activities on streamflow is required.

The Republican River Compact Administration (RRCA), a committee with a representative from each of the three states, administers the Compact. The RRCA Accounting Procedures and Reporting Requirements contain procedures for the quantification of streamflows and the impacts to streamflows attributable to man's activities in each state. These are included as Appendix C to the Final Settlement Stipulations (FSS) of 2002; these will be called the Current Accounting Procedures in this report. The Current Accounting Procedures have been changed multiple times since 2003, most recently in 2010.

One of the activities of man that has had a large impact on streamflow in the Basin is the irrigation of crops with water pumped from the ground. Groundwater pumping intercepts water that might otherwise have discharged to the stream; the impact of this practice cannot be directly measured. Another activity of man that has significantly impacted streamflow in the Basin is the importation of water from the Platte River. This process provides additional water in the ground, increasing the amount of groundwater that can eventually discharge to the stream. This impact also cannot be directly measured. Therefore, the RRCA Groundwater Model (Model) was developed to quantify the impact of these activities. The Model and the Current Accounting Procedures are discussed in greater detail in Section 3.

A conventional way to estimate the impact of a set of activities on a system is to look at the behavior of the system with and without those activities occurring. The difference observed in the system is assumed to be a reasonable estimate of the impacts of those activities. The Model can be utilized to test the impact of groundwater pumping and mound recharge on streamflow in the Basin by running the Model first with both of these activities and running the Model again without these activities. This is a generally accepted scientific practice (e.g., Zume and Tarhule, 2008; Feinstein et al., 2010; Leake and Pool, 2010; Bent et al., 2011; Ely et al., 2011). The difference in streamflow values produced by the Model will be termed the Total Impact in this report.

For the Current Accounting Procedures to be valid, the sum of the impacts attributable to the states, as calculated using these procedures, must equal the Total Impacts. Application of the Current Accounting Procedures fails to accomplish this; rather these procedures produce unreasonable results and provide Kansas and Colorado with an unwarranted benefit. This failure is demonstrated in Section 4. This section also contains a discussion of an analogy intended to illustrate the physical and mathematical reasons for the failure of the Current Accounting Procedures.

In the cases in which the Current Accounting Procedures fail to account for the Total Impacts, a refined approach that overcomes these failures is needed. The best approach to this, termed Nebraska's Proposed Procedures, is presented in Section 5. Application of Nebraska's Proposed Procedures produces realistic results that fully account for the Total Impacts. Section 6 demonstrates the magnitude of the failure of the Current Accounting Procedures to accomplish the equitable division of waters.

2.0 PHYSICAL SYSTEM

This section begins with a brief overview of important general hydrologic principles (Chin, 2006; Dingman, 2002; Fetter, 2001; Schwartz and Zhang, 2003). These generally accepted scientific principles are then related to the specific physical conditions of the Republican River Basin. Throughout this report, volumes of water are discussed in units of acre-feet and rates are discussed in units of acre-feet per year. An acre-foot of water is the volume of water that would cover an area of one acre to a depth of one foot. It is equal to 325,851 gallons. By way of comparison, the public water supply required for an average American city of 100,000 people would be approximately 20,000 acre-feet per year[1] (Hutson et al., 2004).

Important physical features of the Republican River Basin are the land surface and stream network that constitute the surface water drainage basin and the underlying geologic materials that constitute the hydrologically connected aquifer. This system is further complicated by various activities of man, who utilizes the water supply and other resources of the Basin. This entire system can be understood in terms of a total water budget for the Basin. The water budget approach is conceptually similar to maintaining a checkbook; money in and out of the account is recorded, thereby tracking the balance of funds in the account.

2.1 Surface Water Hydrology and the Republican River Basin

The following general discussion of surface water hydrology is a distillation of numerous standard references on the subject, including Dingman (2002). A surface water basin such as the Republican River Basin is characterized on the land surface by a network of streams. A section of a stream is known as a stream reach. Those portions of a stream network that do not continually carry water are generally found in the upper reaches of the networks and are known as intermittent streams. The remaining stream reaches that generally carry flowing water throughout the year are the larger, more centralized portion of the stream network and are known as perennial reaches. Generally speaking, streamflow derives from one of two processes, overland runoff and stream baseflow. Overland runoff occurs during large rainfall events when rainfall rates exceed the capacity of the soils to absorb the water, causing the water to run off the land, generally gather in the nearest drainage (stream reach) and flow down that reach of the stream network. Runoff can enter the stream network through both intermittent reaches and perennial reaches. During periods between rainfall events, streamflow is maintained

[1] More specifically, water for the City of Portland, Maine is supplied by the Portland Water District. This District serves 200,000 people delivering approximately 21 million gallons of water per day or about 23,500 acre-feet per year.

in the perennial reaches by stream baseflow from the aquifer, which is discussed further in the next section.

A drainage basin is defined as the land area that drains to a given location in a stream network. The areal extent of a drainage basin is determined by the topography; the line that may be drawn on a map to separate the locations from which water would flow into one drainage basin versus an adjoining drainage basin is known as the basin divide. A well-known basin divide is the Continental Divide, which divides the North American continent into the area that drains to the Pacific Ocean and the area that drain to the Atlantic Ocean. A given drainage basin can be sub-divided into a number of component sub-basins, which can be further sub-divided. Generally, a stream basin will be characterized by a single "main stem" which constitutes the primary stream that drains to the end, or "outlet" of the basin, and tributary streams that flow into this main stem from "sub-basins". For example, the Mississippi River is the main stem of the Mississippi River Basin, with its outlet near New Orleans where it drains into the Gulf of Mexico; the Missouri River, with its own sub-basin, is a tributary of the Mississippi River.

In the Republican River Basin, the Republican River Compact recognizes twelve (12) sub-basins that are accounted for separately from the remaining tributaries and the main stem reaches, all of which are collectively called the Main Stem of the Republican River, or simply "Main Stem" (figure 1). The Main Stem begins at the confluence of the North Fork of the Republican River and the Arikaree River at Haigler, Nebraska. These two sub-basins begin in eastern Colorado. Four other sub-basins originate in eastern Colorado: 1) the South Fork of the Republican River, which flows from Colorado through Kansas to join the Main Stem at Benkelman, Nebraska; 2) Frenchman Creek and 3) Buffalo Creek flow directly from Colorado into Nebraska; and 4) Beaver Creek, which flows from Colorado into Kansas and then into Nebraska where it joins Sappa Creek. Driftwood Creek, Sappa Creek and Prairie Dog Creek all rise in Kansas and flow into Nebraska where they join the Republican River. Rock Creek, Red Willow Creek and Medicine Creek rise in Nebraska. The Lower Republican River, consisting of the main stem and tributaries downstream of Hardy, Nebraska, is not included as part of the Main Stem or Compact accounting.

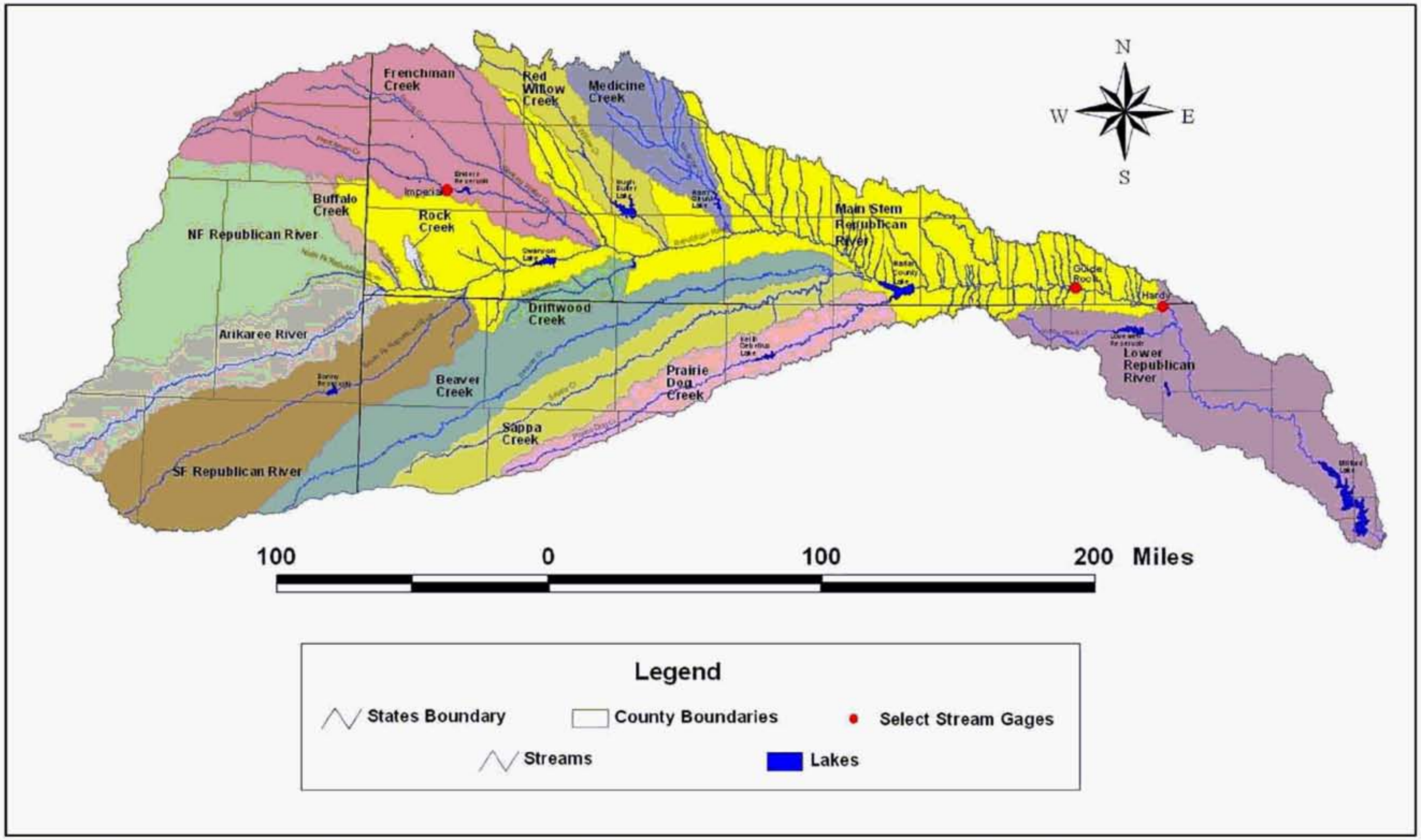

Figure 1. The Republican River Basin, showing the 12 sub-basins and the remaining drainage to the Main Stem

2.2 Groundwater Hydrology and the High Plains Aquifer

The following general discussion of groundwater hydrology is a summary of numerous standard references on the subject, including Fetter (2001) and Schwartz and Zhang (2003). A geologic unit is a volume of the subsurface that contains material with similar properties. A geologic unit (or group of units) that readily transmits water is known as an aquifer. A geologic unit that retards the movement of water through the subsurface is known as an aquitard. An aquifer is generally underlain by an aquitard; this boundary defines the base of the aquifer. Some aquifers are also overlain by an aquitard; these aquifers are known as confined aquifers. Where no aquitard overlies an aquifer it is known as an unconfined aquifer. Within the aquifer, the void space between the geologic material (e.g., the pore space between sand grains) is filled with water and is said to be saturated. The top of an unconfined aquifer is the point at which the pore spaces are no longer saturated. This top boundary is known as the water table.

When an aquifer is unconfined, some of the water that falls on the ground as precipitation (rain or snow) will percolate into the subsurface (figure 2). Some or all of that water will eventually flow downward and reach the water table. Recharge is the process of water reaching the water table and entering the aquifer, and this represents the primary source of water to the aquifer in many cases. A primary pathway for water to be discharged from an aquifer is to a stream; this discharge creates the stream baseflow that contributes to total streamflow. Water levels in an aquifer tend to follow a gradient from recharge areas, where water levels are higher, to discharge areas, where water levels are lower. This difference in water level produces a flow of water away from the recharge areas and toward the discharge areas.

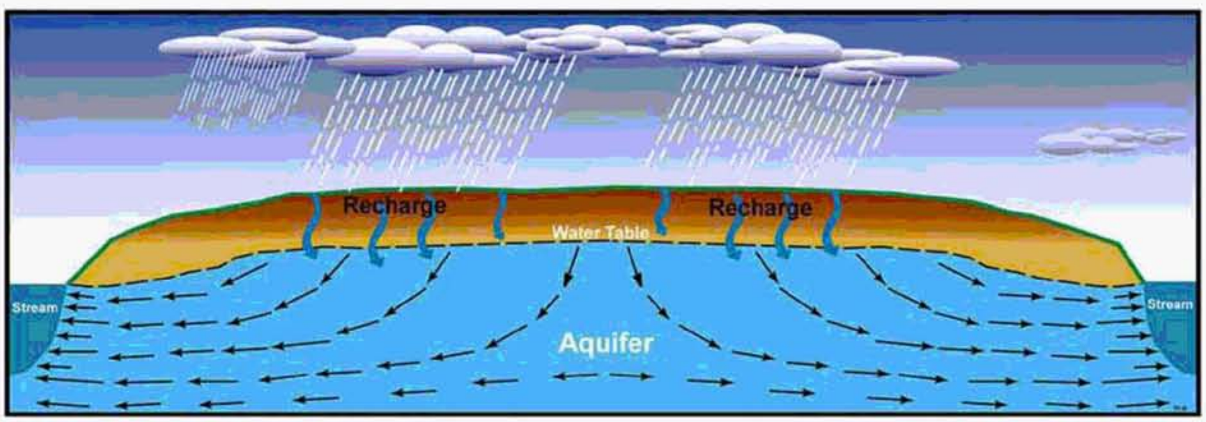

Figure 2. Idealized cross-section showing the movement of water from the atmosphere to the aquifer (recharge), and the subsequent movement of water through the aquifer until it discharges to a stream.

The rate at which groundwater flow occurs depends on the difference in hydraulic head[2] as well as the specific properties of the aquifer. The properties of importance to groundwater flow in the Basin are the thickness of the aquifer and the relative ability of the material to transmit water, known as hydraulic conductivity. A thicker aquifer and/or one with higher hydraulic conductivity (e.g. coarse sand) will transmit water more readily than an aquifer that is thinner and/or has a lower hydraulic conductivity (e.g. silt). Note that the horizontal distance may be quite substantial (many miles) so that the travel time of groundwater through an aquifer can be on the order of many years to decades.

Just as a divide can be delineated for a surface basin (or sub-basins), a groundwater divide defines the boundary between groundwater that flows in one direction and groundwater that flows in other directions. Whereas a surface drainage divide is defined by topography, groundwater divides do not necessarily follow surface water divides. Instead, groundwater divides are influenced by recharge and discharge patterns throughout the aquifer. The implication of this is that groundwater can move across surficial sub-basin divides, and changes in hydrology in one surficial sub-basin (e.g., increasing recharge or discharge in one area relative to another) can cause changes to the aquifer condition (e.g., rate or direction of groundwater flow) in another surficial sub-basin.

The Republican River Basin is underlain by the High Plains Aquifer (Weeks et al., 1988), a vast aquifer underlying the High Plains region of United States from Texas to South Dakota (figure 3). In the Basin, the High Plains Aquifer is made up of a combination of shallow alluvial deposits, which include sands, silts and gravels, and bedrock units. The High Plains Aquifer is an unconfined aquifer, which ranges from being relatively thin at its margins and in the vicinity of streams to being many hundreds of feet thick, and has a generally moderate hydraulic conductivity. The aquifer's characteristics result in a range of groundwater travel times through the aquifer of less than one year from the point of recharge to the point of discharge to times in excess of one hundred years; travel time is also heavily dependent on distance. The aquifer is naturally recharged by precipitation, and water from the aquifer discharges to streams. In some cases water that is discharged to or runs off into a stream may, after flowing downstream, soak from the stream into the aquifer providing recharge in that area. Another mechanism for discharge from the aquifer is directly through plants whose roots have access to the aquifer. These plants, known as phreatophytes, are generally located along stream channels (the riparian zone); this discharge process is known as transpiration. Transpiration and evaporation are sometimes lumped together as an undifferentiated term in hydrologic analyses and referred to as evapotranspiration (ET).

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[2] Hydraulic head is a measure of the energy available in a body of water to drive flow and depends on both the elevation of the water and its pressure.

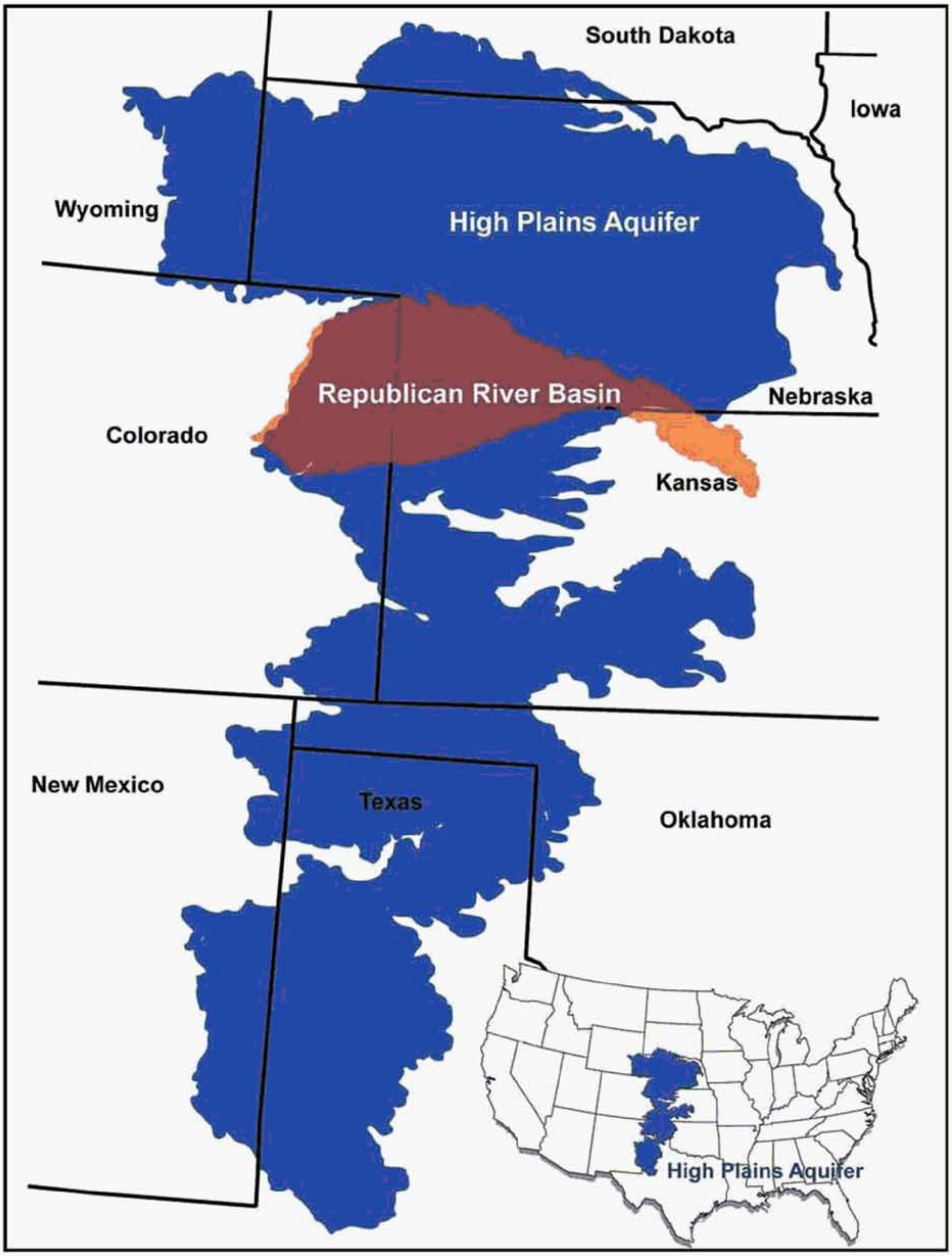

Figure 3. The High Plains Aquifer (Weeks et al., 1988).

2.3 Human Interactions

The natural hydrologic conditions of a surface water basin and/or an associated aquifer can be altered by human activities. In some cases these alterations are dramatic. An obvious example of an activity that significantly affects a stream is the building of a dam to produce a reservoir on the stream. Reservoirs are built for many purposes, including flood control and municipal or irrigation water supply. Seven large reservoirs have been constructed by the United States Bureau of Reclamation in the Republican River Basin. Two primary purposes of these reservoirs are flood control and irrigation. Many other small reservoirs have also been constructed in the Basin for various other purposes. Evaporation from these reservoirs removes water from the Basin.

In general, the advent of irrigated agriculture has caused the most change to the hydrologic system in the Republican River Basin. Beginning well before the large reservoirs were built, water was diverted from the Republican River and its tributaries for distribution on crops. The diversions reduced flow in the streams, increased ET to the atmosphere and increased percolation into the ground from canal seepage and excess irrigation (referred to as return flow). Percolation into the ground increased recharge to the aquifer which, in turn, increased both ET in the riparian zone and baseflow discharge to rivers. The depletion in streamflow caused by the surface water diversion occurs immediately in time. The accretion (or increase) to streamflow caused by return flow, however, is delayed for years, as that additional recharge slowly moves through the aquifer to the stream.

The use of groundwater for irrigation, which first became significant in the Basin in the 1950s, further complicated the hydrologic system. Water pumped from the ground for irrigation intercepted flow that would otherwise have discharged to streams, reduced water available for ET in the riparian zone, and removed water stored in the aquifer causing a drop in the water table. Although much of the water pumped from the ground for irrigation was consumed by the crops being irrigated (i.e., removed from the Basin through ET), some of it percolated back into the ground as excess irrigation water.

Near a well, the water table is depressed as water is removed from the subsurface (figure 4). This depression in the water table causes water in the vicinity of a well to change its pre-pumping flow direction and instead move toward the well. The interception of water that would have otherwise discharged to streams reduces flow in streams. The removal of water stored in the aquifer near a stream can induce flow from the stream to the aquifer. Water removed from aquifer storage far from streams can ultimately reduce flow in the streams but this effect is comparatively less immediate. In addition, because groundwater may flow across surficial basin divides, pumping that occurs in one stream sub-basin may also affect stream baseflow in a different sub-basin.

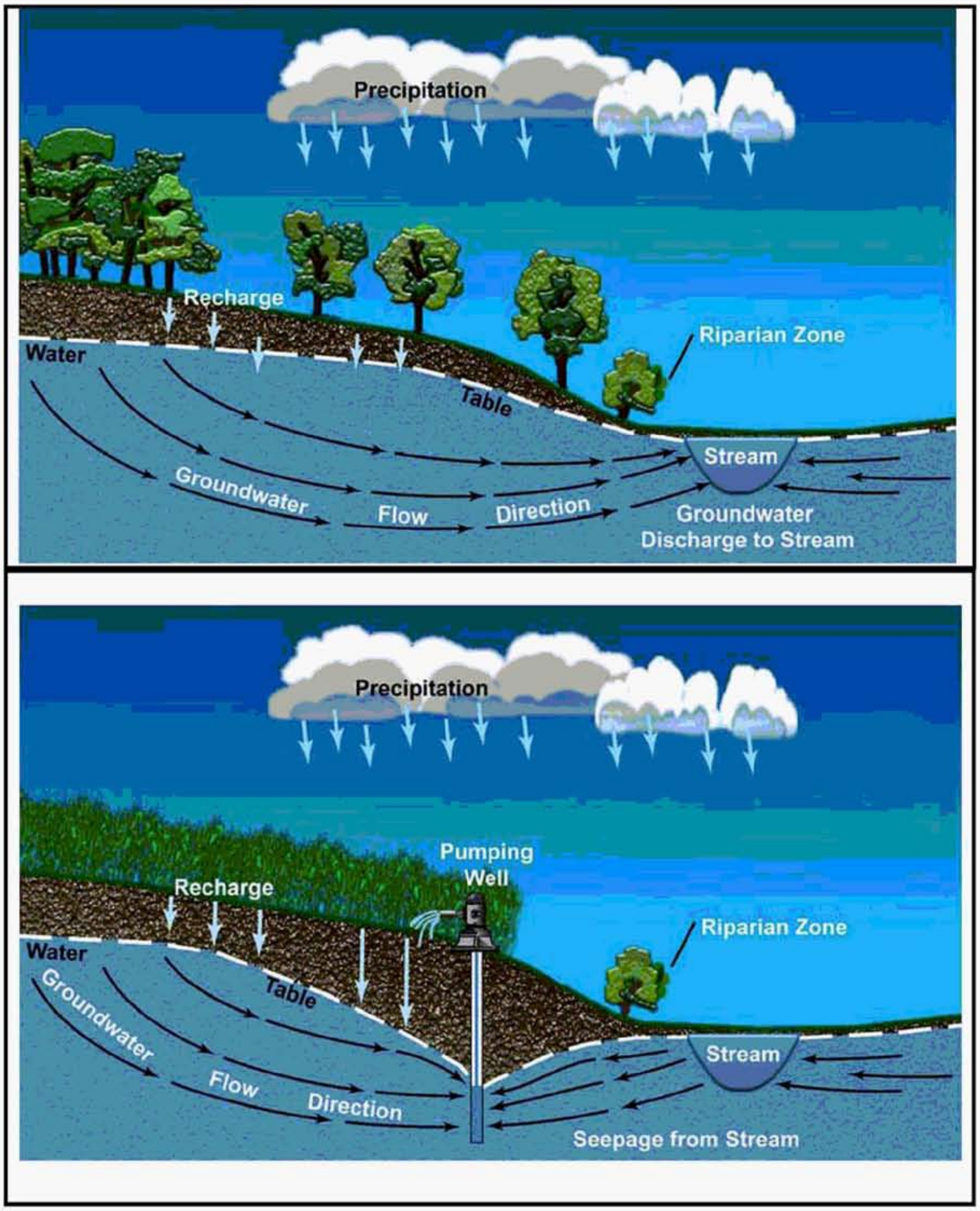

Figure 4. Idealized cross-section showing the effect of a groundwater well on the flow of groundwater through an aquifer, which impacts the discharge to or induces recharge from a nearby stream.

2.4 Water Budget of Basin

These processes involving the stream, the aquifer and the changing recharge and discharge over time in a basin can be analyzed using a water budget approach. Central to this approach is the principle that, over a given period, the difference between total inflows to the basin and total outflows from the basin will equal the change in the amount of water stored in the basin, either in reservoirs or underground.

The water budget for pre-development conditions (i.e., conditions before the addition of human actions on the hydrologic system) in the Basin is relatively simple. Precipitation brought water into the Basin, and streamflow and ET removed water from the Basin. Most of the precipitation that percolated into the ground ultimately discharged to the Republican River or its tributaries as stream baseflow; the remainder was discharged to the atmosphere as ET in the riparian zone. Surface runoff combined with the stream baseflow to produce the total streamflow. The water stored in the aquifer remained relatively constant; increasing somewhat in wet (high precipitation) years and decreasing somewhat in dry (low precipitation) years.

The water budget for post-development conditions is more complicated. In addition to the ongoing processes of recharge from precipitation and discharge through stream baseflow, surface water is diverted from streams, water is withdrawn through groundwater wells and irrigation water not consumed by crops returns to the subsurface. During the post-development period, aquifer storage and streamflow in some portions of the Basin have declined steadily. An additional complication is accounting for surface water diverted from the Platte River, located to the north of the Republican River basin, which is used to produce power and irrigate crops south of the Platte River. A significant portion of this water seeps from canals or percolates from irrigated fields and recharges the groundwater system. The imported Platte River water has caused a groundwater mound to develop, creating a groundwater divide between the Platte and the Republican Rivers (figure 5). Water that percolates south of that divide increases the flow in tributaries to the Republican River, especially Medicine Creek and small tributaries to the east of Medicine Creek. That water will be referred to as "mound recharge" in this report.

Tracking and quantifying the numerous sources of water to the aquifer, the numerous mechanisms for discharge, the change in aquifer storage over time and the streamflow that results from all of these factors is accomplished by the Model. Known sources and discharges of water (e.g., recharge and groundwater pumping, respectively) are input into the Model. The Model then calculates the change in aquifer storage and streamflow as they evolve over time in response to changes in source and discharge magnitudes.

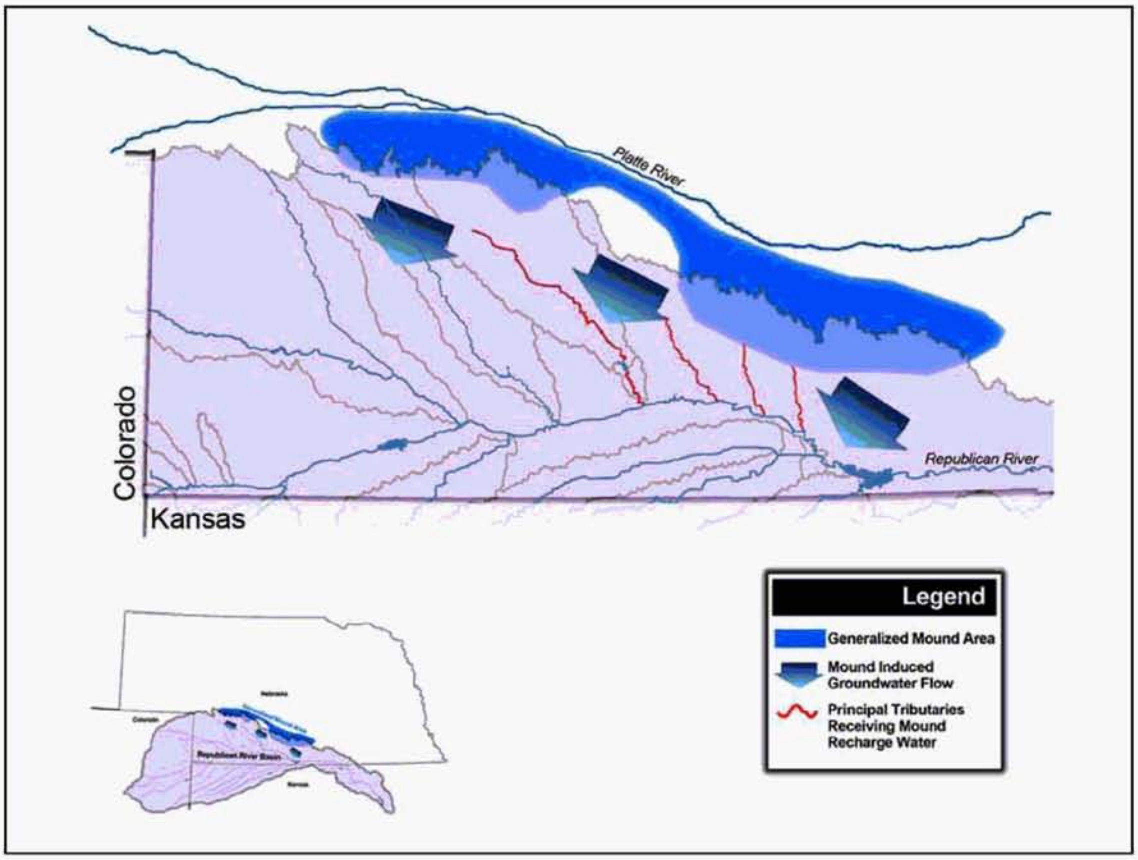

Figure 5. Diversions from the Platte River serve as the source of the mound recharge. This creates groundwater movement as shown, which has contributed to stream baseflow in tributaries of the Republican River.

3.0 RRCA GROUNDWATER MODEL AND CURRENT ACCOUNTING PROCEDURES

This section begins with a discussion of groundwater models in general and the RRCA Groundwater Model specifically. This discussion of groundwater modeling is based on numerous standard references on the subject, including Anderson and Woessner (1992) and Harbaugh et al. (2000). Following the overview of modeling, the Current Accounting Procedures are discussed, both in general terms and in relation to the Model.

The Model and the Current Accounting Procedures were developed to represent the portions of the physical system previously discussed in Section 2. The Compact divides (or allocates) the Virgin Water Supply (VWS) of the Basin, defined as the water supply unaffected by the activities of man. To do so, the impacts of the activities of man on streamflow must be understood. These impact estimates are combined with measured streamflow volumes to determine the VWS[3].

The Model was developed in accordance with the FSS, to be utilized in conjunction with the Current Accounting Procedures. An important objective of the FSS was to account fully for the impact of all groundwater pumping and all mound recharge that has an effect on streamflow in the Basin. The Model is required for this purpose because direct measurement of these impacts is not possible. The Model is the most technically appropriate method for estimating these impacts. The following discussion generally describes the function of a groundwater model, the development of the Model, the function of the Current Accounting Procedures, and the application of the Model within the Current Accounting Procedures.

3.1 Use of Groundwater Models

Many types of hydrologic models are used to simulate and understand different parts of the hydrologic system under differing sets of conditions. The Model is a numerical groundwater model, which is a numerical representation of a groundwater aquifer or aquifers. This type of model is well suited to simulating the conditions within an aquifer and the interactions between an aquifer and stream such as the High Plains Aquifer and the Republican River and its tributaries. Generally speaking, a numerical groundwater model contains specifications for the geometry and properties of the aquifer and any boundary conditions required to represent adequately flow into, through, and out of the model. A boundary condition is a numerical representation of a physical boundary between the aquifer and adjacent underground materials, surface water features, or the atmosphere.

[3] VWS = Measured streamflow + Impacts to streamflow resulting from activities of man

A common boundary condition is a no-flow boundary, so named because water is not allowed to flow across that boundary in the model. This type of boundary condition can define the boundary between an aquifer and an aquitard (e.g., the base of the aquifer). A specified flow boundary condition defines a flow into or out of the model. Recharge to the aquifer or pumping by a well are examples of this. A head-dependent boundary condition allows water to flow into or out of the model in a manner dependent on the difference in the water level (i.e., “head”) between the aquifer and the boundary. A stream or river is an example of this.

When represented by numerical models, water is treated as if flow rates are constant over a small time interval and over a small area. A specified flow of water entering or exiting the groundwater system by a given mechanism over a small time interval and a small area is known as a “stress.” The time interval is referred to as a “stress period;” the small area is referred to as a “cell”. Aquifer parameters (e.g., hydraulic conductivity, top and bottom of aquifer) are specified for each cell in the model, and boundary conditions are specified on a cell-by-cell basis where needed.

There is no one size fits all approach to groundwater modeling. In order to develop a useful modeling tool, the specific questions that the model will be used to answer need to be considered. A common question that a model is used to answer is to determine the impact of an activity or activities on some component of the hydrologic system. In this case hydrologists are typically interested in an impact that cannot be directly measured. In order for such a model to be useful, it needs to be able to simulate the hydrologic system during periods when a given activity is both present and not present. By sufficiently overlapping these periods, the model can be a useful tool in providing estimates of the impact of the activity or activities of interest.

When using a numerical model to represent an actual physical system, such as the Basin, it must undergo some level of calibration—a process of ensuring the model can reasonably replicate the physical system being modeled. The two most common calibration targets are measurements of groundwater levels (i.e. water table elevations) and estimates of stream baseflows. The calibration process involves these steps:

1) A model is constructed and run.

2) The output from the model is then compared to measured and estimated actual conditions.

3) Changes are made to the calibration parameters, most commonly the aquifer properties and the aquifer recharge, in an iterative fashion, until the model results closely match the measured and estimated actual conditions.

It is important also to constrain, as much as possible, the range of the calibration parameters, because there is generally an infinite combination of parameters that can yield a similar calibration to the measured and estimated actual conditions. For example, the range of aquifer properties allowed in the model should be constrained to some pre-defined range that is based on knowledge of the geology. Similarly, the range of recharge values for a given location in the model can be constrained based on knowledge of precipitation, soil types, and land cover. The point at which a model can be considered calibrated is subjective, as the model can never perfectly replicate the complexity of the actual hydrologic system. Professional judgment among the model developers is relied upon to make this decision. Subsequently, new data or understandings may lead to additional calibration efforts.

3.2 Development and Updating of RRCA Groundwater Model

When the FSS was ratified by the three states on December 15, 2002, the Model was not complete. The States had agreed on the calibration targets, the methods to estimate groundwater pumping and recharge, and the process to calibrate the Model. In spite of the incomplete state of the Model, the Current Accounting Procedures that were included in the FSS specified how the Model was to be used to calculate the depletions to streamflow caused by groundwater pumping in each state and the accretions to streamflow caused by mound recharge. The model was completed within the timeframe required by the FSS (RRCA, 2003).

The Model was developed by representing all major sources and discharges for water in the ground and properties of the subsurface material relating to the transmission and storage of water (figure 6). Cells in the Model are one square mile (640 acres) in area, with a vertical extent equal to the saturated thickness of the aquifer (ranging from ten feet to hundreds of feet). The base of the aquifer and lateral boundaries where the aquifer is reduced to zero thickness (i.e., "pinches out") are no-flow boundaries. Much of the northern boundary of the Model is coincident with the Platte River; here water flows into or out of the Model in quantities required by the specified head that represents the water level in the Platte River. The Republican River, its perennial tributaries (as well as several small tributaries to the Platte River) and surface reservoirs are represented in the Model and associated with specific Model cells.

The stress periods for the Model are one month long. Values for recharge and groundwater pumping are specified on a cell-by-cell basis and may change with each stress period. The groundwater pumping values are determined separately by each state for the wells in that state. Initially reviewed by the other states during calibration of the Model and they continue to be reviewed when the Model is updated with new data for ongoing accounting. Recharge from four sources is included: 1) precipitation; 2) canal leakage; 3) recharge of water applied through surface water irrigation; and 4) recharge of water applied through groundwater irrigation.

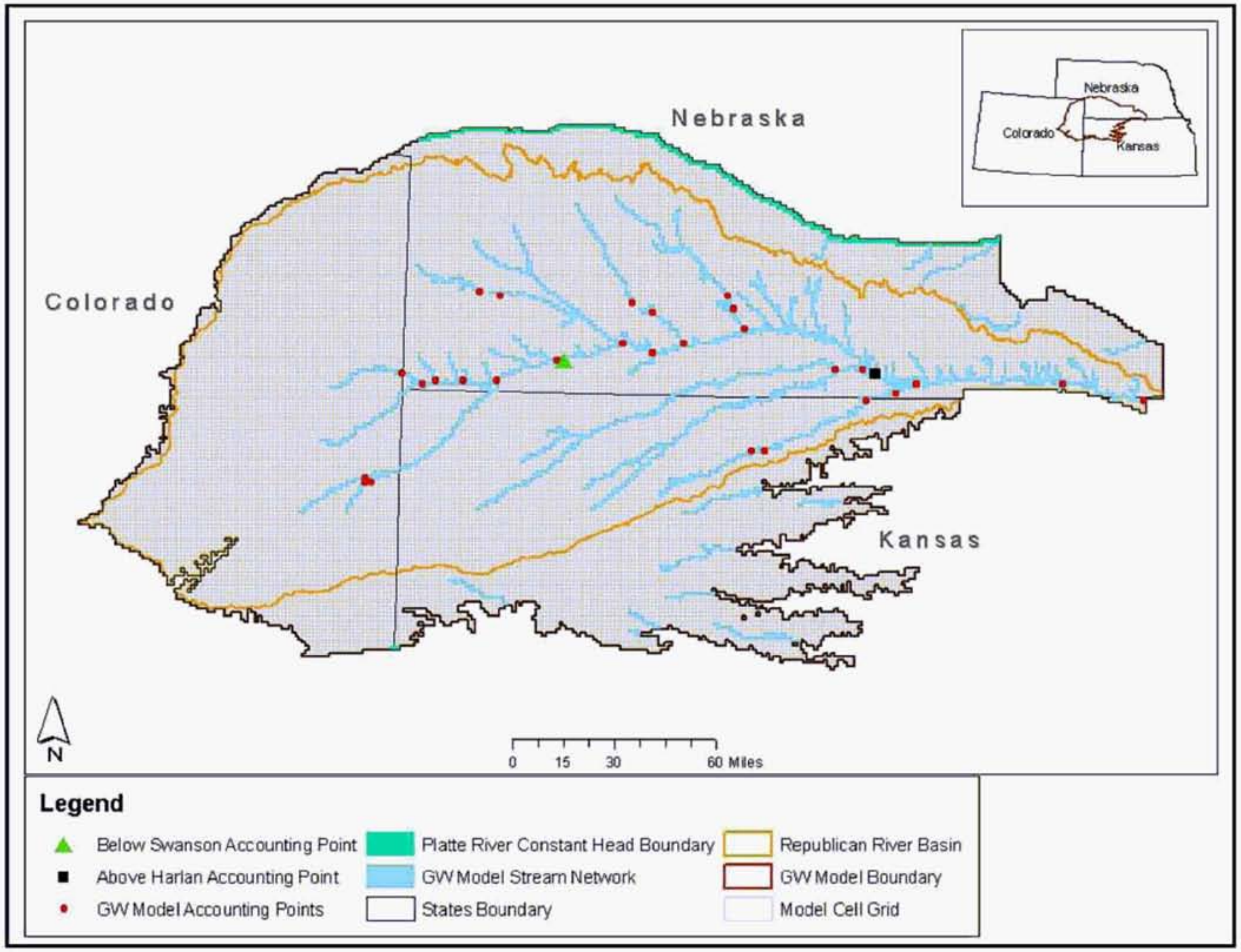

Figure 6. The RRCA Groundwater Model. Note the location of the "Below Swanson" and the "Above Harlan" accounting points, indicating the extent of the Swanson-Harlan Reach, which will be discussed in Section 4.4.

The Model was calibrated by comparing water levels calculated by the Model with those observed in the aquifer and comparing net stream baseflow, as calculated by the Model at gaging stations, with estimates of stream baseflow at the same gaging stations. Calibration parameters included the aquifer properties, the precipitation recharge, and properties associated with ET. The period of record over which such comparisons were made was 1918-2000. This period was chosen in part because it sufficiently overlapped time periods when groundwater pumping and mound recharge had not yet occurred (i.e., pre-development) and a time period when aquifer pumping and mound recharge began to occur (i.e., development period). The pre-development period ended sometime around 1950-60, though the change was not abrupt, but rather a gradual one.[4]

Figure 7 shows an example of the comparison between Model-calculated stream baseflow[5] and estimated stream baseflow for the gaging station on the Frenchman Creek near Imperial (figure 1). The horizontal axis indicates the time at which the stream baseflow (calculated or estimated) occurred. The vertical axis indicates the magnitude of the stream baseflow, given here as a volume of water (acre-feet) that passed the gaging station over the course of the indicated year. While the two lines do not track identically, the fit between them is generally good, particularly the overarching trend in the data. Note that the baseflows are fairly steady at around 45,000 to 50,000 acre-feet per year until around 1965, when they begin to decline, representing the beginning of the development period.

[4] There was some groundwater use and surface water use in the Model area much earlier than 1950, though this was generally minimal. Large scale man-made stresses to the system generally began around/after 1950.
[5] Note that the data from model runs presented in this report produce slightly different values from those officially adopted by the RRCA. The RRCA employs Principia Mathematica, Inc. to produce the official model runs, whereas the runs reported here have been completed on the computers of Nebraska staff. Model runs, using the same input but completed on different computers, can produce slightly different results because of differences in computer hardware. These differences are typically on the order of 0.1%. A slight versioning issue with Model files was discovered prior to submitting this report but subsequent to the stipulation by Nebraska on her overuse in 2006. This issue resulted in a difference of 215 acre-feet in that overuse value.

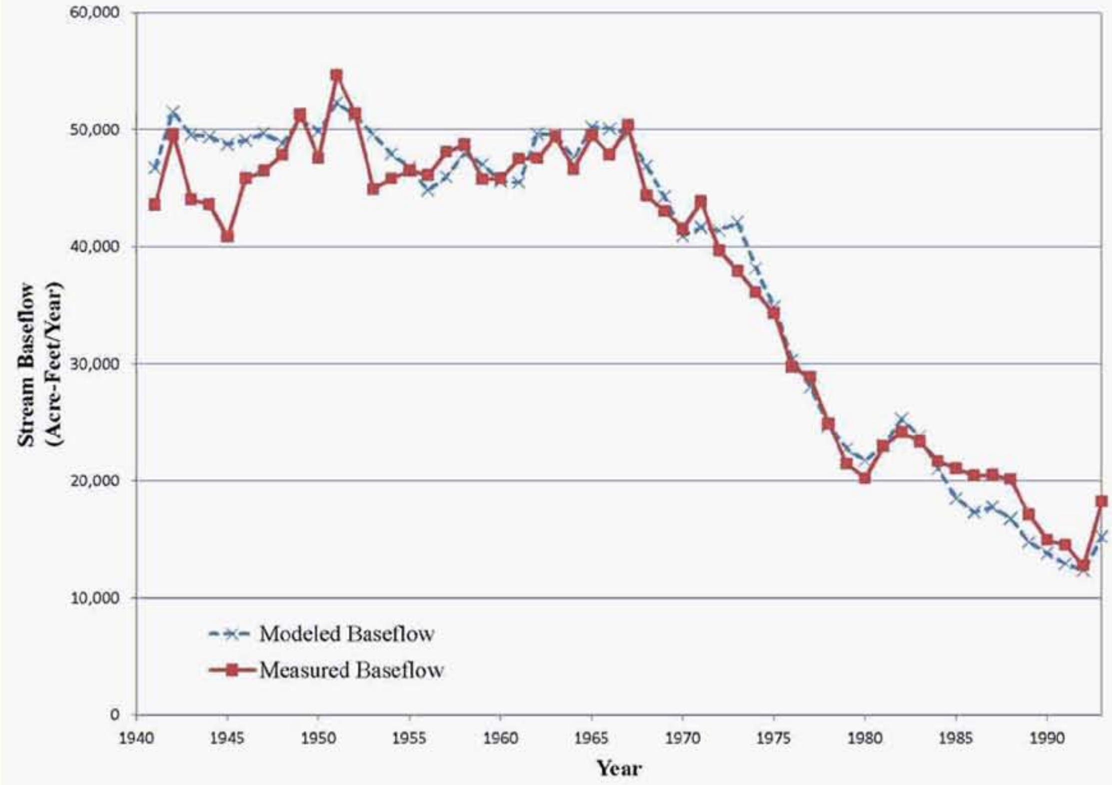

Figure 7. Comparison between estimated stream baseflows from gage data and Model-generated stream baseflows for the Frenchman Creek near Imperial.

It is important to emphasize that Nebraska is not seeking to alter the Model in any way through these proceedings. Rather, it is only the manner in which the outputs of the Model, namely the stream baseflows, are used in the Current Accounting Procedures that are at issue. Although additional runs of the Model are required under Nebraska's Proposed Procedures, none of the Model specifications or input data from a given year would be changed in these runs. Instead, Model input would be applied in some additional combinations in order to estimate better the impact of pumping and mound recharge.

3.3 RRCA Accounting Procedures

The Republican River Compact specifies the VWS for each sub-basin and the Main Stem, as well as the specific Allocations from that VWS provided to each of the states. It also states that if future water supplies vary by more than 10% from the values included in the Compact, then the volume of water each state receives could be adjusted in proportion to the original Allocations (Compact, 1943). The RRCA first developed a system for accounting for the water supplies and uses in 1961. These procedures have been updated and modified through the years to reflect advancing technologies and changing conditions in the Basin. The Current Accounting Procedures were adopted as part of the FSS in 2003, and the FSS included provisions to allow for future updates to these as necessary. For a more detailed discussion of the Current Accounting Procedures, particularly as they relate to the computation of the impact of groundwater pumping and mound recharge, see Ahlfeld et al. (2009).

3.3.1 Compact Allocations

The FSS allocates water in each sub-basin to the states based on fixed percentages of the estimated water supply in a given year (table 1). These fixed percentages are based on the original Compact VWS and Allocations. These fixed percentages are included in the Current Accounting Procedures.

Table 1. Fixed percentages that represent the Compact Allocations.

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%	

To compute the volume of water that each state receives from these fixed percentages, an estimate of the VWS is needed, which involves combining the measured streamflow with estimates of the impact to streamflow for each sub-basin and the Main Stem. ***Thus accurate estimation of these impacts is critical to properly determining the VWS.***

Under the FSS, a new term was introduced, the Computed Water Supply (CWS), which is an adjustment to the VWS.[6] The CWS is now used in conjunction with the fixed percentages described above to determine the volume of water that each state receives from each sub-basin. Many sub-basins do not provide Allocations for all three states. Generally, some percentage of the water supply in each sub-basin is not allocated to a specific state. This unallocated water is combined with the CWS in the Main Stem and split between Kansas and Nebraska in the same manner as the CWS from the Main Stem. This means that:

1) Each state does not receive the same volume of water each year unless the CWS is the same;
2) Even if the total CWS is the same, a state may not receive the same volume of water from year to year, if water originates in different sub-basins; and
3) If the CWS is not determined correctly, then one or more states will not receive the correct volume of water.

Using Sappa Creek as an example, if the impact to stream baseflow from groundwater pumping is misestimated for Kansas ***or*** Nebraska, then ***the estimate of the CWS will be flawed***. Applying the fixed percentages from table 1 to this flawed CWS would result in flawed values for the volumes of water that Kansas ***and*** Nebraska receive. Similarly, a state would also receive the wrong volume of water if the estimates of CWS were correct, but the fixed percentages derived from the Compact were altered such that they no longer reflect Compact entitlements. Therefore, applying a flawed estimate of CWS in the accounting is akin to altering the fixed percentages (Allocations) that are derived from the Compact (i.e., altering Compact entitlements).

3.3.2 Use of Current Accounting Procedures

The Current Accounting Procedures are described in Appendix C (revised August 8, 2010) of the FSS. Definitions and formulas within the FSS and Appendix C make it clear that the working definition of VWS is to be understood as the water supply or streamflow of the Basin unaffected by human activities. To estimate VWS, the Current Accounting Procedures call for the estimation of Computed Beneficial Consumptive Use

[6] The CWS is an adjustment to the VWS to account for changes in storage in federal reservoirs and flood flows. This difference essentially means that water that is stored in federal reservoirs is not counted until it is released and used, and that flows over certain thresholds are not counted.

(CBCU) and the impact of the mound recharge, also referred to as the Imported Water Supply Credit (IWS Credit). The CBCU is the streamflow depletion resulting from a specific list of human activities. The IWS Credit is defined as "the accretions to streamflow due to water imports from outside of the Basin as computed by the RRCA Groundwater Model" (FSS, 2002).

The Compact divides the Republican River Basin into twelve (12) sub-basins and the Main Stem. The VWS is computed independently for each sub-basin on an annual basis. In the case of a sub-basin that does not have any federal reservoirs or imported water supply effects, the VWS is computed as the sum of gaged streamflow, measured in the stream at the sub-basin or Main Stem outlet, and all CBCU in the sub-basin. The CBCU is generally caused by two activities, the stream baseflow depletion caused by groundwater pumping and the streamflow depletion caused by surface water diversions and other non-groundwater activities identified in the Current Accounting Procedures (e.g., evaporation).

In the Current Accounting Procedures, the annual gaged flows for a given sub-basin are determined by direct measurement at stream gages and surface water depletion is estimated based on direct measurements, such as tabulating the volumes of water actually diverted from streams during the year. Direct measurement of the impact of groundwater pumping and mound recharge is impossible. Estimation of these impacts is complicated by the fact that the impacts in one sub-basin may result from pumping or recharge that occurred in earlier years and/or in neighboring sub-basins. Because of these complicating factors, these impacts are estimated using the results of multiple runs of the Model.

In this way, the Current Accounting Procedures are used to estimate the VWS and the CWS. The annual volume of water each state receives is determined as a percentage of the CWS. This volume of water is then compared with an estimate of actual water use (less any IWS Credit) by that state to determine over or under-utilization by that state. The problem with the Current Accounting Procedures is a failure in the estimation of the impacts of groundwater pumping and mound recharge, which in turn affects the VWS, CWS, and the volume of water each state receives, which is derived from the CWS estimates using the fixed percentages. ***Solving this problem does not involve changing the fixed percentages; rather, the problem is solved by ensuring the impacts of groundwater pumping and mound recharge are determined properly.***

3.3.3 Current Accounting Procedures and the Model

The Current Accounting Procedures define a number of "accounting points" (figure 6) at the outlets of each sub-basin or Main Stem reach for the purpose of estimating the impact of groundwater pumping or mound recharge. The Main Stem is subdivided into multiple reaches. Multiple accounting points for a given sub-basin or Main Stem reach are needed in some cases. Each accounting point is located in a numerical cell in the Groundwater Model. Using the calibrated Model, a stream baseflow value is computed at the accounting point at each stress period[7] through the year 2000 (the end of the calibration period).

The Model-computed stream baseflow is not necessarily exactly equivalent to actual streamflow at an accounting point, but is instead only an estimate of that portion of streamflow attributable to groundwater discharge to the stream. Stream baseflow estimates for years following 2000 are obtained on an annual basis by updating the Model with new input data (e.g., pumping, recharge) and other required parameters that can change from year to year (e.g, maximum ET rate, reservoir elevation). Additional Model simulations are also needed for each year to determine the proportion of the total change in stream baseflow that is attributed to groundwater pumping in each state and to mound recharge. The Current Accounting Procedures contain specifications for accomplishing this. These procedures work well in many cases, but, as shown in Section 4, they fail in some cases and therefore require additional refinement.

The Current Accounting Procedures require an estimate of the impact of 1) groundwater pumping in Colorado, 2) groundwater pumping in Kansas, 3) groundwater pumping in Nebraska, and 4) mound recharge. For convenience, this report uses the term "Target Set" to indicate one of these four groups of stresses. For example, the Target Set for Kansas groundwater pumping is all stresses applied, during the entire Model run, at groundwater wells located in Kansas. The Total Impacts of these four Target Sets can be determined by comparing a Model run with all groundwater pumping in Colorado, Kansas, and Nebraska, and mound recharge On, to a run with all groundwater pumping in Colorado, Kansas, and Nebraska, and mound recharge Off. The difference between these two Model runs provides the ***only direct estimate*** of the Total Impacts.

A conventional way to estimate the impact of a Target Set is to run a numerical groundwater flow model, with the Target Set of stresses "On" and then with the Target Set of stresses "Off". The difference in the output is assumed to be a reasonable estimate of the impact of the Target Set of stresses. The Current Accounting Procedures use the model to provide estimates of stream baseflow at accounting points for a Model run with all Targets Sets On and four other Model runs with one of the Target Sets Off. The Current Accounting Procedures then use differences in these stream baseflow estimates to calculate the impacts on stream baseflow caused by each Target Set. The problem with the Current Accounting Procedures identified by Nebraska occurs because these differences do not account for the Total Impacts.

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[7] Terminology in the Current Accounting Procedures (e.g., section III.D.1) is not entirely consistent on the use of streamflow and baseflow. In this report, the net groundwater discharge to the stream is referred to as "stream baseflow."

The Total Impact of groundwater pumping on stream baseflows for the Frenchman Creek near Imperial can be seen in figure 8. This figure shows Model-calculated stream baseflows with all Target Sets On (same as in figure 7 above) and Model-calculated stream baseflows with all Target Sets Off. A comparison of these two lines shows that stream baseflows were essentially identical until around 1955, indicating that groundwater pumping had no effect in this part of the Basin up to that time. The impact of groundwater pumping causes only marginal differences between the two curves until around 1965, after which significant differences become apparent.

The upper line in figure 8 (i.e., all Target Sets Off) is a representation of what the stream baseflows would have been if groundwater pumping had never occurred (mound recharge has little to no impact at this accounting point). The slight increase in stream baseflows over time would be attributable to increases in recharge that occurred over this time period. Notice that the effect of this increased recharge is not evident from the stream baseflows produced with groundwater pumping On.

This is why it would be improper simply to take the stream gage data, pick a point in time, and estimate the impact of groundwater pumping based on the change in gaged flows over time. Using the estimates of stream baseflow from gage data (figure 7), one might choose 1965, thereby missing the impacts that occurred from 1955 to 1965. This single-point choice would also miss the fact that stream baseflows would have otherwise increased somewhat over time. The Model can produce estimates of stream baseflow with and without groundwater development, and the difference between these represents the Total Impact of groundwater pumping on stream baseflow in Frenchman Creek.

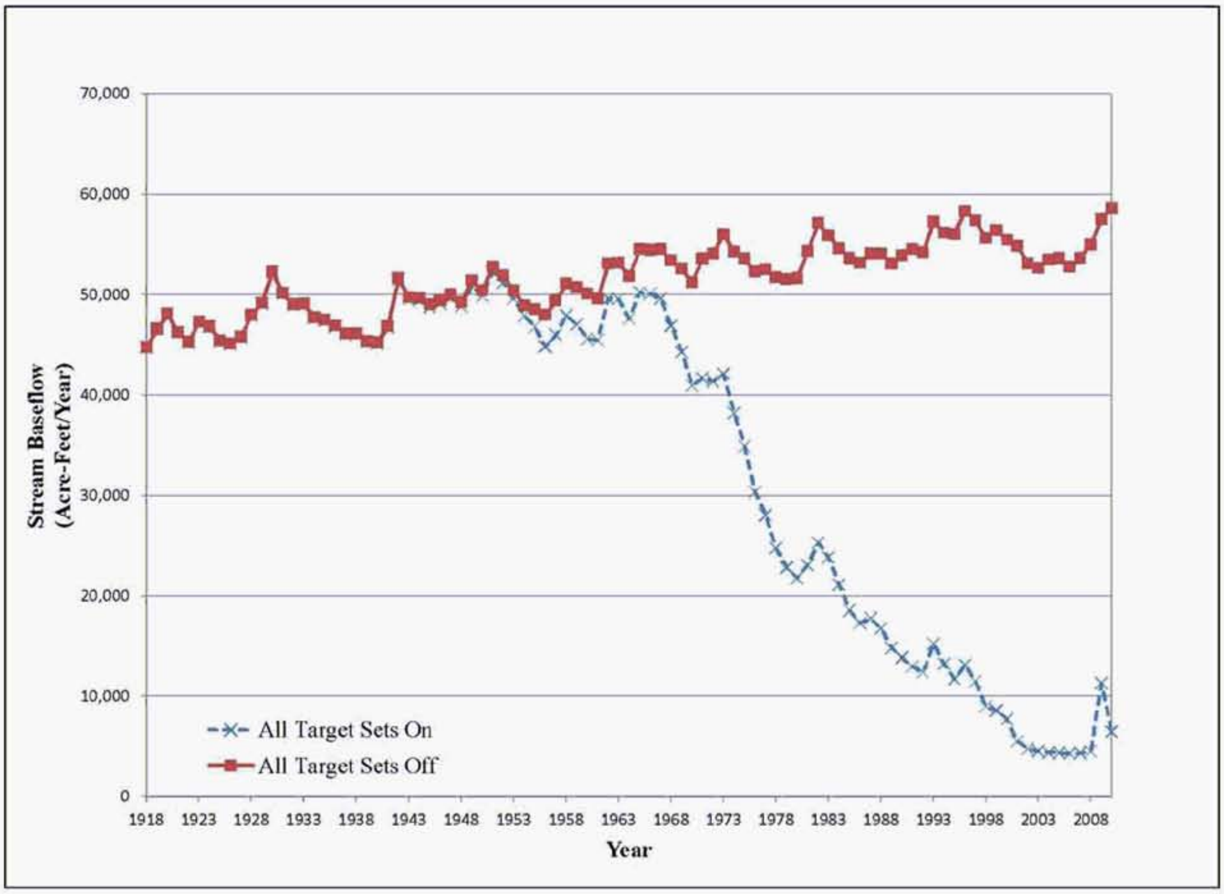

Figure 8. Comparison of Model-generated stream baseflows for the Frenchman Creek near Imperial for 1) all Targets Sets On, and 2) all Target Sets Off.

4.0 PROBLEM WITH CURRENT ACCOUNTING PROCEDURES

Nebraska has identified significant inadequacies in the Current Accounting Procedures' ability to account fully for the VWS of the Basin. This problem arises from the way in which the Model output is applied by the Current Accounting Procedures. No changes to the Model are required or sought by Nebraska to address this problem.

The problem manifests itself in multiple ways, a glaring example of which is presented in Section 4.4.2. This example shows that mound recharge supplied by Nebraska provides no accounting benefit over the long term. Moreover, by continuing to provide mound recharge, Nebraska's Compact accounting balances are ***adversely impacted*** over the long term as compared to discontinuing the mound recharge. This result demonstrates the nature of the problem.

Nebraska's first report (NDNR et al., 2008), along with previous interactions with the RRCA, continually refined Nebraska's Proposed Procedures to the form presented in arbitration (Ahlfeld et al., 2009). These reports contain detailed analyses of the behavior of the Model and provide technical explanations for the results the Model produces when it is used to determine impacts under the Current Accounting Procedures and Nebraska's Proposed Procedures. In this section, the problem with the Current Accounting Procedures will be demonstrated by using a simple analogy, which highlights the unrealistic nature of the results that can be obtained by the Current Accounting Procedures.

The analogy will first demonstrate a non-linear response of a single Target Set. Then, the analogy will demonstrate the complications that arise when a similar non-linear response is caused by two Target Sets. The analogies are useful for understanding these complications and demonstrates the failure in otherwise reasonable approaches to estimating impacts.

4.1 Weighing a Single Person on a Scale (One Target Set Analogy)

Any accounting procedure is fundamentally defined by operational rules. For example, when a person is weighed on a scale, the weight shown is the result of the difference between two readings: the reading of the weight from the scale when the person is on the scale minus the reading of the weight registered by the scale when the person is not on the scale. This procedure is greatly simplified by ensuring the scale reads zero pounds when the person is not on the scale, which eliminates the need for subtraction.

People are typically weighed individually on a scale, and in most cases a person weighs less than the scale capacity, which typical may have a limit of 300 pounds. One person can always be accurately weighed, regardless of the procedure used, as long as that person weighs less than the scale capacity. The person's weight can be derived in one of two ways. First, one can start with the person not on the scale and then have the person step on the scale. The weight will be calculated by comparing the scale reading with and without the person on the scale. Alternatively, one can start with the person on the scale and then have the person step off the scale. Again, the weight will be calculated by comparing the two scale readings. Both approaches yield the same result.

Note that if a 350-pound person is weighed on a scale with a capacity of 300 pounds, the impact the person has on the scale will always be 300 pounds regardless of whether the person starts the weighing procedure on or off the scale. ***The distinction between <u>the actual weight of the person</u> and <u>the impact the person registers on the scale</u> is important because it is the <u>impact</u> that is required for use in the RRCA Accounting Procedures.*** Determining the response of a scale to the weight of a person captures the case in which the person weighs more than the scale capacity.

For example, given a scale capacity of 300 pounds, the maximum impact a person weighing 150 pounds can have on the scale is 150 pounds (figure 9). Given the same person and a scale capacity of 100 pounds, however, the maximum impact the person can have on the scale is only 100 pounds, and the remaining 50 pounds of the person's actual weight has no additional impact on the scale. In this case, we can say that weighing the 150 pound person on a scale with a capacity of 100 pounds generates a non-linear scale response. As the person steps on the scale, the scale reading increases linearly (the scale reading increases by one pound for each additional pound of weight applied) until 100 pounds of the person's weight have been applied to the scale. At this 100-pound point, the scale's response becomes non-linear. After this point, the application of additional weight no longer results in any change in the scale reading.

This type of non-linear response is at the root of the issue regarding the Current Accounting Procedures. As set forth in Section 4.3, further potential complication arises when ***more than one person is on the scale***, and one wishes to determine ***the individual impact of each person.***

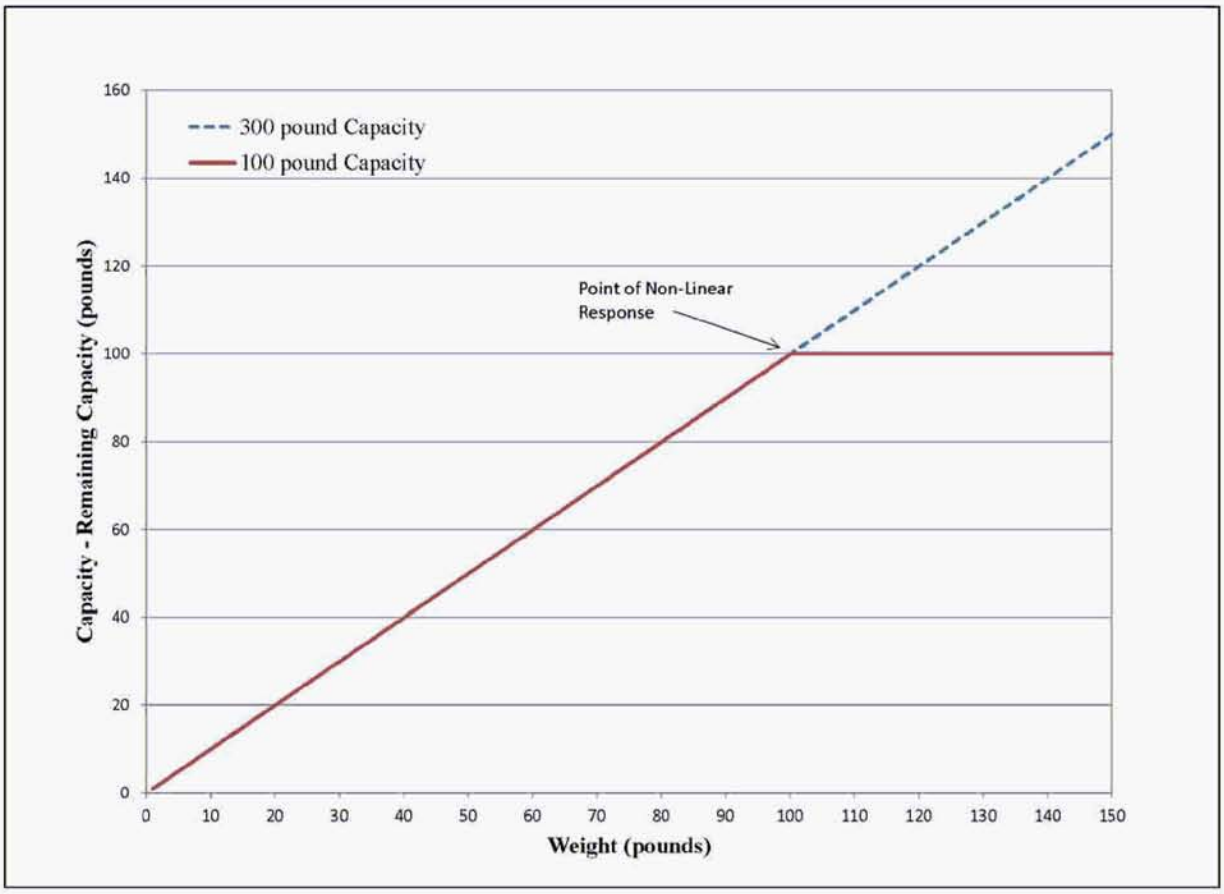

Figure 9. Comparison of the scale response with the application of 150 pounds of weight for scale capacity of 100 pounds and scale capacity of 300 pounds.

4.2 Estimating Impacts of Groundwater Pumping and Mound Recharge

The estimation of the impact of groundwater pumping and mound recharge for accounting purposes has similarities to the scale problem. The scale capacity can be related to the available baseflow in the stream. The impact of each person on the scale is analogous to the impact of groundwater pumping in each state.

The typical scale has an unimpacted reading (reading with nothing being weighed) of zero. The typical unimpacted stream has some non-zero amount of annual flow, termed the "Virgin Stream Baseflow" in this document. Placing people on the scale produces an impacted reading. Similarly, groundwater pumping reduces the stream baseflow to some amount less than the Virgin Stream Baseflow, termed the "Remaining Stream Baseflow" in this document. If sufficient weight is applied, the scale reaches its capacity, at which point the further addition of weight produces no additional response from the scale. Similarly, with enough pumping, the Remaining Stream Baseflow is reduced to zero, at which point additional pumping can have no further impact on the stream.

In order for the Current Accounting Procedures to be valid, they must be able to resolve the Total Impact to Virgin Stream Baseflow from four Target Sets[8] of stresses: 1) Nebraska groundwater pumping, 2) Kansas groundwater pumping, 3) Colorado groundwater pumping, and 4) mound recharge. The Total Impact of these four Target Sets can be directly estimated only by computing the difference between two Model runs: a Model run with all Target Sets On and a Model run with all Target Sets Off. This comparison is the "VWS Metric", conceptualized by Kansas in a memo dated September 18, 2007[9].

The Model-calculated stream baseflows vary nonlinearly with the level of Target Set activity in some cases. Because the approach of the Current Accounting Procedures requires a linear response, the approach utilized by the Current Accounting Procedures (i.e., estimating each individual impact of the four Target Sets, and then summing them together to estimate the Total Impacts), fails to account fully for the Total Impacts in those non-linear cases. ***The arbitrator's ruling recognized the fundamental properties of a non-linear system, by stating that Nebraska's calculation of Virgin Water Supply, which utilized these Total Impacts, was superior to the process outlined in the Current Accounting Procedures.***

In many sub-basins only one or two of the four Target Sets has any impact on Virgin Stream Baseflow. For the cases in which only one Target Set has an impact on Virgin Stream Baseflow, the Current Accounting Procedures are adequate. An example of this is the Driftwood Creek sub-basin, which covers areas of both Kansas and Nebraska (figure 1). In this sub-basin, groundwater pumping in Nebraska is the only Target Set that has an impact on Virgin Stream Baseflow at the accounting point for Driftwood Creek. Reasons for this may include a relative lack of groundwater pumping in the Kansas portion of the Driftwood Creek sub-basin or that Driftwood Creek is only an intermittent stream (i.e., without stream baseflow) in and near Kansas.

Figure 10 shows the Virgin Stream Baseflow in Driftwood Creek and the Remaining Stream Baseflow with groundwater pumping in Nebraska. The Virgin Stream Baseflow values can be obtained from any Model run with Nebraska groundwater pumping Off. From figure 10 it can be observed that the Virgin Stream Baseflows varied between about 1,500 acre-feet and about 3,500 acre-feet per year from 1950 to 2006. This variability is due to the amount of recharge experienced in the Driftwood Creek sub-basin. In a given year, the maximum impact that groundwater pumping in Nebraska can have on Driftwood Creek will depend on the Virgin Stream Baseflow in that same year. This annual change in Virgin Stream Baseflow has an effect on impact accounting analogous to changing the scale capacity.

[8] See Section 2.3.3 for discussion of the use of this term throughout this report.
[9] See Appendix B for discussion of the VWS Memo.

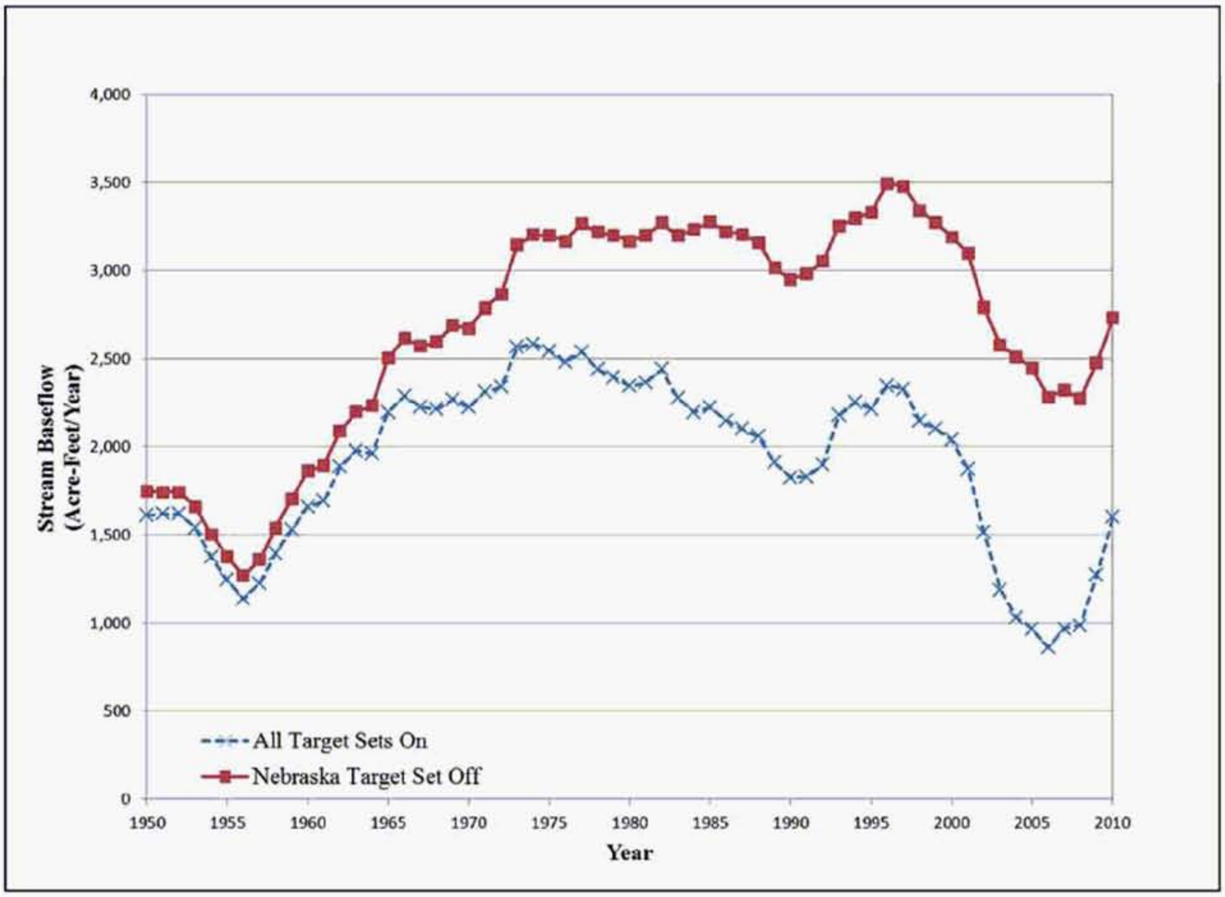

Figure 10. Virgin Stream Baseflow and Remaining Stream Baseflow for Driftwood Creek.

The Remaining Stream Baseflow is also the same for Driftwood Creek whether the other Target Sets (Kansas and Colorado groundwater pumping and the mound recharge) are On or Off. Note that, even with Nebraska groundwater pumping active, the Remaining Stream Baseflows are always significantly greater than zero (i.e., less than the scale capacity). The difference between the two lines in figure 10 is the magnitude of the impact of groundwater pumping in Nebraska to Virgin Stream Baseflow in Driftwood Creek. This result would be obtained with both the Current Accounting Procedures and with the Nebraska's Proposed Procedures.

To summarize this example, groundwater pumping in Nebraska is the only Target Set that has an impact on Virgin Stream Baseflows in Driftwood Creek and the impact of that groundwater pumping has never been greater than the Virgin Stream Baseflow in Driftwood Creek (i.e., the Remaining Stream Baseflow is always greater than zero). In terms of the scale analogy, we are only weighing one person and the impacted reading on our scale is always less than the scale capacity. Therefore, given the range of historic conditions experienced (i.e., recharge due to precipitation, canal leakage, and excess surface water irrigation, groundwater pumping), the relationship between groundwater pumping in Nebraska and Virgin Stream Baseflow in Driftwood Creek has been essentially linear.

Complications can complication can arise when more than one Target Set has an impact on stream baseflow and when Remaining Stream Baseflow reaches zero (i.e. scale capacity is reached). These complications and significant difficulties they can cause, when the Current Accounting Procedures are utilized, are explained by returning to the scale analogy.

4.3 Weighing Two People on a Scale (Two Target Set Analogy)

Consider further the question of a scale with a 300 pound scale capacity, but now with two people (Person A and Person B) each weighing 250 pounds. The weight of each person will also be referred to as their Potential Impact in this discussion. Because of the limitation of the scale capacity, the maximum impact these two people can have on this scale is 300 pounds. If they both step on the scale the reading will be 300 pounds; this will be referred to as the Total Impact caused by the two people being on the scale. Now consider, how much of that 300-pound Total Impact to the scale is caused by each person? There are several ways to test this. If both people are placed on the scale, then Person A could first step off the scale, and the scale readings with and without Person A on the scale could be compared. The reading with Person A and Person B on the scale is 300 pounds, and the reading with only Person B on the scale is 250 pounds, so the impact on the scale of Person A would be calculated as 50 pounds. Repeating the same process for Person B, with Person A back on the scale, would yield the same result, 50 pounds of impact generated by Person B.

Under this system, each person would be charged with causing 50 pounds of impact to the scale. These values will be referred to as the Apparent Impact of these two people. The sum of the Apparent Impact values is 100 pounds, in this case. Thus, of the Total Impact to the scale, 300 pounds, 200 pounds is unaccounted for. ***This set of calculations does not produce a realistic result in this example. This process is analogous to the Current Accounting Procedures.*** The portion of the Total Impact that is not accounted for as part of the Apparent Impact of the two people will be called the Unaccounted Impact (see table 2 for definitions of these and other terms to be used for the remainder of this discussion). This is represented by the following relationship:

Unaccounted Impacts = Total Impacts – Sum of Apparent Impacts

Based on this relationship, the assignment of impact ("Assigned Impact") to each person should be calculated as follows:

Assigned Impact = Apparent Impact + Appropriate Assignment of Unaccounted Impact

The Appropriate Assignment of Unaccounted Impact associated with each person is based on each person's physical ability to have caused those Unaccounted Impacts. This is the basis for Nebraska's Proposed Procedures.

Table 2. Definitions of impact terminology.

Term	Definition
Total Impact	The combined impact of all Target Sets evaluated simultaneously. This is also the Kansas VWS Metric.
Potential Impact	The maximum impact that a single Target Set can have. This is equal to the weight of a person up to the scale capacity in a one or two Target-Set situation.[10]
Apparent Impact	The impact estimate that is obtained when evaluating the impact of a Target Set in the presence of all other Target Sets. For example, the relative impact of a person on the scale when all other people are also on the scale. This is the result obtained from the Current Accounting Procedures.
Unaccounted Impacts	The difference between the Apparent Impacts of all Target Sets and the Total Impacts.
Appropriate Assignment of Unaccounted Impacts	The portion of the Unaccounted Impacts assigned to each Target Set based on that Target Sets ability to have caused the Unaccounted Impacts.
Assigned Impacts	The Apparent Impact plus the Appropriate Assignment of Unaccounted Impacts

In the application of the accounting rules in the preceding example, one or both person's impact on the scale has been significantly underestimated. The Total Impact is 300 pounds, and the methods employed through the Current Accounting Procedures have

[10] The Potential Impacts become somewhat more complex when more than two Target Sets contribute to the Total Impacts. This will be explored further in Section 4.2.

only apportioned 100 of those pounds (i.e., sum of Apparent Impacts above). A second approach to estimating each person's impact on the scale would be to start with neither of them on the scale, and then to have each individual step on the scale in its unimpacted (empty) state. Starting with a reading of zero pounds, and comparing this to a reading of 250 pounds with either person on the scale, we would determine that each person has an impact of 250 pounds on the scale. Although this may accurately represent each individual weight, or Potential Impact, the combination of these two values exceeds the scale capacity (i.e., Virgin Stream Baseflow). Consequently, this accounting process fails to produce a reasonable result. ***Remember, we are not interested in each person's weight; we are interested in each person's individual impact to the scale when both people are on the scale.*** In contrast to the Current Accounting Procedures, summing the Potential Impacts to the scale in this example would significantly overestimate the impact of one or both people toward the Total Impact to the scale of 300 pounds, because our individual estimates total 500 pounds, but the scale capacity (i.e., Virgin Stream Baseflow) is only 300 pounds.

Two additional ways could be used to estimate the contribution of each person's weight towards the Total Impact of 300 pounds, but they are both arbitrary[11]. For example, one could estimate the impact of Person A by placing him on the scale first, and then calculating the difference between the scale reading with no one on the scale (zero pounds) and the scale reading with Person A on the scale (250 pounds); one would conclude, as a result, that Person A caused 250 pounds of the Total Impact. The impact of Person B could then be estimated by calculating the difference in the scale reading with only Person A on the scale (250 pounds) and the scale reading with Person A and B on the scale (300 pounds); this would yield an additional impact by Person B of 50 pounds. Conversely, we could use the same process in the opposite order to estimate that Person B caused 250 pounds of the impact and Person A caused 50 pounds of impact. The preference for which of these two approaches is used would depend on perspective; each person may prefer the order that charges them with the least amount of the impact. Both of these approaches have the advantage of apportioning 300 pounds in total such that the Total Impacts is equaled but not exceeded, but they are both arbitrary and, for that reason, not desirable.[12]

[11] The term arbitrary in this report is used to describe any situation in which an order for testing the impact of two or more Target Sets is needed, but there is no particular reason for the choice of the order for testing the two sets.
[12] An accounting method for the streamflow impacts that has an order might be acceptable if those impacts actually occurred in a certain order in time. For example, if Nebraska groundwater development occurred, and the effects of this development were fully realized at the stream before groundwater development occurred in Kansas and Colorado then an order of evaluating the impacts of Nebraska first may not be arbitrary. Kansas and Colorado could only cause impacts to any remaining streamflow after Nebraska had impacted it., the development of groundwater pumping and mound recharge happened more or less simultaneously throughout the Republican River Basin, however, making any ordering of the evaluation of impacts arbitrary.

So the question remains: how should the impact be apportioned between both people? To consider this question, suppose the scale capacity were to increase by ten pounds. With both Person A and Person B on the scale the Total Impact would increase to 310 pounds. Now, which person contributed the extra ten pounds of impact to the scale? With the methods already described, there is no way to distinguish which pounds of body weight from each person contributed to the extra ten pounds of impact on the scale. In fact, the Apparent Impact estimates for both people would increase by 10 pounds each. That is, the addition of 10 pounds to the scale capacity increases the Apparent Impact of each person from an estimate of 50 pounds, when the scale capacity is 300 pounds, to an estimate of 60 pounds, when the scale capacity became 310 pounds. From this, it would appear that both people fully caused the increased impact. This comparison is summarized in table 3. One can only conclude, based on the above procedure, that each person contributed equally (five pounds) to the additional impact (i.e., their Potential Impact exceeds their Apparent Impact). See Appendix C for additional discussion on this two Target Set analogy.

Table 3. Comparison of results for scale capacity of 300 and 310 pounds respectively with two people who each weigh 250 pounds.

Scale Capacity	Total Impact	Sum Potential Impacts	Sum Apparent Impacts	Unaccounted Impacts
300	300	500	100	200
310	310	500	120	190

Of course, this simple scale analogy cannot, and is not intended to, capture all the complexity of the Model and the Compact Accounting. Nevertheless, some of the concepts introduced by the scale example apply regardless of model complexity. These are summarized as follows:

1) If scale capacity is not exceeded then individual impacts can be easily determined by adding weight to the empty scale or subtracting weight from a loaded scale.

2) If the combined weights (sum of Potential Impacts) exceed the scale capacity, then different methods (i.e. adding vs. subtracting) produce different calculated impacts for each individual contributing weight.

3) In cases in which the sum of the Apparent Impacts does not equal the Total Impacts, an Appropriate Assignment of the Unaccounted Impact is required to ensure that the impacts assigned to each individual add up to the same amount as the Total Impact registered on the scale.

4.4 Impact of Two Target Sets in the Republican River Main Stem

The Current Accounting Procedures do not properly account for the Total Impacts to Virgin Stream Baseflow. This problem is most evident in the Republican River Main Stem reach between Swanson Lake and Harlan County Lake (Swanson-Harlan Reach). This reach lies between the accounting point below Swanson Lake and the accounting point above Harlan County Lake (see figure 6). The three key concepts developed in Section 4.3 will assist in understanding this problem and developing a solution.

Groundwater pumping in Nebraska and the mound recharge are the two Target Sets that cause most of the impacts to Virgin Stream Baseflow in this reach[13]. Contrary to the scale analogy presented in Section 4.3, these Target Sets have an opposing impact on Virgin Stream Baseflow. In spite of this difference, the key concepts developed from the scale analogy are still valid. The Current Accounting Procedures significantly misestimate the combined impact of groundwater pumping in Nebraska and the mound recharge in this reach. The effect on Compact Accounting results is substantial and particularly detrimental to Nebraska.

4.4.1 Demonstration of Problem with Current Accounting Procedures

The discussion begins by considering the Total Impact of groundwater pumping and mound recharge computed as the difference between the Virgin Stream Baseflow (all Target Sets Off) and the Remaining Stream Baseflow with all Target Sets On. These are then compared with the sum of the Apparent Impacts of these two Target Sets using the Current Accounting Procedures. These values are plotted in figure 11. The sum of the Apparent Impacts generally matches the Total Impacts for the period up to around 1980, and then this value is generally greater than the Total Impacts. This discrepancy increases substantially after the year 2000. The difference between these Total Impacts and the sum of the Apparent Impacts derived using the Current Accounting Procedures is shown in figure 12. This difference represents the Unaccounted Impacts, which, in this case, is a negative value.

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[13] Groundwater pumping in Kansas and Colorado do have very small impacts to this reach in some years; these are neglected to simplify this discussion.

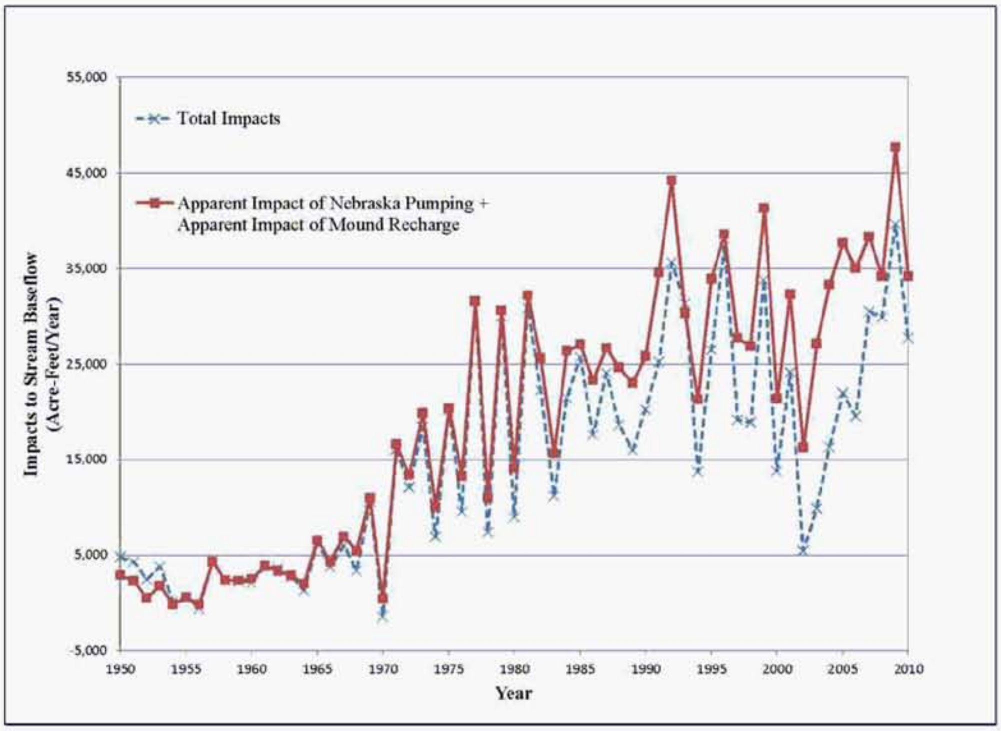

Figure 11. Comparison of the Total Impacts and the sum of Apparent Impact of Nebraska pumping and mound recharge for the Swanson-Harlan Reach.

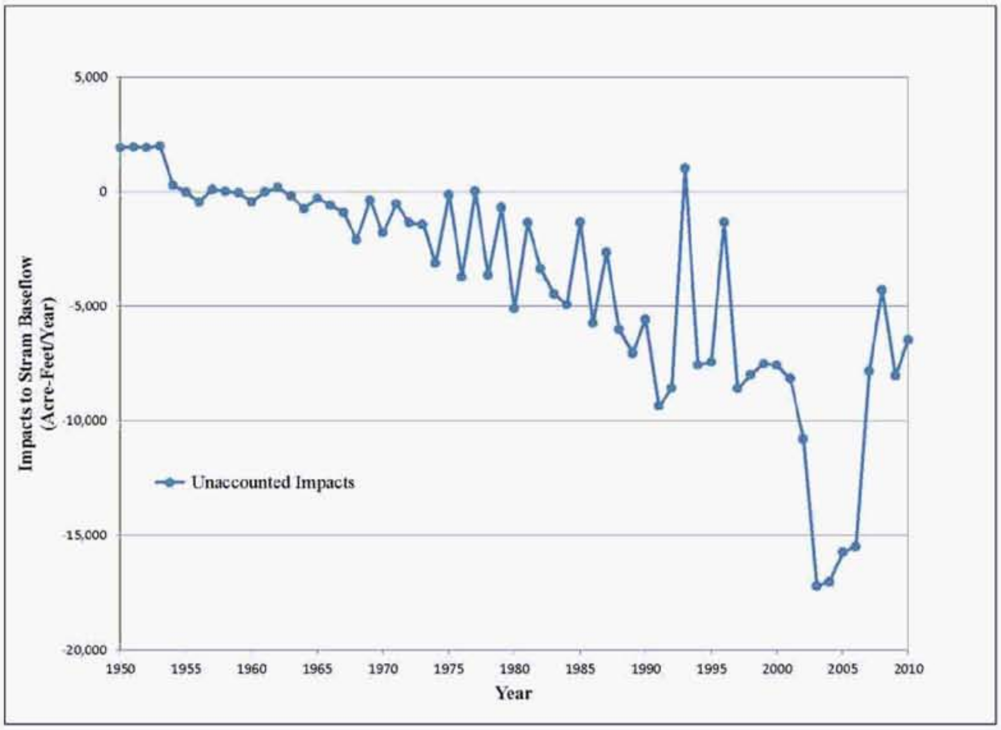

Figure 12. The Unaccounted Impacts for the Swanson-Harlan Reach.

This result is similar to the issue encountered when the Current Accounting Procedures are applied to the problem of weighing two people whose combined weight exceeds the scale capacity. Specifically, the Current Accounting Procedures assign a combined impact to the two Target Sets that differs from the Total Impacts to Virgin Stream Baseflow. In this case, the Current Accounting Procedures produces Apparent Impact values that, when summed, are greater than the Total Impacts, resulting in a negative value for the Unaccounted Impacts. This occurs because the Target Sets of stresses in the Swanson-Harlan Reach impact stream baseflow in opposite directions (groundwater pumping decreases Virgin Stream Baseflow, mound recharge increases Virgin Stream Baseflow). This situation was not specifically discussed in terms of the scale analogy, but it is nonetheless compatible with it. The useful concepts from the scale analogy, summarized at the end of Section 4.3, still hold.

The reasons for the Unaccounted Impacts displayed in figure 12 are technically complex; they are discussed in detail in prior reports (NDNR et al., 2008; Ahlfeld et al., 2009). Some insight into the underlying reasons can be gained from figure 13 which shows the Apparent Impact of the mound recharge and groundwater pumping in Nebraska. Note that the Apparent Impact of groundwater pumping increases overall until around 1980 and are generally between 30,000 and 50,000 acre-feet per year after 1980. The Apparent Impact of the mound recharge (i.e., IWS Credit) increases steadily throughout this entire time period up to about 2000. This trend is expected because the mound recharge generally occurs at some distance from the Main Stem and its tributaries and the impact of mound recharge should grow slowly and steadily over time, in spite of any short-term variability in actual mound recharge rates.

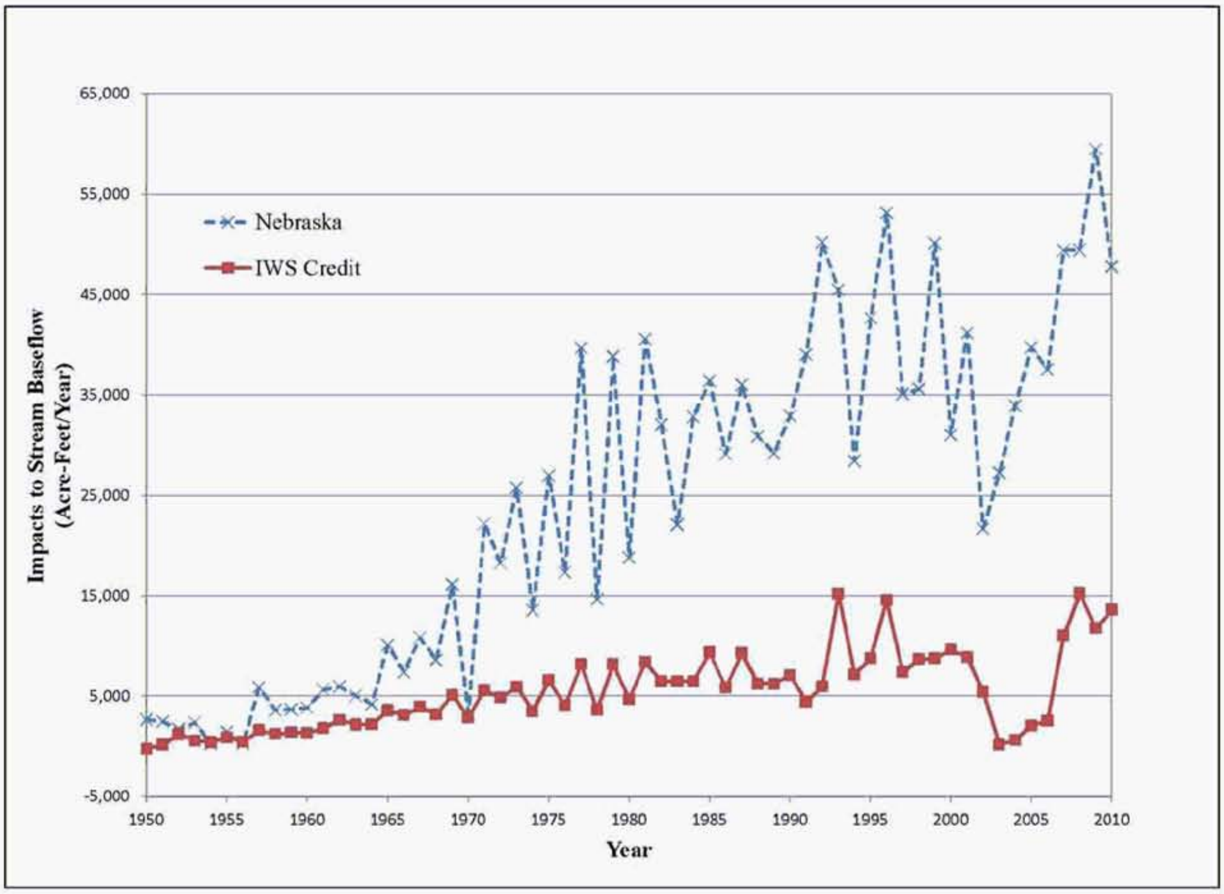

Figure 13. Apparent Impact of Nebraska pumping and mound recharge for the Swanson-Harlan Reach. The IWS Credit is computed as a positive value and subtracted from the impact of groundwater pumping to account for its opposite effect from groundwater pumping.

What is surprising in figure 13 is the sudden change in this increasing trend at about 2000, when the Apparent Impact of mound recharge is reduced to zero or near zero. This anomalous decrease in IWS Credit results from a significant failure in Compact accounting that is detrimental to Nebraska. The harm to Nebraska is essentially 51% of the value shown in figure 12 (see Appendix D), and the magnitude of this harm on Nebraska's annual Compact accounting balance[14] in this reach is shown in figure 14. As long as the Total Impacts are represented properly in the accounting, so that there are no Unaccounted Impacts, a reasonable result is obtained. The effect on Nebraska's annual Compact accounting balance has been approximately 8,000 acre-feet per year in recent years[15]. So, approximately eighty percent of the Basin-wide effect (10,000 acre-

[14] Nebraska's annual Compact balance is calculated as Allocation – (CBCU – IWS Credit).

[15] A positive value in terms of the effect on Nebraska's annual accounting results reflects a value that is detrimental to Nebraska.

feet; see Section 6) in recent years on Nebraska's annual Compact accounting balance, resulting from the failure of the Current Accounting Procedures, originates in the Swanson-Harlan Reach.

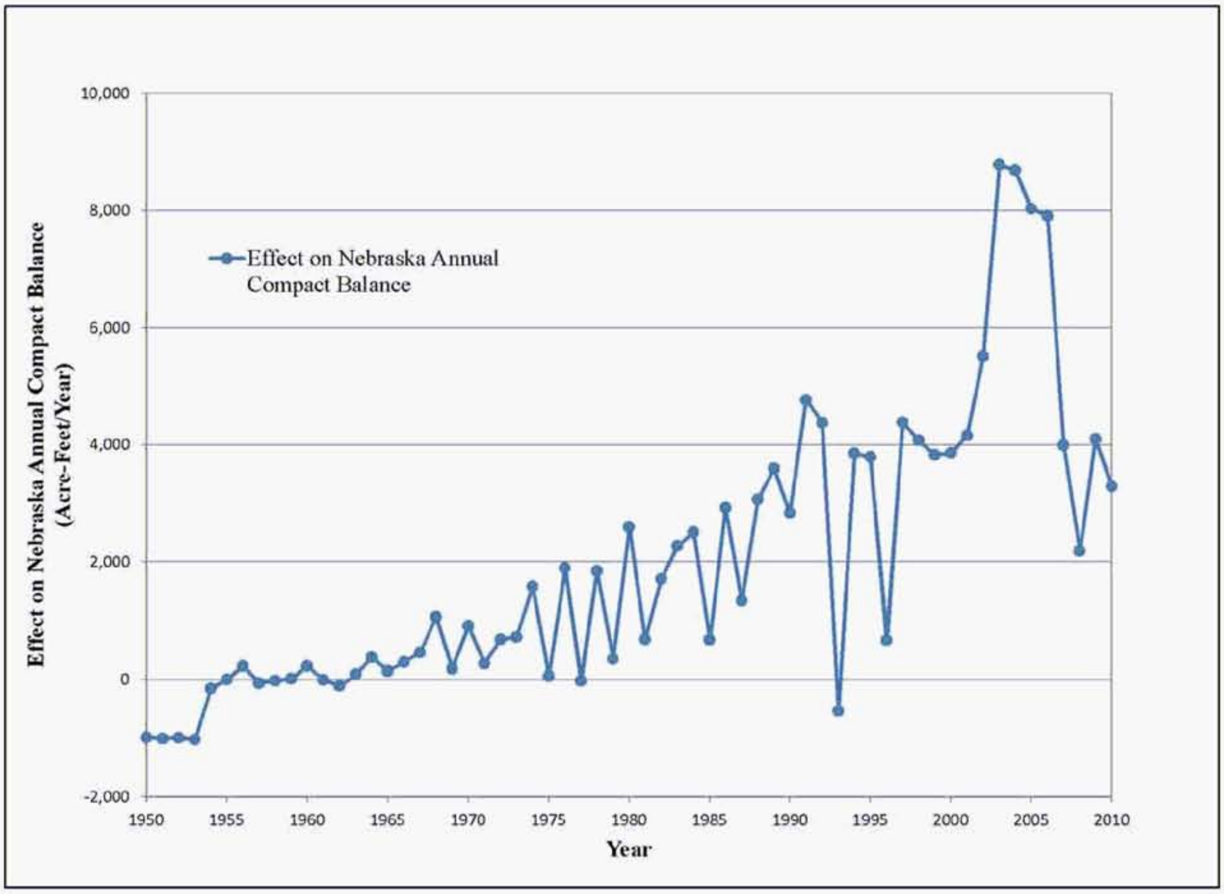

Figure 14. The effect of the Unaccounted Impacts in the Swanson-Harlan Reach on Nebraska's annual Compact balances. A positive value indicates a ***detriment*** to Nebraska's Compact balance.

4.4.2 Future Benefit of the Mound Recharge

The harm to Nebraska in the Swanson-Harlan reach from the Current Accounting Procedures results because the impacts of Nebraska groundwater use and mound recharge are regarded as separate Target Sets in this reach, although no essential reason exists for separating these two Target Sets for the purposes of Compact accounting. If these two Target Sets had been combined together as one Target Set, this problem would not arise in the Swanson-Harlan Reach, and the Unaccounted Impacts in that reach would be zero or near zero.

The recognition of the IWS Credit was critical to Nebraska's agreeing to the terms of the FSS. The mound recharge, approximately 500,000 acre-feet per year, transfers water from the Platte River Basin to the Republican River Basin, thereby increasing water supplies in the Republican River Basin. The intent of including the IWS Credit in the FSS was to recognize this benefit, which provides Nebraska with the incentive to continue this practice.

The misestimations of the impacts of Nebraska pumping and mound recharge derived from the Current Accounting Procedures may create an unrealistic result. This is clearly illustrated by analyzing the scenario offered by Kansas in its filing to the Supreme Court (Kansas petition C20)[16]. Generally speaking, this future scenario described in Kansas' filing simulates average climatic and water-use conditions for a future period of 50 years, beginning in 2009. The Kansas filing shows the impact of Nebraska groundwater pumping over this period under these conditions. For the sake of simplicity, it is more appropriate to combine the impact of Nebraska groundwater pumping and mound recharge to represent the combined impact of activities of man in Nebraska on the VWS. To understand better the failures of the Current Accounting Procedures, Nebraska utilized this same scenario, running it for two conditions: 1) the mound recharge is continued, and 2) the mound recharge is not continued[17]. Conceptually speaking, the combined impact of Nebraska groundwater pumping and mound recharge should be less, with the continuation of the mound recharge, than it would be if the mound recharge were not continued. Otherwise, no credit for Nebraska from the mound recharge could be possible.

Figure 15 shows the combination of the Apparent Impacts of groundwater pumping in Nebraska and mound recharge for the entire Basin (CBCU - IWS Credit), under Kansas' average conditions scenario and using the Current Accounting Procedures. This figure illustrates the value of the (CBCU – IWS Credit) computation that would result with the continuation of mound recharge. It then shows the value of the (CBCU – IWS Credit) computation that would result if the mound recharge were not continued.

Nebraska is more likely to have a negative annual Compact accounting balance when the value for (CBCU – IWS Credit) increases. As can be seen from figure 15, all other things being equal, Nebraska's annual Compact accounting balances in the future would receive no benefit from the mound recharge. Further, Nebraska's annual Compact accounting balances in the future would actually be improved [i.e., (CBCU-IWS Credit) is decreased] if the mound recharge was not continued.

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[16] The files were obtained in July 2011 from http://dwr.kda.ks.gov/20110725Production/KS000010 rrca_model_data.zip

[17] Under this scenario, all recharge associated with the mound is discontinued. It would be as if the diversion of water from the Platte River into the canals south of the Platte River were permanently discontinued.

In short, the Current Accounting Procedures produce the absurd result that the continuation, of groundwater recharge by Nebraska, in amounts in excess of approximately 500,000 acre-feet per year, will cause greater harm toward Nebraska's future compliance efforts than recharging no water at all. This is directly contrary to a reasonably-anticipated conclusion that recharging water should, logically, increase stream baseflows. This accounting outcome fails to reflect the actual benefits of the mound recharge.

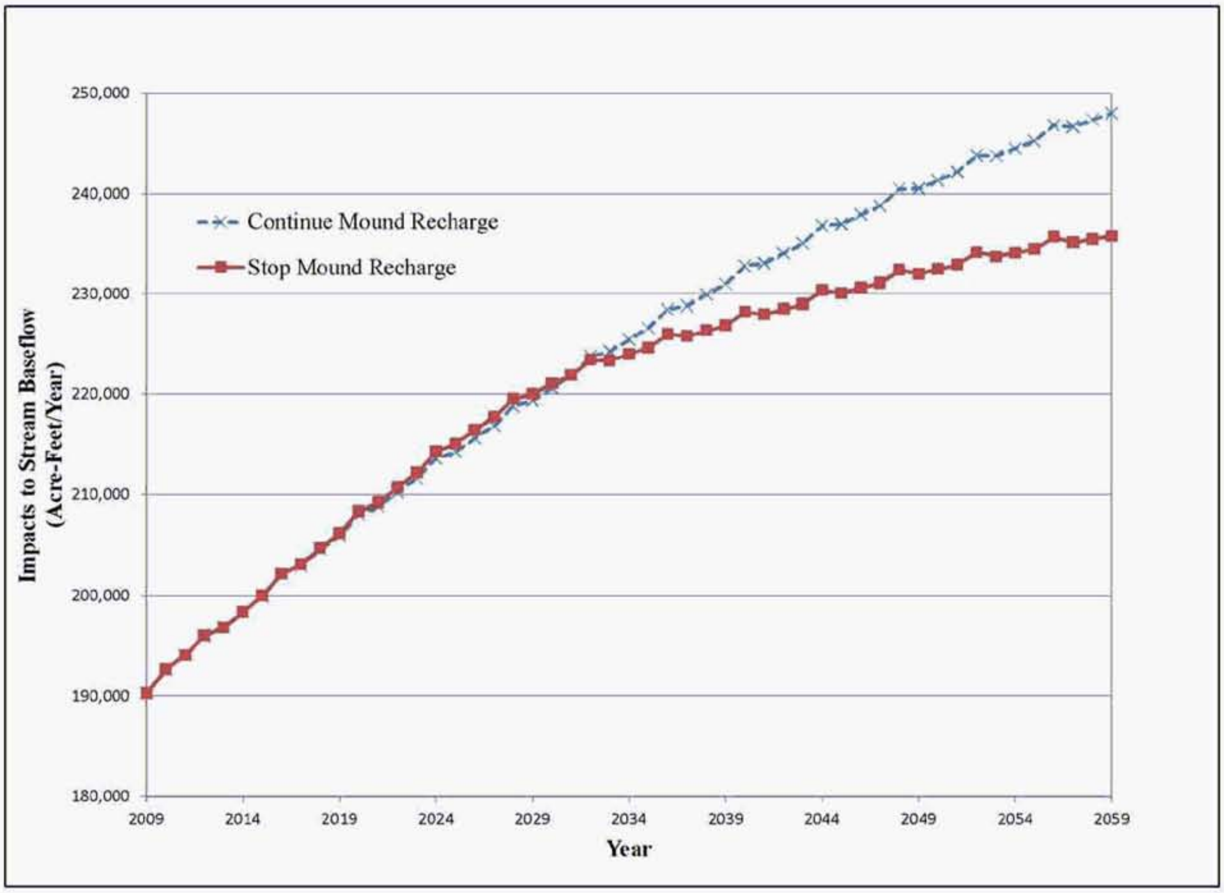
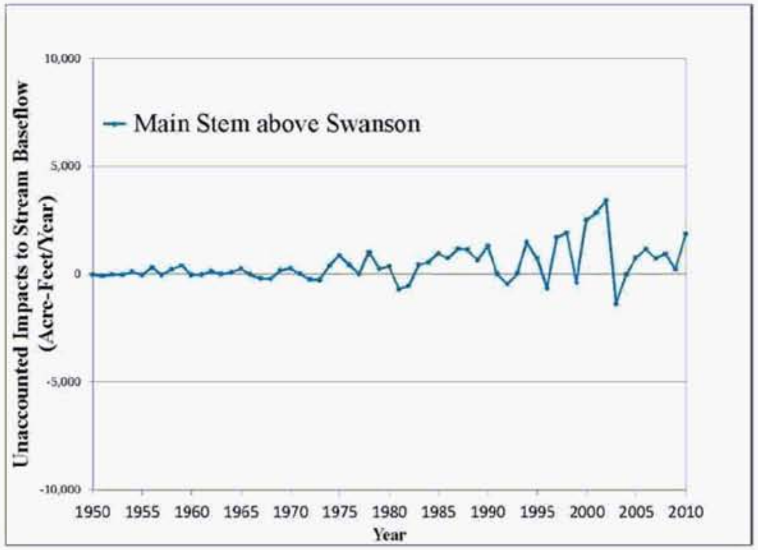


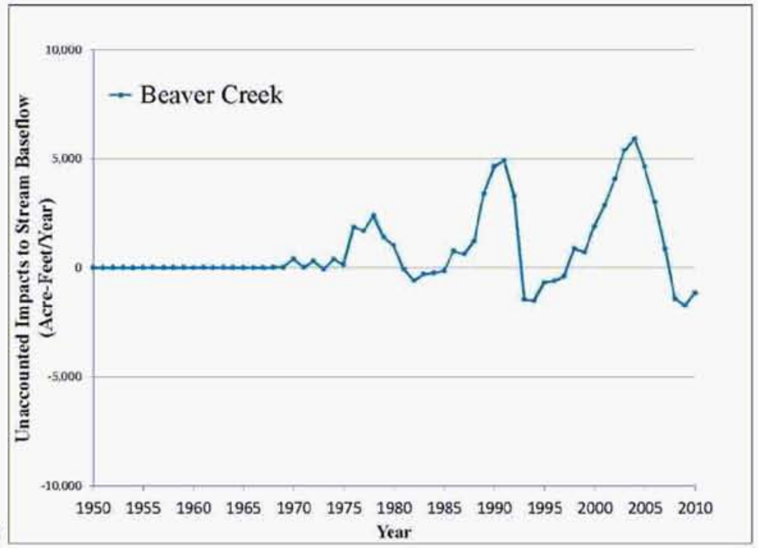
Figure 15. Basin-wide Apparent Impacts of Nebraska pumping and mound recharge (CBCU-IWS Credit) under the Kansas future scenario with mound recharge continuing and mound recharge not continuing. The difference between these two lines was previously illustrated in figure ES-2.

4.5 Impacts in other Sub-basins and Basin-wide

The Current Accounting Procedures also fail to account for the Total Impact due to groundwater pumping and mound recharge in numerous other sub-basins and Main Stem reaches. Figure 16 shows the Unaccounted Impacts for other sub-basins for which the Apparent Impacts of the two or more Target Sets do not equal the Total Impacts.

Detailed technical analysis for some of these sub-basins can be found in NDNR et al. (2008) and Ahlfeld et al. (2009). In some cases, the sum of Apparent Impacts is less than the Total Impact (shown as positive Unaccounted Impacts in figure 16), and, in other cases, the sum of Apparent Impacts is greater than the Total Impacts (shown as negative Unaccounted Impacts in figure 16). Using procedures that yield more scientifically reasonable and realistic results, the values in figure 16 would always be zero. Nebraska's Proposed Procedures accomplish just this anticipated result.

a)


b)


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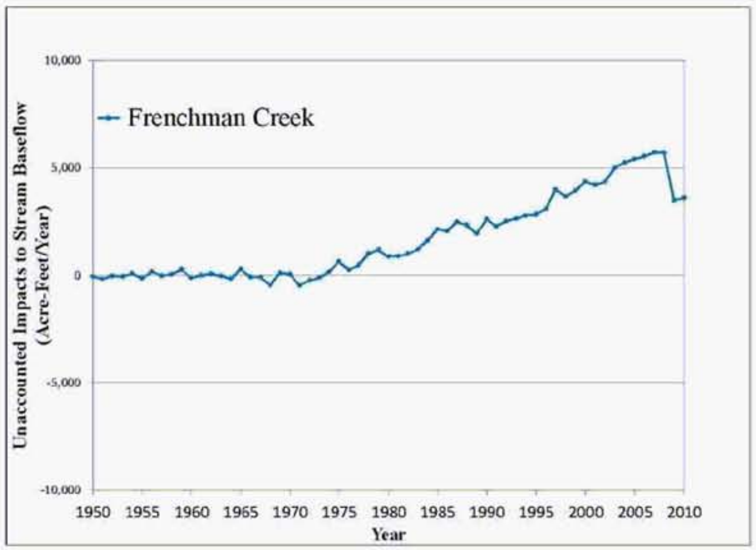

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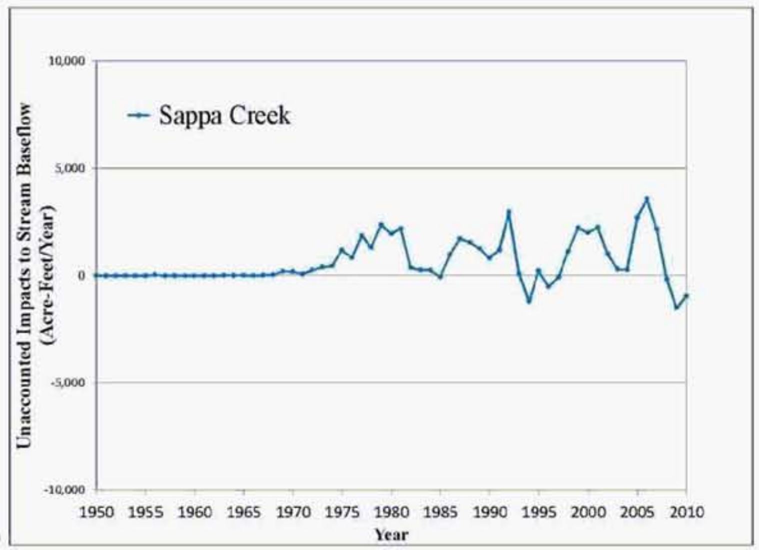

Figure 16. The Unaccounted Impacts for a) the Main Stem above Swanson, b) Beaver Creek, c) Frenchman Creek, and d) Sappa Creek.

Recall from Section 4.4.1 that the Unaccounted Impacts in the Swanson-Harlan Reach were negative (figure 12). Notice that for many of the sub-basins and years in figure 16, the Unaccounted Impacts are positive. If the Unaccounted Impacts are summed for the entire Basin, these problems are masked because, in many years, negative and positive values roughly balance each other (figure 17). This is a false assessment of this problem, however, for several reasons. First, the various sub-basins and the Main Stem all have different Allocations assigned to each of the three states out of the sub-basins. Second, regarding the impacts of groundwater pumping, the presence and magnitude of each state's impact on the sub-basins and the Main Stem vary across the Basin. Finally, and most importantly, the accounting problems that arise in the sub-basins and Main Stem reaches impacted primarily by mound recharge and Nebraska groundwater pumping (e.g., Swanson-Harlan Reach) dramatically impact Nebraska, as discussed in Section 4.4.1 and shown in figure 14. ***The Unaccounted Impacts in the Swanson-Harlan Reach cannot be balanced under current Compact accounting by additional Unaccounted Impacts in other sub-basins.*** In other words, these two wrongs do not make it right. The Unaccounted Impacts in the other sub-basins simply add to the total problem of adverse effects on Nebraska's annual Compact accounting balance.

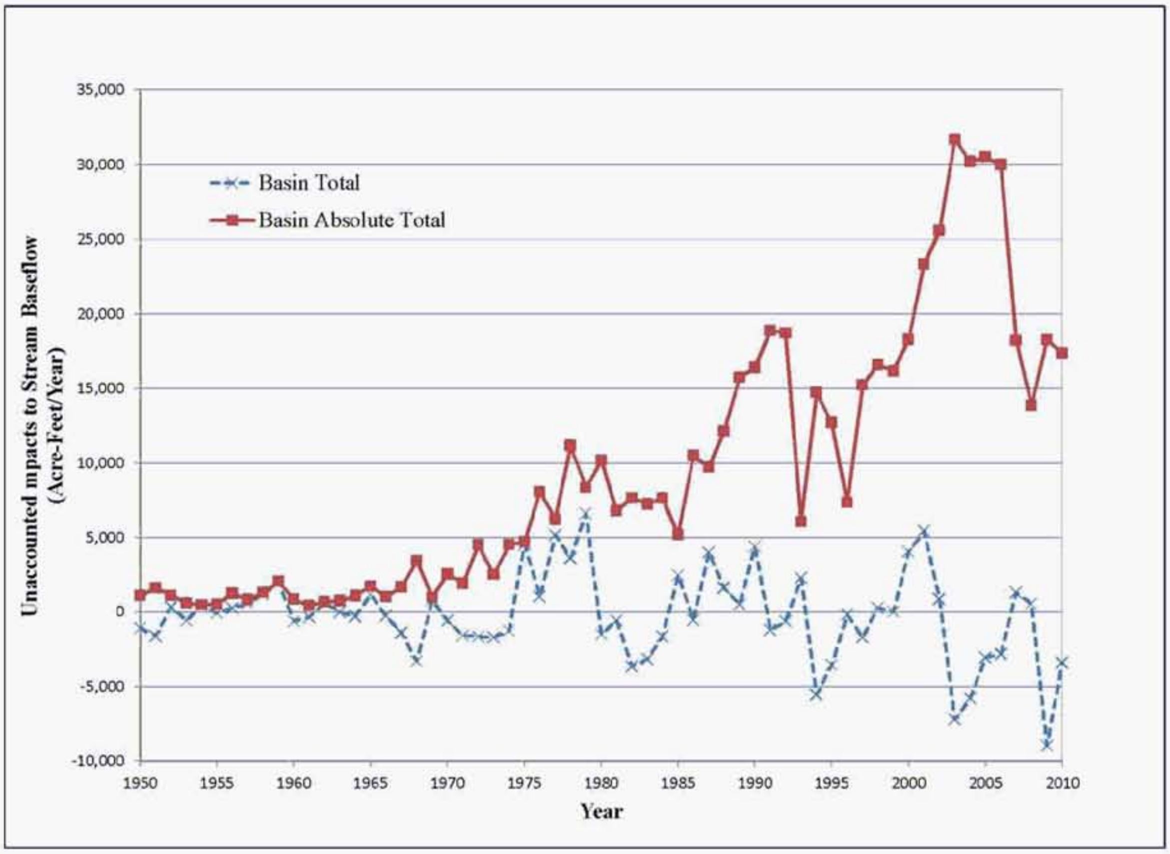

Figure 17. The sum of Unaccounted Impacts for the entire Basin (Basin Total), and the sum of the absolute value of the Unaccounted Impacts for the entire Basin (Basin Absolute Total).

Computing the absolute values[18] of the Unaccounted Impacts shows the full magnitude of the failure of the Current Accounting Procedures across the Basin. All values are assigned a positive sign, and then summed together as shown by the Basin Absolute Total in figure 17. In recent years the total magnitude of the Unaccounted Impacts has been approximately 30,000 acre-feet per year. The failure of the Current Accounting Procedures has deprived Nebraska of Compact entitlements of up to 10,000 acre-feet per year in recent years, as shown in Section 6.1.

[18] The absolute value of a number is the numerical value of that number regardless of its sign. The absolute value of a number can be thought of as its distance from zero.

5.0 THE SOLUTION

As demonstrated in Section 4, the problem with the Current Accounting Procedures occurs in many sub-basins and Main Stem reaches. Four total Target Sets are present in Republican River Compact Accounting, and the number of individual Target Sets involved in determining impacts from these Target Sets varies by sub-basin/Main Stem reach and over time. Therefore, a solution that can deal with any combination of these four Target Sets is developed below. The changes to the RRCA Accounting Procedures and Reporting Requirements (revised August 8, 2010) required to implement Nebraska's Proposed Procedures are explained in Appendix E.

5.1 Criteria for Appropriate Solution

Several important general qualities are desirable in any procedure that is used to estimate the quantity of something (e.g., the individual impact of two people on a scale or of two Target Sets on Virgin Stream Baseflow). First, the procedure needs to produce reasonable and realistic results. Second, the procedure should not be arbitrary. When no reason to apply any ordering exists, the assignment of impacts should not depend on an arbitrary ordering.

In order to develop, Nebraska's Proposed Procedures, two criteria were defined to be consistent with these qualities. The first criterion is that Nebraska's Proposed Procedures should produce individual values for impacts of Target Sets that when summed together are equal to the Total Impact of the combination of the Target Sets. This concept is identical to the VWS Metric proposed by Kansas (Appendix B). This criterion meets the requirement for apparently realistic results, but, more precisely, the results should not just seem realistic but should be verifiable and reproducible by a separate test. This process of verification involves running the Model with all Target Sets On, running the Model with all Target Sets Off, and comparing the resulting stream baseflows.

The second criterion is that impacts should be determined using the same modeling approach used in the Current Accounting Procedures, and when the Current Accounting Procedures already meet the first criterion, the result of Nebraska's Proposed Procedures should be identical. Thus, in addition to the general qualities that the accounting process produce realistic results and not be arbitrary, the following specific criteria are also met in development of Nebraska's Proposed Procedures:

1) The sum of the individually derived impacts should equal the Total Impacts.

2) The result obtained from Nebraska's Proposed Procedures should be identical to that of the Current Accounting Procedures in all cases in which the Current Accounting Procedures' results already satisfy criterion (1) above. This also

means that any given Target Set would only be simulated as fully On or fully Off[19].

Nebraska Proposed Procedures, outlined below, are consistent with these criteria.

5.2 Nebraska's Proposed Procedures

As previously mentioned, four Target Sets are applied in the Model in the Republican River Compact Accounting: 1) groundwater pumping in Nebraska, 2) groundwater pumping in Kansas, 3) groundwater pumping in Colorado, and 4) the mound recharge. The number of combinations that are possible for a given number of Target Sets, assuming each Target Set is either fully On or fully Off, is equal to 2^n (two to the power of n), where n is equal to the number of Target Sets of interest. For the case in which four Target Sets are of interest, the total number of combinations is equal to 16 ($2^n = 2^4$ = two to the power of four = 2 * 2 * 2 * 2 = 16). These are shown in table 4.

Nebraska's Proposed Procedures utilize the Model to complete simulations that represent these 16 combinations. The letters in the Run Name column represent which Target Set is On during the run. For instance, C indicates that groundwater pumping in Colorado is On, K indicates that groundwater pumping in Kansas is On, N indicates that groundwater pumping in Nebraska is On, and M indicates that the mound recharge is On. The symbol θ (the Greek letter "Theta") is used to indicate the model run with all four Target Sets Off.

The output of Model run θ includes the Virgin Stream Baseflows in the sub-basins and Main Stem reaches. The other runs represent the Remaining Stream Baseflow in the presence of one or more of the Target Sets of stresses. Table 5 shows the combinations of Model runs that represent the Apparent Impact calculation obtained from the Current Accounting Procedures.

Recall that the Unaccounted Impacts are the difference between the Total Impacts and the sum of Apparent Impacts:

Unaccounted Impacts = Total Impacts – Sum of Apparent Impacts.

[19] This criterion was separated into two criteria in earlier reports (NDNR et al., 2008; Ahlfeld et al., 2009).

Table 4. The 16 potential combinations of Target Sets with each Target Set either fully On or fully Off.

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

When the sum of the Apparent Impact values is equal to the Total Impacts, there are no Unaccounted Impacts and the result of the calculations in table 5 is adequate. When there are Unaccounted Impacts, these must be assigned to each Target Set in some manner by combining some portion of the Unaccounted Impact with the Target Set's Apparent Impact. This assignment must be based on the Targets Set's ability to have caused the Unaccounted Impact. In Nebraska's Proposed Procedures, this is accomplished by using the difference of the Potential Impact and the Apparent Impact. In contrast to the situation with only two Target Sets, the evaluation of Potential Impact with four Target Sets is complex. For each Target Set of interest, eight differences can be evaluated, in which the Target Set is On in one Model run and Off in another Model run, while all other Target Sets remain unchanged. These are all considered in developing the methodology for determination of the Potential Impact for each Target Set, as described in Appendix F.

Table 5. The Apparent Impact calculations used in the Current Accounting Procedures.

Calculation	Result
CKMN-KMN	Apparent Impact of Colorado pumping
CKMN-CMN	Apparent Impact of Kansas pumping
CKN-CKMN[20]	Apparent Impact of mound recharge
CKMN-CKM	Apparent Impact of Nebraska pumping

The basic equation for calculating the Assigned Impact with four Target Sets is:

Assigned Impact = Apparent Impact + [(Potential Impact – Apparent Impact)/4]

Combining the Potential Impact with the Apparent Impact according to this equation, and rearranging terms yields the following equations for determining the Assigned Impact for these four Target Sets:

Assigned Impact of groundwater pumping in Colorado = [(θ-C) + ((K-CK) + (M-CM) + (N-CN))/3 + ((KM-CKM) + (KN-CKN) + (MN-CMN))/3 + (KMN-CKMN)]/4

Assigned Impact of groundwater pumping in Kansas = [(θ-K) + ((C-CK) + (M-KM) + (N-KN))/3 + ((CM-CKM) + (CN-CKN) + (MN-KMN))/3 + (CMN-CKMN)]/4

Assigned Impact of groundwater pumping in Nebraska = [(θ-N) + ((C-CN) + (M-MN) + (K-KN))/3 + ((CM-CMN) + (CK-CKN) + (KM-KMN))/3 + (CKM-CKMN)]/4

Assigned Impact of mound recharge = [(M-θ) + ((CM-C) + (KM-K) + (MN-N))/3 + ((CKM-CK) + (CMN-CN) + (KMN-KN))/3 + (CKMN-CKN)]/4

These are Nebraska's Proposed Procedures. Application of these equations, utilizing the appropriate Model output for each Model run, produces results that:

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[20] The differences in this equation, and all other equations for calculation of the impact of mound recharge (IWS Credit) are reversed to produce a positive result. The convention in Compact Accounting is to represent the IWS Credit as a positive value, then to subtract it in the accounting to generate a "credit." The effect is the same as producing a negative value and then adding it into the Accounting balances.

- Always fully distribute any Unaccounted Impacts, such that the sum of these impact estimates always equals the Total Impacts;
- Always produce the same results as the Current Accounting Procedures when there are no Unaccounted Impacts; and
- Always produce the same results as the simpler equations for two Target Sets (see Appendix C) when there are only two Target Sets that impact a given sub-basin or Main Stem reach.

Examples of these cases using the scale analogy are presented in Appendix G.

5.3 Application to the Swanson - Harlan Reach

For the purpose of demonstrating the effect of the Nebraska's Proposed Procedures relative to the Current Accounting Procedures, results are presented for the Swanson-Harlan Reach for groundwater pumping in Nebraska and for mound recharge. Kansas and Colorado both have minor impacts to this reach in some years. Nebraska's Proposed Procedures produce individual values for the impact of groundwater pumping and mound recharge that sum to the Total Impact of these Target Sets on the Swanson to Harlan Reach. Recall that Nebraska's Proposed Procedures start with the Apparent Impact (result of Current Accounting Procedure) and add an Appropriate Assignment of the Unaccounted Impacts (if any) to each Target Set based on their ability to have caused the Unaccounted Impacts.

Figures 18 and 19 show the Apparent Impacts and Assigned Impacts from Nebraska's Proposed Procedures for groundwater pumping in Nebraska and mound recharge, respectively. Notice that Nebraska's Proposed Procedures only produce a different result when Unaccounted Impacts exist. The same is true for the impact due to groundwater pumping in Kansas and the mound recharge. The difference between the Apparent Impact and the Assigned Impact is roughly proportional to the difference between the Potential Impact and the Assigned Impact. This is because only two Target Sets (Nebraska groundwater pumping and mound recharge) have a significant effect on Virgin Stream Baseflow in this reach.

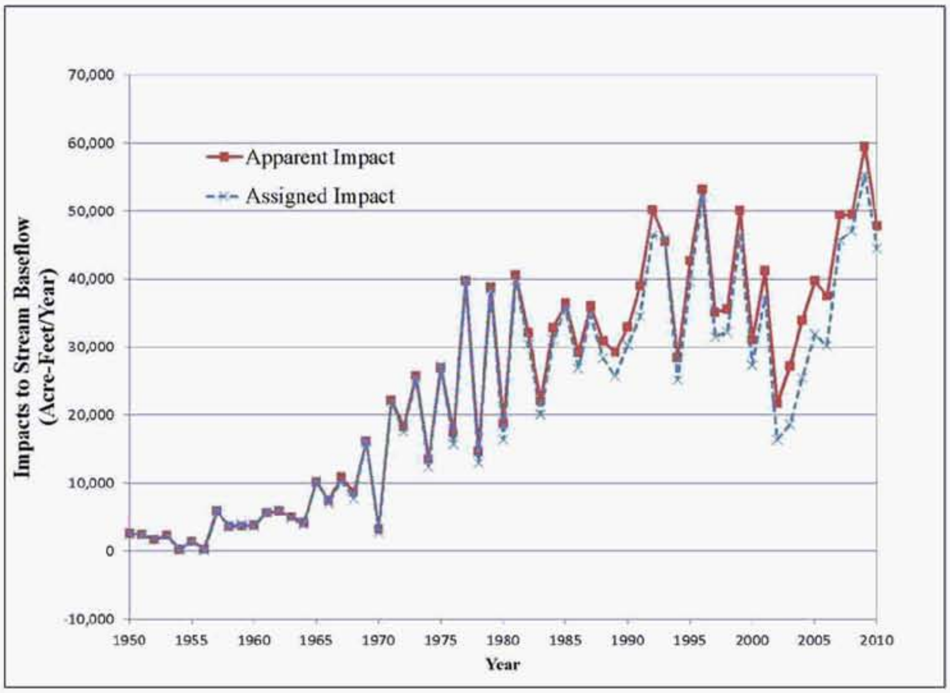

Figure 18. The Assigned Impact and the Apparent Impact for groundwater pumping in Nebraska in the Swanson-Harlan Reach.

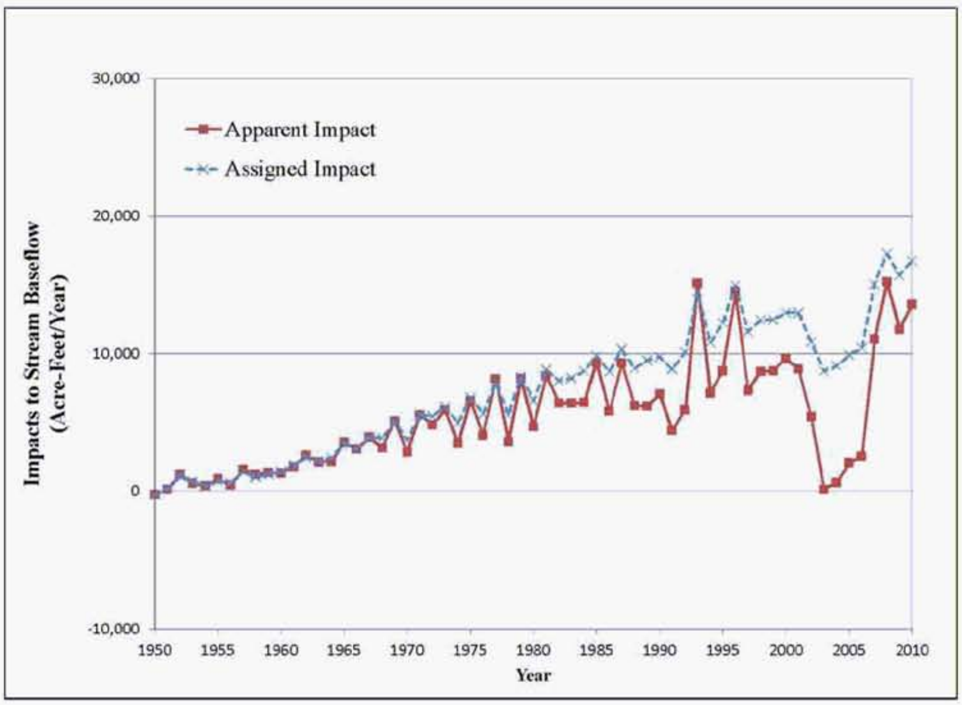

Figure 19. The Assigned Impact and the Apparent Impact for mound recharge in the Swanson-Harlan Reach.

The Appropriate Assignment of Unaccounted Impacts is approximately equally split between Nebraska groundwater pumping and mound recharge (figure 20). The Unaccounted Impacts assigned to groundwater pumping in Kansas and Colorado are essentially zero. Therefore, the Assigned Impact from Nebraska's Proposed Procedures is essentially equal to the results of the Current Accounting Procedures for these two Target Sets. This is because Kansas groundwater pumping and Colorado groundwater pumping have little or no ability to cause the Unaccounted Impacts in this reach.

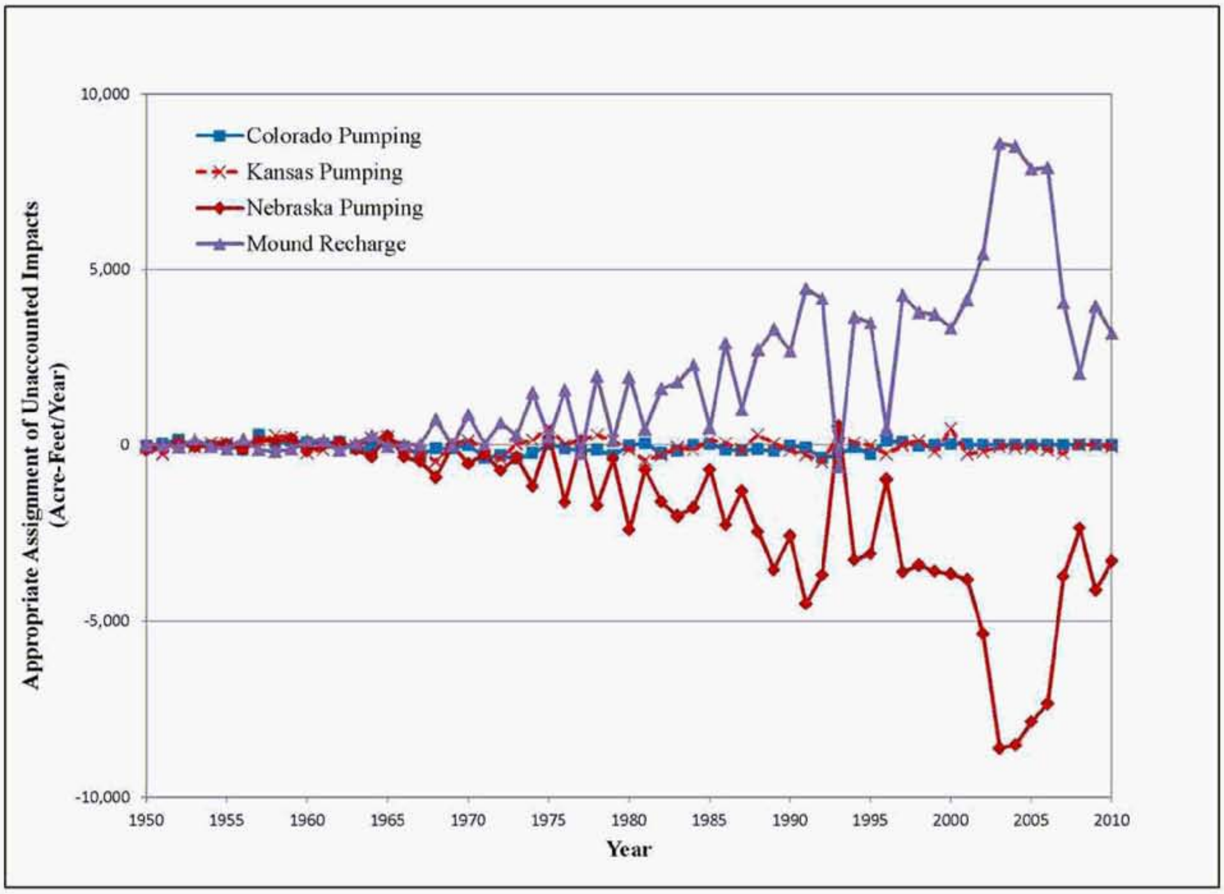

Figure 20. The Appropriate Assignment of Unaccounted Impacts for Colorado groundwater pumping, Kansas groundwater pumping, Nebraska groundwater pumping and mound recharge in the Swanson-Harlan Reach.

5.4 Future Benefit of Mound Recharge under Proposal

Recall from Section 4.4.2 (see figure 15) that the Current Accounting Procedures produce an absurd result with respect to the benefit of continued mound recharge. Using the future scenario developed by Kansas, the Current Accounting Procedures would make it appear that continuing the mound recharge would actually be harmful to the Basin and to Nebraska's compliance ability in the future. Mound recharge is an activity of man that actually increases the water supply of the Basin; the FSS recognized that Nebraska should receive full credit for that beneficial activity. Under the Current Accounting Procedures, for the simulations presented here, the continuation of the mound recharge is detrimental to Nebraska.

Figure 21 shows the same information for the same scenario shown in figure 15 above, except that the depletions due to groundwater pumping in Nebraska and the mound recharge are determined using Nebraska's Proposed Procedures. Under these latter procedures, the continuation of the IWS recharge actually does create a credit for Nebraska and if the mound recharge were to be permanently discontinued (all other things being equal) Nebraska's annual Compact balance would be diminished. This is a reasonable result. This is a perfect example of how Nebraska's Proposed Procedures address the issues arising from the application of the Current Accounting Procedures in certain instances.

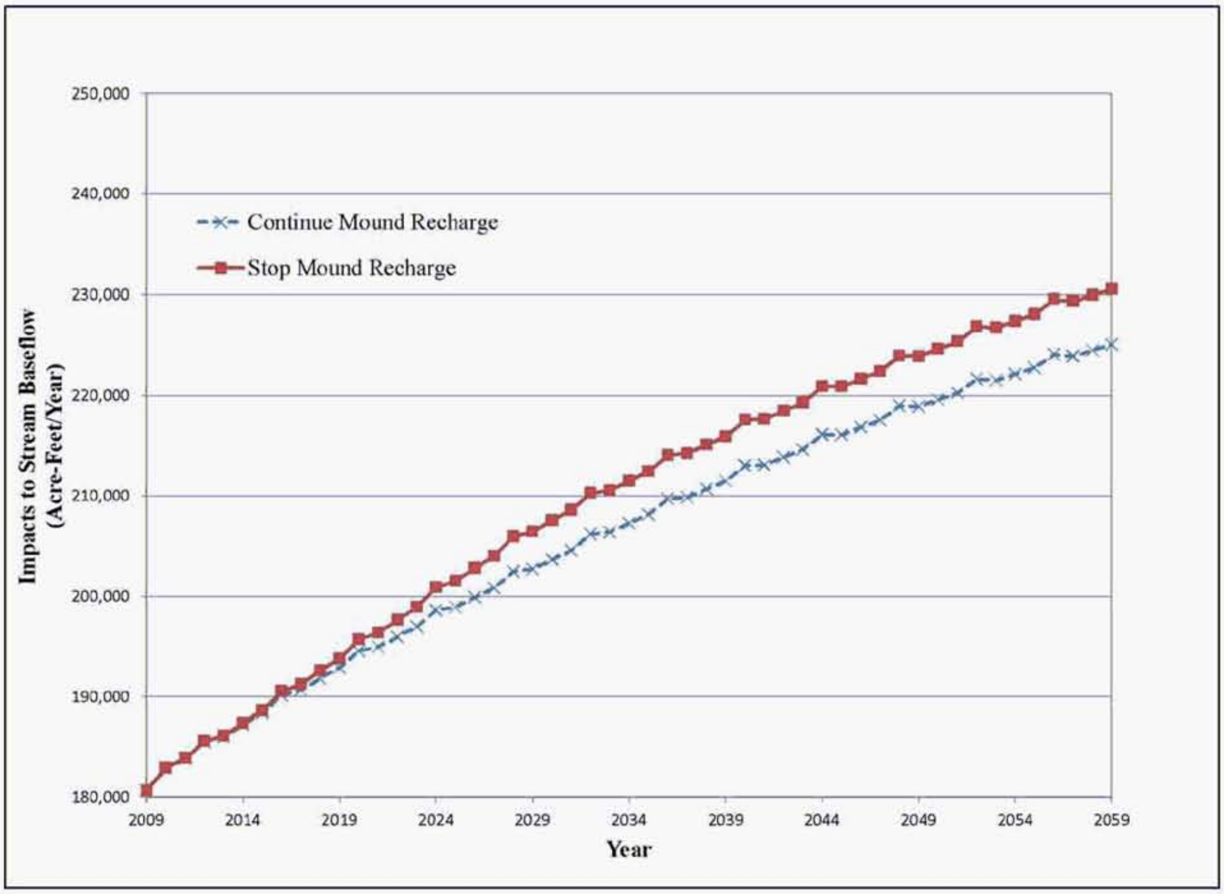

Figure 21. Basin-wide Assigned Impact of Nebraska pumping and mound recharge (CBCU-IWS Credit) under the Kansas future scenario with mound recharge continuing and mound recharge not continuing. The difference between these two lines was previously illustrated in figure ES-3.

6.0 SIGNIFICANCE

In Section 4, the problem with the Current Accounting Procedures in the Swanson-Harlan Reach was analyzed. The results of the Current Accounting Procedures cause harm to Nebraska's annual Compact accounting balances, in amounts exceeding 8,000 acre-feet per year in recent years. Using Nebraska's Proposed Procedures developed in Section 5, the annual Compact accounting balances from previous years can be computed in a manner that accounts for the Total Impacts. In this section, the Basin-wide effect of this problem, if left unresolved, will be illustrated for past and future years. In the recent past, the basin-wide harm to Nebraska was approximately 10,000 acre-feet per year. The potential effect of this problem in future years may exceed 20,000 acre-feet per year.

6.1 Results of Previous Accounting

Figure 22 shows the net change (Nebraska's Proposed Procedures minus Current Accounting Procedures) in Nebraska's annual Compact accounting balance[21] calculated back to 1981. Note several things from this graph. First of all, the Current Accounting Procedures are always detrimental to Nebraska. In one year (1993), the difference was very nearly zero. Otherwise, the difference has generally been at least 1,000 acre-feet per year. Second, for the period 1981-2000, the difference was generally between 1,000 and 5,000 acre-feet per year; the five-year moving average was generally between 2,000 and 4,000 acre-feet per year; and the average difference was about 3,300 acre-feet per year. The difference slowly increases by about 150 acre-feet per year during this period. Also note that, during the drought of 1988-1991, no significant change in this discrepancy can be seen. Next, notice that for the period after 2000, the difference increases dramatically. The average difference during this time period is about 8,000 acre-feet per year. In four of these years, including the period 2005-2006, the difference is approximately 10,000 acre-feet per year. Based on the trend from 1981-2000, even if this issue had been fully understood at the time of the settlement, this level of discrepancy should not have been expected until the year 2035. Although any discrepancy is unacceptable, this alarming increase in recent years, coming during a critical dry period with regard to Compact compliance, underscores the importance of resolving this issue.

[21] These Compact balances were derived from Table 3C of accounting procedures.

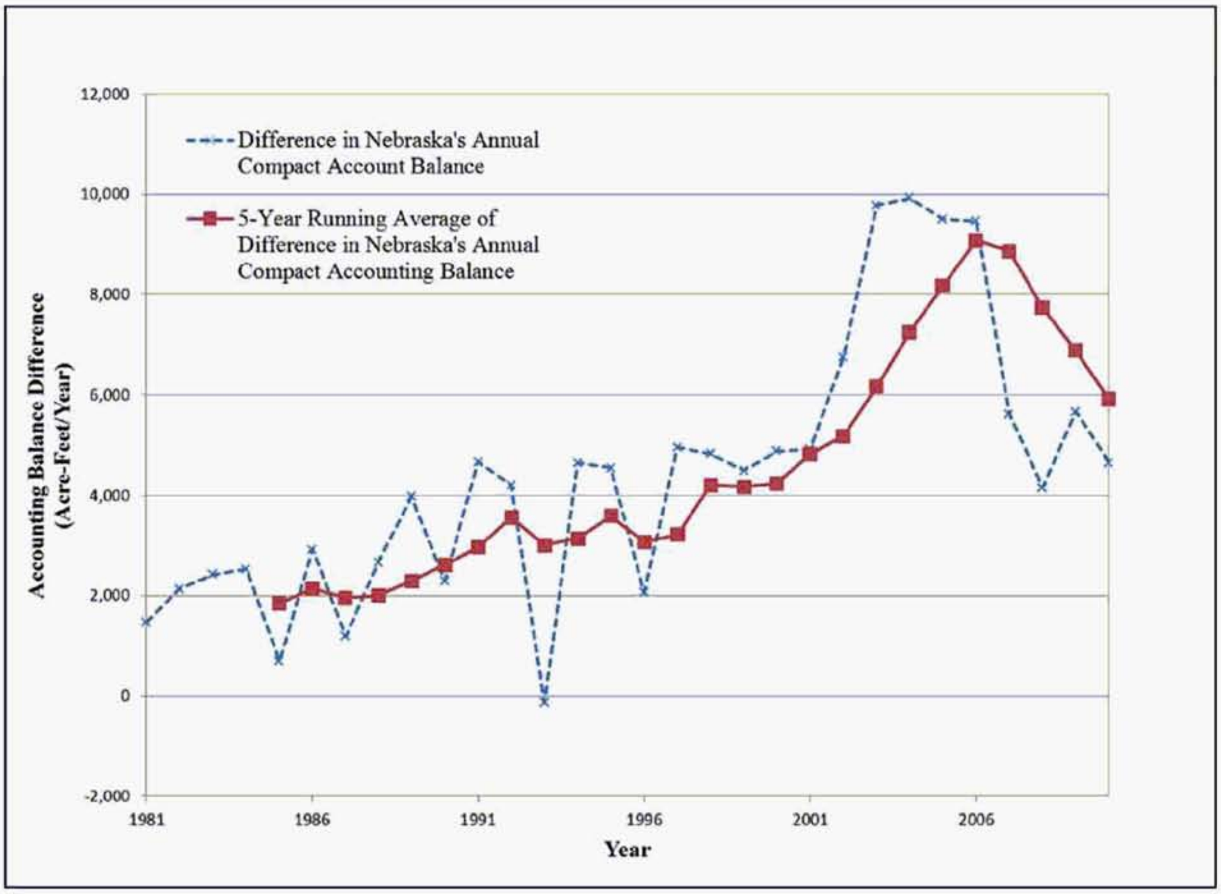

Figure 22. The historic difference in Nebraska's annual Compact accounting balances between the Apparent Impact and the Assigned Impact. A positive value indicates a ***detriment*** to Nebraska's Compact balance.

6.2 Future Results if Left Unresolved

It is not possible to know with certainty if this discrepancy, left unresolved, will continue to increase at such an alarming rate. The analysis presented by Kansas in their Petition to the Supreme Court (Kansas Petition C20) can be used to examine how this discrepancy affects the future compliance picture for Nebraska. This analysis utilized average conditions that were repeated for a period of 50 years. The difference (Nebraska's Proposed Procedures minus Current Accounting Procedures) in Nebraska's annual compliance balance under this future scenario is shown in figure 23.

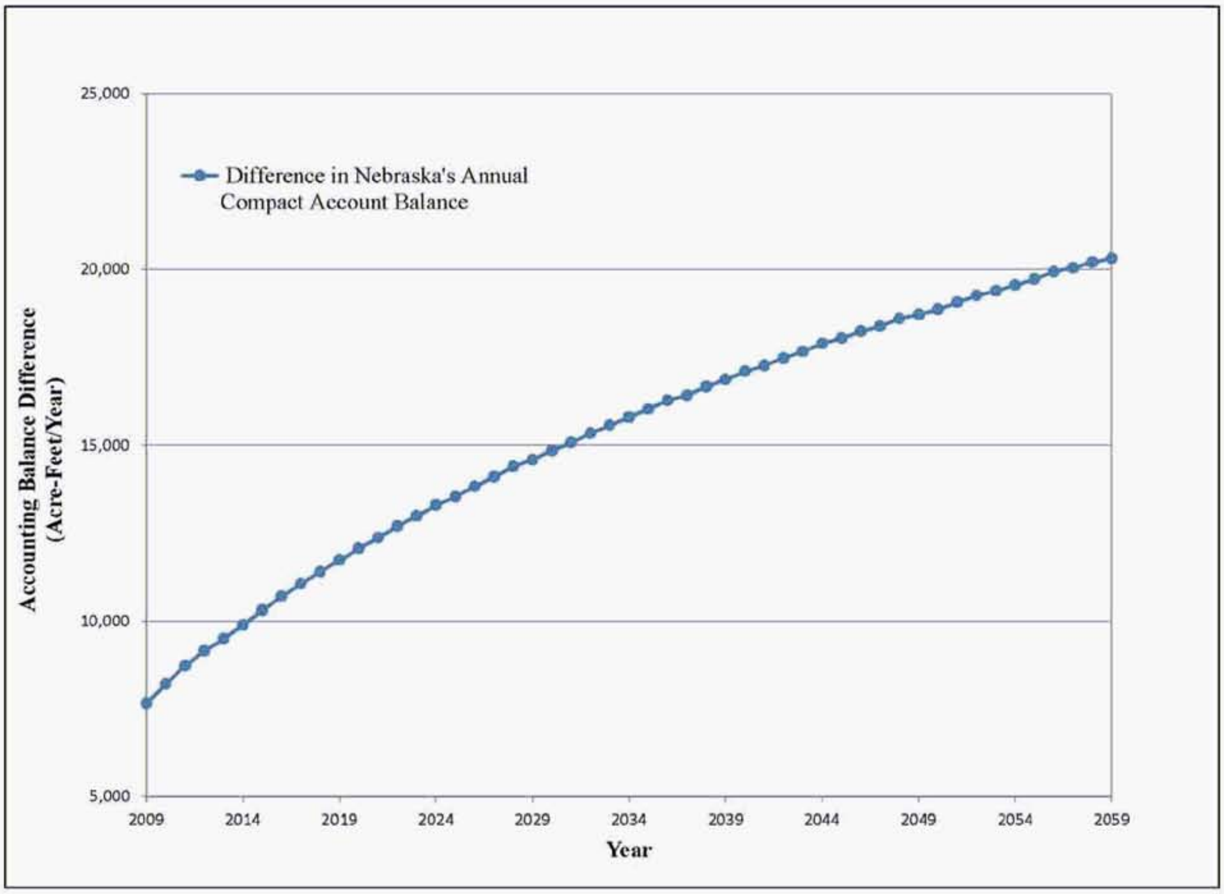

Figure 23. The future difference in Nebraska's annual Compact accounting balances between the Apparent Impact and the Assigned Impact, using the Kansas future scenario. A positive value indicates a ***detriment*** to Nebraska's Compact balance.

As this figure shows, the discrepancy grows significantly over time under this scenario, increasing to greater than 20,000 acre-feet per year after 50 years. Remember that this scenario utilizes average conditions; recent experience has shown that this discrepancy is worst in dry years. Without question, the Current Accounting Procedures cause a result that is significantly injurious to the State of Nebraska and her water users. The economic impact that would be created by a future need to compensate for this accounting problem would be immense. Over this fifty-year period, Nebraska would need to under-utilize its Compact entitlement by nearly 800,000 acre-feet of water. This amounts to approximately one-quarter of a ***trillion*** gallons of water. Put another way, this would provide an average annual public water supply for a city of 80,000 people (Hutson et al., 2004), larger than the city of Portland, Maine. In agricultural terms, tens of thousands to hundreds of thousands of acres[22] of irrigation would need to cease. In addition, this is only a fifty-year projection; the Compact has already been in place for longer than 60 years, and water use for irrigation has existed in the basin for more than 100 years. Therefore, the insistence by Kansas and Colorado on continuing the use of the Current Accounting Procedures produces a gross harm to the State of Nebraska and its water users. These accounting procedures must be changed, and Nebraska's Proposed Procedures should be implemented.

[22] Generally, irrigators in the Republican Basin are allowed between 9 to 12 inches of water per year. However, pumping one acre-foot of groundwater can have a much lower effect to streamflow, depending on the proximity to the stream. Therefore, an acre-foot of stream depletions can irrigate much more than an acre of ground in some cases.

7.0 SUMMARY

Republican River Compact Accounting began approximately 50 years ago and has been refined numerous times, as engineering knowledge has advanced and as physical changes have occurred in the basin. The Current Accounting Procedures fail to determine the impacts of groundwater pumping in each state and of mound recharge. Nebraska's Proposed Procedures must be adopted because

- They eliminate Unaccounted Impacts, effecting a better accounting of the VWS, the volume of water each state receives, the IWS Credit, and the State's annual Compact accounting balances.
- The Current Accounting Procedures yield an absurd result for the Total Impact of groundwater pumping and the mound recharge.
- The result of the Current Accounting Procedures is detrimental to Nebraska, and provides unwarranted benefits to Kansas and Colorado.
- Nebraska's Proposed Procedures are not a wholesale alteration, but rather a necessary refinement, that yields essentially the same result as the Current Accounting Procedures in cases in which there are no Unaccounted Impacts.
- If the problem remains uncorrected, Nebraska will be required to consume less water than the quantity to which it is entitled under the Compact. This is tantamount to a redistribution of the Virgin Water Supply Allocations specified in the Compact.

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APPENDIX A. Curriculum Vitae for James C. Schneider, Ph.D.

Areas of Specialization

- Water resources management and planning
- Ground-water flow modeling
- Administration of interstate water Compacts, Decrees, and Agreements
- Hydrogeology
- Statistical analysis of hydrologic data
- Surface-water hydrology
- Environmental geophysics

Education

- Ph.D. in Geology (May 2003) - University of South Florida, Tampa, FL
- M.S. in Geology (May 1998) - Northern Illinois University, DeKalb, IL
- B.S. in Geology (May 1996) - Northern Illinois University, DeKalb, IL

Professional History

- **Deputy Director (2010-)** ***Nebraska Department of Natural Resources (DNR)***

  Responsibilities: Advising and assisting the Director in formulating and administering department policies, budget, organization, and work assignments; assisting in formulation of state water policies, particularly as they pertain to water quantity issues, including serving as liaison with the legislature, other state and local agencies, and public interest groups; overseeing the general administration of the department and assuming responsibility for the department's operation in the Director's absence; assisting the Director in administration of interstate compacts and decrees; serving as the State's Representative on technical committees for compacts and decrees; overseeing the work of consultants and preparing special reports related to surface water or surface and ground water interactions; assisting the Director in reviewing permit applications and groundwater management plans; and assisting the Director in water rights hearings and analysis of permit applications; supervising the Integrated Water Management Division.

- **Head, Integrated Water Management Division (2008-2009)** ***Nebraska DNR***

  Responsibilities: Manage the integrated water management planning process at the Department, including oversight of surface- and groundwater related studies, development and implementation of integrated management plans, supervision of the Integrated Water Management Division and coordination with other Department Divisions, Natural Resources Districts, and other State and Federal agencies.

- **Senior Groundwater Modeler (2007)** ***Nebraska DNR***

  Responsibilities: Serve as NDNR groundwater flow modeling expert.

- **Senior Hydrogeologist/Geophysicist (2006)** ***SDII Global Corporation***

  Responsibilities: Manage hydrogeology and geophysics projects and prepare contract reports and publications. Serve as company groundwater flow modeling expert. Serve as company geophysics expert.

- **Staff Geologist (2003 – 2005)** ***SDII Global Corporation***

  Responsibilities: Conduct hydrogeology projects and prepare hydrogeology contract reports and publications. Assist senior staff as technical resource for litigation and peer reviews of technical reports. Serve as company groundwater flow modeling expert. Serve as resource to subsidence investigation group.

- **Research Assistant (1998 – 2002)** ***University of South Florida, Geology Dept.***

  Responsibilities: Conducting field research, data interpretation, geophysical surveys and groundwater model development for a variety of projects throughout Florida as well as in other states and in Jamaica. Teaching undergraduate and graduate level lab and lecture courses.

Publications

Schneider, J.C., S.B. Upchurch, J. Chen, C. Cain, J. Good, 2008. Simulation of groundwater flow in North Florida and South-central Georgia. Peer reviewed technical report issued to the Suwannee River Water Management District.

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Interstate Organizations

- **Republican River Compact Administration (2007-)**

  Responsibilities: Participate in Engineering Committee and Compact Administration Meetings representing State of Nebraska. Serve as official representative on the Engineering Committee beginning in 2010.

- **Platte River Recovery Implementation Program (2007-)**

  Responsibilities: Participate in Water Advisory Committee and in implementation of Nebraska New Depletions Plan. Represent Nebraska on the Governance Committee (Chair 2011) and the Finance Committee beginning in 2010.

- **North Platte Decree Committee (2010-)**

  Responsibilities: Nebraska alternate to the North Platte Decree Committee.

- **Interstate Council on Water Policy (2010 -)**

  Responsibilities: Represent Nebraska on Committees and at annual meetings. Elected to the Board of Directors in 2011.

Expert Witness Testimony

- **Non-binding arbitration in *Kansas v. Nebraska & Colorado*, No. 126 Orig. (2008)**

  Responsibilities: Provide deposition and trial testimony in non-binding arbitration initiated in October 2008 relating to Kansas' claims for damages and future compliance and Nebraska's proposal to fix accounting errors.

- **Non-binding arbitration in *Kansas v. Nebraska & Colorado*, No. 126 Orig. (2010)**

  Responsibilities: Provide deposition and trial testimony in non-binding arbitration initiated in May 2010 relating to Nebraska's crediting issue and Colorado's augmentation pipeline.

APPENDIX B. The Kansas Virgin Water Supply Metric

On September 18, 2007, Kansas provided Nebraska with a memo[23] summarizing their views of the Current Accounting Procedures and the issues Nebraska had brought up relative to those procedures (herein referred to as the VWS Metric Memo). This memo is attached to the end of this Appendix as Exhibit A.

Kansas began the VWS Metric Memo by summarizing their understanding of Nebraska's concerns at that time. Then Kansas went on to describe what the model is intended to accomplish, some of the consideration given to this in developing the Current Accounting Procedures leading up to the signing of the FSS, and a test they applied to Nebraska's proposal and the results of the Current Accounting Procedures.

Kansas points out that '[t]he only question with respect to the Model's result s (sic) that affect compact compliance is the extent to which activities in a state, either pumping or importation of water, affect base flow in the Republican River. To the extent these activities affect base flows in the river, ***they must be counted***." (Emphasis added) Kansas further noted that "[i]t is clear that (sic) only quantification that is relevant to the compact accounting is the depletion or accretion to Republican River stream flow."

After a brief discussion about impacts to the Republican River from pumping and recharge that occurs outside the basin, Kansas continued:

> In order to provide this quantification using the groundwater model, it was agreed in the settlement that the impact of each state's pumping or water importation would be determined by comparing the model-computed historical base flow condition to the model-computed base flow condition without that activity. The states recognized that the sum of the impacts of these individual activities would not necessarily exactly equal the model-computed impact of all of the activities considered simultaneously. If the groundwater model were mathematically linear, it would, in fact, be the case that the sum of the individual affects (sic) would equal the affect (sic) determined by considering all of the activities simultaneously. However, because the groundwater model is mildly non-linear, this mathematical equality does not occur.
>
> It should be noted that if the impact of all activities considered simultaneously were used, it would be necessary to have a method for apportioning the impact among the various activities. Such a process was considered unnecessary and it was agreed that the impacts from each state's activity would be computed separately in spite of the fact that the sum of those impacts may not exactly equal the impact of all activities considered simultaneously.

[23] Kansas' Review of Nebraska's Request for Change in Accounting Procedure, September 18, 2007

Nebraska understands that the Current Accounting Procedures, as included in the FSS, determine the impact of each activity (pumping in a state or recharge of the IWS) by comparing the historic model run with all activities included to a run with the specific activity not included. Kansas is apparently arguing here that the States accepted this process, in spite of clear understanding that the sum of the impacts of these activities would not ***exactly*** equal the model computed impacts of all of these activities considered simultaneously (i.e. total impacts, VWS Metric). Nebraska agrees that a very small departure between the sum of these impacts and the total impact might be acceptable, considering that, as Kansas further notes, a method for apportioning the total impacts would otherwise need to be developed. In fact, the definition of Computed Beneficial Consumptive Use included in the RRCA Accounting Procedures specifically excludes small uses of water (e.g., irrigation of less than two acres of land, non-irrigation diversions of less than 50 acre-feet). However, as demonstrated in this report, in several of the sub-basins, particularly in recent years (post-FSS), it is not a matter of whether the two methods match exactly, but rather a situation where the Current Accounting Procedures deviate from the total impact by ***thousands*** of acre-feet per year. Therefore, Nebraska has determined that a process for apportioning the total impact among the various activities is now necessary, because it is now clearly not simply a matter of the sum of the currently determined impacts matching somewhat less than exactly.

Kansas next goes on to define a VWS Metric and describe what it represents:

> The ultimate goal of the RRCA Groundwater Model is to provide a measure of what base flows would have been if the States had not pumped groundwater or recharged imported water. That overall measure could be determined by comparing the model-computed historical stream flows to the model-computed stream flows with all pumping and recharge of imported water removed from the analysis (herein referred to as the "virgin water supply metric"). This measure gives us the total impact on stream flows caused by the States' pumping and the recharge of imported water. As described above, however, this result does not apportion the impact among the States. Conceptually, the condition with no pumping and no imported water represents what the stream flows would have been if none of this activity had occurred. In that sense, it represents a "virgin water supply" condition with respect to the modeled elements of the groundwater model and their impact on Republican River stream flows.
>
> This measure does provide a metric for comparing the accounting method agreed to in the settlement with Nebraska's alternative accounting proposal. It is a relatively straightforward process to add up the impacts using the accounting method agreed to in the settlement or to add up the impacts from Nebraska's alternative accounting proposal and compare those totals to the virgin water supply metric described above. If the Nebraska alternative accounting proposal provides a better approximation of this metric, it is worthy of further consideration.

The second paragraph in this quote from the VWS Metric Memo might seem to indicate that the VWS Metric is only a test of potential alternative methodologies for determining the impact of the three States pumping and the IWS. However, subsequent to receiving this Memo, in order to fully understand the VWS Metric, Nebraska requested clarification from Kansas as to the exact Model runs that were performed to compute the VWS Metric. The reply stated:

> The "virgin water supply metric" is the difference [between] two runs: 1) a new run which simultaneously turns off CO pumping, KS pumping, NE pumping, and the mound imports minus 2) the Base run done as per the RRCA accounting procedures. ***It thus determines the net impact of all these effects of man in one impact run*** (emphasis added).[24]

This makes the Kansas position regarding the VWS Metric very clear; it represents the "net impact" of these four activities of man, namely pumping in the three States and the mound recharge. Nebraska agrees that this VWS Metric is the best estimate that we can generate (given the current Model) of the net impact of these four activities of man. This is identical to the Total Impact values used throughout this report.

[24] Email transmission from David Barfield sent September 18, 2007, attached to this Appendix as Exhibit B.

Exhibit A

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

This memo is intended to summarize Kansas' understanding of the Nebraska's proposal for changing the agreed upon method of computing pumping impacts using results from the Republican River Compact Administration Groundwater Model (Model) and to summarize our initial response to the proposal.

Nebraska believes that the calculation of pumping impacts using results from the groundwater model improperly includes the consumption of imported water. Nebraska argues that because some of the water pumped by wells is or could be water that originated from imported water, the consumption of that water should not be counted in determining the virgin water supply in the accounting process. This argument is difficult to understand since no one has ever determined the specific origin of groundwater that is pumped and consumed. In other words, whether the origin of the pumped water is from natural recharge within the Republican River basin, natural recharge outside the Republican River basin, stored groundwater, or imported water has never been determined and probably cannot be determined with any degree of reliability.

In terms of the use of the Model to determine compliance with the Compact, however, the specific origin of the water that is pumped and consumed is not the determining factor. The only question with respect to the Model's result s that affect compact compliance is the extent to which activities in a state, either pumping or importation of water, affect base flow in the Republican River. To the extent these activities affect base flows in the river, they must be counted. In other words, it is not the source of water that counts, but the depletion or accretion to base flow that is associated with the activity that determines the amount of impact that must be considered in the compact accounting process. This concept is precisely what is included in the Accounting Procedures adopted by the Settlement and what the special master based his rulings on in determining that those effects to stream flows in the Republican River are regulated by the compact. As it is stated in the Final Report of the Special Master's With Certification of Adoption of Republican River Compact Administration Groundwater Model, September 2003: "*... the RRCA Groundwater Model which would, for use in the accounting formulas for administering the Republican River Compact, determine both stream flow depletions caused by groundwater pumping and streamflow accretions resulting from recharge by imported water*" (Page 1). It is clear that only quantification that is relevant to the compact accounting is the depletion or accretion to Republican River stream flow.

The quantification of depletion or accretion to Republican River base flow is not limited to activities that are solely within the boundaries of the Republican River Basin. Recharge from imported water can cause accretion to Republican River base flow even if the recharge occurs outside the boundary of the basin. To the extent that such recharge provides accretions to Republican River base flow, it is counted in the accounting process. Similarly, pumping from locations outside the basin can cause depletions to Republican River base flow. To the extent that such pumping causes depletions to base flow, it is counted in the accounting process. Thus both positive effects (accretions) and negative effects (depletions) on Republican River base flows caused by activities outside the physical boundaries of the basin are treated equally.

In order to provide this quantification using the groundwater model, it was agreed in the settlement that the impact of each state's pumping or water importation would be determined by comparing the model-computed historical base flow condition to the model-computed base flow condition without that activity. The states recognized that the sum of the impacts of these individual activities would not necessarily exactly equal the model-computed impact of all of the activities considered simultaneously. If the groundwater model were mathematically linear, it would, in fact, be the case that the sum of the individual affects would equal the affect determined by considering all of the activities simultaneously. However, because the groundwater model is mildly non-linear, this mathematical equality does not occur.

It should be noted that if the impact of all activities considered simultaneously were used, it would be necessary to have a method for apportioning the impact among the various activities. Such a process was considered unnecessary and it was agreed that the impacts from each state's activity would be computed separately in spite of the fact that the sum of those impacts may not exactly equal the impact of all activities considered simultaneously.

Nebraska has proposed an alternative method of computing the impacts associated with each state's activity. This alternative has been proposed to correct what they see as an inappropriate accounting of consumed water. While the connection between Nebraska's proposed alternative accounting method and their concept of what water is actually consumed is far from apparent, we have evaluated the merits of this alternative method regardless of its basis.

The ultimate goal of the RRCA Groundwater Model is to provide a measure of what base flows would have been if the States had not pumped groundwater or recharged imported water. That overall measure could be determined by comparing the model-computed historical stream flows to the model-computed stream flows with all pumping and recharge of imported water removed from the analysis (herein referred to as the "virgin water supply metric"). This measure gives us the total impact on stream flows caused by the States' pumping and the recharge of imported water. As described above, however, this result does not apportion the impact among the States. Conceptually, the condition with no pumping and no imported water represents what the stream flows would have been if none of this activity had occurred. In that sense, it represents a "virgin water supply" condition with respect to the modeled elements of the groundwater model and their impact on Republican River stream flows.

This measure does provide a metric for comparing the accounting method agreed to in the settlement with Nebraska's alternative accounting proposal. It is a relatively straightforward process to add up the impacts using the accounting method agreed to in the settlement or to add up the impacts from Nebraska's alternative accounting proposal and compare those totals to the virgin water supply metric described above. If the Nebraska alternative accounting proposal provides a better approximation of this metric, it is worthy of further consideration.

Our calculations, as summarized in the table below, show that the accounting agreed to in the settlement provides a better approximation of the virgin water supply metric than the Nebraska proposed accounting method. The table shows that the accounting agreed to in the settlement results in both positive and negative annual differences from the virgin water supply metric. The resultant average for the years 1990 – 2000, the last ten years of the calibration of the model is -150 acre-feet. For the last six years, 2001-2006, the average difference is 2,053 acre-feet. The Nebraska alternative accounting proposal departs significantly further from the virgin water supply metric than the accounting method agreed to in the settlement, has a negative bias, and for the period studied is increasing.

It remains our view, based on our understanding of the agreement of the States at the time of the settlement and these results, that the current accounting methods are appropriate.

Table: Comparison of total impacts under adopted procedures and as proposed by Nebraska versus the virgin water supply metric.

Year	Virgin Water Supply Metric	Compact Method Total	Nebraska Proposed Alternative	Difference [Compact Method – Metric]	Difference [Nebraska Proposal – Metric]
1990	180542	176749	170646	-3793	-9896
1991	200582	200424	191432	-158	-9150
1992	206037	204478	195938	-1559	-10099
1993	213153	210926	212593	-2227	-560
1994	188954	194203	186345	5249	-2609
1995	219075	220673	213807	1598	-5268
1996	229586	228517	228167	-1069	-1419
1997	208878	212730	202992	3852	-5886
1998	210089	208778	200587	-1311	-9502
1999	230055	231109	222053	1054	-8002

2000	203222	199934	192856	-3288	-10366
2001	236771	230905	221333	-5866	-15438
2002	196546	195685	183123	-861	-13423
2003	221307	228528	210485	7221	-10822
2004	231704	237594	219651	5890	-12053
2005	237802	240969	224287	3167	-13515
2006	219356	222122	204589	2766	-14767
Averages:					
1990-2000	208198	208047	201583	-150	-6614
1990-2006	213745	214372	204758	627	-8987
2001-2006	223914	225967	210578	2053	-13336

Exhibit B

Schneider, Jim

From: Schneider, Jim
Sent: Tuesday, November 15, 2011 1:08 PM
To: Schneider, Jim
Subject: FW: Nebraska proposal--Privileged and Confidential Attorney-Client Communication Regarding the Republican River

James C. Schneider, Ph.D.
Deputy Director
Nebraska Department of Natural Resources

301 Centennial Mall South
Fourth Floor, State Office Building
P.O. Box 94676
Lincoln, NE 68509-4676

Office: 402-471-3141
Fax: 402-471-2900
Cell: 402-450-2744
E-Mail: jim.schneider@nebraska.gov
Web: www.dnr.ne.gov

-----Original Message-----
From: Barfield, Dave [mailto:DBARFIELD@KDA.STATE.KS.US]
Sent: Tuesday, September 18, 2007 8:14 PM
To: Schneider, Jim; Sullivan, Megan; Williams, Jim; Koester, Paul; gndwater@aol.com; mmacps@aol.com; Willem.Schreuder@prinmath.com
Cc: Justin Lavene; Theis, Ron; Steve Larson; Perkins, Sam; Dale Book; Willem.Schreuder@prinmath.com; Knox, Ken; Ann Bleed
Subject: RE: Nebraska proposal--Privileged and Confidential Attorney-Client Communication Regarding the Republican River

Jim,

The "virgin water supply metric" is the difference two runs: 1) a new run which simultaneously turns off CO pumping, KS pumping, NE pumping, and the mound imports minus 2) the Base run done as per the RRCA accounting procedures. It thus determines the net impact of all these effects of man in one impact run.

The "Compact method total" sums the CO pumping impacts, KS pumping impacts, NE pumping impacts and Mound credits as done according to the current accounting procedures.

The "NE proposed alternative" sums these same 4 impacts according to NE's proposed method.

Let me know if this is still unclear.

Thanks.

David

-----Original Message-----
From: Schneider, Jim [mailto:jschneider@dnr.ne.gov]
Sent: Tuesday, September 18, 2007 4:08 PM
To: Barfield, Dave; Sullivan, Megan; Williams, Jim; Paul Koester; gndwater@aol.com; mmacps@aol.com; Willem.Schreuder@prinmath.com
Cc: Justin Lavene; Theis, Ron
Subject: RE: Nebraska proposal--Privileged and Confidential Attorney-Client Communication Regarding the Republican River

Dave,

Thank you for providing us with your comments. One thing that would really help would be some information on exactly what model runs where performed to get those numbers for the "Virgin Water Supply Metric". We understand the rest but it is not clear exactly what runs you are using for that. Thanks.

Jim

-----Original Message-----
From: Williams, Jim
Sent: Tuesday, September 18, 2007 11:31 AM
To: Jim Schneider; Paul Koester; Mike McDonald (gndwater@aol.com); Chuck Spaulding (mmacps@aol.com)
Cc: Justin Lavene; Theis, Ron
Subject: Nebraska proposal--Privileged and Confidential Attorney-Client Communication Regarding the Republican River

Privileged and Confidential Attorney-Client Communication Regarding the Republican River

----

Jim, Paul: Please review and let's discuss between now and Thursday.

--Jim

James R. Williams, P.E., CFM
Republican River Coordinator

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E-Mail: jwilliams@dnr.ne.gov
301 Centennial Mall South
P.O. Box 94676, Lincoln, Nebraska 68509-4676 www.dnr.ne.gov
-----Original Message-----

From: Barfield, Dave [mailto:DBARFIELD@KDA.STATE.KS.US]
Sent: Tuesday, September 18, 2007 10:02 AM
To: Williams, Jim; Sullivan, Megan; Willem Schreuder
Cc: Ann Bleed; Knox, Ken; Steve Larson; Austin, George; Dale Book; Perkins, Sam; Billinger, Mark; Ross, Scott
Subject: RE: Nebraska proposal

Jim and others,

Attached is a document that provides Kansas comments from its initial review of Nebraska proposal for our discussion on Thursday.

See you then.

David Barfield

APPENDIX C – Further discussion of two Target Set scale analogy

This Appendix continues the discussion of the two Target Set analogy. The specific equations for a two Target Set situation are developed and applied. The analogy is developed by considering a scale capacity of 300 pounds and two people with a Potential Impact (weight) of 250 pounds. Using the Current Accounting Procedures, the Apparent Impact is 50 pounds for each person. The Apparent Impacts add up to 100 pounds, leaving 200 pounds as the Unaccounted Impacts. With only 50 pounds assigned as a portion of the Total Impact, each person has enough remaining Potential Impact (200 pounds) to cause all of the Unaccounted Impacts. This is a general quality of a two Target Set situation; if there are any Unaccounted Impacts, the difference between each person's Apparent Impact and Potential Impact will always be equal to the Unaccounted Impacts. This leads to the conclusion that any Unaccounted Impact in a two Target Set situation should be equally divided between the two people in proportion to the remaining ability of each person to cause additional impact. In other words the appropriate assignment of Unaccounted Impacts is equal to the Potential Impact minus the Apparent Impact, divided by two. The 200 pounds of Unaccounted Impact is equally divided between the two people so that each is assigned 150 pounds out of the total of 300 pounds. This relationship can be summarized in this equation:

Assigned Impact = Apparent Impact + (Potential Impact – Apparent Impact)/2

For a situation with impact from two Target Sets this general relationship corresponds to the following mathematical equations:

Assigned Impact of Person A = (AB-B) + [(A-θ) – (AB-B)]/2

Assigned Impact of Person B = (AB-A) + [(B-θ) – (AB-A)]/2

Where:

AB = the reading with both persons on the scale

A = the reading with only Person A on the scale

B = the reading with only Person B on the scale

θ = the reading with no one on the scale (the unimpacted reading)

(AB-B) and (AB-A) = the Apparent Impact for Person A and B, respectively

(A-θ) and (B-θ) = the Potential Impact for Person A and B, respectively

The computations using these equations would then look like:

AB = 300 pounds

A = 250 pounds

B = 250 pounds

θ = zero pounds

Assigned Impact of Person A = (300-250) + [(250-0)-(300-250)]/2

= 50 + [250-50]/2

= 50 + 100 = 150 pounds

Assigned Impact of Person B = (300-250) + [(250-0)-(300-250)]/2

= 50 + [250-50]/2

= 50 + 100 = 150 pounds

These equations reduce to the following forms:

Assigned Impact of Person A = [(AB-B) + (A-θ)]/2

Assigned Impact of Person B = [(AB-A) + (B-θ)]/2

In this example, the Appropriate Assignment of the Unaccounted Impacts can probably be deduced without these equations. However, the equations are very useful in situations where the answer is less obvious. For example, what if the two persons weigh 170 pounds and 220 pounds? Using these equations we can determine that they should be assigned 125 pounds and 175 pounds of the impact to the scale, respectively. ***Note that if the combined weight of the two persons is less than 300 pounds, the equations simply yield the persons Potential Impact (weight).*** In other words, this procedure, which is Nebraska's Proposed Procedure for two Target Sets, yields the same result as the Current Accounting Procedures when there are no Unaccounted Impacts. Table 6 shows combinations of the two persons' Potential Impact, Apparent Impacts, the Unaccounted Impacts, and the appropriate assignment of the impact for each of those weights using the equations presented above.

Table 6. Apparent Impact, Unaccounted Impact, and Assigned Impact for two people with different combinations of Potential Impact (weight).

Person A Potential Impact	Person B Potential Impact	Person A Apparent Impact	Person B Apparent Impact	Unaccounted Impact	Person A impact	Person B impact
130	160	130	160	0	130	160
170	220	80	130	90	125	175
100	400	0	200	100	50	250
300	500	0	0	300	150	150
150	200	100	150	50	125	175
150	400	0	150	150	75	225
10	500	0	290	10	5	295
50	280	20	250	30	35	265

One question that could arise from these relationships is, why a person weighing very little (e.g., 20 pounds) is assigned any impact, even when the other person weighs much more (e.g., 480 pounds) than the scale capacity (e.g., 300 pounds)?[25] In this example Person A, weighing 20 pounds, would have an Apparent Impact of 0 pounds, and Person B, weighing 480 pounds, would have an Apparent Impact of 280 pounds, leaving Unaccounted Impacts of 10 pounds (table 7). Is it reasonable to assign Person 1 with any of the Unaccounted Impacts, given that Person B could cause all of the impact on their own (i.e., Potential Impact of Person B is equal to or greater than the Total Impact)? The problem with this argument is that it relies on an arbitrary ordering of the causes of the impacts. Person A is assumed to be in place on the scale before Person B steps on. ***One of the fundamental considerations for any method of assigning the impacts is that it should not be arbitrary.*** Given the Apparent Impact values for each person, they are both equally capable of causing all of the Unaccounted Impacts (i.e., Person A has an Apparent Impact of zero pounds and a Potential Impact of 20 pounds; this difference is equal to the Unaccounted Impacts). Therefore, the appropriate impact

[25] While this issue may seem more significant by taking it to much further extremes (e.g., 1 pound versus 1 million pounds), this is extremely hypothetical and not relevant to the ultimate issue, the RRCA Accounting Procedures, where difference of two orders of magnitude (e.g., 10 versus 1,000) are generally the extreme. There do exist some situations where one or more Target Sets has an impact to the stream baseflow of thousands or tens of thousands of acre-feet, and one other Target Set appears to have an impact to stream baseflow of one or a couple of acre-feet. These occurrences of very small impacts are most likely due to minor rounding issues between model runs and should not be considered in this discussion. Official RRCA accounting generally rounds values to the nearest ten acre-feet.

assignment for each person should be 10 pounds greater than each Person's Apparent Impact.

Table 7. Comparison of results for a range of scale capacities with two people weighing 20 pounds and 480 pounds.

Scale Capacity	Person A Apparent Impact	Person B Apparent Impact	Unaccounted Impact	Person A Assigned Impact	Person B Assigned Impact
300	0	280	20	10	290
400	0	380	20	10	390
480	0	460	20	10	470
490	10	470	10	15	475
500	20	480	0	20	480

Consider again what would happen if the scale capacity was to increase to 400 pounds (table 7). The Total Impact would increase from 300 to 400 pounds, however, the only change under the Current Accounting Procedures would be an increase in the Apparent Impact of Person B. The Unaccounted Impact is the same, whether the scale capacity is 300 pounds or 400 pounds. Therefore, the appropriate assignment of impact to Person A would remain the same (10 pounds); for Person B it would change to 390 pounds. In other words, all of the increase in the appropriate assignment of impact would be assigned to Person B under the Current Accounting Procedures.

Now increase the scale capacity to 490 pounds. The Total Impact to the scale increases to 490 pounds, and the Unaccounted Impact is now only 10 pounds. Using the Assigned Impact equation, the appropriate assignment of impacts would change to 15 pounds for Person A and 475 pounds for Person B. Notice this is the first time the Unaccounted Impacts are less than either Persons Potential Impacts (i.e., neither person could cause the Total Impact alone). So it is clear that when the sum of the Potential Impacts exceed the scale capacity by an amount greater than or equal to the smaller of the two Potential Impacts, this smaller value will be the amount of Unaccounted Impacts (20 pounds in this example). This Unaccounted Impact is split, because we cannot know which of the two people caused it, and either person is equally capable of causing it (i.e., both people can cause an impact of 20 pounds by themselves).

APPENDIX D. Mound Recharge and Nebraska Groundwater Pumping

The behavior of the Current Accounting Procedures when Nebraska groundwater pumping and mound recharge are the only Target Sets that impact Virgin Stream Baseflow can only be detrimental to Nebraska (i.e., it can never benefit Nebraska). When the impact of groundwater pumping in Nebraska is overestimated, this results in a detriment to Nebraska. When the impact of mound recharge is underestimated, Nebraska is deprived of water that it is entitled to under the FSS. This is much different than the effect of the Current Accounting Procedures in their application to the scale. This situation in the Swanson-Harlan reach underscores the importance of this issue to Nebraska.

This problem could be fixed in two arbitrary manners, or through a system of averaging. For example, we could attribute the entire misestimation to the impact of groundwater pumping in Nebraska, reducing this value accordingly and not changing the impact of mound recharge. We could also take the opposite approach, changing the impact of mound recharge and not changing the impact of groundwater pumping. The system of averaging introduced above would essentially split the difference between these two extremes. It actually turns out that the manner in which we modify the Current Accounting Procedures to appropriately account for the Total Impact of these two Target Sets in the Swanson-Harlan reach is largely immaterial, because of the way in which these results percolate through Current Accounting Procedures[26]. In fact, there is no practical reason for differentiating these two terms as separate Target Sets.-

This is basically due to the fact that the impacts of groundwater pumping and mound recharge are both Nebraska terms in the accounting. The annual Compact accounting balances developed for Colorado and Kansas simply compare the annual volume of water that each state receives to the annual uses (termed Computed Beneficial Consumptive Use, or CBCU). For Nebraska the annual volume of water that it receives is compared to the CBCU adjusted for any impact of the mound recharge (term the Imported Water Supply Credit, or IWS Credit). Adjusting either the CBCU or the IWS Credit effects not only the balance of CBCU – IWS Credit, but also the VWS and ultimately the volume of water each state receives. This results from the way in which the VWS is computed, which is essentially the gaged stream flows plus all CBCU minus any IWS Credit. So a smaller value for CBCU results in a smaller VWS, and a larger value for IWS results in a smaller VWS. If the magnitude of either is the same, the effect is exactly the same. So the VWS is reduced by the same amount as the CBCU-IWS Credit is reduced, however the volume of water Nebraska receives, when computed is reduced

[26] This again ignores minor effects of pumping in Kansas and Colorado, and the minor changes this would make in this result.

by a lesser amount (because the Allocation is always less than the VWS in every sub-basin and the Main Stem. The following simple example illustrates these relationships.

Current Accounting Procedures:

Sum of Apparent Impacts of Nebraska groundwater pumping and mound recharge = 1,100 acre-feet

Gaged streamflow = 1,100 acre-feet

VWS = 2,200 acre-feet

Nebraska's water supply = VWS * Allocation = 2,200 * 48.9% = 1,076 acre-feet

Nebraska's water supply – (CBCU – IWS Credit) = 1,076 – 1,100 = -24 acre-feet

Corrected Accounting:

Total Impacts = 1,000 acre-feet

Gaged streamflow = 1,100 acre-feet

VWS = 2,100 acre-feet

Nebraska's water supply = 2,100 * 48.9% = 1,027 acre-feet

Nebraska's water supply – (CBCU – IWS Credit) = 1,027 – 1,000 = 27 acre-feet

The overestimate of Total Impacts by the Current Accounting Procedures is 100 acre-feet in this example. This results in harm to Nebraska of approximately 51 acre feet. Generally speaking, Nebraska is harmed by approximately 51% of the misestimate of the Total Impacts in this reach. This results from the fact that Nebraska receives an Allocation of approximately 49% in the Main Stem. The volume of water Nebraska receives is reduced by 49% of the difference between the results of the Current Accounting Procedures and the Total Impacts, and the CBCU – IWS Credit is reduced by 100% of this difference, for a net effect of 51%. This is evident in the example above. The difference in the impacts is 100 acre-feet, the volume of water Nebraska receives is changed by 49 acre-feet, thus the balance increases by 51 acre-feet.

The exact effect in any given year does depend on the magnitude of any impacts from Kansas or Colorado pumping. To resolve any effect of these impacts Nebraska's Proposed Procedures are required, however the difference between those results and the results demonstrated in this Appendix are very minor.

APPENDIX E. Changes to RRCA Accounting Procedures and Reporting Requirements to implement Nebraska's Proposed Procedures

In order to implement Nebraska's Proposed Procedures, Section III.A.3 and Section III.D.1 of the RRCA Accounting Procedures and Reporting Requirements would need to be revised. The specific revisions were included as Exhibit A to the Answer and Amended Counterclaims and Cross-claim of the State of Nebraska. This exhibit is reproduced as Exhibit A to this Appendix.

EXHIBIT A

III.A.3. Imported Water Supply Credit Calculation:

The amount of Imported Water Supply Credit shall be determined by the RRCA Groundwater Model. The Imported Water Supply Credit of a State shall not be included in the Virgin Water Supply and shall be counted as a credit/offset against the Computed Beneficial Consumptive Use of water allocated to that State. Currently, the Imported Water Supply Credits shall be determined using sixteentwo runs of the RRCA Groundwater Model. These runs are named using a combination of variables representing Colorado groundwater pumping and pumping recharge (C), Kansas groundwater pumping and pumping recharge (K), the surface water recharge associated with Nebraska's Imported Water Supply, or "mound" (M), and Nebraska groundwater pumping and pumping recharge (N), with the presence of the variable indicating that the stress is "on" and the absence of the variable indicating that the stress is "off". These will be the same runs used to determine groundwater Computed Beneficial Consumptive Uses, as described in Section III.D.1.

CKMNThe "base" run shall be the "base" 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.~~

CKN~~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."

KMN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado shall be turned "off."

CMN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas shall be turned "off."

CKM shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska shall be turned "off."

CK shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

CM shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and Kansas shall be turned "off."

CN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

KM shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and Colorado shall be turned "off."

KN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

MN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Kansas shall be turned "off."

C shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

K shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

M shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado, Kansas, and Nebraska shall be turned "off."

N shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Kansas and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

θ ("theta") shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado, Kansas and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

The Imported Water Supply Credit shall be based on the difference in stream flows between ~~these~~ eight pairs~~two~~ of model runs where the only difference between the two runs is that the surface water recharge associated with Nebraska's Imported Water is "on" in one run and "off" in the other (e.g., CKMN vs. CKN). The formula to be used is:

Imported Water Supply Credit = [(M-θ) + ((CM-C) + (KM-K) + (MN-N))/3 +
((CKM-CK) + (CMN-CN) + (KMN-KN))/3 + (CKMN-CKN)]/4

Differences in stream flows shall be determined at the same locations as identified in Subsection III.D.1~~for the "no pumping" runs~~. Should another State import water into the Basin in the future, the RRCA will develop a similar procedure to determine Imported Water Supply Credits.

III.D.1. Groundwater

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 sixteen~~two~~ runs of the model. These runs are named using a combination of variables representing Colorado groundwater pumping and pumping recharge (C), Kansas groundwater pumping and pumping recharge (K), the surface water recharge associated with Nebraska's Imported Water Supply, or "mound" (M), and Nebraska groundwater pumping and pumping recharge (N), with the presence of the variable indicating that the stress is "on" and the absence of the variable indicating that the stress is "off".

CKMN~~The "base" run~~ shall be the "base" run with all groundwater pumping, groundwater pumping recharge, and surface water recharge within the model study boundary for the current accounting year "on".

CKM~~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 in Nebraska~~of that State~~ shall be turned "off."

CKN 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."

CMN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas shall be turned "off."

KMN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado shall be turned "off."

CK shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

CM shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and Kansas shall be turned "off."

CN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

KM shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Nebraska and Colorado shall be turned "off."

KN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

MN shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Kansas shall be turned "off."

C shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Kansas and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

K shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

M shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado, Kansas, and Nebraska shall be turned "off."

N shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado and Kansas and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

θ ("theta") shall be the run with the same model inputs as the base run with the exception that all groundwater pumping and pumping recharge in Colorado, Kansas and Nebraska and surface water recharge associated with Nebraska's Imported Water Supply shall be turned "off."

An output of the model is baseflows at selected stream cells. Changes in the baseflows predicted by the model between eight pairs of model runs where the only difference between the two runs is that the groundwater pumping and pumping recharge in a state is "on" in one run and "off" in the other run (e.g., CKMN vs. CKM) will" base" run and the "no State pumping" model run is assumed to be used to determine the depletions to streamflows. i.e., groundwater computed beneficial consumptive use, due to State groundwater pumping at that location. The formulas to be used are:

Colorado groundwater computed beneficial consumptive use =
[(θ-C) + ((K-CK) + (M-CM) + (N-CN))/3 + ((KM-CKM) + (KN-CKN) + (MN-CMN))/3 + (KMN-CKMN)]/4

Kansas groundwater computed beneficial consumptive use =
[(θ-K) + ((C-CK) + (M-KM) + (N-KN))/3 + ((CM-CKM) + (CN-CKN) + (MN-KMN))/3 + (CMN-CKMN)]/4

Nebraska groundwater computed beneficial consumptive use =
[(θ-N) + ((C-CN) + (M-MN) + (K-KN))/3 + ((CM-CMN) + (CK-CKN) + (KM-KMN))/3 + (CKM-CKMN)]/4

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.

APPENDIX F. Development of Nebraska's Proposed Procedures

Nebraska's Proposed Procedures essentially begin with the Apparent Impact calculation from the Current Accounting Procedures and assign any Unaccounted Impacts to the Target Sets in a manner related to their ability to cause those Unaccounted Impacts. The Unaccounted Impacts are the difference between the Total Impacts and the sum of Apparent Impacts:

Unaccounted Impacts = Total Impacts – Sum of Apparent Impacts.

Under certain circumstances, the Apparent Impacts produced by the Current Accounting Procedures sum to a value different than the Total Impacts causing Unaccounted Impacts.

The Nebraska's Proposed Procedures eliminate Unaccounted Impacts. This is accomplished by defining an Assigned Impact which is calculated by adding an Appropriate Assignment of Unaccounted Impacts (AAUI) to the Apparent Impact of each Target Set so that:

Assigned Impact = Apparent Impact + AAUI.

The AAUI values are determined in such a way that the Total Impacts minus the sum of Assigned Impacts equal zero, that is,

Unaccounted Impacts = Total Impacts – Sum of Assigned Impacts = 0.

The AAUI values are only relevant in those cases where Unaccounted Impacts occur. If there are no Unaccounted Impacts then all AAUI values will be zero. Describing how the AAUI values are determined is the subject of this Appendix.

To avoid arbitrariness, the assignment of Unaccounted Impacts should be shared over all Target Sets. That is, when multiple Target Sets have impact, it should not be the case that the AAUI value for only one Target Set is set to a non-zero value with all others set to zero.

To be realistic, the value of AAUI for each Target Set should be related to the ability of that Target Set to have caused the Unaccounted Impact. In the Nebraska's Proposed Procedures, the remaining ability of the Target Set to cause an impact is determined as the difference between the Potential Impact and Apparent Impact. This difference is computed for each Target Set. By subtracting the impact already assigned to the Target Set (the Apparent Impact) from the maximum impact that could be caused by the Target Set (the Potential Impact) we arrive at an estimate of the maximum

Unaccounted Impact that can be attributed to the Target Set. The AAUI is taken to be a fraction of this remaining ability. In the case of four Target Sets this fraction is ¼. The resulting definition of AAUI for four Target Sets is:

AAUI = ¼(Potential Impact – Apparent Impact).

Note that the AAUI is realistic because its value is proportional to the remaining ability of the Target Set to have an impact. The AAUI value is non-arbitrary because the same fraction (1/4) of the remaining ability is assigned to each Target Set.

We now turn to defining the Potential Impact. The case of two Target Sets was the subject of the scale analogy as discussed in Section 4.3. In this case, since only two Target Sets are relevant, the fraction applied to the difference between Potential Impact and Apparent Impact is ½ rather than ¼. The two Target Set case has two characteristics that are not present when three or four Target Sets are present. The first is that the difference between the Potential Impact and the Apparent Impact takes the same value for each Target Set. This, in turn, causes the AAUI for each Target Set to have the same value. The second characteristic is that the Potential Impact can be computed as the actual weight of the person up to the scale capacity. If the person's weight exceeds the scale capacity we say a nonlinearity has been encountered.

In the Model, nonlinearities occur for more complex reasons than in the scale analogy and can have more subtle effects on impact estimates. These nonlinearities have been analyzed in detail in prior reports (NDNR et al. 2008 and Ahlfeld et al.. 2009). They are generally caused by stream-drying, that is, the reduction, to zero, of modeled stream baseflow at a stream cell. The nonlinearities effects on the Virgin Stream Baseflow at an accounting point may be caused by stream drying at the accounting point, stream drying upstream of the accounting point and stream drying along the length of a stream at during prior stress periods.

If only two Target Sets are present, then these Model nonlinearities can still be addressed by also examining the impact of one Target Set alone in a manner analogous to the scale example (See Section 4.3 and Appendix C). However, when three or four Target Sets are present the complexity of these nonlinearities requires an expanded approach. Prior analysis by Nebraska has indicated that an effective way to address these nonlinearities is to consider the impact of the Target Set in every combination of all other Target Sets either On or Off. As defined in table 4 the four Target Sets are notated C, K, and N for Colorado, Kansas, and Nebraska pumping and M for mound recharge. There are 16 possible model runs with each stress either On or Off. Using the presence of the letter in the run name to indicate that the corresponding stress is On, these are:

θ, C, K, M, N, CK, CM, CN, KM, KN, MN, CKM, CKN, CMN, KMN, CKMN with θ representing the run with all stresses Off. Each run will produce computed baseflow at a given accounting point. For each Target Set of interest, there are eight differences that can be evaluated where the Target Set is On in one Model run and Off in another Model run, with all other Target Sets being unchanged. The Nebraska's Proposed Procedures consider all eight of these runs in arriving at a value for Potential Impact[27].

The Potential Impacts for each of the four Target Sets are given by combination of these eight differences as follows:

Potential Impact of groundwater pumping in Colorado =

$$x_1(\theta\text{-}C) + x_2(K\text{-}CK) + x_3(M\text{-}CM) + x_4(N\text{-}CN) + x_5(KM\text{-}CKM) +$$

$$x_6(KN\text{-}CKN) + x_7(MN\text{-}CMN) + x_8(KMN\text{-}CKMN)$$

Potential Impact of groundwater pumping in Kansas =

$$x_1(\theta\text{-}K) + x_2(C\text{-}CK) + x_3(M\text{-}KM) + x_4(N\text{-}KN) + x_5(CM\text{-}CKM) +$$

$$x_6(CN\text{-}CKN) + x_7(MN\text{-}KMN) + x_8(CMN\text{-}CKMN)$$

Potential Impact of groundwater pumping in Nebraska =

$$x_1(\theta\text{-}N) + x_2(C\text{-}CN) + x_3(M\text{-}MN) + x_4(K\text{-}KN) + x_5(CM\text{-}CMN) +$$

$$x_6(CK\text{-}CKN) + x_7(KM\text{-}KMN) + x_8(CKM\text{-}CKMN)$$

Potential Impact of mound recharge =

$$x_1(\theta\text{-}M) + x_2(C\text{-}CM) + x_3(K\text{-}KM) + x_4(N\text{-}MN) + x_5(CK\text{-}CKM) +$$

$$x_6(CN\text{-}CMN) + x_7(KN\text{-}KMN) + x_8(CKN\text{-}CKMN)$$

---

[27] The mathematical basis for the Nebraska's Proposed Procedures has been discussed in both NDNR et al. (2008) and Ahlfeld et al. (2009). In brief, streamflow at an accounting point can be viewed as a continuous function of the level of activity at the four Target Sets. The 16 runs used in the proposed Accounting Procedures constitute the corner points of the four-dimensional domain space for this function. Taking the difference between two of these runs, one with the Target Set present and one without the Target Set gives an estimate of the gradient of the function surface. There are eight possible differences that can be taken, given the 16 available corner point runs. When the surface is nonlinear, an interpolation of these eight gradient estimates provides a better estimate of the gradient than the single difference used by the current Accounting Procedures. The interpolation is formed with eight coefficients that need to be determined. They are determined by enforcing the requirement that the Proposed Impact produce no Unaccounted Impact.

where x_n represents the coefficient on the n[th] difference pair. Note that the Current Accounting Procedures assign a value of one to x_8 and zero to all other coefficients.

Combining the Potential Impacts with the Apparent Impacts in the following equation:

Assigned Impact = Apparent Impact + (Potential Impact – Apparent Impact)/4

The Assigned Impact for each Target Set becomes:

Assigned Impact of groundwater pumping in Colorado = (KMN – CKMN) +

$$\{[x_1(\theta\text{-}C) + x_2(K\text{-}CK) + x_3(M\text{-}CM) + x_4(N\text{-}CN) + x_5(KM\text{-}CKM) + x_6(KN\text{-}CKN) + x_7(MN\text{-}CMN) + x_8(KMN\text{-}CKMN)] - (KMN\text{-}CKMN)\}/4$$

Assigned Impact of groundwater pumping in Kansas = (KMN – CKMN) +

$$\{[x_1(\theta\text{-}K) + x_2(C\text{-}CK) + x_3(M\text{-}KM) + x_4(N\text{-}KN) + x_5(CM\text{-}CKM) + x_6(CN\text{-}CKN) + x_7(MN\text{-}KMN) + x_8(CMN\text{-}CKMN)] - (KMN\text{-}CKMN)\}/4$$

Assigned Impact of groundwater pumping in Nebraska = (CKM – CKMN) +

$$\{[x_1(\theta\text{-}N) + x_2(C\text{-}CN) + x_3(M\text{-}MN) + x_4(K\text{-}KN) + x_5(CM\text{-}CMN) + x_6(CK\text{-}CKN) + x_7(KM\text{-}KMN) + x_8(CKM\text{-}CKMN)] - (CKM\text{-}CKMN)\}/4$$

Assigned Impact of mound recharge[28] = (CKN – CKMN) +

$$\{[x_1(\theta\text{-}M) + x_2(C\text{-}CM) + x_3(K\text{-}KM) + x_4(N\text{-}MN) + x_5(CK\text{-}CKM) + x_6(CN\text{-}CMN) + x_7(KN\text{-}KMN) + x_8(CKN\text{-}CKMN)] - (CKN\text{-}CKMN)\}/4$$

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[28] For convenience of presentation in this Appendix, the differences in the equation for Mound recharge are arranged the same as the other Target Sets, which produces a negative result. For example, (θ-M) would be expected to produce a negative result because a run with Mound recharge present (M) will have more baseflow than a run without Mound recharge (θ). The convention in Compact Accounting is to compute the IWS Credit in a manner that produces a positive value, then subtract it in the accounting to generate a "credit." Insteadwe calculate a negative value and add it into the Accounting balances. The effect is the same.

Note that the same coefficients have been applied to similar terms in each equation. For example, (θ-C) and (θ-K) have the same coefficient. The intent of this assignment of coefficients is to avoid arbitrariness. As will be seen, all coefficients except x_1 and x_8 will take the same value so that the ordering of Target Sets is not important.

Determination of the eight unknown coefficients proceeds by imposing the requirement that the Unaccounted Impacts take the value of zero. That is,

Total Impacts = Sum of Assigned Impacts.

$$
\begin{aligned}
&(\theta - CKMN) = \\
&\quad (KMN - CKMN) + \\
&\qquad \{[x_1(\theta\text{-}C) + x_2(K\text{-}CK) + x_3(M\text{-}CM) + x_4(N\text{-}CN) + x_5(KM\text{-}CKM) + \\
&\qquad x_6(KN\text{-}CKN) + x_7(MN\text{-}CMN) + x_8(KMN\text{-}CKMN)] - (KMN\text{-}CKMN)\}/4 \\
&+ (KMN - CKMN) + \\
&\qquad \{[x_1(\theta\text{-}K) + x_2(C\text{-}CK) + x_3(M\text{-}KM) + x_4(N\text{-}KN) + x_5(CM\text{-}CKM) + \\
&\qquad x_6(CN\text{-}CKN) + x_7(MN\text{-}KMN) + x_8(CMN\text{-}CKMN)] - (KMN\text{-}CKMN)\}/4 \\
&+ (CKM - CKMN) + \\
&\qquad \{[x_1(\theta\text{-}N) + x_2(C\text{-}CN) + x_3(M\text{-}MN) + x_4(K\text{-}KN) + x_5(CM\text{-}CMN) + \\
&\qquad x_6(CK\text{-}CKN) + x_7(KM\text{-}KMN) + x_8(CKM\text{-}CKMN)] - (CKM\text{-}CKMN)\}/4 \\
&+ (CKN - CKMN) + \\
&\qquad \{[x_1(\theta\text{-}M) + x_2(C\text{-}CM) + x_3(K\text{-}KM) + x_4(N\text{-}MN) + x_5(CK\text{-}CKM) + \\
&\qquad x_6(CN\text{-}CMN) + x_7(KN\text{-}KMN) + x_8(CKN\text{-}CKMN)] - (CKN\text{-}CKMN)\}/4
\end{aligned}
$$

The correct value for each coefficient (x_n) can be determined by direct examination of this equation. The run θ occurs four times on the right side of the equation, each time divided by four, and only once on the left side of the equation. It follows that x_1 must equal 1 for the occurrences of θ to equate. The run CKMN occurs once on the left side of the equation, and eight times on the right side. To make these occurrences balance x_8 must equal -2. Given the values assigned to these two coefficients, the runs C, K, M, and N occur once with a negative sign and three times with a positive sign on the right side of the equation. They do not occur on the left side. The negative term already has a coefficient of 1, so each positive term must have a coefficient of $^1/_3$ so that they cancel. This results in x_2, x_3, and x_4 equaling $^1/_3$. Each run with two stresses on and two stresses off occur twice as a positive (after x_5, x_6, or x_7) and twice as a negative (after x_2, x_3, or x_4), requiring that these two sets of coefficients must be equal. In summary,

$$x_1 = 1 \; ; \; x_8 = -2 \text{ and } \; x_2 = x_3 = x_4 = x_5 = x_6 = x_7 = {}^1/_3$$

These coefficients also ensure that the occurrences of CKM, CKN, KMN, and CMN cancel each other. Substituting these coefficients into the equations for the Assigned Impact of each Target Set yields:

Assigned Impact of groundwater pumping in Colorado = (KMN – CKMN) +

{[(θ-C) + 1/3(K-CK) + 1/3(M-CM) + 1/3(N-CN) + 1/3(KM-CKM) +

1/3(KN-CKN) + 1/3(MN-CMN) - 2(KMN-CKMN)]– (KMN-CKMN)}/4

Assigned Impact of groundwater pumping in Kansas = (CMN – CKMN) +

{[(θ-K) + 1/3(C-CK) + 1/3(M-KM) + 1/3(N-KN) + 1/3(CM-CKM) +

1/3(CN-CKN) + 1/3(MN-KMN) - 2(CMN-CKMN)]– (CMN-CKMN)}/4

Assigned Impact of groundwater pumping in Nebraska = (CKM – CKMN) +

{[(θ-N) + 1/3(C-CN) + 1/3(M-MN) + 1/3(K-KN) + 1/3(CM-CMN) +

1/3(CK-CKN) + 1/3(KM-KMN) - 2(CKM-CKMN)] – (CKM-CKMN)}/4

Assigned Impact of mound recharge = (CKN – CKMN) +

{[(θ-M) + 1/3(C-CM) + 1/3(K-KM) + 1/3(N-MN) + 1/3(CK-CKM) +

1/3(CN-CMN) + 1/3(KN-KMN) - 2(CKN-CKMN)] – (CKN-CKMN)}/4

The values for the Potential Impact of each Target Set are then:

Potential Impact of groundwater pumping in Colorado = {(θ-C) + [(K-CK) + (M-CM) + (N-CN)]/3 + [(KM – CKM) + (KN – CKN) + (MN – CMN)]/3 – 2(KMN-CKMN)}

Potential Impact of groundwater pumping in Kansas = {(θ-K) + [(C-CK) + (M-KM) + (N-KN)]/3 + [(CM – CKM) + (CN – CKN) + (MN – KMN)]/3 – 2(CMN-CKMN)}

Potential Impact of groundwater pumping in Nebraska = {(θ-N) + [(C-CN) + (K-KN) + (M-MN)]/3 + [(CK – CKN) + (KM – KMN) + (CM – CMN)]/3 – 2(CKM-CKMN)}

Potential Impact of mound recharge = {(θ-M) + [(C-CM) + (K-KM) + (N-MN)]/3 + [(CK – CKM) + (CN – CMN) + (KN – KMN)]/3 – 2(CKN-CKMN)}

Notice that the first term in each equation is the same as the definition of the Potential Impact for the situation with Two Target sets. The remaining seven terms are necessary for a better estimate of Potential Impacts when four Target Sets are present. Note that the first six of the seven terms have coefficients of 1/3 while the final term of the seven has a coefficient of minus 2. If all of these terms have the same value then they will tend to cancel with the first terms remaining dominant. Differences in the values of the terms reflect the nonlinear features of the four-dimensional surface that defines the impact of the four Target Sets.

Note that when nonlinearities are not present, each of the eight differences, for a given Target Set, will produce the same value. When the stream baseflow responds linearly, the Potential Impact will equal the Apparent Impact and the Assigned Impact will be identical to the impact calculated using the Current Accounting Procedures.

These equations can be conveniently rearranged to the following forms:

Assigned Impact of groundwater pumping in Colorado = [(θ-C) + ((K-CK) + (M-CM) + (N-CN))/3 + ((KM-CKM) + (KN-CKN) + (MN-CMN))/3 + (KMN-CKMN)]/4

Assigned Impact of groundwater pumping in Kansas = [(θ-K) + ((C-CK) + (M-KM) + (N-KN))/3 + ((CM-CKM) + (CN-CKN) + (MN-KMN))/3 + (CMN-CKMN)]/4

Assigned Impact of groundwater pumping in Nebraska = [(θ-N) + ((C-CN) + (M-MN) + (K-KN))/3 + ((CM-CMN) + (CK-CKN) + (KM-KMN))/3 + (CKM-CKMN)]/4

Assigned Impact of the IWS = [(θ-M) + ((C-CM) + (K-KM) + (N-MN))/3 + ((CK-CKM) + (CN-CMN) + (KN-KMN))/3 + (CKN-CKMN)]/4

The Assigned Impact equations are derived for the most general case of four Target Sets, however, they easily cover the cases when three, two or only one Target Set have significant impact on an accounting point. For example, consider a case in which Kansas and Nebraska pumping are the only Target Sets that cause significant change in baseflow at an accounting point. For this case, the following observations can be made:

1) C = M = CM = θ (turning on Colorado pumping and/or Mound recharge produces no change from the all-off condition)
2) CK =KM = CKM =K (adding Colorado pumping and/or Mound recharge does not change the impact of Kansas pumping)
3) CN =MN = CMN = N (adding Colorado pumping and/or Mound recharge does not change the impact of Nebraska pumping)
4) KMN = CKN = CKMN = KN (adding Colorado pumping and/or Mound recharge does not change the combined impact of Kansas pumping and Nebraska pumping)

Substituting these 4 statements into the Assigned Impact equations produces the following results:

Assigned Impact of groundwater pumping in Colorado = 0

Assigned Impact of groundwater pumping in Kansas = [(θ-K) + ((θ-K) + (θ-K) + (N-KN))/3 + ((θ-K) + (N-KN) + (N-KN))/3 + (N-KN)]/4

= [(θ-K) + (N-KN)]/2

Assigned Impact of groundwater pumping in Nebraska = [(θ-N) + ((θ-N) + (θ-N) + (K-KN))/3 + ((θ-N) + (K-KN) + (K-KN))/3 + (K-KN)]/4

= [(θ-N) + (K-KN)]/2

Assigned Impact of the IWS = 0

As can be seen, with the observations, the general four target equation reduces to the simpler two Target Set equation discussed in Section 4.3 when only two Target Sets are relevant. A similar analysis could be conducted for any combination of two stresses. In a similar fashion, if only three Target Sets are relevant to an accounting point, the impact of the irrelevant Target Set will be assigned a value of zero in Nebraska's Proposed Procedures.

APPENDIX G. Application of Nebraska's Proposed Procedures

The following examples demonstrate the behavior of Nebraska's Proposed Procedures under a range of conditions. The scale analogy is utilized for these examples. First, an example is presented in which there are no Unaccounted Impacts. In this case, the results of Nebraska's Proposed Procedures are identical to the Current Accounting Procedures. Next, the same example from Section 4.3 and Appendix C, with two people exceeding the scale capacity, is utilized. Here, Person C and Person D are simply represented with zero weight (impact). The results are identical to those obtained in Appendix C using the simplified equations for only two Target Sets. Finally, an example with four people whose combined Potential Impact is well in excess of the scale capacity. Here the Current Accouting Procedures account for zero pounds of impact. Nebraska's Proposed Procedures assign the Unaccounted Impact to each Person according to the ability of that person to cause those impacts. The result is that all impacts are accounted for.

Application of Nebraska's Proposed Procedures when there are no Unaccounted Impacts

When the sum of the Potential Impacts for the targets set(s) is equal to less than the scale capacity, Nebraska's Proposed Procedures produce the same values for the individual impacts Target Setas the Current Accounting Procedures. In this case, the Potential Impact will be the same as the Apparent Impact, and there are no Unaccounted Impacts. While Nebraska's Proposed Procedures are not necessary in this example, they do not change the result, instead simply making a few more computations than might be needed. Consider for example applying Nebraska's Proposed Procedures to the following situation:

Person A = 50 pounds

Person B = 75 pounds

Person C = 60 pounds

Person D = 80 pounds

Capacity = 300 pounds

The capacity of the scale in the following equations is represented by θ, and the remaining capacity with some combination of persons on the scale is represented by a variable with the number of those persons (e.g., 12 = remaining capacity with person 1 and 2 on the scale). So the values and computations would look like this:

θ = 0 pounds

A = 50 pounds

B = 75 pounds

C = 60 pounds

D = 80 pounds

AB = 125 pounds

AC = 110 pounds

AD = 130 pounds

BC = 135 pounds

BD = 155 pounds

CD = 140 pounds

ABC = 185 pounds

ABD = 205 pounds

ACD = 190 pounds

BCD = 215 pounds

ABCD = 265 pounds

The equations for the impact of each person would look similar to the equations presented in Section 5.2, with the substitution of the variable representing Persons A, B, C, and D for the variable representing Colorado pumping (C), Kansas pumping (K), Nebraska pumping (N), and mound recharge (M). The only other change is that each of the differences in reversed in order to produce a positive result (i.e., instead of θ-C, these equations would use C-θ). Therefore the appropriate equations representing the proposed accounting procedures are:

Impact of person A = [(A-θ) + ((AB-B) + (AC-C) + (AD-D))/3 + ((ABC-BC) + (ABD-BD) + (ACD-CD))/3 + (ABCD-BCD)]/4

Impact of person B = [(B-θ) + ((AB-A) + (BC-C) + (BD-D))/3 + ((ABC-AC) + (ABD-AD) + (BCD-CD))/3 + (ABCD-ACD)]/4

Impact of person C = [(C-θ) + ((AC-A) + (BC-B) + (CD-D))/3 + ((ABC-AB) + (ACD-AD) + (BCD-BD))/3 + (ABCD-ABD)]/4

Impact of person D = [(D-θ) + ((AD-A) + (BD-B) + (CD-C))/3 + ((ABD-AB) + (ACD-AC) + (BCD-BC))/3 + (ABCD-ABC)]/4

Inserting the appropriate values and making all the calculations results in:

Impact of person A = [(50-0) + ((125-75) + (110-60) + (130-80))/3 + ((185-135) + (205-155) + (190-140))/3 + (265-215)]/4

= [50 + (50 + 50 + 50)/3 + (50 + 50 + 50)/3 +50]/4 = 50 pounds

Impact of person B = [(75-0) + ((125-50) + (135-60) + (155-80))/3 + ((185-110) + (205-130) + (215-140))/3 + (265-190)]/4

= [75 + (75 + 75 + 75)/3 + (75 + 75 + 75)/3 +75]/4 = 75 pounds

Impact of person C = [(60-0) + ((110-50) + (135-75) + (140-80))/3 + ((185-125) + (190-130) + (215-155))/3 + (265-205)]/4

= [60 + (60 + 60 + 60)/3 + (60 + 60 + 60)/3 +60]/4 = 60 pounds

Impact of person D = [(80-0) + ((130-50) + (155-75) + (140-60))/3 + ((205-125) + (190-110) + (215-135))/3 + (265-185)]/4

= [80 + (80 + 80 + 80)/3 + (80 + 80 + 80)/3 +80]/4 = 80 pounds

As we can see, each of the 8 differences in any one of the impact equations has the same value. Multiplying each value by the appropriate weight and summing the results simply produces that value. Note that the last difference in each equation (e.g., 123-1234) represents the Current Accounting Procedures. Therefore, the Current Accounting Procedures would be sufficient in this case.

Application of Nebraska's Proposed Procedures with Two Target Sets exceeding Scale Capacity

It is not required to have four persons of interest in order to apply the equations for four Target Sets. In fact if there is only one person being weighed these equations are still appropriate, though certainly not necessary. As previously noted, most sub-basins and Main Stem reaches are not impacted significantly by all four Target Sets in the Model. We can apply the equations to the example from Section 4.3 and Appendix C, where only two people are being weighed, by simply accounting for Persons C and D with zero impact. The calculations would look like this:

θ = 0 pounds

A = 250 pounds

B = 250 pounds

C = 0 pounds

D = 0 pounds

AB = 300 pounds

AC = 250 pounds

AD = 250 pounds

BC = 250 pounds

BD = 250 pounds

CD = 0 pounds

ABC = 300 pounds

ABD = 300 pounds

ACD = 250 pounds

BCD = 250 pounds

ABCD = 300 pounds

Impact of person A = [(A-θ) + ((AB-B) + (AC-C) + (AD-D))/3 + ((ABC-BC) + (ABD-BD) + (ACD-CD))/3 + (ABCD-BCD)]/4

Impact of person B = [(B-θ) + ((AB-A) + (BC-C) + (BD-D))/3 + ((ABC-AC) + (ABD-AD) + (BCD-CD))/3 + (ABCD-ACD)]/4

Inserting the appropriate values and making all the calculations results in:

Impact of person A = [(250-0) + ((300-250) + (250-0) + (250-0))/3 + ((300-250) + (300-250) + (250-0))/3 + (300-250)]/4

= [250 + (50 + 250 + 250)/3 + (50 + 50 + 250)/3 +50]/4

= [250 + 550/3 + 350/3 + 50]/4 = [250 + 900/3 + 50]/4 = [250 + 300 + 50]/4

= 600/4 = 150 pounds

Impact of person B = [(250-0) + ((300-250) + (250-0) + (250-0))/3 + ((300-250) + (300-250) + (250-0))/3 + (300-250)]/4

= [250 + (50 + 250 + 250)/3 + (50 + 50 + 250)/3 +50]/4

= [250 + 550/3 + 350/3 + 50]/4 = [250 + 900/3 + 50]/4 = [250 + 300 + 50]/4

= 600/4 = 150 pounds

The result that is obtained from these more general equations (i.e., can accommodate four Target Sets as opposed to only two Target Sets) is exactly the same. More computations are involved, but these computations are readily automated through programing or other computing means. If there may be as many as four Target Sets to consider at some times, it would be much more efficient to implement the use of these equations in all cases (even when there are not four Target Sets), rather than to switch between sets of equations depending on the number of Target Sets. Note that inserting the appropriate values into the Impact equations for persons C and D produce values of zero impact for each.

Application of Nebraska's Proposed Procedures with Four Target Sets exceeding Scale Capacity

Now consider a similar example, except these people were each 100 pounds heavier (i.e., person 1 = 150 pounds, person 2 = 175 pounds, person 3 = 160 pounds, person 4 = 180 pounds). In this case the Current Accounting Procedures would produce an impact estimate for each person of zero pounds. The computations using Nebraska's Proposed Procedures would look like this:

θ = 0 pounds

A = 150 pounds

B = 175 pounds

C = 160 pounds

D = 180 pounds

AB = 300 pounds

AC = 300 pounds

AD = 300 pounds

BC = 300 pounds

BD = 300 pounds

CD = 300 pounds

ABC = 300 pounds

ABD = 300 pounds

ACD = 300 pounds

BCD = 300 pounds

ABCD = 300 pounds

Impact of person A = [(A-θ) + ((AB-B) + (AC-C) + (AD-D))/3 + ((ABC-BC) + (ABD-BD) + (ACD-CD))/3 + (ABCD-BCD)]/4

Impact of person B = [(B-θ) + ((AB-A) + (BC-C) + (BD-D))/3 + ((ABC-AC) + (ABD-AD) + (BCD-CD))/3 + (ABCD-ACD)]/4

Impact of person C = [(C-θ) + ((AC-A) + (BC-B) + (CD-D))/3 + ((ABC-AB) + (ACD-AD) + (BCD-BD))/3 + (ABCD-ABD)]/4

Impact of person D = [(D-θ) + ((AD-A) + (BD-B) + (CD-C))/3 + ((ABD-AB) + (ACD-AC) + (BCD-BC))/3 + (ABCD-ABC)]/4

Inserting the appropriate values and making all the calculations results in:

Impact of person A = [(150-0) + ((300-175) + (300-160) + (300-180))/3 + ((300-300) + (300-300) + (300-300))/3 + (300-300)]/4

= [150 + (125 + 140 + 120)/3 + (0 + 0 + 0)/3 +0]/4

= [150 + (385/3)]/4 = [150 + 128.3]/4 = 69.6 pounds

Impact of person B = [(175-0) + ((300-150) + (300-160) + (300-180))/3 + ((300-300) + (300-300) + (300-300))/3 + (300-300)]/4

= [175 + (150 + 140 + 120)/3 + (0 + 0 + 0)/3 +0]/4

= [175 + (410/3]/4 = [175 + 136.7]/4 = 77.9 pounds

Impact of person C = [(160-0) + ((300-150) + (300-175) + (300-180))/3 + ((300-300) + (300-300) + (300-300))/3 + (300-300)]/4

= [160 + (150 + 125 + 120)/3 + (0 + 0 + 0)/3 +0]/4

= [160 + (395/3)]/4 = [160 + 131.7]/4 = 72.9 pounds

Impact of person D = [(180-0) + ((300-150) + (300-175) + (300-160))/3 + ((300-300) + (300-300) + (300-300))/3 + (300-300)]/4

= [180 + (150 + 125 + 140)/3 + (0 + 0 + 0)/3 +0]/4

= [180 + (415/3)]/4 = [180 + 138.3]/4 = 79.6 pounds

Table 8 summarizes the weight of these four people and their impact as determined by the Current Accounting Procedures and the proposed accounting procedures.

Table 8. Comparison of Apparent Impact and Assigned Impact for case with four Target Sets that exceed the scale capacity.

Person	Weight	Impact – Current Accounting Procedures	Impact – Proposed Accounting Procedures
1	150	0	69.6
2	175	0	77.9
3	160	0	72.9
4	180	0	79.6
Sum	665	0	300

Notice that the proposed accounting procedures do account for the full 300 pounds of impacts. The heaviest person is assigned the greatest impact and the lightest person is assigned the smallest impacts. This is clearly preferred to the results of the Current Accounting Procedures, which allocate none of the impacts in this case.

Nebraska Expert Report in Support of Counterclaim and Crossclaim

Reference Materials

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November 18, 2011

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

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August 6, 2008

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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.

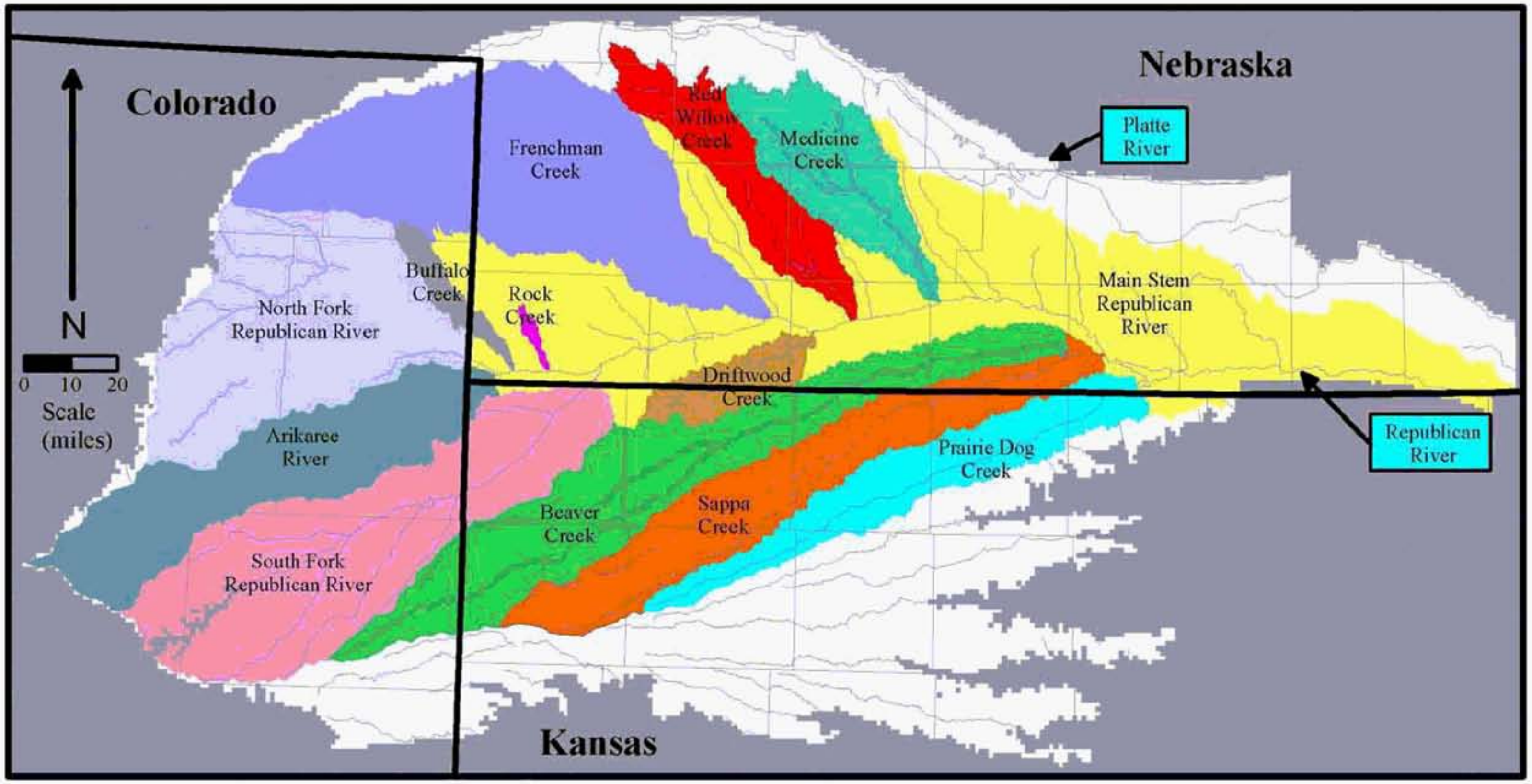

Figure 1.1. Map showing location of Republican River and the Republican River Compact sub-basins.

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 **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"; 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 **<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"; "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

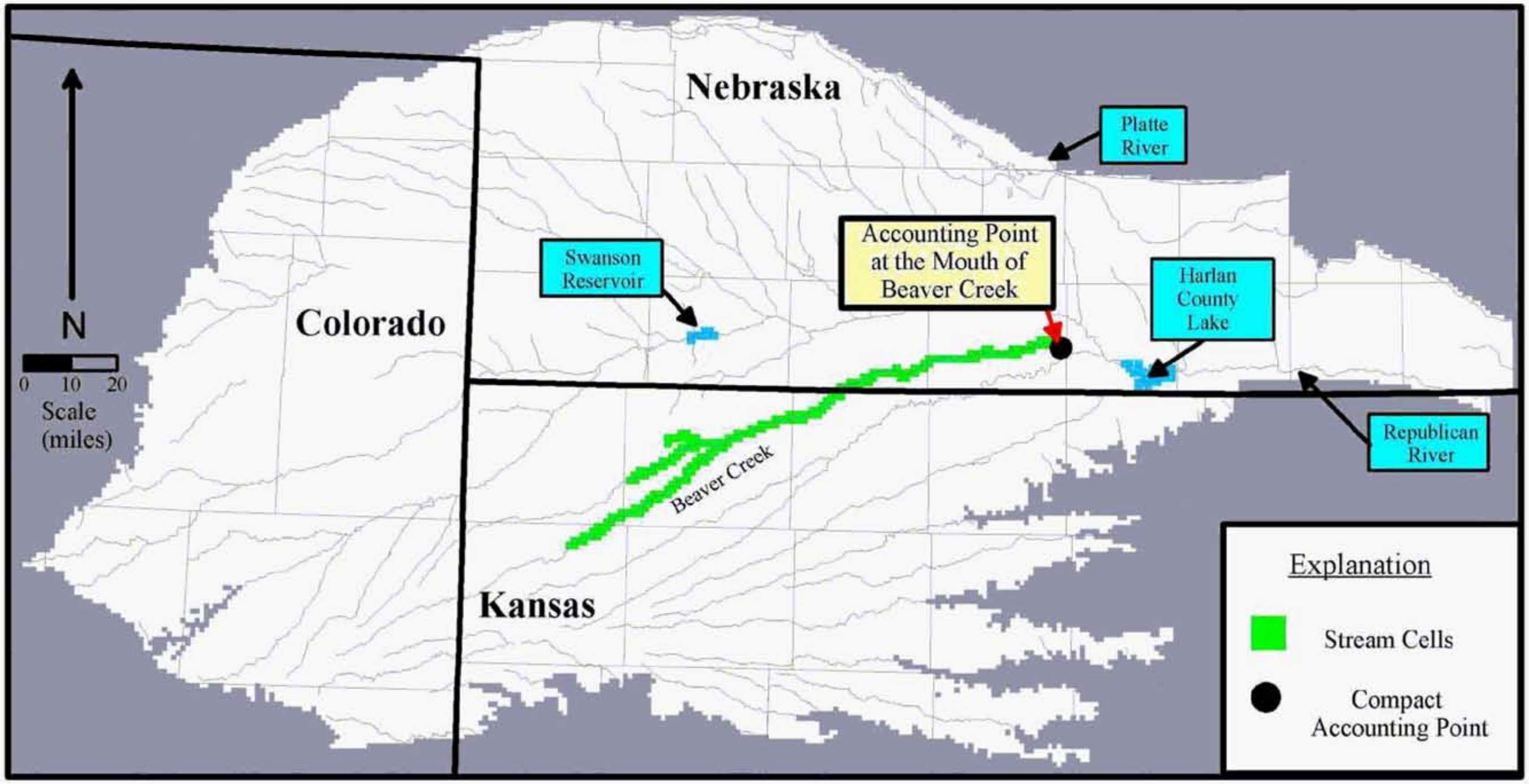

Figure 1.2. Map showing location of cells with stream boundary condition in Beaver Creek.

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 *0*) 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.”

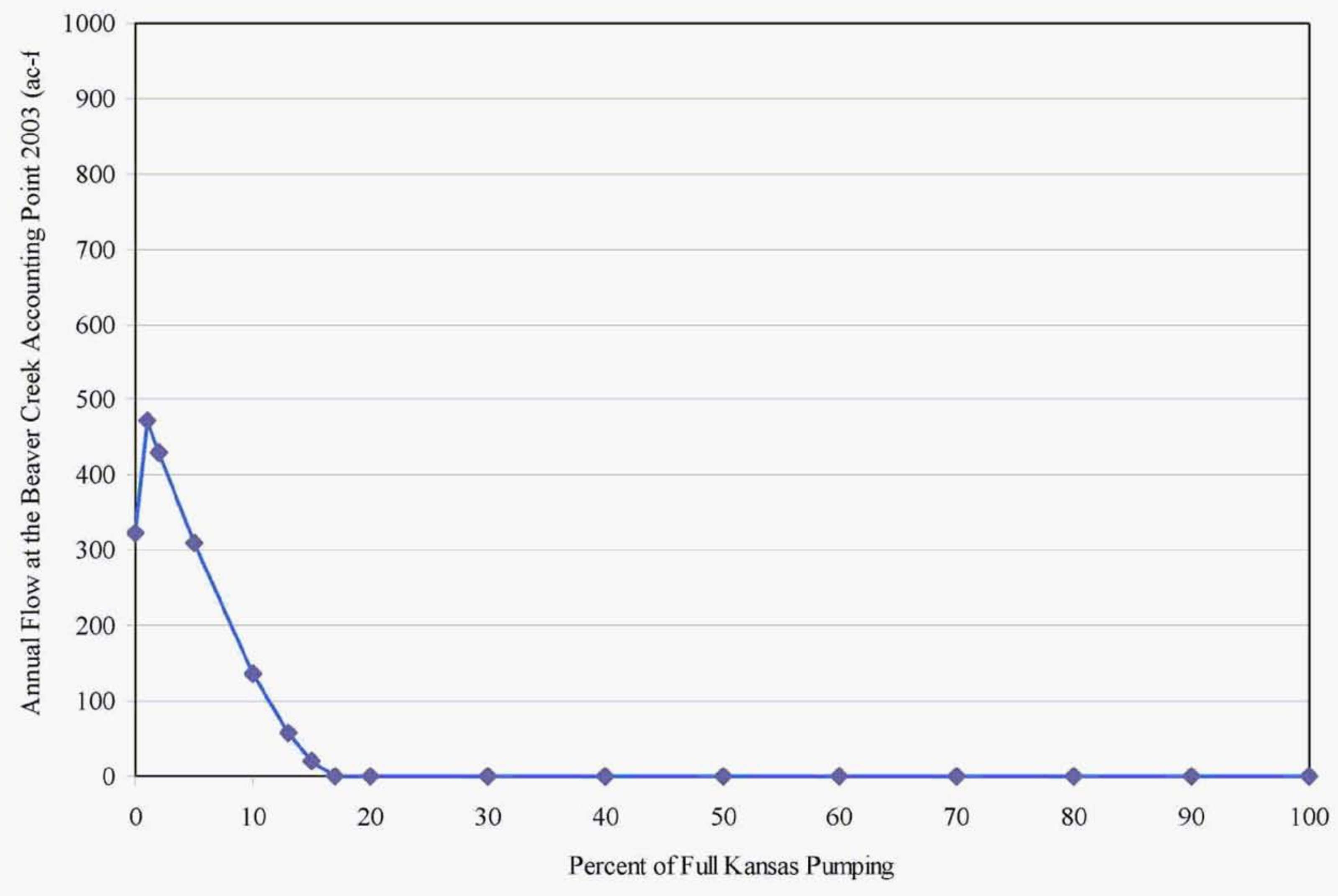

Figure 2.1. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

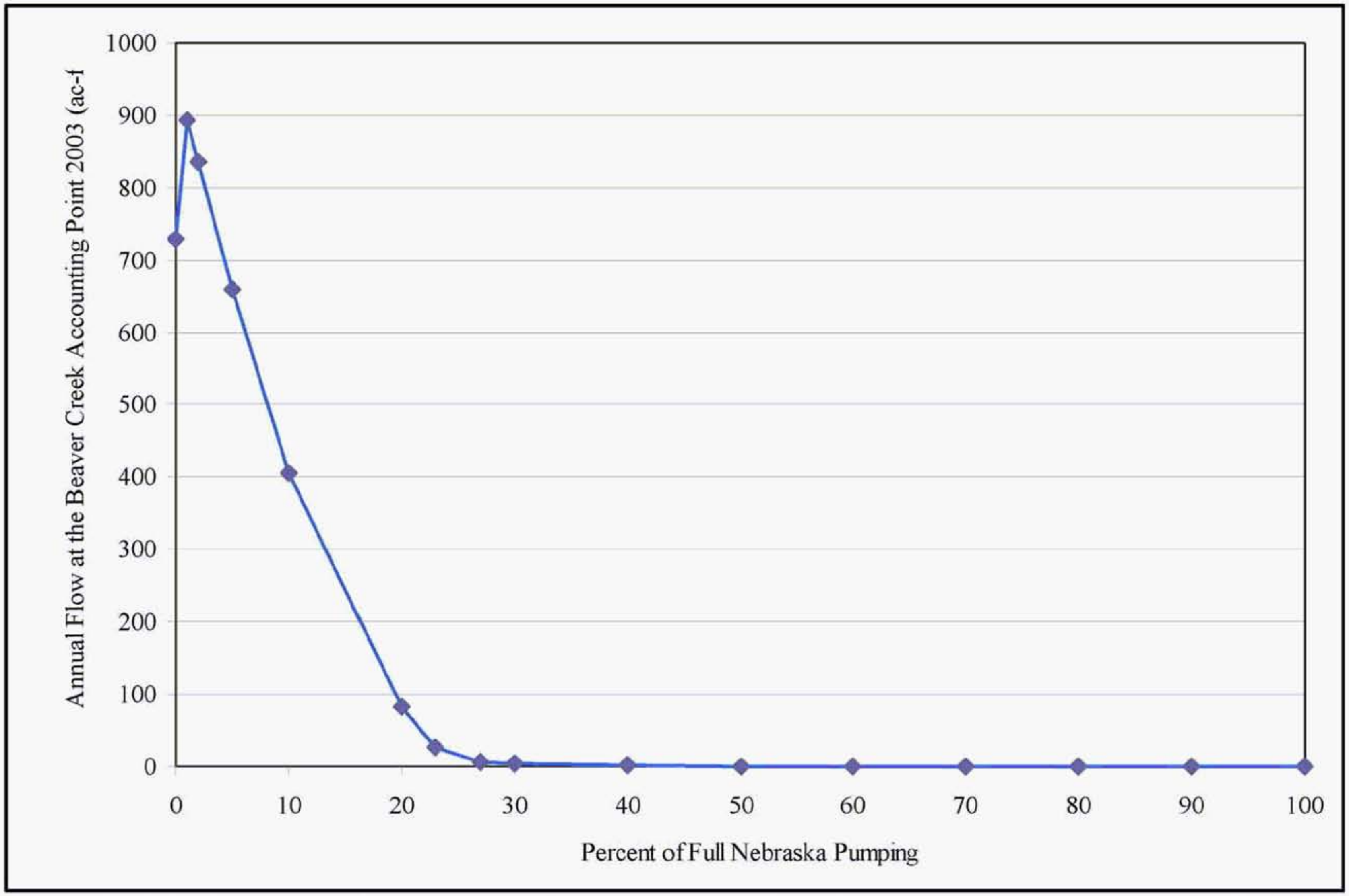

Figure 2.2. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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.

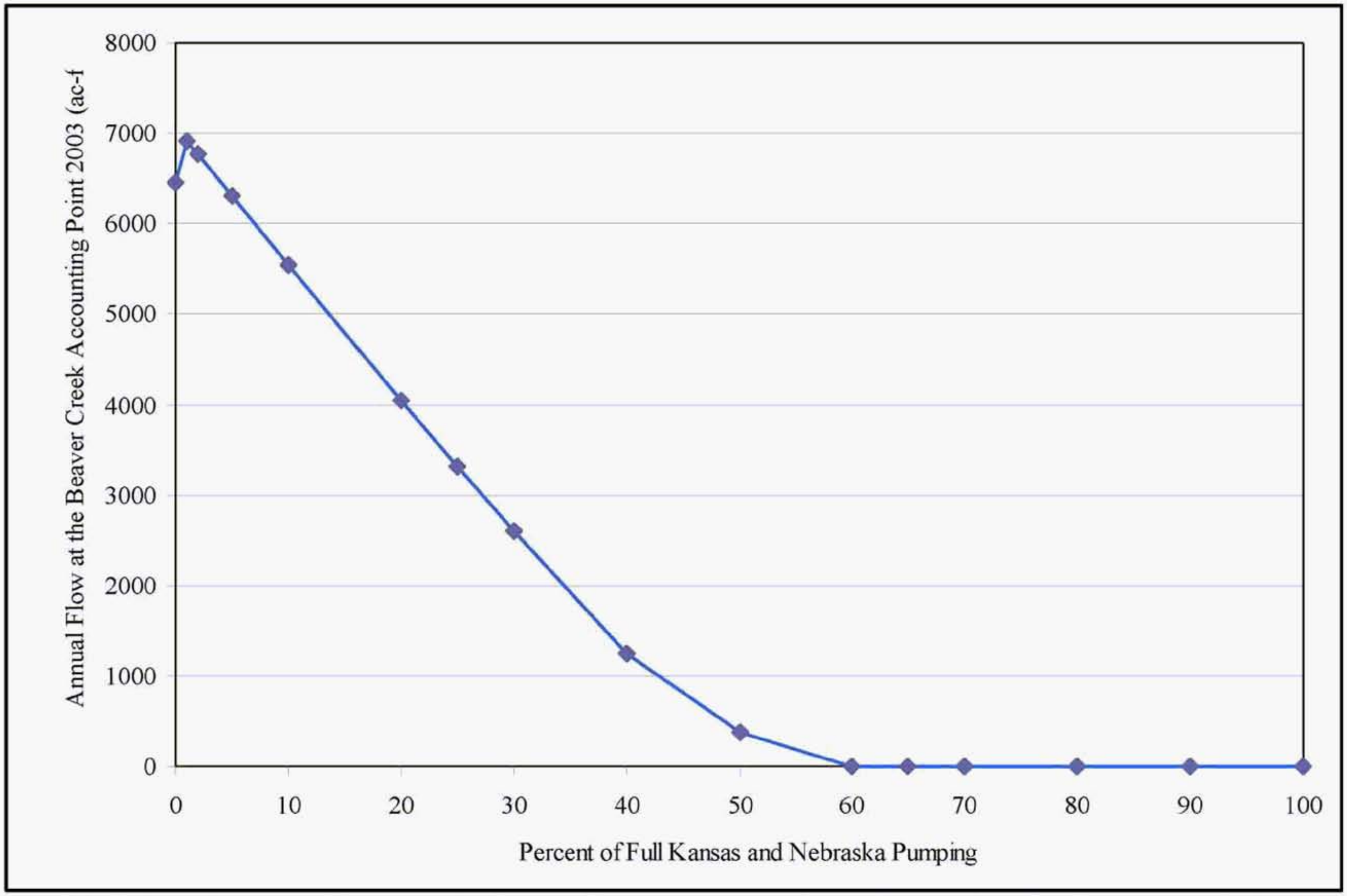

Figure 2.3. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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.

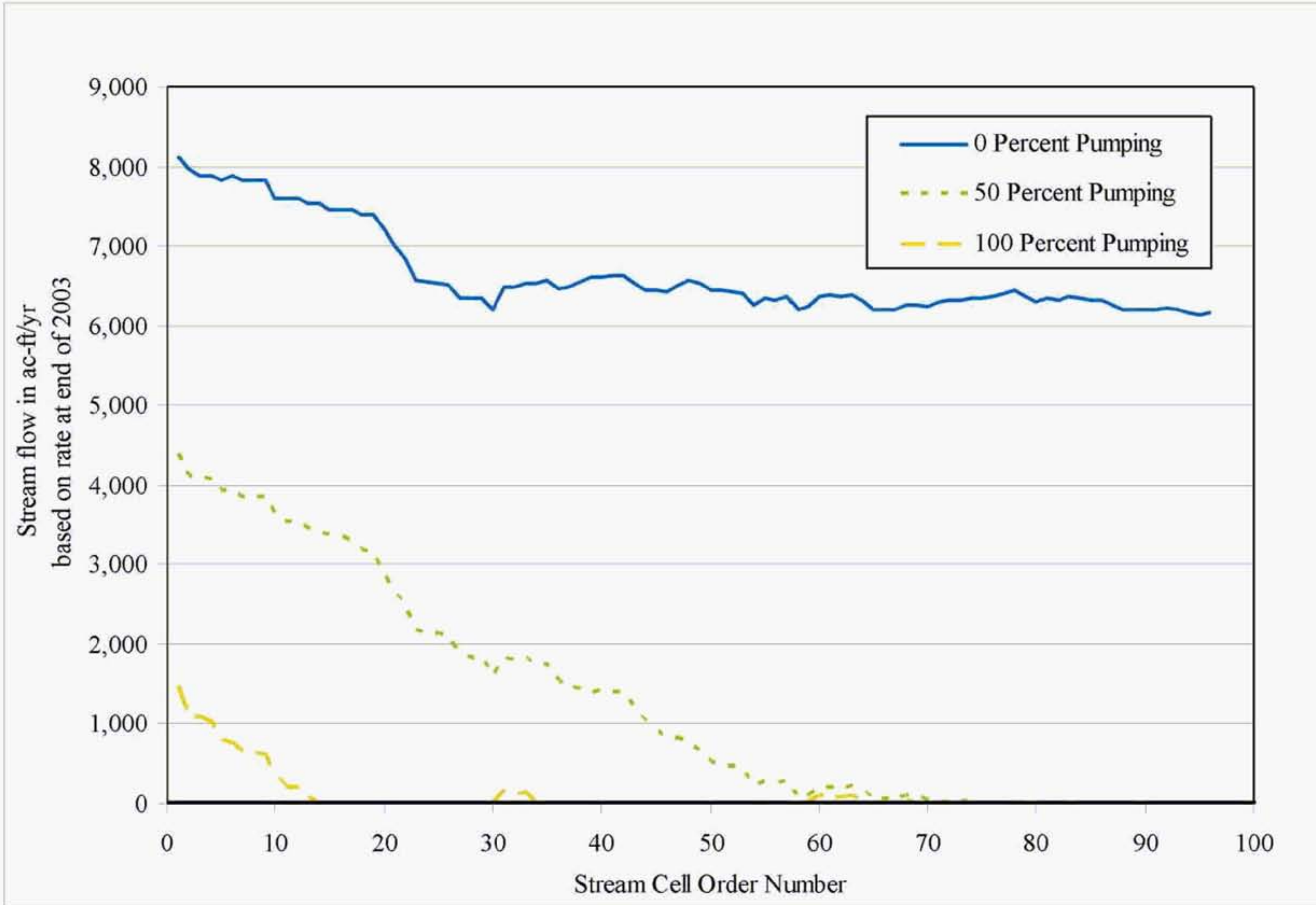

Figure 2.4. Graph showing stream cell order vs flow for various percents of full pumping for Kansas and Nebraska pumping, Beaver Creek at the end of 2003.

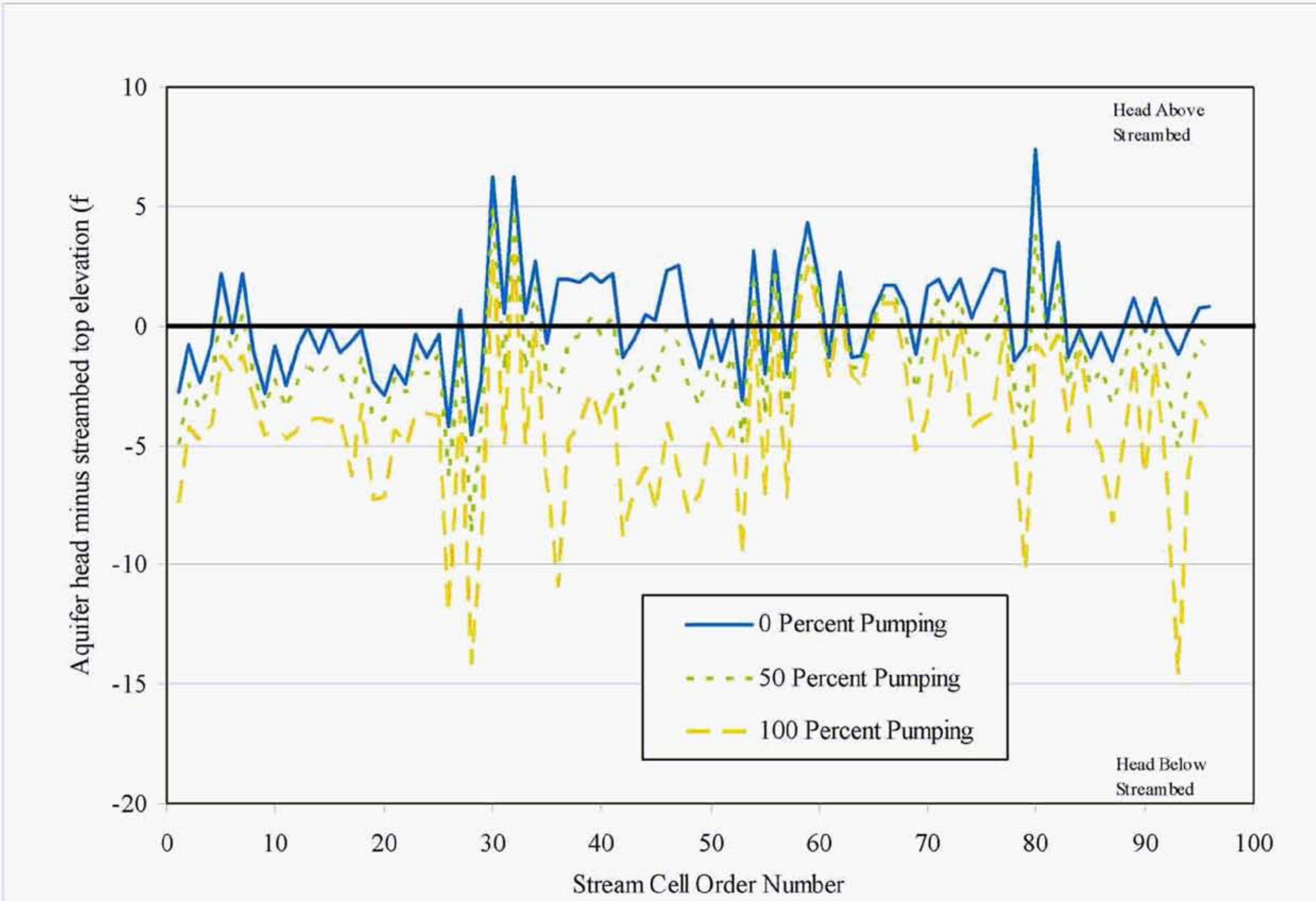

Figure 2.5. Graph showing stream cell order vs aquifer head minus stream top for various percents of full pumping for Kansas and Nebraska pumping, Beaver Creek at end of 2003

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.

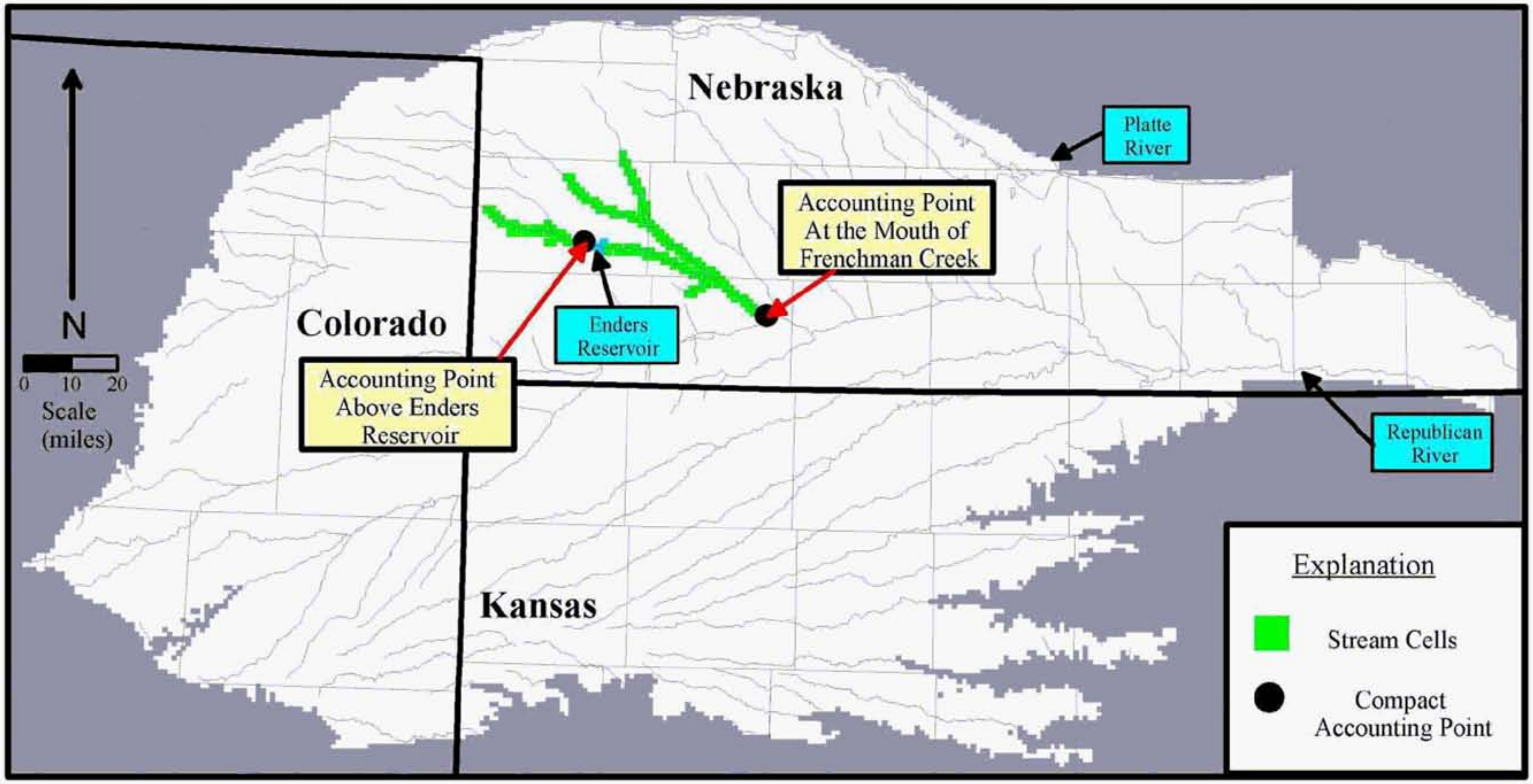

Figure 2.6. Map showing location of cells with stream boundary condition in Frenchman Creek.

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 [θ] (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 [θ] (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.

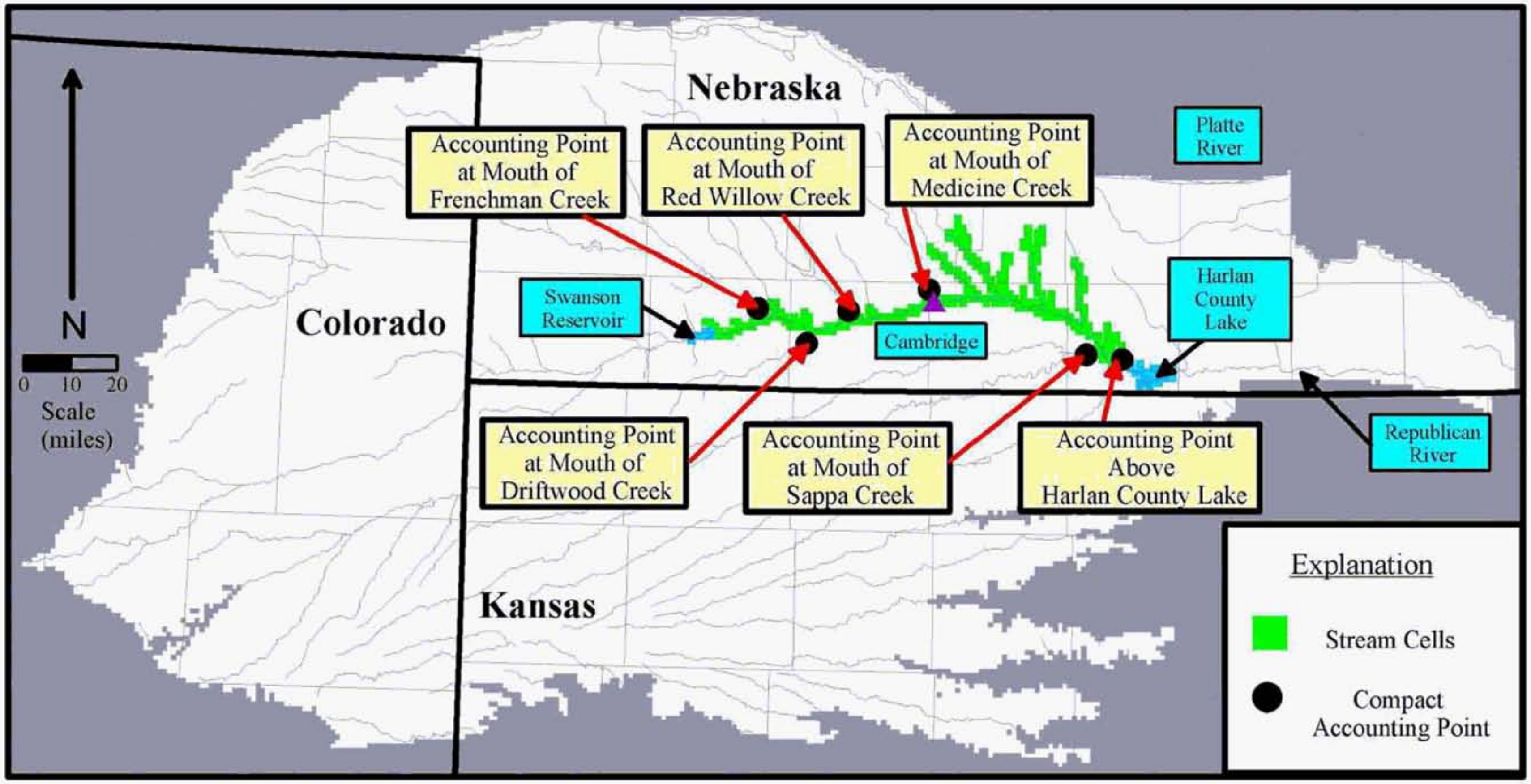

Figure 2.7. Map showing location of cells with stream boundary condition along the Main Stem of the Republican River from Swanson Reservoir to Harlan County Lake.

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 [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
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 [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
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 [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
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 [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
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)

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,

$$I_C + I_K + I_N + I_M = T \qquad (1)$$

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;

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

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

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

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

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

The proposed method yields an impact calculation for Nebraska given by

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

Substituting Equation 9 into Equation 10 yields

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

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

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

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

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:

$$R = T - (I_C + I_K + I_N + I_M) \tag{14}$$

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

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

Canceling common terms the residual is given by

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

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) $C = 0$ (turning on Colorado pumping produces no change from the all-off condition)
2) $M = 0$ (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,

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

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,

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

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,

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

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.

		Current Accounting		Directly Computed		
	Gage + $CBCU_S$	$CBCU_G$ - IWS	CWS	$CBCU_G$ - IWS	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)

	Gage + $CBCU_S$	Current Accounting $CBCU_G$ - IWS	CWS	Directly Computed $CBCU_G$ - 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)

	Gage + $CBCU_S$	Current Accounting $CBCU_G$ - IWS	CWS	Directly Computed $CBCU_G$ - 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).

NON-BINDING ARBITRATION
Pursuant to Arbitration Agreement of October 23, 2008

IN ACCORDANCE WITH:
FINAL SETTLEMENT STIPULATION

Kansas v. Nebraska and Colorado
No. 126, Original, U.S. Supreme Court
Decree of May 19, 2003, 538 U.S. 720

ARBITRATOR'S FINAL DECISION

June 30, 2009

BACKGROUND

On December 15, 2002, the states of Kansas, Nebraska, and Colorado (the "States") executed the Final Settlement Stipulation (the "FSS") "... to resolve the currently pending litigation in the United States Supreme Court regarding the Republican River Compact by means of this Stipulation and the Proposed Consent Judgment ... ." FSS, Volume 1 of 5, at 1. The FSS was filed with the Special Master appointed by the U.S. Supreme Court (the "Court") in *Kansas v. Nebraska and Colorado*, No. 126, Original, who recommended entry of the proposed consent judgment which would approve the FSS. Second Report of the Special Master (Subject: Final Settlement Stipulation) at 77. On May 19, 2003, the Court entered a consent decree approving the FSS (the "Consent Decree").

By 2007, disputes arose between the States regarding compliance with the FSS and the Republican River Compact (the "Compact"). The disputes were submitted to the Republican River Compact Administration (the "RRCA") pursuant to the provision in the FSS for dispute resolution. *See* FSS, Volume 1 of 5, § VII., at 34-40. The RRCA addressed the disputes, but no resolution of certain disputes was reached. *See* Resolution of the RRCA dated May 16, 2008; Exhibit 1 to Arbitration Agreement dated October 23, 2008. The RRCA submitted these disputes to non-binding arbitration pursuant to the provisions of § VII. of the FSS, the States executed the Arbitration Agreement on October 23, 2008 (the "Arbitration Agreement"), and I was retained by the States to serve as the Arbitrator.

Exhibit 2 to the Arbitration Agreement sets forth the "Time Frame Designation" for the non-binding arbitration, Exhibit 3 to the Arbitration Agreement sets forth the disputed issues identified by the State of Kansas to be arbitrated, and Exhibit 4 to the Arbitration Agreement sets forth the disputed issues identified by the State of Nebraska to be arbitrated. The disputed issue originally raised by the State of Colorado with the RRCA, which the RRCA submitted to non-binding arbitration pursuant to the provisions of § VII. of the FSS (*See* Attachment 3 to Resolution of the RRCA dated May 16, 2008), has been withdrawn from this arbitration and is not included in the Arbitration Agreement.

From the issues set forth in Exhibit 3 and Exhibit 4 to the Arbitration Agreement, the States identified six legal issues to be decided by the Arbitrator by December 19, 2008, for the purpose of narrowing discovery and the hearing on the merits. Based on a disagreement regarding the appropriate scope of the arbitration, the Arbitrator identified a seventh legal issue during a prehearing conference held telephonically on November 5, 2008. Each of the States filed opening briefs on these seven legal issues with the Arbitrator on November 10, 2008. (The State of Colorado briefed 3 arguments pertaining to only 4 of the legal issues.) Responsive briefs were filed on November 24, 2008, and reply briefs were filed on December 5, 2008. Oral argument on these legal issues was heard at the University of Denver, Strum College of Law, on December 10, 2008.

The Arbitrator treated the briefs filed by the States as being analogous to cross-motions for summary judgment under Rule 56 of the Federal Rules of Civil Procedure. "A party claiming relief may move, with or without supporting affidavits, for summary judgment on all or part of the claim." Fed. R. Civ. P. 56(a). "The judgment sought should be rendered if the pleadings, the discovery and disclosure materials on file, and any affidavits show that there is no genuine issue as to any material fact and that the movant is entitled to judgment as a matter of law." Fed. R. Civ. P. 56(c).

The Arbitrator issued his preliminary decision on these seven legal issues, including a summary of his reasons for deciding each issue, on December 19, 2008. On January 22, 2009, the Arbitrator issued his final decision on these seven legal issues. With minor corrections and the addition of supporting analysis for each of the seven issues, the final decision is materially the same as the preliminary decision issued on December 19, 2008. The *Arbitrator's Final Decision on Legal Issues* is attached hereto[1] and fully incorporated herein by reference.

The States submitted expert reports on the remaining issues to the Arbitrator in lieu of extensive direct testimony on February 23, 2009. The Arbitrator subsequently conducted a hearing on those issues at the Byron Rogers U. S. Courthouse in Denver, Colorado, beginning on March 9, 2009. The hearing was recessed on March 19, 2009, and reconvened and concluded on April 14, 2009. The Arbitrator has carefully considered the reports and testimony of the expert witnesses for the States together with post-hearing briefs submitted by counsel for the States and issues the following decision.

FINDINGS

Accounting Procedures – Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply

1. The Final Settlement Stipulation (the "FSS") executed by the States on December 15, 2002, and approved by the U. S. Supreme Court on May 19, 2003, incorporates detailed Accounting Procedures and Reporting Requirements ("Accounting Procedures"), which were subsequently adopted and revised by the Republican River Compact Administration (the "RRCA")[2], as provided in § I.F. of the FSS. The adopted Accounting Procedures, as revised, include procedures for estimating Computed Beneficial Consumptive Use ("CBCU") for groundwater and determining the Imported Water Supply Credit ("IWS").

2. In their respective post-hearing briefs (each titled *Post-Trial Brief*),[3] counsel for the states of Colorado and Kansas assert that the issue of estimating CBCU of groundwater and determining the IWS is not a proper subject for this arbitration because Nebraska's expert

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[1] The date in the first line of the attached Arbitrator's F*inal Decision on Legal Issues*, dated January 22, 2009, has been corrected to December 15, 2002.

[2] Final Settlement Stipulation, Volume 1 of 5, Appendix C, as revised (July 2005) and adopted (August 10, 2006) by the RRCA.

[3] Counsel for Colorado, Kansas, and Nebraska signed and submitted briefs by FedEx sent on April 24, 2009.

report on this issue[4] has not been submitted to the RRCA for its consideration,[5] and therefore, the Arbitrator should not consider the issue.

3. Exhibits 1, 3, and 4 of the Arbitration Agreement executed by each of the States on October 23, 2008, identify the procedures used to estimate CBCU of groundwater and determine the IWS as a disputed issue "which may be taken to the next step in the dispute resolution process"[6] and an issue "to be Arbitrated."[7]

4. The difference between what Colorado and Kansas contend was submitted to the RRCA and included in the Arbitration Agreement, as compared with what is before the Arbitrator, is the weighting coefficients proposed by Nebraska to be applied to results from 8 differences calculated using 16 runs of the RRCA Groundwater Model.[8] Although the weighting coefficients involved in the proposal currently before the Arbitrator are different than the equal weighting coefficients resulting from averaging the 8 differences, which was the approach presented to the RRCA in August of 2008,[9] Nebraska's proposal to use 8 differences calculated using 16 runs of the RRCA Groundwater Model is essentially the same as it was in August of 2008.

5. Prior to submitting their respective post-hearing briefs, neither Colorado nor Kansas asserted that because Nebraska's expert report on this issue had not been submitted to the RRCA for its consideration, the issue of estimating CBCU of groundwater and determining the IWS was not a proper subject for this arbitration. Neither Colorado nor Kansas timely made this assertion when they submitted their respective expert reports[10, 11] in response to Nebraska's expert report on this issue, and neither timely raised this assertion during the hearing conducted from March 9 through March 19 and on April 14, 2009. Therefore, Nebraska's

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[4] Nebraska Exhibit 30, Expert Report of Dr. David P. Ahlfeld, Michael G. McDonald, and James C. Schneider, *Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact*, January 20, 2009.

[5] *State of Colorado's Post-Trial Brief* at 30-33; *Kansas' Post-Trial Brief* at 65-66.

[6] Exhibit 1 of the Arbitration Agreement, *see* Attachment 2: Commissioner Dunnigan's letter to Commissioners Barfield and Wolfe dated April 15, 2008.

[7] Exhibit 3 and Exhibit 4 of the Arbitration Agreement.

[8] *State of Colorado's Post-Trial Brief* at 32; *Kansas' Post-Trial Brief* at 65; *State of Nebraska's Post-Hearing Brief* at 43 and 49.

[9] *Id.*

[10] Colorado Exhibit 7, Expert Report of Willem A. Schreüder, Ph.D., *Report in Response to: Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact, Ahfed* [*sic*] *et al. (January 20, 2009)*, February 16, 2009.

[11] Kansas Exhibit 28, Expert Report of David W. Barfield, Steven P. Larson, and Dale E. Book, *Kansas's Expert Response to Nebraska's Expert Report, "Estimating Computed Beneficial Use for Groundwater and Imported Water Supply under the Republican River Compact,"* February 17, 2009.

issue of estimating CBCU of groundwater and determining the IWS, as presented in its expert report,[4] is properly included as an issue in this arbitration.

6. Subsection III.A.1. of the Accounting Procedures specifies how the annual Virgin Water Supply for each sub-basin is to be determined as follows:

> The annual Virgin Water Supply for each Sub-basin will be calculated by adding: a) the annual stream flow in that Sub-basin at the Sub-basin stream gage designated in Section II., b) the annual Computed Beneficial Consumptive Use above that gaging station, and c) the Change in Federal Reservoir Storage in the Sub-basin; and from that total subtract any Imported Water Supply Credit. The Computed Beneficial Consumptive Use will be calculated as described in Subsection III. D.

7. Subsection III.A.2. of the Accounting procedures specifies how the annual Virgin Water Supply for main stem is to be calculated as follows:

> The annual Virgin Water Supply for the Main Stem will be calculated by adding: a) the flow at the Hardy gage minus the flows from the Sub-basin gages listed in Section II, b) the annual Computed Beneficial consumptive Use in the Main Stem, and c) the Change in Federal Reservoir Storage from Swanson Lake and Harlan County Lake; and from that total subtract any Imported Water Supply Credit for the Main Stem.

8. Section II. of the Accounting Procedures define the terms Virgin Water Supply, Computed Beneficial Consumptive Use, and Imported Water Supply Credit as follows:

> **Virgin Water Supply:** the Water Supply within the Basin undepleted by the activities of man;
>
> **Computed Beneficial Consumptive Use:** for purposes of Compact accounting, the stream flow depletion resulting from the following activities of man:
>
> Irrigation of lands in excess of two acres;
> Any non-irrigation diversion of more than 50 Acre-feet per year;
> Multiple diversions of 50 Acre-feet or less that are connected or otherwise combined to serve a single project will be considered as a single diversion for accounting purposes if they total more than 50 Acre-feet;
> Net evaporation from Federal Reservoirs;
> Net evaporation form Non-federal Reservoirs within the surface boundaries of the Basin;
> Any other activities that may be included by amendment of these formulas by the RRCA;
>
> **Imported Water Supply Credit:** the accretions to stream flow due to water imports from outside of the Basin as computed by the RRCA Groundwater Model. The Imported Water Supply Credit of a State shall not be included in the Virgin Water Supply and shall be counted as a credit/offset against the Computed Beneficial Consumptive Use of water allocated to that State …

9. Subsection III.D.1. of the Accounting Procedures specifies how Computed Beneficial Consumptive Use of groundwater is to be determined for an accounting year as follows:

> 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 period 1940 to 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."

10. Subsection III.A.3. of the Accounting Procedures specifies how the Imported Water Supply Credit is to be determined for an accounting year as follows:

> The amount of Imported Water Supply Credit shall be determined by the RRCA Groundwater Model. The Imported Water Supply Credit of a State shall not be included in the Virgin Water Supply and shall be counted as a credit/offset against the Computed Beneficial Consumptive Use of water allocated to that State. Currently, the Imported Water Supply Credits shall be determined using two runs of the RRCA Groundwater Model:
>
> a. 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 period 1940 to the current accounting year turned "on." This will be the same "base" run used to determine groundwater Computed Beneficial Consumptive Uses.
>
> b. 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.

11. Nebraska has proposed essentially three changes in the Accounting Procedures adopted by the RRCA involving computation of CBCU for groundwater and IWS that would modify (1) the annual calculation of Virgin Water Supply ("VWS") in each Sub-basin and the Main Stem; (2) the annual determination of CBCU in each Sub-basin and the Main Stem; and (3) the annual determination of the IWS in each Sub-basin and the Main Stem.[4] None of these changes have been adopted by the RRCA, as provided in § I.F. of the FSS , and are at issue in this arbitration pursuant to § VII.A., ¶ 1. and ¶ 7., of the FSS.

12. The calculation of annual VWS for any Sub-basin, as specified in § III.A.1. of the Accounting Procedures and described in Finding 6 is:

$$VWS = Gage + CBCU + \Delta S - IWS.$$

Alternatively, this relationship can be written:

$$VWS = Gage + CBCU_S + CBCU_G + \Delta S - IWS$$

or

$$VWS = Gage + CBCU_S + (CBCU_C + CBCU_K + CBCU_N) + \Delta S - IWS$$

In these relationships, "Gage" is the annual streamflow in that Sub-basin measured at the stream gage designated in § II. of the Accounting Procedures, CBCU is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use, and ΔS is the Change in Federal Reservoir Storage. Using the notation of Nebraska,[4] $CBCU_S$ is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use of surface water, $CBCU_G$ is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use of groundwater, $CBCU_C$ is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use of groundwater by Colorado, $CBCU_K$ is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use of groundwater by Kansas, and $CBCU_N$ is the computed depletion of streamflow in that Sub-basin from all Beneficial Consumptive Use of groundwater by Nebraska.

13. The calculation of annual VWS for the Main Stem, as specified in § III.A.2. of the Accounting Procedures and described in Finding 7 is the same as shown in Finding 12 except the from the "Gage" (which for the Main Stem is the annual streamflow measured at the Hardy gage), the sum of the annual streamflows measured at all Sub-basin gages upstream of the Hardy gage is subtracted.

14. The first change proposed by Nebraska in the Accounting Procedures pertaining to $CBCU_G$ and IWS would modify the determination VWS in Finding 12 to:

$$VWS = VWS_S + VWS_G$$

where

$$VWS_G = (\theta - CKMN).$$

In these relationships, again using the notation of Nebraska,[4] VWS_S is the surface-water-related portion of VWS, VWS_G is the groundwater-related portion of VWS, θ is the annual base flow in a Sub-basin or the Main Stem determined from running the RRCA Groundwater Model with all groundwater pumping, groundwater pumping recharge, and surface water recharge within the model study boundary for the period 1940 to a particular accounting year "off," and CKMN, is the base flow in a Sub-basin or the Main Stem determined from running the RRCA Groundwater Model with all Colorado groundwater pumping and recharge (C), Kansas groundwater pumping and recharge (K), all surface water recharge from Imported Water Supply (M), and all Nebraska groundwater pumping and recharge (N) within the model study boundary for the period 1940 to a particular accounting year "on."

15. The reason stated by Nebraska for the proposed change in determining VWS is: "This independently-computed value of VWS_G is the best estimate of the impact of all groundwater-related human activity on streamflow and should be viewed as the true value of this property."[12]

16. While the independently-computed value of VWS_G (θ – CKMN) may be the best estimate of base flow discharged from the groundwater system to surface water sources "undepleted by the activities of man" over the period 1940 to a particular accounting year, it is an estimated value derived from running the RRCA groundwater model and should not be viewed as the "true value" as suggested by Nebraska. Although the RRCA Groundwater Model has presumably been properly designed and calibrated and can provide reliable estimates of base flow, the RRCA groundwater model is still an idealization of a complex hydrogeologic system, and the results derived from running the model are not necessarily the true values.

17. The second and third changes proposed by Nebraska in the Accounting Procedures pertaining to $CBCU_G$ and IWS would modify the determination of $CBCU_C$, $CBCU_K$, and $CBCU_N$ specified in § III.D.1. of the Accounting Procedures as described in Finding 9 and the determination of IWS specified in § III.A.3. of the Accounting Procedures described in Finding 10 such that:

$$CBCU_C + CBCU_K + CBCU_N - IWS = (\theta - CKMN) = VWS_G$$

under all conditions.

18. As described in Findings 9 and 10, the current Accounting Procedures require differencing the results from two runs of the RRCA Groundwater Model (requiring 5 runs of the RRCA Groundwater Model) to determine each of the four man-caused stresses to the groundwater system; i.e., Colorado groundwater consumptive use ($CBCU_C$), Kansas groundwater consumptive use ($CBCU_K$), Nebraska groundwater use ($CBCU_N$), and recharge from imported surface water (IWS). Nebraska proposes differencing the results from 16 runs of the RRCA Groundwater Model (8 differences) for each of the four man-caused stresses to the groundwater system and summing the 8 differences using weighting factors, which weighting factors sum to one, for each of the four man-caused stresses such that the relationship in Finding 17 is satisfied.[13]

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[12] Nebraska Exhibit 30, Expert Report of Dr. David P. Ahlfeld, Michael G. McDonald, and James C. Schneider, *Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact*, January 20, 2009, p. 9.

[13] *Id.*, p. 48. Also, *see* Nebraska Exhibit 33.

19. The reasons stated by Nebraska for the proposed changes in determining $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS include:

> … the current Accounting Procedures assume that VWS_G can be computed using the individually-computed impacts in a sub-basin ($CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS) as $VWS_G = CBCU_C + CBCU_K + CBCU_N - IWS$[14]
>
> … under some stream drying conditions, the current Accounting Procedures do not produce values that combine to the independently-computed value of VWS_G. This leads to the conclusion that the values of $CBCU_C$, $CBCU_K$, $CBCU_N$ and IWS computed using the current Accounting Procedures are in error.[15]
>
> The deviation from additivity can be substantial and is of critical importance since this additivity is assumed to hold under the current Accounting Procedures.[16]
>
> The selection of the additional model runs to be used is based on the idea that using a base condition with any one human activity either on or off may bias the results for or against one state. … As a result, analysis should be performed using all possible base conditions in which human activities are either on or off.[17]
>
> The proposed method provides values for impact that satisfy the expectation that individual impacts will sum to the total impact of human activity for a given sub-basin.[18]

20. In the context of the changes proposed by Nebraska, "additivity" means that the relationship described in Finding 17 is valid under all conditions. The "error" or "deviation from additivity" asserted by Nebraska occurs when modeled groundwater use by any of the three States, individually or in combination, fully depletes streamflow. That is, so long as groundwater-caused depletions to a flowing stream do not cause streamflow to approach zero, an increase or decrease in the use of groundwater that is hydraulically connected to the stream will result in a decrease or increase in streamflow, respectively, that essentially is linearly proportionate[19] to the increase or decrease in groundwater use. The modeled response of the stream is basically linear and the condition of "additivity" holds when $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS are determined in accordance with the current Accounting Procedures as described in Findings 9 and 10. However, when modeled groundwater use is increased such that groundwater-caused depletions result in stream drying and a break in the hydraulic connection between the groundwater system and the stream,

[14] *Id.*, p. 9.

[15] *Id.*

[16] *Id.*, p. 12.

[17] *Id.*, p. 47.

[18] *Id.*, p. 51.

[19] Ignoring minor nonlinearities from unrelated factors.

there is no remaining streamflow to deplete. Under such conditions, the modeled response of the stream becomes nonlinear, and the condition of "additivity" no longer holds when $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS are determined in accordance with the current Accounting Procedures.

21. As described in Finding 19, Nebraska contends that the current Accounting Procedures assume that VWS_G, defined by Nebraska as (θ – CKMN), can be computed using the individually-computed impacts in a sub-basin. That is: $CBCU_C + CBCU_K + CBCU_N - IWS$ would equal (θ – CKMN) under all conditions. However, careful readings of the Accounting Procedures[20] and the Final Report of the Special Master,[21] which includes a detailed description of the significant attributes of the RRCA Groundwater Model and use of the Model output, do not reveal that the assumption of "additivity" to (θ – CKMN) under all conditions was made by either the representatives of the States that developed the Accounting Procedures or the representatives of the States that developed the RRCA Groundwater Model.

22. One of the co-authors of Nebraska's expert report on estimating CBCU for groundwater and IWS, Michael McDonald, was a member of the Technical Groundwater Modeling Committee that developed the RRCA Groundwater Model.[22] However, Nebraska did not offer any testimony during the hearing on this issue that would corroborate the assertion that the Technical Groundwater Modeling Committee intended that $CBCU_C + CBCU_K + CBCU_N - IWS$ would equal (θ – CKMN) under all conditions. The fact that this "additivity" holds when streamflow response to groundwater depletions is linear does not establish that the representatives of the States that developed the RRCA Groundwater Model and the Accounting Procedures assumed or intended that this condition of additivity would hold when streamflow response to groundwater depletions is nonlinear.

23. The description of the significant attributes of the RRCA Groundwater Model and use of the Model output contained in the Final Report of the Special Master specifically includes a description of how the Model is used to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS,[23] which is the same as specified in the Accounting Procedures as described in Findings 9 and 10.

24. The fact that "[t]he 'base' run is the simulation with all groundwater pumping, groundwater pumping recharge, and surface water recharge within the model study boundary for the

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[20] Final Settlement Stipulation, Volume 1 of 5, Appendix C, as revised (July 2005) and adopted (August 10, 2006) by the RRCA.

[21] Final Report of the Special Master With Certificate of Adoption of RRCA Groundwater Model, *Kansas v. Nebraska and Colorado*, No. 126, Original, September 17, 2003.

[22] *See* Kansas Exhibit 72.

[23] *See* Final Report of the Special Master With Certificate of Adoption of RRCA Groundwater Model, *Kansas v. Nebraska and Colorado*, No. 126, Original, September 17, 2003, pp. 49-50.

period 1918 to the current accounting year 'on',"[24] and that this base run would likely simulate stream drying at some locations during certain years, resulting in nonlinear response, suggests that such an outcome was anticipated by the Technical Groundwater Modeling Committee that developed the RRCA Groundwater Model. This is supported by the testimony of both Kansas' expert witness on this issue, Mr. Steve Larson,[25] and Colorado's expert witness on this issue, Dr. Willem Schreüder,[26] both of whom served on the Technical Groundwater Modeling Committee that developed the RRCA Groundwater Model.

25. Using flows in Beaver Creek in 2003 as an example, Nebraska correctly points out that:

> … increasing pumping by either Kansas or Nebraska alone or both states together causes baseflow at the Beaver Creek accounting point to drop to zero after a threshold is reached. Baseflow remains zero beyond this threshold as pumping is further increased. Clearly, increasing pumping beyond this point by either state must have some impact on the groundwater/stream system. Where in the system is this impact felt?[27]

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[24] *Id.*

[25] MR. DRAPER: Was it clear to you that the model, the groundwater model, has nonlinear features related to stream depletions?

MR. LARSON: Yes, it was. There were several nonlinear features in the model that were, in my view, pretty obvious. And one of them -- that is, the changes in saturated thickness with changes in water levels -- there were some idealizations made, primarily for computational stability reasons, to at least linearize that feature; but there were other nonlinear features that were pretty obvious. Evapotranspiration, function is a method of piecewise linear; but, overall, similiarly [*sic*] the rain is nonlinear, similarly the stream-drying-sort-of feature, if you will, is a piecewise linear feature as well.

Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1233:23-1234:13.

[26] DR. SCHREÜDER: The first point is that Nebraska is using 2003 as an example of how the modeling is not behaving in an appropriate way.

That is not correct.

In the first place, 2003 is a fairly extreme year; but, nevertheless, none of the behavior that we observe in 2003 -- wasn't known to the committee at the time that the model was put together. …

But we looked in great detail at the period prior to 2000 and this similar kind of behavior did, in fact, occur and was well known to many members.

MR. AMPE: Doctor, when did you first become aware of the nonlinearity of the model?

DR. SCHREÜDER: About 15 minutes after I saw it the first time.

Transcript of Arbitration Proceedings, March 18, 2009, Volume VIII at 1388:13-1389:3.

[27] Nebraska Exhibit 30, Expert Report of Dr. David P. Ahlfeld, Michael G. McDonald, and James C. Schneider, *Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact*, January 20, 2009, p. 22.

Increasing groundwater consumption by either Kansas or Nebraska after base flow drops to zero will result in additional reductions in groundwater storage than would have occurred had the base flow not been fully depleted, unless streamflow other than from base flow is available for depletion by the increased groundwater consumption. Obviously, once the consumptive use of groundwater from a groundwater system that is hydraulically connected to a stream has fully depleted the flow in that stream, any additional consumption of groundwater from that system cannot be supplied from depletions to streamflow, but has to be supplied from other sources including much larger increases in withdrawals from groundwater storage.

26. While Nebraska's experts clearly understand the response described in Finding 25,[28] its proposed changes to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS are based on depletions to streamflow that cannot occur once streamflow has been fully depleted. Using Beaver Creek in 2003 as an example, differencing results from the RRCA Groundwater Model as described in Finding 9 produces an estimate of the base flow in 2003 subject to depletion by consumptive groundwater use in Kansas of 323 acre-feet, with full groundwater use in Nebraska. Because of consumptive groundwater use in Nebraska during the period 1940 through 2003, the estimated 323 acre-feet is the most amount of base flow that consumptive groundwater use in Kansas could deplete from Beaver Creek. Once flows in Beaver Creek are depleted, the consumptive use of groundwater in Kansas that would cause additional depletions to streamflow in Beaver Creek, if such flow existed, must be satisfied with groundwater from other sources, primarily groundwater storage. Similarly, with full groundwater use in Kansas the estimated base flow in 2003 subject to depletion by consumptive groundwater use in Nebraska is 727 acre-feet. Because of consumptive groundwater use in Kansas during the period 1940 through 2003, the estimated 727 acre-feet is the most base flow that consumptive groundwater use in Nebraska could deplete from Beaver Creek. As for Kansas, the consumptive use of groundwater in Nebraska that would cause additional depletions to streamflow in Beaver Creek, if such flow existed, must be satisfied with groundwater from other sources, primarily groundwater storage. The estimated streamflow in 2003 that can be depleted by Kansas with full groundwater use in Nebraska added to the estimated streamflow in 2003 that can be depleted by Nebraska with full groundwater use in Kansas is 1,050 acre-ft.

Nebraska contends that the "true total impact" is 6,445 acre-feet, calculated as (θ – KN),[29] and that "[t]he difference between the true total impact, 6,445 ac-ft, and the total impact estimated by summing individual impacts is 5,395 acre-feet." Nebraska further contends that "[t]his amount of streamflow depletion is occurring but not being accounted for in the current procedure."[30] Nebraska's contention is flawed because although the consumptive beneficial

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28 *Id.*, p. 22-24.

29 Historically, there have not been any effects on streamflow in Beaver Creek other than from consumptive use of groundwater in Kansas (K) and in Nebraska (N).

30 *Id.*, p. 19.

use of groundwater in Kansas and Nebraska during 2003 must have been significantly greater than 1,050 acre-feet, the sum of $CBCU_K$ and $CBCU_N$, there could not have been 6,445 acre-feet of base flow from groundwater discharge that could have been depleted from Beaver Creek in 2003. The additional consumptive beneficial use of groundwater by Kansas and Nebraska beyond what would deplete streamflow to zero had to have consumed groundwater from other sources, primarily groundwater storage. Historically, there have obviously been significant groundwater consumptive uses in both Kansas and Nebraska that have reduced groundwater storage, lowered groundwater levels, and largely depleted the base flow that was available in 2003. The Beaver Creek base flow in 2003 estimated by Nebraska to have been 6,445 acre-feet would be a viable estimate only if there had never been consumptive groundwater use in Kansas or Nebraska, which obviously is not what has actually occurred.

27. Nebraska terms the difference between VSW_G, calculated as (θ – CKMN), and the sum of $CBCU_C$, $CBCU_K$, and $CBCU_N$, less IWS, a residual.[31] As described in Finding 17, Nebraska's proposed changes to the procedures for calculating $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS, result in the sum of $CBCU_C$, $CBCU_K$, and $CBCU_N$, less IWS, equaling (θ – CKMN), and a residual of zero.

28. One result from the analysis in Finding 26 is that Nebraska's proposed procedure for determining VWS, whereby

$$VWS = VWS_S + VWS_G$$

and

VWS_G = (θ – CKMN), also referred to by Kansas as the "virgin water supply metric,"[32]

is more consistent with the definition of VWS established in the Compact and adopted in the Accounting Procedures (*see* Finding 8) than is summing $CBCU_C$, $CBCU_K$, and $CBCU_N$, less IWS, each determined in accordance with the existing Accounting Procedures, to compute what Nebraska terms VWS_G.

29. While Nebraska's proposal for determining what it terms VWS_G, or what Kansas terms the virgin water supply metric, is more consistent with the definition of VWS established in the Compact and adopted in the Accounting Procedures, than is the definition implied by summing $CBCU_C$, $CBCU_K$, and $CBCU_N$, less IWS, Nebraska's proposed changes to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS are problematic. Again using flows in Beaver Creek in 2003 as an example, Nebraska's proposed methodology results in a value for $CBCU_K$ of 3,021 acre-feet and a value for $CBCU_N$ of 3,425 acre-feet for a total VWS_G of

[31] *Id.* at 46.

[32] Nebraska Exhibit 36, *Kansas' Review of Nebraska's Request for Change in Accounting Procedure*, September 18, 2007, p. 2.

6,445 acre-feet.[33] These values are equivalent to adding one-half of the residual (one-half of 5,395 acre-feet) to $CBCU_K$ (323 acre-feet) and one-half of the residual to $CBCU_N$ (727 acre-feet), when $CBCU_K$ and $CBCU_N$ are calculated using the methodology prescribed in the existing Accounting Procedures as described in Finding 9.[34] The residual of 5,395 acre-feet is essentially the amount of groundwater consumptive use beyond the sum of 323 acre-feet and 727 acre-feet from streamflow depletion that must come from other groundwater sources, primarily groundwater storage, and is equally divided between Kansas and Nebraska using Nebraska's proposed methodology.[35]

30. Equally dividing what are primarily additional withdrawals from groundwater storage between Kansas and Nebraska, when streamflow is depleted and there is no longer a hydraulic connection with the groundwater system, to determine $CBCU_K$ and $CBCU_N$ without regard to the decrease in groundwater storage caused by groundwater use in each state is not appropriate. Similarly, equally dividing what are primarily additional withdrawals from groundwater storage between Colorado and Nebraska in the case of Frenchman Creek, when streamflow is depleted and there is no longer a hydraulic connection with the groundwater system, to determine $CBCU_C$ and $CBCU_N$ without regard to the decrease in groundwater storage caused by groundwater use in each state is problematic given that "the majority of the Frenchman Basin is in Nebraska and Nebraska pumping can be expected to have the largest influence."[36]

31. Using the examples of Beaver Creek and Frenchman Creek, equally dividing what are primarily additional withdrawals from groundwater storage between two states when streamflow is depleted and there is no longer a hydraulic connection with the groundwater system to determine CBCU, without regard to the decrease in groundwater storage caused by groundwater use in each state, is also inconsistent with there being "very little propagation of head change across statelines."[37]

32. When the groundwater being consumptively used involves all three states, or when there is significant IWS, the residual described in Finding 27 is divided in "a more complicated way"[38] but the residual must still be related to changes in groundwater storage.

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[33] Nebraska Exhibit 30, Expert Report of Dr. David P. Ahlfeld, Michael G. McDonald, and James C. Schneider, *Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact*, January 20, 2009, p. 50.

[34] Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1148:19-1149:4 (Ahlfeld).

[35] Transcript of Arbitration Proceedings, March 19, 2009, Volume IX at 1466:9-1470:8 (Ahlfeld).

[36] Nebraska Exhibit 30, Expert Report of Dr. David P. Ahlfeld, Michael G. McDonald, and James C. Schneider, *Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact*, January 20, 2009, p. 30.

[37] Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1173:8-9 (Ahlfeld).

[38] *Id.*at 1149:7 (Ahlfeld).

33. Groundwater consumptively used from groundwater storage is not streamflow depletion, and inclusion of the consumptive use of groundwater storage in the calculation of $CBCU_C$, $CBCU_K$, and $CBCU_N$ is inconsistent with the definition of CBCU as set forth in § II. of the Accounting Procedures. Similarly, including the base flow in VWS_G that would be discharged from groundwater as though groundwater storage had not been reduced by consumptive groundwater use, or θ, results in overstating the Computed Water Supply (the "CWS") that is available to be allocated to each state in any drainage basin during a year where simulated stream drying in that basin occurs and there is no hydraulic connection between the groundwater system and the stream.

34. Nebraska's proposed procedure for determining IWS has a related problem. Half of the model runs and differences, and half of the weighting, proposed for determining IWS do not include any simulated groundwater use by Nebraska. This means that for half of the model runs, groundwater storage is undepleted by Nebraska groundwater use and simulated groundwater levels are higher than historical levels. As a result, IWS determined as proposed by Nebraska will generally be greater than IWS determined using the existing procedure specified in § III.A.3. of the Accounting Procedures as described in Finding 10.[39] In fact, the Main Stem IWS and the total IWS determined using Nebraska's proposed method is greater than the corresponding IWS determined using the existing procedure described in Finding 10 for all years from 1981 through 2006, except for 1993.[40] The reason for the anomaly in the 1993 IWS is unknown, but may be the result of computational error.

35. Colorado's expert on this issue, Dr. Willem A. Schreüder, identified another concern with Nebraska's proposed changes. In his report, Dr. Schreüder states that: "The method proposed by Nebraska, on the other hand, ***does*** included the consumption of imported water."[41] Dr. Schreüder shows that $CBCU_N$ calculated "... for the Swanson-Harlan reach are greater with imported water than without imported water"[42] and further states that: "As shown in Figure 10, any simulation where surface water imports are on will include consumption of imported water."[43] Thus, the current Accounting Procedures for calculating $CBCU_C$, $CBCU_K$, $CBCU_N$, as described in Finding 9, may also include consumption of imported water, since both the "base" run and the "no State pumping" run include surface

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39 *See* testimony of Mr. Steve Larson, Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1240:25-1241:5.

40 *See* Tables 1a through 1z in Colorado Exhibit 7, Expert Report of Willem A. Schreüder, Ph.D., *Report in Response to: Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply under the Republican River Compact, Ahfed* [*sic*] *et al. (January 20, 2009)*, February 16, 2009.

41 *Id.* at 18.

42 *Id.*

43 *Id.* at 19.

water imports.[44] Including the consumption of imported water in the calculation of CBCU is not consistent with § IV.F. of the FSS, which specifically provides that: "Beneficial Consumptive Use of Imported Water Supply shall not count as Computed Beneficial Consumptive Use or Virgin Water Supply Credit."[45]

36. Although Nebraska's proposed changes to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS are problematic, the RRCA should consider reconvening the Technical Groundwater Modeling Committee to thoroughly re-evaluate the nonlinear response of the RRCA Groundwater Model when simulated stream drying occurs, re-evaluate the existing procedures for determining CBCU and IWS described in Findings 9 and 10, and document its conclusions and any recommendations in a report to the RRCA.

Accounting Procedures – Haigler Canal

37. Nebraska has proposed three changes in the Accounting Procedures adopted by the RRCA involving the Haigler Canal that would modify (1) the annual determination of water diverted from the North Fork Republican River in Colorado into the Haigler Canal[46] for irrigation in Nebraska; (2) the annual apportionment of return flows from irrigation in Nebraska between the Main Stem, measured at the USGS stream gage near Hardy, Nebraska, station 06853500 (the "Hardy Gage"), and the Arikaree River, measured at the USGS stream gage at Haigler, Nebraska, station 06821500 (the "Arikaree Gage); and (3) the annual calculation of VWS for the North Fork of Republican River in Colorado and the Arikaree River.

38. Under the current Accounting Procedures, the Nebraska CBCU attributable to the annual diversions from the North Fork Republican River to the Haigler Canal for irrigation in Nebraska is based on using the total amounts of water diverted as measured at the Haigler Canal Stateline Gage, station 00061400.[47] The first change to the Accounting Procedures involving the Haigler Canal proposed by Nebraska would reduce the amount of these annual diversions from the North Fork Republican River by an amount equal to the annual discharges from the Haigler Canal to the Arikaree River, as measured by Nebraska at the Haigler Canal Spillback gage, station 00061500, which is located approximately one-half mile west of the point of discharge to the Arikaree River,[48] less some adjustments for

[44] Colorado's expert, Willem A. Schreüder, proposed alternative methodology using differences between 5 runs of the RRCA Groundwater Model to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS, which do not include imported water in the calculation of $CBCU_C$, $CBCU_K$, and $CBCU_N$, *Id.*, p. 7. However, there is no evidence that this alternative methodology has been presented to the RRCA as required by the FSS.

[45] Final Settlement Stipulation, Volume 1 of 5, p. 25.

[46] The Pioneer Canal in Article V, Republican River Compact.

[47] *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (on title page, revised August 10, 2006), § IV.B.3. [*sic*], p. 26.

[48] Transcript of Arbitration Proceedings March 17, 2009, Volume VII at 1226:23-1227:1 (Williams).

precipitation inflow to the canal.[49] Nebraska has maintained the Haigler Canal Spillback gage and recorded the flow in the canal at this location for approximately the last 20 years.[50]

39. Nebraska's proposed change to subtract the amount of water measured annually at the Haigler Canal Spillback gage from the amount of water measured annually at the Haigler Canal Stateline Gage to determine the amount of water diverted from the North Fork of the Republican River for irrigation in Nebraska assumes that much if not all of the water measured at the Haigler Canal Spillback gage is discharged from the Haigler Canal to the Arikaree River and is surface water in the Arikaree River that can be measured at the Arikaree Gage.[51]

40. Nebraska's expert witness on this issue, Mr. James Williams, testified that "… we have seen much of the [Haigler Canal Spillback] water, if not all, in past six or seven years showing up at the Arikaree gage … ."[52] Beginning in about 2001, streamflows measured at the Arikaree Gage decreased significantly. During the years 2002, 2003, 2004, and 2005, the annual amounts of water measured at the Haigler Canal Spillback gage exceeded the actual annual amounts of water measured at the Arikaree Gage by 58 acre-feet (20 percent of spillback), 610 acre-feet (37 percent of spillback), 314 acre-feet (48 percent of spillback), and 187 acre-feet (14 percent of spillback), respectively.[53] Thus contrary to Mr. Williams' testimony, significant portions of the Haigler Canal Spillback water did not reach the Arikaree Gage during the years 2002 through 2005.

41. When asked whether analyses of losses and gains had been made between the Haigler Canal Spillback gage and the point of discharge to the Arikaree River and between the point of discharge and the Arikaree Gage, Mr. Williams testified: "No, we did not."[54]

42. In its post-hearing brief, Nebraska asserts:

> There is no dispute that the Arikaree is now frequently dry and that spillback/return water may not get to the Arikaree gage – but that doesn't change the fact that North Fork water

[49] *Id.* at 1206:23-1207:11 (Williams).

[50] *Id.* at 1193:3-5 (Williams).

[51] *Id.* at 1193:8-14; 1222:23-1223:3.

[52] *Id.*

[53] Nebraska Exhibit 31, Expert Report of James C. Schneider and James R. Williams, *Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, January 20, 2009, Table 1 (p. 4) and Table 2 (p. 7); Kansas Exhibit 29, Expert Report of David Barfield and Scott Ross, *Kansas's Responsive Expert Report Concerning Haigler Canal and Groundwater Modeling Accounting Points*, February 17, 2009, Table 1 (Arikaree gage value).

[54] Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1208:4-13.

is nevertheless discharged into the Arikaree River and thereby directly or indirectly inflates the VWS.[55]

The calculation for the Arikaree River VWS specified in the Accounting Procedures is:

VWS = Arikaree Gage at Haigler Stn. No. 06821500 + CBCUc + CBCUk + CBCUn – IWS.[56]

For VWS for the Arikaree River to increase, flows at the Arikaree Gage must increase and/or CBCU must increase. As described in Finding 40, during four of the six years from 2001 through 2006, significant portions of the flows from the Haigler Canal Spillback did not reach the Arikaree River Gage and could not have increased VWS. Also, there is no evidence that CBCU has increased as a result of the Haigler Canal Spillback. Therefore, Nebraska's assertion is flawed.

43. In its post-hearing brief, Nebraska also asserts:

> The diminished streamflows [at the Arikaree Gage] could be the result of many different human activities but it is clear that any discharge [from the Haigler Canal Spillback] into the stream, is a direct credit to that stream whether it is lost to seepage or not.[57]

This assertion would hold if the amount of the Haigler Canal Spillback lost to seepage resulted in an equivalent amount of groundwater discharge to the Arikaree River. However as described in Findings 55 and 56, the prevalent direction of groundwater flow, at least on the north side of the Arikaree River, is to the north towards the Main Stem, not towards the Arikaree River, which is consistent with Finding 40 that during recent years significant portions of the Haigler Canal Spillback water did not reach the Arikaree Gage.

44. Based on the available information, a significant portion of the water measured at the Haigler Canal Spillback gage, at least during the years since about 2001, does not remain in the Arikaree River as measurable surface water at the Arikaree Gage. While some of the water measured at the Haigler Canal Spillback gage undoubtedly reaches the Arikaree Gage under certain conditions, there is insufficient information to justify changing the Accounting Procedures to reduce the diversions from the North Fork Republican River into the Haigler Canal by the amount of water measured at the Haigler Canal Spillback gage.

45. As a result, the changes proposed by Nebraska to the Accounting Procedures involving VWS calculations for the North Fork of Republican River in Colorado and the Arikaree River are not justified.

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55 *State of Nebraska's Post-Hearing Brief* at 54.

56 *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (on title page, revised August 10, 2006), § IV.B.4. [*sic*], p. 26.

57 *State of Nebraska's Post-Hearing Brief* at 54.

46. Under the current Accounting Procedures, the Nebraska CBCU attributable to the annual diversions from the North Fork Republican River to the Haigler Canal for irrigation in Nebraska is calculated as 60 percent of the total amounts of water diverted as measured at the Haigler Canal Stateline Gage.[58] The remaining 40 percent of the total amounts of water diverted is return flow,[59] which is accounted for as returning to the Main Stem in the calculation of VWS.[60] The second change to the Accounting Procedures involving the Haigler Canal proposed by Nebraska would apportion the return flows from irrigation in Nebraska between the Main Stem, calculated at the Hardy Gage, and the Arikaree River, calculated at the Arikaree Gage, in proportion to the acreage irrigated using water from the Haigler Canal in the Main Stem drainage (51 percent) and the Arikaree River drainage (49 percent).[61]

47. Nebraska proposes the change described in Finding 46 to implement the directive in § IV.B.3. [*sic*][62] of the Accounting Procedures which states:

> The RRCA will investigate whether return flows from the Haigler Canal diversion in Colorado may return to the Arikaree River, not the North Fork of the Republican River, as indicated in the formulas. If there are return flows from the Haigler Canal to the Arikaree River, these formulas will be changed to recognize those returns.

48. The term "return flow" is not defined in the Accounting Procedures but as commonly used, return flow is that part of a diverted flow that is not consumptively used and is returned to its original source or another source of water.[63] In the context of the Accounting Procedures, return flow is that part of a diverted flow returned to the Main Stem and its tributaries as surface water by overland flow or through groundwater discharge.

49. Nebraska's proposal to apportion return flows returned to the Main Stem and the Arikaree River from irrigation in Nebraska in proportion to the acreage irrigated using water from the Haigler Canal in the Main Stem drainage (51 percent) and the Arikaree River drainage (49 percent) is appropriate for that portion of the return flows comprised by overland flow, since overland flow would remain within the drainage where the associated irrigation occurred.

50. Nebraska's proposal to apportion return flows returned to the Main Stem and the Arikaree River in proportion to the acreage irrigated using water from the Haigler Canal in the Main

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58 *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (revised date on title page: August 10, 2006), § IV.B.3. [*sic*], p. 26.

59 *Id.* at § IV.A.2.a)., p. 20.

60 *Id.* at § IV.B.3. [*sic*], p. 26; § IV.B.15 [*sic*], p 36.

61 Nebraska Exhibit 31, Expert Report of James C. Schneider and James R. Williams, *Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, January 20, 2009, p. 5-6.

62 § IV.B.1. in Final Settlement Stipulation, Volume 1 of 5, Appendix C.

63 *See* USGS Water Science Glossary of Terms, http://ga.water.usgs.gov/edu/dictionary.html#main.

Stem drainage and the Arikaree River drainage is not necessarily appropriate for that portion of the return flows comprised by groundwater discharge, since groundwater flow is not constrained to the drainage where the associated irrigation occurs because groundwater level gradients do not necessarily conform to the overlying topographical gradients.

51. Nebraska's expert witness on this issue, Mr. James Williams, did not provide any testimony or other evidence regarding the portion of return flows from irrigation in Nebraska returning to the Main Stem or the Arikaree River as overland flow.

52. Mr. Williams did testify that the soils in the Arikaree drainage near Haigler "tend to be somewhat sandy."[64] Colorado's expert on this issue, Mr. James Slattery, testified that the soils in the Arikaree drainage near Haigler are "extremely sandy" and that because "the majority of this land has been converted over to center pivot sprinklers … there is just very little surface water runoff … ."[65] This suggests that there may be minimal return flow to the Arikaree River comprised by overland flow.

53. During the period of years from 1995 through 2006, the annual amounts of water returning to the Arikaree River from irrigation using water from the Haigler Canal, as estimated in accordance with only this change to the Accounting Procedures as proposed by Nebraska,[66] exceeded the actual annual amounts of water measured at the Arikaree Gage by 515 acre-feet (48 percent of the proposed return flow), 767 acre-feet (77 percent of the proposed return flow), 70 acre-feet (6 percent of the proposed return flow), and 385 acre-feet (53 percent of the proposed return flow) for the years 2001, 2002, 2003, and 2004, respectively.[53] Thus, significant portions of the annual amounts of return flow estimated in accordance with Nebraska's proposed change to the Accounting Procedures did not reach the Arikaree Gage during the years 2001 through 2004.

54. When asked whether he knew the direction of groundwater flow in the Haigler area, Mr. Williams testified: "No, I do not."[67]

55. Simulations using the RRCA Groundwater Model indicate that the prevalent direction of groundwater flow under lands irrigated using water from the Haigler Canal in the Haigler area (on the north side of the Arikaree River) is to the north towards the Main Stem, not the Arikaree River.[68]

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64 Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1210:20-1211:8.

65 Transcript of Arbitration Proceedings, March 18, 2009, Volume VIII at 1360:9-18.

66 Without reducing the amounts of water measured at the Haiglar Canal Stateline Gage by the amounts of water from the Haiglar Canal Spillback.

67 *Id.* at 1210:1-3.

68 *Id.* at 1365:24-1366:7; Colorado Exhibit 11, Expert Report of James E. Slattery, *State of Colorado's Response to Nebraska's Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, February 16, 2009, p. 5.

56. In its post-hearing brief, Nebraska contends:

> Such a determination [that the prevalent direction of groundwater flow is to the north towards the Main Stem] seems doubtful given that the Groundwater Model uses one-mile cells and the distance between the Haigler Canal and the Republican River is less than one mile. If the Haigler Canal and Republican River are in the same model cell, or even in adjacent cells, no gradient would likely be determined.[69]

However, it is not the location of Haigler Canal that is pertinent to the direction of groundwater flow for that portion of return flows that return from groundwater discharge. Rather, it is the location of the lands irrigated that is pertinent, and the lands irrigated with water from the Haigler Canal are located from one to three miles south of the Republican River. Thus, results from simulations using the RRCA Groundwater Model can be used to estimate the prevalent direction of groundwater return flow under lands irrigated with water from the Haigler Canal.

57. Based on the available information, most of the return flow comprised by groundwater discharge from irrigation in Nebraska using water from the Haigler Canal returns to the Main Stem, not the Arikaree River, at least during the years since 2001. While some of the water measured at the Arikaree Gage may be comprised of return flow from groundwater discharge under certain conditions, there is insufficient information to justify changing the Accounting Procedures to apportion any of the return flow to the Arikaree River.

<u>Accounting Procedures – Groundwater Model Accounting Points</u>

58. Article II of the Republican River Compact defines the Republican River Basin as follows:

> The Basin is all the area in Colorado, Kansas, and Nebraska, which is naturally drained by the Republican River, and its tributaries, to its junction with the Smoky Hill River in Kansas. The main stem of the Republican River extends from the junction near Haigler, Nebraska, of its North Fork and the Arikaree River, to its junction with Smoky Hill River near Junction City Kansas.[70]

59. The "equitable division" or "allocation" of the waters of the Republican River Basin between the States is set forth in Article IV of the Compact, subject to the proportionate adjustment required in Article III. Article IV of the Compact specifies the amounts of water allocated to each state from each source of water in the Republican River Basin and identifies each source of water from which an allocation is made as a named "drainage basin."

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69 *State of Nebraska's Post-Hearing Brief* at 55.

70 Republican River Compact, Pub. Law No. 78-60, 57 Stat. 86 (1943); codified at § 82a-518, K.S.A. (2007); App. § 1-106, 2A N.R.S. (1995); and § 37-67-101 C.R.S. (2008).

60. The term "drainage basin" is not defined in the Compact but as commonly used, a drainage basin is a land area where precipitation runs off into streams, rivers, lakes, and reservoirs.[63] A drainage basin ends where there is no longer an area from which precipitation runs off, which corresponds to the lowest point in elevation above which a delineated area is drained. The end of a drainage basin is also located at the point where the collected precipitation runoff discharges into another surface water feature, which is termed the "confluence" when one stream or river joins another stream or river.

61. The "equitable division" or "allocation" of the waters of the Republican River Basin set forth in Article IV of the Compact for a named "drainage basin" is derived from the "computed average annual virgin water supply"[71] originating in that drainage basin, which ends at the confluence of the stream draining that basin and the main stem of the Republican River,[72] as set forth in Article III of the Compact.

62. In § II. of the Accounting Procedures, the term "Designated Drainage Basins" is defined as "the drainage basins of the specific tributaries and the Main Stem of the Republican River as described in Article III of the Compact." The term "Sub-basin" is defined as:

> [T]he Designated Drainage Basins, except for the Main Stem, identified in Article III of the Compact. For purposes of Compact accounting the following Sub-basins will be defined as described below:
>
> > North Fork of the Republican River in Colorado drainage basin is that drainage area above USGS gaging station number 06823000, North Fork Republican River at the Colorado-Nebraska State Line,
> >
> > Arikaree River drainage basin is that drainage area above USGS gaging station number 06821500, Arikaree River at Haigler, Nebraska,
> >
> > Buffalo Creek drainage basin is that drainage area above USGS gaging station number 06823500, Buffalo Creek near Haigler, Nebraska,
> >
> > Rock Creek drainage basin is that drainage area above USGS gaging station number 06824000, Rock Creek at Parks, Nebraska,
> >
> > South Fork of the Republican River drainage basin is that drainage area above USGS gaging station number 06827500, South Fork Republican River near Benkelman, Nebraska,

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71 Pursuant to the Accounting Procedures, the "computed average annual virgin water supply" is termed the Computed Water Supply (the "CWS"), which equals the VWS reduced by changes in Federal reservoir storage and flood flows. The CWS is used to calculate the allocations between the States (*See Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 [revised date on title page: August 10, 2006], p. 10).

72 Or the North Fork of the Republican River in Nebraska for the drainage basins specified in the Compact as the "North Fork of the Republican River drainage basin in Colorado" and the "Arikaree River drainage basin."

> Frenchman Creek (River) drainage basin in Nebraska is that drainage area above USGS gaging station number 06835500, Frenchman Creek in Culbertson, Nebraska,
>
> Driftwood Creek drainage basin is that drainage area above USGS gaging station number 06836500, Driftwood Creek near McCook, Nebraska,
>
> Red Willow Creek drainage basin is that drainage area above USGS gaging station number 06838000, Red Willow Creek near Red Willow, Nebraska,
>
> Medicine Creek drainage basin is that drainage area above the Medicine Creek below Harry Strunk Lake, State of Nebraska gaging station number 06842500; and the drainage area between the gage and the confluence with the Main Stem,
>
> Sappa Creek drainage basin is that drainage area above USGS gaging station number 06847500, Sappa Creek near Stamford, Nebraska and the drainage area between the gage and the confluence with the Main Stem; and excluding the Beaver Creek drainage basin area downstream from the State of Nebraska gaging station number 06847000 Beaver Creek near Beaver City, Nebraska to the confluence with Sappa Creek,
>
> Beaver Creek drainage basin is that drainage area above State of Nebraska gaging station number 06847000, Beaver Creek near Beaver City, Nebraska, and the drainage area between the gage and the confluence with Sappa Creek,
>
> Prairie Dog Creek drainage basin is that drainage area above USGS gaging station number 06848500, Prairie Dog Creek near Woodruff, Kansas, and the drainage area between the gage and the confluence with the Main Stem;

63. In § II. of the Accounting Procedures, the term "Main Stem" is defined as:

> [T]he Designated Drainage Basin identified in Article III of the Compact as the North Fork of the Republican River in Nebraska and the main stem of the Republican River between the junction of the North Fork and the Arikaree River and the lowest crossing of the river at the Nebraska-Kansas state line and the small tributaries thereof, and also including the drainage basin Blackwood Creek;

This definition for "Main Stem" differs from the description of the main stem in Article II of the Compact, as set forth in Finding 58, in that it includes the North Fork of the Republican River in Nebraska and ends at "the lowest crossing of the river at the Nebraska-Kansas state line" rather than at "its junction with the Smoky Hill River in Kansas." However, this definition for "Main Stem" is wholly consistent with the designated drainage basin defined in the next to the last full paragraph in Article III of the Compact.

64. The Accounting Procedures, § III.D.1., specify that CBCU of groundwater

> … 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.

This is consistent with the allocations made by named drainage basin in Article IV of the Compact as described in Finding 61.

65. In § III.D.2. of the Accounting Procedures, the procedure for determining CBCU of surface water is specified as follows:

> For Sub-basins where the gage designated in Section II. is near the confluence with the Main Stem, each State's Sub-basin Computed Beneficial Consumptive Use of surface water shall be the State's Computed Beneficial Consumptive Use of surface water above the Sub-basin gage. For Medicine Creek, Sappa Creek, Beaver Creek and Prairie Dog Creek, where the gage is not near the confluence with the Main Stem, each State's Computed Beneficial Consumptive Use of surface water shall be the sum of the State's Computed Beneficial Consumptive Use of surface water above the gage, and its Computed Beneficial Consumptive Use of surface water between the gage and the confluence with the Main Stem.

This is consistent with the allocations made by named drainage basin in Article IV of the Compact as described in Finding 61, assuming there is no significant CBCU of surface water downstream from the Sub-basin gages, other than for Medicine Creek, Sappa Creek, Beaver Creek, and Prairie Dog Creek, where CBCU of surface water downstream from each Sub-basin gage is added to the CBCU of surface water above each Sub-basin gage. However, since the CBCU of surface water below the gage in each of these four sub-basins is already included in the amount of water measured at the gage for each Sub-basin, the CBCU of surface water below the gage for each Sub-basin is subtracted from the VWS for that Sub-basin and added to the VWS for the Main Stem,[73] to avoid a double-accounting of water in that Sub-basin.

66. Nebraska has identified four sub-basins where the stream gaging station designated in § II. of the Accounting Procedures is located several miles upstream of the confluence with the Main Stem, where the cell in the RRCA Groundwater Model is used to simulate base flow for determining CBCU of groundwater (the "accounting point"): Frenchman Creek (River) drainage basin in Nebraska, North Fork of the Republican River in Colorado drainage basin, South Fork of the Republican River drainage basin, and Driftwood Creek drainage basin. Nebraska contends that: "A discrepancy is introduced because VWS is calculated by adding streamflow at one location to estimated groundwater impacts at a separate location."[74] Nebraska further contends that this results in "… the potential for some of the surface water passing that gage to then be consumed by the groundwater [pumping] and, in effect, a double-accounting."[75]

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[73] *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (revised date on title page: August 10, 2006), § IV.B.11.-14. [*sic*], pp. 30-33.

[74] Nebraska Exhibit 31, Expert Report of James C. Schneider and James R. Williams, *Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, January 20, 2009, p. 9.

[75] Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1220:7-9 (Williams).

67. Because stream gages must be sited where the hydraulic characteristics of a stream channel are suitable for accurate measurements of streamflow in that channel, stream gages in the named drainage basins for the Republican River are generally not located at their confluences with the Main Stem.[76]

68. Nebraska notes that § II. of the Accounting Procedures defines the "Frenchman Creek (River) drainage basin in Nebraska," "North Fork of the Republican River in Colorado drainage basin," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," in each instance as being that drainage area above the corresponding gage designated for each Sub-basin. Nebraska asserts that the "accounting points must be moved to match the locations of the gages, and thus the Sub-basin definitions from Appendix C."[77]

69. As described in Findings 60 and 61, the allocations of water made to the States, as specified by the Compact, are made for individual drainage basins, and each drainage basin implicitly ends at the confluence between the stream associated with a particular drainage basin and the Main Stem. The Accounting Procedures provided for by the FSS cannot change the definitions of individual drainage basins implicit in the Compact.[78] For the stated purposes of Compact accounting, the sub-basins as defined in § II. of the Accounting Procedures are appropriate provided adjustments are made such that the VWS is correctly estimated for the drainage basin above the confluence between the stream associated with a particular drainage basin and the Main Stem.

70. For the "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," moving the accounting points for determining the CBCU of groundwater to correspond to the locations of the gages designated in § II. of the Accounting Procedures would result in the CBCU of groundwater between a designated gage and the confluence of that Sub-basin's stream with the Main Stem being included in the CBCU for the Main Stem rather than in the CBCU for the tributary drainage basins. These changes would be inconsistent with the definitions of these drainage basins implicit in Article III of the Compact and are not appropriate.

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[76] Colorado Exhibit 11, Expert Report of James E. Slattery, *State of Colorado's Response to Nebraska's Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, February 16, 2009, p. 7.

[77] Nebraska Exhibit 31, Expert Report of James C. Schneider and James R. Williams, *Expert Report on Accounting Issues: Haigler Canal and Groundwater Model Accounting Points*, January 20, 2009, p. 9.

[78] *See* § I.D. of the FSS, which provides that:

> The States agree that this Stipulation and the Proposed Consent Judgment are not intended to, nor could they, change the States' respective rights and obligations under the Compact. The States reserve their respective rights under the Compact to raise any issue of Compact interpretation and enforcement in the future.

71. However, to the extent groundwater pumping causes depletions to streamflows downstream of the gages designated in § II. of the Accounting Procedures for the "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," and upstream of the confluence of each associated stream with the Main Stem, the current Accounting Procedures for estimating VWS result in a double-accounting of these depletions. The measured streamflow at each of these Sub-basin gages already includes the amount of the streamflow depletion between the gage for each Sub-basin and the confluence of the stream for each Sub-basin with the Main Stem. Adding the CBCU of groundwater between the gage for a particular Sub-basin and the confluence of that Sub-basin's stream with the Main Stem to the measured streamflow at that gage counts the same water twice in calculating VWS,[79] and is not appropriate.

72. While it is not appropriate to move the accounting points as described in Finding 70, the RRCA should modify the Accounting Procedures for the "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," to subtract the CBCU of groundwater below the designated gage for each Sub-basin and above the confluence of that Sub-basin's stream with the Main Stem from the VWS for that Sub-basin, to avoid double-accounting, and add that increment of groundwater CBCU in the VWS for the Main Stem, such as is currently done in accounting for the CBCU of surface water below the Sub-basin gages for Medicine Creek, Sappa Creek, Beaver Creek, and Prairie Dog Creek.

73. At the hearing and in its post-trial brief, Colorado asserts that the Special Master appointed by the Court in *Kansas v. Nebraska and Colorado*, No. 126, Original, made a specific finding that the Republican River is formed at the junction of the Arikaree River and the North Fork of the Republican River, near Haigler, Nebraska,[80] which Colorado uses as the basis for its contention that the current accounting point for the North Fork of the Republican River is at the correct location. The statement made by the Special Master quoted by Colorado occurs in the First Report of the Special Master (Subject: Nebraska's Motion to Dismiss) at the beginning of § II. titled "BACKGROUND" (on page 6) and is simply a restatement of the description of the Republican River Basin from Article II of the Compact, as partially set forth in Finding 58. The Special Master's statement can not be a "finding" that the Main Stem of the Republican River begins at the junction of the Arikaree River and the North Fork of the Republican River for Compact accounting purposes pursuant to the FSS when Article III of the Compact explicitly defines two separate drainage basins, from which allocations of water are made in Article IV that include the North Fork: "North of the Republican River drainage basin in Colorado" and "The North Fork of the Republican River in Nebraska and the main stem of the Republican River between the junction of the North Fork and Arikaree River and the lowest crossing of the river at the Nebraska-Kansas state line and the small tributaries thereof … ." The latter drainage basin is the Main Stem in § II. of the Accounting

79 *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (revised date on title page: August 10, 2006), § IV.B.7.-9. [*sic*], pp. 28-29.

80 Transcript of Arbitration Proceedings, March 17, 2009, Volume VII at 1205:2-22 (Williams); *State of Colorado's Post-Trial Brief* at 54.

Procedures, which were incorporated in the FSS and as part of the FSS were found by the Special Master to be "... in all respects compatible with the controlling provisions and purposes of the Compact."[81]

74. The accounting point currently used to determine the CBCU of groundwater in the "North Fork of the Republican River in Colorado drainage basin" is not located at the confluence with the Main Stem, as the Main Stem is defined in Section II. of the Accounting Procedures and set forth in Finding 63. This is inconsistent with the explicit meaning of the "North Fork of the Republican River drainage basin in Colorado" in Article III of the Compact and results in CBCU of groundwater in Kansas and Nebraska that should be included in the CBCU for the Main Stem being included instead in the CBCU for the "North Fork of the Republican River in Colorado drainage basin."

75. The accounting point used to determine the CBCU of groundwater in the "North Fork of the Republican River in Colorado drainage basin" should be moved to the cell of the RRCA Groundwater Model in which the North Fork of the Republican River crosses the Colorado-Nebraska state line. This will result in reduced VWS for the "North Fork of the Republican River in Colorado drainage basin" to the extent of "GWk" and "GWn" between the Colorado-Nebraska state line and the confluence between the North Fork of the Republican River in Nebraska and the Arikaree River.[82] This will also result in increased VWS for the Main Stem by the same amounts.

76. The changes to the Accounting Procedures described in Findings 72 and 75 should apply to all years for which the accounting of water use has not been finalized and approved by the RRCA. This is consistent with the positions of both Colorado and Nebraska[83] (Kansas did not address this issue). This is also consistent with the decision of the Special Master.[84]

<u>Damages – Losses to Kansas Water Users from Overuse in Nebraska</u>

77. Subsection V.B.2.a. of the FSS explicitly requires that:

    a. During Water-Short Year Administration, Nebraska will limit its Computed Beneficial Consumptive Use above Guide Rock to not more than Nebraska's Allocation that is derived from sources above Guide Rock, and Nebraska's share of

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[81] Second Report of the Special Master (Subject: Final Settlement Stipulation), *Kansas v. Nebraska and Colorado*, No. 126, Original, April 15, 2003, p. 3.

[82] *See Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (revised date on title page: August 10, 2006), § IV.B.3. [*sic*], p. 26.

[83] *State of Colorado's Post-Trial Brief* at 56; *State of Nebraska's Post-Hearing Brief* at 57.

[84] Second Report of the Special Master (Subject: Final Settlement Stipulation), *Kansas v. Nebraska and Colorado*, No. 126, Original, April 15, 2003, p. 32.

> any unused portion of Colorado's Allocation (no entitlement to Colorado's unused Allocation is implied or expressly granted by this provision).[85]

Subsection V.B.2.c. of the FSS provides that:

> e. For purposes of determining Nebraska's compliance with Subsection V.B.2.:
>
> i. Virgin Water Supply, Computed Water Supply, Allocations and Computed Beneficial Consumptive Use will be calculated on a two-year running average, as computed above Guide Rock, with any Water-Short Year Administration year treated as the second year of the two-year running average and using the prior year as the first year;[86]

Subsection V.B.2.e. of the FSS does not explicitly address the **amount** of the violation when Nebraska is not in compliance with § V.B.2. based on calculated two-year running averages for Virgin Water Supply, Computed Water Supply, Allocations, and Computed Beneficial Consumptive Use.

78. The States agreed "to implement the obligations and agreements in this Stipulation in accordance with the schedule attached hereto as Appendix B."[87] Appendix B of the FSS unambiguously sets the "First year Water-Short Year Administration compliance" as 2006.[88]

79. Nebraska does not deny that it exceeded its basin-wide allocations in 2005 and 2006[89] and its Water-Short Year allocations above Guide Rock in 2005 and 2006,[90] based on the Accounting Procedures currently approved by the RRCA, although Nebraska disagrees with the amount of the violations estimated by Kansas for 2006.

80. Based on the accounting approved by the RRCA for 2005, Nebraska exceeded its 2005 Water-Short Year Administration allocation above Guide Rock by 42,860 acre-feet, when the evaporation from Non-Federal Reservoirs below Harlan County Lake is included.[91] Kansas' estimate of the amount of Nebraska's exceedance of its 2006 Water-Short Year Administration allocation above Guide Rock is 36,100 acre-feet, using data approved by the

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[85] Final Settlement Stipulation, Volume 1 of 5, p. 28.

[86] *Id.*, p. 30.

[87] *Id.*, p. 1.

[88] *Id.*, p. B1.

[89] *State of Nebraska's Post-Hearing Brief* at 4.

[90] Nebraska Exhibit 8, Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Table 2-2, p. 5.

[91] Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Attachment 1.

RRCA.[92] The total of Nebraska's exceedance in 2005 and in 2006, as estimated by Kansas, is 78,960 acre-feet.

81. The basin-wide exceedance by Nebraska in 2005, based on the accounting approved by the RRCA for 2005, is 42,330 acre-feet.[93] The two-year running average of Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock for 2006, using the exceedance estimated by Kansas for 2006, is 39,480 acre-feet.[94] The total of Nebraska's basin-wide exceedance in 2005 and the two-year running average of Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock for 2006, using the exceedance estimated by Kansas for 2006, is 81,810 acre-feet. This total amount is greater than the sum of Nebraska's basin-wide exceedance in 2005 and Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock in 2006 only, as estimated by Kansas, by 3,380 acre-feet.[95] The total amount of 81,810 acre-feet is also greater than the sum of Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock in 2005 and in 2006, as estimated by Kansas, by 2,850 acre-feet.[96]

82. Because § V.B.2.e. of the FSS explicitly provides for using two-year running averages for Virgin Water Supply, Computed Water Supply, Allocations, and Computed Beneficial Consumptive Use to determine whether Nebraska is in compliance with § V.B.2. but does not explicitly address the amount of the violation when Nebraska is not in compliance with § V.B.2. and based on the comparisons in Finding 81, the two-year average of Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock for 2006 should not be used to determine the amount of Nebraska's violation for 2006. Rather, the amount of Nebraska's violation for 2006 should be equal to Nebraska's exceedance of its 2006 Water-Short Year Administration allocation above Guide Rock. Similarly, the amount of Nebraska's violation for 2005 should be equal to Nebraska's exceedance of its 2005 Water-Short Year Administration allocation above Guide Rock. Both Kansas and Nebraska used Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock for both 2005 and 2006 to establish the amount Nebraska's violation during these years,[91, 90] although Kansas estimates the amount of the 2006 violation as being 36,100 acre-feet whereas Nebraska estimates the amount of the 2006 violation as being 28,615 acre-feet, a difference of 7,485 acre-feet.

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92 *Id.*

93 Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Attachment 2.

94 (42,860 acre-feet + 36,100 acre-feet) / 2.

95 81,810 acre-feet – (42,330 acre-feet + 36,100 acre-feet).

96 81,810 acre-feet – 78,960 acre-feet.

83. The primary reason for the difference of 7,485 acre-feet between Kansas' estimate of Nebraska's 2006 violation and Nebraska's estimate is the assignment of evaporation from Harlan County Lake. Kansas assigned evaporation to both Kansas and Nebraska,[91] whereas Nebraska assigned 100 percent of the Harlan County Lake evaporation to Kansas since only KBID diverted water from Harlan County Lake in 2006.[97]

84. In the *Arbitrator's Final Decision on Legal Issues*, which is attached hereto, the Arbitrator decided the following concerning Question 3:

> The current Republican River Compact Administration Accounting Procedures allocate evaporative losses from Harlan County Lake entirely to Kansas when the Kansas Bostwick Irrigation District is the only entity actually diverting stored water from Harlan County Lake for irrigation.[98]

This decision was based on the assumption that Nebraska did not "[choose] to substitute supply for the Superior Canal from Nebraska's allocation below Guide Rock" in 2006 pursuant to § IV.A.e)(1) of the Accounting Procedures. The Arbitrator made this assumption because in their respective briefs on legal issues, neither Kansas nor Nebraska identified Nebraska's use of substitute supply for the Superior Canal from Nebraska's allocation below Guide Rock in 2006.

85. On the last day of the arbitration hearing, Kansas introduced as its Exhibit 84 a copy of a 2006 letter from Nebraska which stated the following:

> As identified in the Final Settlement Stipulation Section V.B.2.d., Nebraska is advising you of the following measures Nebraska plans to take in anticipation of a Water Short Year. The measures are cited by the corresponding Section in the Final Settlement Stipulation:
>
>> V.B.2.a.i. – "supplementing water for Nebraska Bostwick Irrigation District by providing alternate supplies from below Guide Rock or from outside the Basin". Nebraska intends to enter into an agreement with the Nebraska Bostwick Irrigation District whereby it is unlikely that Superior Canal will be diverting surface water during 2006. … Some irrigators in the Superior Canal surface water delivery area will be using an alternate supply from ground water wells located below Guide Rock Diversion Dam.[99]

This fact was not known by the Arbitrator when he decided Question 3.

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97 Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbook *NE 2006 Corrected*, Tab *Fed_Reservoir*.

98 *Arbitrator's Final Decision on Legal Issues* at 10.

99 Kansas Exhibit 84, Letter from Ann Bleed, Acting Director, Nebraska Department of Natural Resources, to Hal Simpson, Colorado State Engineer, David Pope, Kansas Chief Engineer, and Steve Raunshagen, Acting Area Manager, Great Plains Region (USBR), May 1, 2006, p. 1.

86. In light of Finding 85 and given the explicit provision in § IV.A.e)(1) of the Accounting Procedures pertaining to use of substitute supplies for the Superior Canal from Nebraska's allocation below Guide Rock, a portion of the 2006 evaporation from Harlan County Lake should be assigned to Nebraska.

87. The actual amount of groundwater diverted from wells below Guide Rock in 2006 is unknown,[100] which prevents a proportionate determination of the amount of Harlan County Lake evaporation in 2006 that should be assigned to Nebraska. However, for 2005 the allocation of net evaporation for Harlan County Lake between Kansas and Nebraska was very nearly 50 percent for each state.[101] Equally splitting the 2006 evaporation from Harlan County Lake between Kansas and Nebraska using Kansas' 2006 net evaporation of 16,298 acre-feet[102] or Nebraska's 2006 net evaporation of 16,182 acre-feet[103] would increase Nebraska's estimate of its Water-Short Year Administration exceedance above Guide Rock in 2006 by about 8,100 acre-feet, for a total violation in 2006 of about 36,715 acre-feet. This revised estimate of Nebraska's 2006 exceedance is sufficiently close to Kansas' estimate of the 2006 violation of 36,100 acre-feet to justify acceptance of Kansas' estimate, which allocated evaporation from Harlan County Lake "… based on long-term average uses."[104]

88. To provide a basis for estimating the direct economic impacts to Kansas caused by Nebraska's exceedance of its Water-Short Year allocation above Guide Rock, the additional amount of water that should have been available for use in Kansas was routed in accounting simulations by the experts for Kansas and Nebraska to where the direct economic of impacts of the shortages occurred: the farm headgates in KBID and downstream of KBID. To perform these simulations the experts for both Kansas and Nebraska assumed that the additional amount of water that should have been available for use in Kansas was regulated through Harlan County Lake.[105, 106]

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[100] *Kansas' Post-Trial Brief* at 14.

[101] Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbook *NE 2005 With Comment*, Tab *Fed_Reservoir*.

[102] Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Appendix A.

[103] Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbook *NE 2006 Corrected*, Tab *Fed_Reservoir*.

[104] *Kansas' Post-Trial Brief* at 14.

[105] Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, p. 2.

[106] Nebraska Exhibit 8, Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, p. 6.

89. Nebraska's experts used the same methods as Kansas' expert to estimate the additional net evaporation from Harlan County Lake in 2005 and 2006 that would have resulted from the additional supplies that should have been available for release from Harlan County Lake for use in Kansas.[107] Also, Nebraska's experts and Kansas' expert both assumed that the conveyance losses between Harlan County Lake and the diversion to the Courtland Canal, which conveys water to KBID, were insignificant in 2005 and 2006.[108, 109]

90. To estimate the conveyance losses between the Courtland Canal diversion and the Nebraska-Kansas state line, Kansas' expert used the procedure for determining Courtland Canal losses between the diversion and the state line chargeable to Kansas CBCU as specified in § IV.B.13. of the Accounting Procedures.[110, 111] The Accounting Procedures specify that:

> The allocation of transportation losses in the Courtland Canal above Lovewell between Kansas and Nebraska shall be done by the Bureau of Reclamation and reported in their "Courtland Canal Above Lovewell" spreadsheet. Deliveries and losses associated with deliveries to both Nebraska and Kansas above Lovewell shall be reflected in the Bureau's Monthly Water District reports. Losses associated with delivering water to Lovewell shall be separately computed.
>
> Amount of transportation loss of the Courtland Canal deliveries to Lovewell that does not return to the river, charged to Kansas shall be 18% of the Bureau's estimate of losses associated with these deliveries.[112]

The above provision sets the amounts of conveyance losses from Courtland Canal deliveries to Lovewell Reservoir that do not "return to the river," which are chargeable to Kansas CBCU, at 18 percent. The amounts of conveyance losses from Courtland Canal deliveries to Kansas irrigators above Lovewell Reservoir that are chargeable to Kansas CBCU are to equal "1-%BRF," where %BRF is defined as "Percent of Diversion from Bureau Canals that returns to the stream."[113]

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107 *Id.*

108 *Id.*, p. 7.

109 Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Appendix B (Note that the only "Additional Transportation Losses" are for water diverted to the Upper Courtland unit and for water diverted for delivery to Lovewell Reservoir).

110 *Id.*, p. 2.

111 *Republican River Compact Administration Accounting Procedures and Reporting Requirements*, revised July 2005 (on title page, revised August 10, 2006), § IV.B.15. [*sic*], p. 33-34.

112 *Id.*, p. 34.

113 *Id.*, p. 25.

91. The losses from the Courtland Canal assigned to Kansas in 2005 and 2006 for deliveries to Kansas irrigators and for deliveries to Lovewell Reservoir adopted by Kansas' expert[114] are the same as those reported for 2005 and 2006 in the RRCA Compact accounting spreadsheets provided by Nebraska's experts,[115] which reference the Bureau of Reclamation as the source. For 2005 those losses total 8,651 acre-feet, and for 2006 the losses total 12,158 acre-feet.

92. The RRCA Compact accounting spreadsheets provided by Nebraska's experts confirm that for 2005 and 2006, 18 percent of the conveyance losses from Courtland Canal deliveries to Lovewell Reservoir were attributed to Kansas CBCU.[116] The spreadsheets also show that for 2005 and 2006, 18 percent of the conveyance losses from Courtland Canal deliveries to Kansas irrigators above Lovewell Reservoir, referred to as "Upper Courtland", "does not recharge"[117] as adopted by Kansas' expert[118]. Therefore, %BRF for both 2005 and 2006 was 82 percent.

93. Kansas' expert assumed that only the conveyance losses that do not recharge (i.e., consumptive losses) were lost from the Courtland Canal. As a result, Kansas' expert estimated that the additional amount of water that would have been available at the Nebraska-Kansas state line in 2005 for delivery to Kansas irrigators, but for Nebraska's overuse, would equal the amount of Nebraska's exceedance (42,860 acre-feet), less the additional net evaporation from Harlan County Lake (1,341 acre-feet), and less the average of the conveyance losses "that do not recharge (18%)" as a percentage of Courland Canal diversions over the period 1995 through 2006 (968 acre-feet), for an adjusted additional supply of 40,551 acre-feet (rounded to 40,600 acre-feet).[119] Using this same procedure for 2006, Kansas' expert estimated an adjusted additional supply of 32,605 acre-feet (rounded to 32,600 acre-feet). These are the additional amounts of water Kansas' expert assumed would be available in the Courtland Canal at the Nebraska-Kansas state line for delivery to KBID in 2005 and 2006.[120] This assumption is incorrect.

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114 Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Appendix B.

115 Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbooks *NE 2005 With Comment* and *NE 2006 Corrected*, Tab *CourtlandAvLove*.

116 *Id.*, Tab *MAINSTEM.*

117 *Id.*

118 Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Appendix B.

119 *Id.*

120 *Id.*, Table 1.

94. As described in Finding 91, the total amounts lost from the Courtland Canal in Nebraska in 2005 and 2006 were 8,651 acre-feet and 12,158 acre-feet, respectively. Because these amounts of water were lost from the Courtland Canal in Nebraska, these amounts of water could not be in the Courtland Canal at the Nebraska-Kansas state line, even though only 18 percent of these losses (the consumptive losses) were allocated to Kansas CBCU. Therefore, the actual amounts of water presumably determined by the Bureau of Reclamation to be available in the Courtland Canal at the Nebraska-Kansas state line for delivery to KBID in 2005 and 2006 were 40,086 acre-feet[121] and 38,473 acre-feet,[122] respectively, not the amounts of 47,180 acre-feet and 48,442 acre-feet implied by the flawed assumption of Kansas' expert.

95. Applying the computational methodology used by Kansas' expert to estimate the additional amounts of water that would have been available in the Courtland Canal at the Nebraska-Kansas state line in 2005 and 2006 for delivery to KBID, but using the average of the total conveyance losses as a percentage of Courland Canal diversions over the period 1995 through 2006 instead of the average of the conveyance losses that do not recharge as a percentage of Courland Canal diversions, results in adjusted additional supplies of 36,143 acre-feet[123] and 29,060 acre-feet,[124] respectively.

96. Some, if not all, of the amounts of water equal to the differences between the revised estimates in Finding 95 and the estimates of Kansas' expert described in Finding 93 (i.e., non-consumptive losses of 4,408 acre-feet for 2005 and 3,545 acre-feet for 2006) would reasonably be assumed to be available to Kansas as groundwater and as additional flow in the Republican River. There is insufficient information in the record to allow a reasonably reliable estimate of how this additional groundwater and flow in the Republican River might have been used in Kansas. However, it is not reasonable to assume these amounts of water would have been available to KBID at the Nebraska-Kansas state line from the Courtland Canal. Kansas' expert has overstated the additional amounts of water that would have available to KBID at the Nebraska-Kansas state line from the Courtland Canal, but for Nebraska's overuse in 2005 and 2006, by at least approximately 12 percent.

97. Nebraska's experts use a different approach to estimate the additional amounts of water that would have available to KBID at the Nebraska-Kansas state line from the Courtland Canal in

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[121] 48,737 acre-feet less total losses of 8,651 acre-feet. This equals the quantity of water at Courtland Canal 15.1 in Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbook *NE 2005 With Comment*, Tab *CourtlandAvLove*.

[122] 50,631 acre-feet less total losses of 12,158 acre-feet. This equals the quantity of water at Courtland Canal 15.1 in Nebraska Exhibit 26, Electronic Data for Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Excel Workbook *NE 2006 Corrected*, Tab *CourtlandAvLove*.

[123] 42,860 acre-feet, less additional net evaporation of 1,341 acre-feet, less total additional losses of 5,376 acre-feet.

[124] 36,100 acre-feet, less additional net evaporation of 2,717 acre-feet, less total additional losses of 4,323 acre-feet.

2005 and 2006, but for Nebraska's overuse in those years.[125] While the methodology employed by Nebraska's experts properly excluded all of the estimated canal losses from the Courtland Canal in Nebraska, Nebraska's experts made no attempt to estimate the amounts of canal losses that would have been available to Kansas as groundwater or as additional flow in the Republican River. Nebraska's experts have understated the additional amounts of water that would have available to Kansas below the Nebraska-Kansas state line in 2005 and 2006.

Damages – Direct Economic Impacts

98. To estimate the economic impacts (damages) incurred by irrigators within KBID and downstream of KBID caused by overuse of water by Nebraska in 2005 and 2006, Kansas' experts estimated the difference in irrigated and non-irrigated crop mix and yields between: (1) the crop mix and yields Kansas' experts projected would have been realized, had overuse not occurred in Nebraska and irrigators in Kansas received the full amount of water to which they were entitled under the FSS; and (2) the reported crop mix and yields realized by impacted Kansas farmers in 2005 and 2006. The crop prices used by Kansas' experts to estimate the direct economic impacts as lost profits were the same for (1) and (2).[126]

99. To project irrigated crop yields that would have been realized, had overuse of water by Nebraska not occurred, Kansas' experts utilized a crop-yield model called IPYsim, which is named after irrigation and precipitation yield simulation.[127] While based in part on crop-yield-water-response functions reported in Stone et al., 2006[128] ("Stone's response functions"),[129] IPYsim differs from Stone's response functions in at least four respects that are important. First, Stone's response functions were based on the response of crop yield to precipitation and irrigation only,[130] whereas the version of IPYsim employed by Kansas' experts includes not only crop-yield response to precipitation and irrigation but also includes

125 Nebraska Exhibit 8, Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, pp. 7-10.

126 Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 178:24-179:4 (Kastens).

127 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 2.

128 Loyd Stone is a Professor of Agronomy at Kansas State University and was a rebuttal expert for Kansas in *Kansas v. Colorado*, No. 105, Original. The Special Master appointed by the U. S. Supreme Court in this matter, Arthur L. Littleworth, believed that "Professor Stone's testimony is entitled to great weight." *See* Third Report of Special Master Littleworth, August 2000, p. 56.

129 *Id.*; Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 179:7-16 (Kastens).

130 *See* Kansas Exhibit 18, *Water Supply: Yield Relationships Developed for Study of Water Management*, L. R. Stone, et al., Journal of Natural Resources & Life Sciences Education, Volume 35, 2006, p. 162.

crop-yield response to total usable nitrogen.[131, 132] Second, Stone's response functions do not include economic considerations,[133] whereas IPYsim incorporates both nitrogen fertilizer costs (average nitrogen fertilizer to crop price ratio by crop observed over the 1994-2000 time period) and water costs (after accounting for delivery efficiency).[134] Third, Kansas' experts adjusted the IPYsim response functions, as described in Finding 103, and did not provide any information to verify the reasonableness of the resulting response functions that were then used to assess impacts, whereas Stone's response functions were based on empirical relationships; that is, relationships based on observations that can be verified or disproved by observation or experiment.[135] Fourth, Stone's response functions in Kansas' Exhibit 18 were not developed or used to assess economic impacts. Rather Stone's response functions were developed "for use in water resource education."[136] While Stone's response functions may be "similar in all material respects" to those used in *Kansas v. Colorado*, No. 105, Original, the IPYsim crop-yield response functions employed by Kansas' experts in this arbitration proceeding are not,[137] contrary to Kansas' assertion in its closing brief.[138]

100. The IPYsim response functions are quadratic and of the mathematical form: $Y = A + BX - CX^2$ where for a particular crop Y is the calculated yield, A, B, and C are positive numerical constants, and X is the level of crop input.[139] With this quadratic form, as X increases Y

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131 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 2; Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 180:3-9 (Kastens); Kansas Exhibit 17, *Background for KSU-NPI_CropBudgets.xls*, January 2009, p. 4 (referenced in FN 1 of Kansas Exhibit 5, p. 2).

132 When asked what effect the inclusion of phosphate would have on his analysis, as is done in a newer version of IPYsim, Dr. Kastens testified:

> Actually, I can't even answer the effect the nitrogen has on the analysis in terms of the magnitude, say, of the moneys owed. I have not done that. Too [*sic*] me – and I'm not even sure that I have the intuition, without going back and studying it and analyzing it, what that would do.

Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 201:2-11.

133 Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 173:11-16 (Kastens).

134 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 6.

135 Kansas Exhibit 18, *Water Supply: Yield Relationships Developed for Study of Water Management*, L. R. Stone, et al., Journal of Natural Resources & Life Sciences Education, Volume 35, 2006.

136 *Id.*, p. 162.

137 *See* Third Report of Special Master Littleworth, August 2000, p. 47-48.

138 *Kansas' Post-Trial Brief* at 21.

139 Kansas Exhibit 17, *Background for KSU-NPI_CropBudgets.xls*, January 2009, p. 4 (referenced in FN 1 of Kansas Exhibit 5, p. 2).

increases at a diminishing rate until Y reaches its maximum value, after which Y begins to decrease as X increases. The response functions have a horizontal slope when Y is at its maximum value for a particular crop. Kansas' experts call this point "the maximum of the quadratic plateau function that defines yield,"[140] and the response function for a particular crop is adjusted such that when Y is at its maximum value, it equals what Kansas' experts term the "yield goal",[141] which is defined as "the expected crop yield given that neither nitrogen fertilizer nor water is limiting."[142]

101. The "yield goal" is determined using IPYsim by assuming that the economically optimal yield for a particular crop, considering costs for nitrogen fertilizer and irrigation water, equals what the Kansas' experts term "trend yield" for that crop.[143] As a result of this assumption, the "trend yield" for a particular crop must be less than or equal to the calculated "yield goal" for that crop. The "trend yield" was determined by fitting a linear trend line through the observed yields by year for each crop within KBID (excluding ensilage) for the years 1962 through 2006, including or excluding yields during water-short years to derive the maximum yield along the trend line for the year 2006. The resulting "trend yield" was used for 2006 as well as 2005.[144]

102. The IPYsim response functions for each crop (excluding ensilage), adjusted such that the "trend yield" equaled the economically optimal yield, as described in Finding 101, were then used to simulate yields assuming KBID irrigators could have all of the irrigation water they desired during 2005 and 2006 ("full irrigation") and to simulate yields for the actual water available during 2005 and 2006.[145] (It is not clear why Kansas' experts assumed KBID irrigators could have all of the irrigation water they desired instead of assuming KBID irrigators would have received the quantity of water to which they were entitled had there been no overuse of water by Nebraska, although adjustments were subsequently made to account for this difference.)[146]

103. For each crop in the areas above and below Lovewell Reservoir, the actual crop yields reported for KBID were then multiplied by the ratio of the "full irrigation" yield simulated by

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140 Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 183:8-10 (Kastens).

141 *Id.*

142 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 6.

143 *Id.*

144 *Id.*

145 *Id.*, p. 7.

146 *Id.*, p. 9; Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 186:4-15 (Kastens).

IPYsim divided by the yield simulated for the actual amount of irrigation water received to derive what Kansas' experts term the fully irrigated "expected yield."[147] The effect of this adjustment is to change the shape of the IPYsim response functions for each crop, assuming the Y intercept of the function does not change, and to increase the "yield goal." For corn in 2005,[148] for which the actual yield was 187 bushels/acre, this adjustment results in a fully irrigated "expected yield" of 206 bushels/acre. If the relationship between fully irrigated yield and "yield goal" remains proportionate or nearly proportionate, a fully irrigated "expected yield" of 206 bushels/acre implies a "yield goal" of 212 bushels/acre. Both the fully irrigated "expected yield" of 206 bushels/acre and the implied "yield goal" of 212 bushels/acre are close to the yield for maximum crop ET for corn from Stone et al., 2006, 14.0 megagrams/hectare or 222 bushels/acre.[149]

104. Kansas' experts did not use the adjustment procedure described in Finding 103 to derive the fully irrigated "expected yield" for crops above Lovewell Reservoir in 2005 and instead assumed the "expected yield" values above Lovewell Reservoir were the same as those derived for crops below Lovewell Reservoir.[150] Kansas' experts did not state why this assumption was made, but applying the adjustment procedure described in Finding 103 for corn in 2005 above Lovewell Reservoir would result in a fully irrigated "expected yield" of 258 bushels/acre, which is nearly 40 percent higher than the highest historical yield of 187 bushels/acre as of 2006 and more than 15 percent higher than the yield for maximum crop ET for corn from Stone et al., 2006, which is clearly not reasonable.

105. The fully irrigated "expected yield" is associated with the expectation of irrigators in KBID that all of the irrigation water "economically desired" would be available, which is more than the amount of water KBID irrigators would have received had there been no overuse of water in Nebraska.[151] Therefore Kansas' experts revised the "expected yield" for each crop downward to the yields simulated using the IPYsim crop response functions that would have been realized for amounts of irrigation water equal to the actual amounts received plus the

147 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 7 and Table 10.

148 Kansas' experts identified corn as the most appropriate crop for this "base yield modeling framework … since it is the crop where yield-response-to-irrigation data are most prevalent and the crop most frequently managed in an irrigation setting." *Id.*, p. 7.

149 -11.55 + 0.416 x 61.3 = 14.0 megagrams/hectare, Kansas Exhibit 18, *Water Supply: Yield Relationships Developed for Study of Water Management*, L. R. Stone, et al., Journal of Natural Resources & Life Sciences Education, Volume 35, 2006, Table 2, p. 164.

150 Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, Table 10.

151 *Id.*, pp. 8-9.

additional amounts estimated by Kansas' experts[152] that would have been received had there been no overuse of water in Nebraska.[153]

106. Kansas' experts then used the revised crop-specific "expected yield" together with other relevant factors for 2005 and 2006 with and without overuse of water in Nebraska including actual crop yields (both irrigated and non-irrigated), growing season precipitation, acres irrigated, irrigation technology and efficiency, irrigated crop mix, non-irrigated crop mix, crop prices, and production costs to estimate the lost profit in KBID for 2005 and 2006 from overuse of water in Nebraska. The estimated lost profits in KBID for 2005 and 2006 were then divided by the amounts of farm-gate water shortages estimated from overuse of water in Nebraska for 2005 and 2006, respectively, and the resulting value per acre-foot of water shortage were multiplied by the estimated shortages caused by reductions in return flows outside of KBID.[154] The total direct economic impacts for each of 2005 and 2006 were calculated as the sum of the estimated lost profit in KBID and the value of the estimated shortages outside of KBID.[155]

107. The reasonableness of the estimates of total direct economic impacts in 2005 and 2006 proffered by Kansas' experts is dependent on the reasonableness of the many assumptions made by Kansas' experts. Besides the estimated shortages in irrigation water resulting from Nebraska's overuse of water in 2005 and 2006, the core of Kansas' estimates of total direct economic impacts centers on the IPYsim crop response functions.

108. One of Kansas' experts, Dr. Terry Kastens, testified that although "IPYsim has not been really academically reviewed, … it has been very critically reviewed by many users who continue to use it on a regular basis for making crop decisions."[156] While IPYsim may have been "critically reviewed by many users," Kansas did not provide or offer any evidence that the adjusted IPYsim crop response functions used to estimate the fully irrigated "expected yield" for crops in KBID, as described in Finding 103, have been peer-reviewed by anyone other than the six authors of Kansas' expert report on this issue. While acknowledging that the adjustments made to the IPYsim crop response functions described in Finding 103 were

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[152] Kansas Exhibit 1, Expert Report of Dale E. Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska 2005 and 2006*, January 20, 2009, p. 6.

[153] Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 9; Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 186:4-11 (Kastens).

[154] Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 8-9.

[155] Apparently, the total direct economic impacts were not reduced to account for Federal income tax that would have been paid on increased farm net income, as was done in *Kansas v. Colorado. See* Third Report of Special Master Littleworth, August 2000, p. 72.

[156] Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 180:25-181:3.

"not suggested by Stone,"[157, 158] Kansas did not provide or offer any empirical data demonstrating that the adjusted IPYsim crop response functions and the estimates of fully irrigated "expected yield" are consistent with actual observations.

109. The experts for Colorado and Nebraska on this issue were both critical of the adjustment of the IPYsim crop response functions to estimate the crop-specific fully irrigated "expected yield." In his report, Colorado's expert, Dr. James Pritchett stated the following:

> In my opinion, the IPYsim model is accurate in suggesting the predicted yield under actual irrigation is 90% of the predicted model yield under full irrigation. However, I do not find documentation that the percentage difference [10%] may be applied to higher yield levels with accuracy.
>
> More specifically, the IPYsim model predicts that if the crop receives 6.12 fewer inches of water than is necessary, a yield loss of 15.4 bushels (165.9 bu. – 150.5 bu.) results. When scaled up, the EIA [Kansas Exhibit 5, *Economic Impacts on Kansas of Diminished Surface Water Supplies* ...] reports that if the crop receives 6.12 fewer inches of water a yield loss of 19.1 bushels (206.1 bu. – 187.0 bu.) results. Implicitly, at [*sic*] higher base yield generates increasingly *larger* incremental yields with additional water. I believe this to be inaccurate as the accepted relationship between applied water and crop yield is one of diminishing returns.[159]

In his direct testimony, Dr. Pritchett testified:

> What I do note is that in terms of its yield prediction, those seem to fit trend yields and also the National Ag Statistic Service yields. And so I felt comfortable in that sense, that the yields [Model Yield in Table 10, Kansas Exhibit 5] were representative.
>
> Later, the Kansas experts boot-strapped those yields to a higher level [fully irrigated Expected Yield in Table 10, Kansas Exhibit 5] and I'm not sure I'm comfortable with that.[160]

Nebraska's expert, Dr. David Sunding, testified in his direct testimony:

> So now the next step in what they describe as their calibration procedure, we have Stone down here. We have the quote/unquote, calibrated IPYsim to hit their assumptions about the 2005 trend yield.

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157 It is unknown why Kansas did not utilize Professor Loyd Stone of Kansas State University as an expert witness on this issue, given that his testimony in *Kansas v. Colorado*, No. 105, Original, was given great weight. *See* FN 128.

158 Transcript of Arbitration Proceedings, March 11, 2009, Volume III at 498:7-10 (Kastens).

159 Colorado Exhibit 2, Expert Report of Dr. James Pritchett, *Reviewing the Assumptions, Methods and Results of: Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, February 16, 2008 [*sic*], p. 6.

160 Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 287:6-13.

> Well, as you just pointed out, actual yield was somewhere up here, again off the front tier [*sic*].
>
> So how do we deal with that?
>
> And the way they deal with that is simply by taking the ratio between these two points and applying it up here. So whatever this vertical distance is, they take the actual observed yield and boost it up by that amount. That was what Dr. Pritchett referred to as this boot-strapping procedure.
>
> So this is the 187. And this is, I believe, 206, which is, as Dr. Kastens described, 10 percent higher than the highest observed yield ever; and I think, frankly, lacking credibility.[161]
>
> …
>
> Now, why does that matter? That matters because the heart of their valuation analysis or their damage analysis is to answer the question: What would have been the extra yield and, hence, the extra profit earned from a few extra units of water, few extra inches of water per acre?
>
> So this slope matters a lot for their damage analysis. It's not derived from Stone. It is, I would submit, totally made up to fit this particular trend yield and, therefore, I think inadequate as a basis for a damage calculation.[162]

110. Kansas' expert report on economic impacts states that: "IPYsim was developed using expected yield response to water data reported in Stone et al., 2006, which were the same data underlying KSU's Crop Water Allocator (KSU-CWA)."[163] Stone et al. states that: "Crop-water production relationships are altered by variations in soil and climate and have not been well defined for most crops in most areas (internal citations omitted)."[164] However, Kansas' experts did not address variations in soil types and climate between western Kansas, for which Stone's response functions were developed, and north-central Kansas several hundred miles to the northeast, where KBID and the other impacted areas in Kansas are located, other than in Dr. Kasten's testimony when he stated:

> And though it's said that, you know, it makes a point, for example, about soil types mattering, we don't believe that the difference in the silt loam soils of western Kansas

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161 *Id.*, at 322:4-20.

162 *Id.*, at 323:16-324:1.

163 Kansas Exhibit 5, *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, Dr. Bill Golden et al., January 20, 2009, p. 2.

164 Kansas Exhibit 18, *Water Supply: Yield Relationships Developed for Study of Water Management*, L. R. Stone, et al., Journal of Natural Resources & Life Sciences Education, Volume 35, 2006, p. 161.

> and those of the KBID area, for example, are sufficiently large that they would diminish our efforts of using this model specifically for KBID.[165]

Kansas did not provide or offer any empirical data confirming Dr. Kasten's testimony and did not address the significance of any climate variations.

111. Since the assumed lack of significance of soil and climate variations and the methodology applied by Kansas' experts for the purposes of estimating lost profits and establishing damages have not been shown to be reasonable, the assumptions and methodology should be validated by peer review or by empirical data before being accepted for the purposes of estimating lost profits and establishing damages. Even if validated, the estimates of lost profits can not be adopted because Kansas has overstated the additional amounts of water that would have available to KBID, but for Nebraska's overuse in 2005 and 2006, as described in Finding 96.[166] The preponderance of evidence at this juncture does not support the assumed lack of significance of soil and climate variations, the methodology used, or the estimates of the total direct economic impacts in 2005 and 2006 made by Kansas' experts with reasonable certainty.

112. The alternative estimates of total direct economic impacts developed by Nebraska's expert, Dr. David Sunding, based on the difference between the rental rates paid by farmers to rent irrigated land in 2005 and 2006 and the rental rates paid for non-irrigated land are not sufficiently reliable. Dr. Sunding relied on land prices and cash rental rates for 2005 and 2006 published by the Kansas State University Agricultural Experiment Station and Cooperative Extension Service.[167] The introduction for this published data contains the following qualifier:

> These data are useful to farm managers in determining cash rental rates, to farmland appraisers in calculating indexes for making time adjustments to land prices, and to landowners and investors who base expectations on historical price and return levels for farmland. The average prices in this guide encompass parcels of land that vary widely in

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[165] Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 182:16-22.

[166] When asked what the effect would be if the estimated amounts of additional water that should have been available to KBID were reduced, the following exchange occurred:

> DR. KASTENS: I can't say exactly. I can say that the dollars per acre-foot likely would go up. The total dollars likely would go down, but I can't say to what magnitude.
>
> MR. WILMOTH: Thank you.
>
> ARBITRATOR DREHER: So Mr. Wilmoth, just so I understand. It's not a linear relationship then?
>
> DR. KASTENS: That's correct.

Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 216:4-12.

[167] Nebraska Exhibit 6, Expert Report of Dr. David Sunding, *Analysis of Kansas' Economic Losses Caused by Nebraska's Overuse of Water in the Republican River Basin in 2005 and 2006*, February 17, 2009, p. 14.

> productivity. Thus, these data are more appropriate for analyzing trends than for establishing market value or rental rates for specific tracts of farmland.[168]

The limited applicability of the data relied on by Dr. Sunding was further confirmed by the following testimony of Dr. Kastens, who was co-publisher of the data:

> I don't like to say we don't trust the data, but we don't. And I can say that because anybody that has ever heard me speaking in Kansas have heard us say this for years and for hundreds of presentations, the irrigated rent data in Kansas, we don't believe them. That's all I can say.
>
> We have plenty of anecdotal evidence to suggest otherwise, but we don't believe the data and so we don't use them for anything.[169]

113. In its closing brief, Nebraska argues that: "When checked against reality, it is clear Kansas suffered relatively little economic harm from any loss of Republican River water she sustained."[170] Nebraska further concludes that: "In sum, the actual, direct economic harm suffered by Kansas as a result of Nebraska's overuse is somewhere between 'nearly zero' and $930,630.00."[171] Yet in 2006, Nebraska[172] may have spent as much as $3.5 million[173] to lease a total of 23,518 acre-feet of surface water in Nebraska from the Frenchman Valley Irrigation District, Riverside Irrigation Company, and Bostwick Irrigation District in Nebraska.[174] The leased surface water was relinquished by Nebraska for diversion by KBID at the Guide Rock Diversion Dam.[175] Nebraska would not have paid $ 3.0 or $3.5 million to lease 23,518 acre-feet of surface water, for an average volume-weighted unit cost as high as $149/acre-foot,[176] if the additional water that would have been available to KBID but for overuse by Nebraska had an economic value of nearly zero.

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168 *Id.*, p. 1 of attachment marked MF-1100 in upper right-hand corner.

169 Transcript of Arbitration Proceedings, March 11, 2009, Volume III at 518:19-519:2.

170 *State of Nebraska's Post-Hearing Brief* at 17.

171 *Id.* at 22.

172 The Middle Republican Natural Resources District paid $50,000 of the total. Kansas Exhibit 44, p. 1; Kansas Exhibit 51, p. 2.

173 Kansas Exhibit 44 shows $3.0 million paid to Bostwick Irrigation District in Nebraska whereas Kansas Exhibit 52 shows $2.5 million plus $64,500 was paid to the District.

174 Kansas Exhibit 44, *Memorandum to Jeanne Glenn from Ann Bleed*, March 5, 2007, p. 1.

175 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, p. 12.

176 $3,500,000 / 23,518 acre-feet.

114. Other than the leasing transactions by the state of Nebraska described in Finding 113, there is no evidence in the record of an active water market in or adjacent to south-central Nebraska. Therefore, the unit cost that Nebraska paid to lease water in its attempt to comply with the FSS in 2006 is not the same as the unit value of water to Kansas from lost profits due to overuse by Nebraska in 2006. As Nebraska's expert correctly noted regarding Nebraska's lease payments:

> So you have basically a monopolist, on one side, as opposed to what you would have in a land rental market, where you have many participants on either side of the transaction.[177]

115. The alternative estimates of total direct economic impacts in 2005 and 2006 developed by Colorado's expert, Dr. James Pritchett, based on modifications to the methodology used by Kansas' experts are also not sufficiently reliable. Dr. Pritchett used the IPYsim crop response functions to predict yield under actual irrigation and under full irrigation and did not perform the adjustment described in Finding 103 to adjust the response functions upward to the fully irrigated "expected yield."[178] However, Dr. Pritchett used crop production costs from northwest Kansas, which is predominantly irrigated using groundwater from the Ogallala Aquifer,[179] and did not investigate whether these costs were comparable to the crop production costs in the KBID, which is predominantly irrigated using surface water.[180] Because the production costs associated with using groundwater from the Ogallala Aquifer in northwest Kansas include pumping costs to lift water from wells that are 250 ft to 300 ft deep,[181] as compared to the pumping costs to operate "relatively small centrifugal [booster] pumps" to deliver surface water to center pivots in KBID,[182] the farm production costs used by Dr. Pritchett are not representative of the farm production costs in KBID. Since the alternative estimates of total direct economic impacts in 2005 and 2006 developed by Dr. Pritchett necessarily incorporate his estimates of farm production costs, his estimates of lost profits in 2005 and 2006 are not sufficiently reliable.

116. There presently is not a sufficiently reliable basis to form an appropriate recommendation for awarding damages to Kansas for overuse of water by Nebraska in 2005 and 2006. Clearly Kansas incurred damages and those damages may well be in the range of one to several million dollars. However, until such time Kansas can demonstrate with a preponderance of evidence that its assumptions and methodology for estimating lost profits, including its estimate of the amount of water that would have been available at the headgates of Kansas

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177 Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 374:22-25 (Sunding).

178 Colorado Exhibit 2, Expert Report of Dr. James Pritchett, *Reviewing the Assumptions, Methods and Results of: Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, February 16, 2008 [*sic*], p. 6.

179 Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 125:25-126:3 (Ross).

180 *Id.* at 121:13-5; Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 292:7-293:25.

181 Transcript of Arbitration Proceedings, March 9, 2009, Volume I at 125:18-126:3 (Ross).

182 *Id.* at 124:3-17.

irrigators, and establishing actual damages is reasonably reliable (either through independent peer review or with empirical data), during subsequent arbitration or before the Court, only an award of nominal damages should be made.

Damages – Indirect Economic Impacts

117. Kansas' experts estimated indirect economic impacts from their estimates of reduced farm income resulting from Nebraska's overuse of water in 2005 and 2006 by modeling the Kansas state economy using an input-output accounting system termed "Social Accounting Matrix" ("SAM"). The SAM system used by Kansas' experts was the Micro-IMPLAN (Impact analysis for PLANing) system, which was also used to estimate indirect or secondary impacts in *Kansas v. Colorado*, No. 105, Original.[183]

118. The indirect economic impacts, or "Value Added Impact" or "Indirect Value Added Loss" estimated by Kansas' experts for both 2005 and 2006 are listed in Table 16 of their report[184] and total 44 percent of the direct economic impacts (gross income loss), meaning that total economic impacts were estimated to be 1.44 times the estimated direct economic impacts.[185]

119. In his report, Colorado's expert stated that:

> While I have not been able to independently verify the SAM used in the EIA [Kansas Exhibit 5, *Economic Impacts on Kansas of Diminished Surface Water Supplies* ...], the multiplier [1.44] is consistent with my own research in the regional economic activity generated by irrigated agriculture.[186]

120. Nebraska's expert stated in his report that:

> While the method is standard, the use of IMPLAN to assess indirect impacts resulting from changes in water availability is fraught with problems relating to the generally poor quality of the input purchase and consumer expenditure data, including information on "export" coefficients, for rural area in the United States.[187]

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[183] Kansas Exhibit 5, Expert Report of Dr. Bill Golden et al., *Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, January 20, 2009, p. 9-10.

[184] *Id.*, p. 21.

[185] *Id.*, Table 16 and Table 17, p. 21.

[186] Colorado Exhibit 2, Expert Report of Dr. James Pritchett, *Reviewing the Assumptions, Methods and Results of: Economic Impacts on Kansas of Diminished Surface Water Supplies to the Lower Republican River Basin Caused by Nebraska in 2005 and 2006*, February 16, 2008 [*sic*], p. 13.

[187] Nebraska Exhibit 6, Expert Report of Dr. David Sunding, *Analysis of Kansas' Economic Losses Caused by Nebraska's Overuse of Water in the Republican River Basin in 2005 and 2006*, February 17, 2009, p. 4. Also, *see* Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 363:15-364:17.

When asked whether a multiplier of "1.44 would be appropriate for indirect effects or do you think it's too high or too low?"[188] Nebraska's expert responded:

> I think it's a – well, it's hard to know for sure if it's too high or too low without getting in supplemental information specific to Kansas that I discussed; but within the confines of the analysis that Kansas has proffered, I think the multiplier would be the same for both years. 1.44, I think, is not out of the realm of what I have seen in other contacts [*sic*], so that particular part of their analysis didn't stick out particularly.[189]

121. Nebraska's expert also stated in his report that:

> More importantly … indirect impacts are not a legitimate consideration in a proceeding of this type … because any damage payment from Nebraska to Kansas will generate its own multiplier effects, and a damage payment that compensates for direct losses should result in indirect benefits that compensate for indirect losses.[190]

122. In response, Kansas' expert, Dr. John Leatherman, testified that:

> [T]heoretically, there could, in fact, be offsetting impacts, positive impacts associated with the payments versus the damage occurred by the loss of family income. But, once again, that would be under a very narrow set of circumstances. You would essentially have to replicate as closely as possible in terms of the amount of damage, as well as the timing of those payments, as well as what ultimately happened to stimulate economic activity. And, here again, it's simply not feasible. Indeed, the State of Kansas, perhaps, would take any – any type of moneys awarded to them and they would – they would do something with that; but exactly what, I really don't know. And so that is something that would be very speculative on my part to try to estimate any kind of offsetting damages, absent there being specific information with regard to how they would spend the money.[191]

123. During cross, Nebraska's expert testified that:

> There are indirect impacts and I have never challenged that in this case. I do challenge their relevance to the proceeding going on here, both because I have questions about the reliability of the results and the Kansas analysis failed to consider the indirect benefits that result from Nebraska's payments.[192]

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188 *Id.* at 371:1-2.

189 *Id.* at 371:3-11.

190 Nebraska Exhibit 6, Expert Report of Dr. David Sunding, *Analysis of Kansas' Economic Losses Caused by Nebraska's Overuse of Water in the Republican River Basin in 2005 and 2006*, February 17, 2009, pp. 4, 2.

191 Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 264:14-265:8.

192 Transcript of Arbitration Proceedings, March 10, 2009, Volume II at 364:18-23 (Sunding).

124. Even though the indirect benefits resulting from Nebraska's payments may be "speculative," they are nonetheless real, and Kansas' experts should have attempted to reasonably quantify them.

125. In *Kansas v. Colorado*, No. 105, Original, the Court accepted the use of the IMPLAN model to assess secondary impacts to the economy of Kansas, and did not consider the indirect benefits that result from Colorado's payment of money damages.[193] However, based on the testimony of different experts for Kansas in that case, the Court found that "[s]econdary economic impacts are also affected by a concept known among economists as 'opportunity costs'"[194] and that "[o]nly 20 percent of the total secondary impacts were counted as net gains or losses."[195]

126. There is no evidence in the record for this proceeding whether opportunity costs offsetting or reducing gross secondary impacts were considered by Kansas' experts or whether such offsets are even relevant.

127. Since an award of only nominal damages for direct economic impacts is recommended in this proceeding, no award of damages for indirect economic impacts should be made.

128. If Kansas seeks to demonstrate with a preponderance of evidence that its assumptions and methodology for estimating lost profits and establishing actual damages is reasonably reliable during subsequent arbitration or before the Court, Kansas should also attempt to reasonably quantify indirect benefits resulting from Nebraska's payment for actual damages and should also include any offsetting opportunity costs if relevant.

Future Compliance

129. To ensure future compliance with the FSS, "Kansas has proposed that Nebraska reduce its groundwater-irrigated acreage in the Basin by approximately 515,000 acres of approximately 1.2 million acres which receive groundwater irrigation in the Nebraska portion of the Basin."[196] This would represent a reduction of 43 percent from the approximately 1.2 million acres in the Nebraska portion of the Republican River Basin estimated by Kansas as being

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[193] Third Report of Special Master Littleworth, August 2000, p. 65-71.

[194] *Id.*, p. 68.

[195] *Id.*, p. 69.

[196] Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, § III. Remedies.

irrigated with groundwater, which Kansas's experts estimate would reduce consumptive groundwater withdrawals by an average of 619,000 acre-feet per year.[197]

130. To derive the amount of reduction in groundwater-irrigated acreage proposed by Kansas, one of Kansas' experts on this issue, Mr. Dale Book, first estimated the reduction in the Nebraska groundwater CBCU that would have been necessary for compliance with the FSS on a 5-year average basis for the years 2002 through 2006 as follows:

> … I reviewed and utilized the Compact Administration, RRCA, the accounting data for the five years. I compared the results of the beneficial consumptive use in the state of Nebraska with the Nebraska allocation and computed the difference and determined what the resulting required reduction in beneficial consumptive use would be to achieve a balance between the allocation and consumptive use for the five years. I then made an estimate of the amount of reduced consumptive use resulting from reducing groundwater pumping that would be resulting in increased surface water use within the state of Nebraska [45 percent of the reduction in groundwater CBCU] and adjusted for that in the calculation. The result of the analysis was a recommendation for a level of groundwater consumptive use that would balance with the allocations for this five-year period.[198]
> …
>
> The imported water supply credit … was obtained from the RRCA Groundwater Model results with the – this level of pumping and that was averaging 30,000 acre-feet per year. The result is a balance for the five-year period.[199]

The result of this analysis is an ongoing, year-to-year, estimated limitation on groundwater CBCU in the Nebraska portion of the Republican River Basin of 175,000 acre-feet.[200]

131. Assuming that 45 percent of the reduction in groundwater CBCU would approximately equal the amount of increased streamflow resulting from curtailment of groundwater irrigation that would then be consumptively used by surface water irrigators in Nebraska[188] has the effect of increasing the amount of the reduction in groundwater CBCU that must be achieved to comply with the FSS. While reducing groundwater CBCU in Nebraska would clearly increase streamflows in Nebraska, a portion of which would undoubtedly be diverted and consumed by surface water irrigators, there is presently insufficient evidence to support the assumption that the increased surface water CBCU in Nebraska would equal 45 percent of the reduction in groundwater CBCU.

132. The RRCA Groundwater Model was then used:

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[197] Kansas Exhibit 3, Expert Report of Samuel P. Perkins and Steven P. Larson, *Attachment 5: RRCA groundwater model analysis (revised) Impact of Nebraska pumping and proposed remedy*, January 4, 2008, p. 4.

[198] Transcript of Arbitration Proceedings, March 11, 2009, Volume III at 533:9-534:1.

[199] *Id.* at 539:3-7.

[200] Kansas Exhibit 2, Expert Report of Dale E. Book, *Requirements for Nebraska's Compliance with the Republican River Compact*, January 20, 2009, p. 3-4 and Table 1.

> … in a trial-and-error process … [to look] at various levels of curtailment of pumping, again focusing on, in part, looking at what we call quick response areas, or areas near the stream system that would respond relatively quickly to reductions in groundwater irrigation and upland areas that respond more slowly, looking at combinations of those to determine how much reduction would be necessary in order to achieve the level of groundwater consumptive use that Mr. Book had determined.
>
> Ultimately, what we determined was that if we -- if we curtailed pumping within about 2 ½ miles of the stream system and if we also held the pumping outside that -- that corridor along the stream system to the amount of acreage that was in place in the year 2000, that the combination of those two things would produce a reduction in groundwater beneficial consumptive use that would, over the long haul, stay below the level that Mr. Book had determined.[201]

In the simulated reductions of groundwater consumption using the RRCA Groundwater Model, the amount of irrigated acreage using comingled groundwater and surface water supplies was "held at 2006 levels at all distances from stream cells within the Republican River basin in Nebraska."[202] The result of this analysis was a reduction of "350,970 acres within the no-pumping zone and 163,640 acres outside the no-pumping zone."[203]

133. In performing the simulations described in Finding 132:

> Model datasets for historical years 1990-2006 were used to construct future scenarios. These years were chosen initially because of the higher quality of Kansas water use reporting data beginning in 1990. The sequence of historical years 1990-2006, beginning with year 1990, was repeated three times to represent future scenarios for years 2007-2057. Median annual precipitation for years 1990-2006, spatially averaged over the groundwater model domain, is 19.58 inches/year. Compared against the model's years of record 1918-2006, this corresponds to a probability of 54.5 percentile, which is slightly above median rainfall of 19.28 in/yr for years 1918-2006. This indicates that the sequence is a reasonable projection, at least with respect to the historical record. Additionally, the sequence consists of a relatively wet period (1990-1999) followed by a relatively dry period (2000-2006).[204]

Nebraska's experts on this issue reported that the annual precipitation for the years 1990 – 2006 was at the 60th percentile, meaning that the annual precipitation for this period of years

201 Transcript of Arbitration Proceedings, March 11, 2009, Volume III at 554:20-555:14 (Larson).

202 Kansas Exhibit 3, Expert Report of Samuel P. Perkins and Steven P. Larson, *Attachment 5: RRCA groundwater model analysis (revised) Impact of Nebraska pumping and proposed remedy*, January 4, 2008, p. 1.

203 *Id.*

204 *Id.*, pp. 1-2.

was above average and equaled or exceeded 60 percent of the measurements of annual precipitation over the longer term of 1918 through 2006.[205]

134. Because of the nonlinear response of the RRCA Groundwater Model when stream-drying occurs,[206] introducing streamflow to de-watered streams in the RRCA Groundwater Model increases the simulated streamflows that can be depleted by groundwater consumption, which increases groundwater CBCU. For example, 1993 was a year with unusually high amounts of precipitation,[207] and 1993 was used to represent the years 2010, 2027, and 2044[208] in Kansas' simulations using the RRCA Groundwater Model described in Finding 132. For each of the three years during the simulations, when the dataset for 1993 is introduced (i.e., 2010, 2027, and 2044), computed impacts from pumping in Nebraska increase significantly, except for the simulation of Kansas' proposed remedy.[209] The reason why simulated impacts from pumping in Nebraska do not increase significantly in 2010, 2027, and 2044 for the simulation of Kansas' proposed remedy may result from the reduction in the acreage irrigated with groundwater being so significant that simulated de-watering of streams is relatively limited and the response of the Groundwater Model is for the most part linear.

135. Kansas has adequately demonstrated that its proposed remedy would result in Nebraska's compliance with the FSS, even during dry-year conditions similar to what occurred during the period 2002 through 2006.[210] However, given the magnitude of the assumed increase in

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[205] Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, p. 16.

[206] *See* Finding 20.

[207]

> MR. DRAPER: Dr. Schneider, you've mentioned several times that 1993 was the wettest year on record?.
>
> DR. SCHNEIDER: I may not be completely accurate on that. I believe I'm referring to the rainfall precipitation gages within the model that are located in Nebraska and looking at the -- that's generally what I'm looking at. And if it's not the wettest year, it's second or third, but it's my -- it's my recollection that it's the wettest year in terms of precipitation in Nebraska.
>
> MR. DRAPER: In fact, I have no quarrel with that. I think it's often referred to as the "Great Flood of 1993," isn't it?

Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 940:10-23.

[208] *See* Finding 133.

[209] *See* Kansas Exhibit 65, *Comparison of Nebraska pumping impact under baseline conditions, Kansas proposed remedy, and NRD Pumping Alternatives*, 3/16/2009.

[210] For this decision, the period of years 2002 through 2006 is considered a period of dry years, even though the probability of non-exceedance over the period of record (1918 – 2007) for precipitation in the Nebraska portion of the Republican River Basin during 2004 through 2006 was more than 0.5 (*See* Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, Figure 7), since both 2005 and 2006 were years of Water-Short Year Administration.

surface water CBCU from reductions in groundwater CBCU described in Finding 131 and the fact that Kansas' experts used datasets from years when precipitation was above average overall as described in Finding 133, Kansas' experts likely have overstated the amount of reduction in groundwater irrigated acreage that is necessary in Nebraska for Nebraska to comply with the FSS. Therefore, Kansas has not adequately demonstrated that its proposed remedy is the "minimum remedy necessary for compliance" as it has asserted.[211] Based on the testimony and evidence in the record for this proceeding, it is not possible to reasonably assess the extent that Kansas' experts may have overestimated the reduction in groundwater irrigated acreage in Nebraska that is necessary for Nebraska's compliance with the FSS.

136. Nebraska asserts that:

> Following the signing of the FSS, Nebraska has implemented landmark changes to its system of water regulation. The resulting integrated management planning process mandates a cooperative effort between the Department [of Natural Resources] (historically responsible for surface water administration), and the NRDs [Upper Republican Natural Resources District, Middle Republican Natural Resources District, and Lower Republican Natural Resources District] (historically responsible for groundwater management). Taking into account all proposed future scenarios by Kansas and Nebraska, and assuming there are no changes to the current RRCA Accounting Procedures, Nebraska will under the worst case, have only a modest shortfall of 8,288 acre feet on average (less than 3.5%). Recently, through dry year leasing of surface water supplies, Nebraska has shown the ability to make up substantially greater than this amount annually. We are confident the IMPs [Integrated Management Plans] are more than sufficient to maintain compliance with the Compact [and the FSS] through 2012, when they will be reevaluated and modified to ensure compliance into the future.[212]

137. One of Nebraska's experts, Mr. Williams, testified that the Upper Republican Natural Resources District (URNRD), Middle Republican Natural Resources District (MRNRD), and Lower Republican Natural Resources District (LRNRD) account for 95 percent of the depletions to surface water sources in the Republican River Basin caused by consumptive groundwater withdrawals.[213] The Nebraska Department of Water Resources and each of these three NRDs jointly developed an individual Integrated Management Plan and associated rules and regulations ("IMP") for each NRD.[214] While there are differences between each of the IMPs, the three IMPs are substantially similar. Each IMP, as revised in

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211 Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, § III.a.

212 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, p. 18.

213 Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 829:7-9; 831:24-832:2.

214 *Id.* at 964:10-16 (Dunnigan).

late 2007 or early 2008,[215] generally has three increasingly stringent requirements limiting consumptive groundwater withdrawals, although the IMP for the LRNRD only has two requirements. The first requirement is a limitation on the amount of groundwater that may be withdrawn and applied to crops by individual irrigators. The second, and more stringent, requirement is a limitation on the average annual volume of groundwater withdrawals for each NRD, averaged over the period 2008 through 2012, which is 20 percent less than the baseline average groundwater withdrawals for the years 1998 through 2006, excluding the LRNRD in which the allotments for individual irrigators were further reduced with the intent of achieving a 20 percent reduction from the 1998 through 2006 baseline.[216] The average annual groundwater withdrawals for the URNRD, MRNRD, and LRNRD during the period of 1998 through 2006 are reported to be 531,763 acre-feet, 309,479 acre-feet, and 242,289 acre-feet, respectively, totaling just more than 1,083,530 acre-feet per year.[217] The limitations on the average annual volume of groundwater withdrawals for the URNRD and MRNRD, averaged over the period 2008 through 2012, are 425,000 acre-feet and 247,580 acre-feet, respectively.[218, 219] The intended limitation for the LRNRD is 193,830 acre-feet.[220] The sum of the required limitations on the average annual volume of groundwater withdrawals for the URNRD and MRNRD plus the intended limitation for the LRNRD total 866,410 acre-feet per year, a reduction of 217,120 acre-feet from the 1998 – 2006 average of 1,083,530 acre-feet per year.

The third and most stringent requirement, at least during dry years, is a limitation on either the annual net groundwater depletions (URNRD and LRNRD) or the groundwater depletions averaged over the period 2008 through 2012 (MRNRD). The net groundwater depletions for the URNRD, MRNRD, and LRNRD are not to exceed 44 percent, 30 percent, and 26 percent, respectively, of Nebraska's allowable groundwater CBCU determined from using the RRCA Groundwater Model.[221, 222, 223] Although the limitations on net groundwater

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[215] For IMPs adopted for URNRD, MRNRD, and LRNRD, respectively, *see* Nebraska Exibits: 16; 17; and 15, Appendix A.

[216] Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 893:7-13; 963:3-10 (Williams).

[217] Nebraska Exhibit 16, *Integrated Management Plan Jointly Developed by the Department of Natural Resources and the Upper Republican Natural Resources District*, p. 2.

[218] *Id.*, p. 7.

[219] Nebraska Exhibit 17, *Rules and Regulations and the Integrated Management Plan for the Middle Republican Natural Resources District and the Nebraska Department of Natural Resources*, February 8, 2008, p. 8 (Integrated Management Plan revised January 8, 2008).

[220] 242,289 acre-feet x 0.80.

[221] Nebraska Exhibit 16, *Integrated Management Plan Jointly Developed by the Department of Natural Resources and the Upper Republican Natural Resources District*, p. 7.

[222] Nebraska Exhibit 17, *Rules and Regulations and the Integrated Management Plan for the Middle Republican Natural Resources District and the Nebraska Department of Natural Resources*, February 8, 2008, p. 8-9 (Integrated Management Plan revised January 8, 2008).

depletions for the URNRD and LRNRD are stated as annual requirements in the respective IMPs, these are effectively average limitations, at least for a two-year period, since the accounting is done after-the-fact during the following year. Consequently, whether or not compliance with the FSS was achieved and whether further reductions in groundwater use are needed is not known until the year following the year in which the groundwater depletions actually occurred.

138. The IMPs for the URNRD, MRNRD, and LRNRD have considerable flexibility in that average limitations are used, meaning that the limitations can be exceeded during any given year. The IMPs also provide for variances, carryover of unused individual allocations, pooling of individual allocations (URNRD and MRNRD), and bonus inches (MRNRD) when compliance is achieved in a preceding year. Despite this flexibility, a careful reading of the IMPs indicates that there are no exceptions to the overall limitations on the average annual volume of groundwater withdrawals for the URNRD and MRNRD, as well as the overall limitations on allowable net groundwater depletions for all three Republican River NRDs.

139. When asked whether the IMPs were enforceable, the Nebraska official responsible for ensuring compliance with the Compact and the FSS, Mr. Brian Dunnigan[224], answered: "Absolutely."[225] When asked "what happens if an NRD refuses to honor an IMP?"[226] Mr. Dunnigan answered as follows:

> Well, certainly the department would look at that; and if there was an issue with that, we would certainly confer with the Attorney General's office to see if action would be taken by the State against [the] Natural Resources District. The department could also look at and the State could look at enforcement actions against individuals.[227]

When asked what if there is a failure of compliance, Mr. Dunnigan answered:

> I would say it's both and, ultimately, it would come to the DNR and we would take whatever measures we needed to take to make sure that we were in compliance.[228]

Mr. Dunnigan also testified that: "The State will do what is necessary to achieve Compact compliance."[229]

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223 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, Appendix A, p. 16.

224 Director, Nebraska Department of Natural Resources.

225 Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 948:6.

226 *Id.*, at 948:25-949:1.

227 *Id.*, at 949:2-8.

228 *Id.* at 970:5-8.

140. Although Mr. Dunnigan was not appointed as the Director for the Nebraska Department of Natural Resources ("DNR") until December 9, 2008,[230] his statements set forth in Finding 139 that "we [DNR] would take whatever measures we needed to take to make sure that we were in compliance" and "The State will do what is necessary to achieve Compact compliance" are presumably accurate statements of Nebraska's intentions when it entered into the FSS on December 15, 2002. Yet, in the very first year for Water-Short Year Administration compliance (2006), Nebraska concedes it violated the FSS.[231] Similarly, in the very first normal compliance year (2007), Nebraska concedes it again violated the FSS.[232]

141. In its attempts to ensure future compliance with the Compact and FSS, Nebraska first relies on the 20 percent reduction in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, as described in Finding 137. Assuming the URNRD and MRNRD do not exceed their average annual withdrawal limitations of 425,000 acre-feet and 247,580 acre-feet, respectively, and assuming that the additional reductions in the allotments for individual irrigators in the LRNRD results in a 20 percent reduction in LRNRD's average annual groundwater withdrawal as compared to its average withdrawals for 1998 through 2006, resulting in a reduced average annual LRNRD withdrawal of 193,830 acre-feet, the average annual groundwater withdrawals in the NRDs for the period 2008 through 2012 will not total more than 866,410 acre-feet per year, a reduction of 217,120 acre-feet from the 1998 – 2006 average of 1,083,530 acre-feet per year.[233] For comparison, this amount of reduction in average annual groundwater withdrawals is 35 percent of the average annual reduction of 619,000 acre-feet per year that Kansas estimates would result from its proposed remedy.[234]

142. Nebraska's experts simulated the performance of the IMPs, assuming 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, under "average climatic conditions" using the RRCA Groundwater Model and the Accounting Procedures.[235] The results from these simulations showed that Nebraska would be in compliance under normal

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229 *Id.* at 980:15-16.

230 *Id.* at 946:22-24.

231 Nebraska Exhibit 8, Expert Report of Marc Groff, Tom Riley, and David Kracman, *Review of the 20 January 2009 Report Prepared by Spronk Water Engineers, Inc for the State of Kansas*, February 17, 2009, Table 2-2, p. 5.

232 *State of Nebraska's Post-Hearing Brief* at 4 (row in table for average 2003 – 2007).

233 *See* Finding 137.

234 *See* Finding 129.

235 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, p. 7.

year administration and under its allocation by an average amount of 18,950 acre-feet per year over the 5-year simulation period.[236]

143. However, it is not during "average climatic conditions" that compliance with the Compact and FSS are the most challenging for Nebraska and the Republican River NRDs. Rather, it is during dry-year conditions that compliance with the Compact and FSS will be the most difficult, and as correctly noted by Kansas' expert, Mr. David Barfield, it is under those conditions in particular "when the Compact needs to work."[237]

144. Nebraska's experts also simulated the performance of the IMPs, assuming 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, under an "exceptionally (arguably unrealistic) scenario of repeated dry conditions" using the RRCA Groundwater Model and the Accounting Procedures.[235] The results from these simulations showed that Nebraska would be over its allocation under normal year administration by an average amount of 340 acre-feet per year over the 5-year simulation period[238] and would be over by 8,288 acre-feet per year under Water-Short Year Administration.[239] However, Nebraska's basin-wide allocation from these simulations averaged 231,360 acre-feet per year over the 5-year simulation period,[238] which is 20,000 acre-feet per year more than the average basin-wide allocation of about 211,000 acre-feet per year that was determined by the RRCA for the actual dry-year period of 2002 through 2006.[240] Similarly, Nebraska's allocation above Guide Rock from these simulations for Water-Short Year Administration averaged 221,680 acre-feet per year over the 5-year simulation period,[239] which is nearly 32,000 acre-feet per year more than the actual average allocation above Guide Rock of 189,820 acre-feet per year that was determined by the RRCA for the Water-Short Year Administration in 2005 and 2006.[241] These computed allocations that are larger than the actual allocations for 2002 through 2006 likely primarily result from Nebraska's experts using the average streamflows for the years 2000 through 2005, which totaled 195,250 acre-feet,[242] as compared to the actual average streamflows for 2002 through 2006, which were

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236 *Id.*, Appendix B to Appendix E, Table 3C.

237 Transcript of Arbitration Proceedings, March 16, 2009, Volume VI at 1049:15-16.

238 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, Appendix B to Appendix G, Table 3C.

239 *Id.*, Table 5C.

240 Kansas Exhibit 2, Expert Report of Dale E. Book, *Requirements for Nebraska's Compliance with the Republican River Compact*, January 20, 2009, Table 1.

241 Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Attachment 1.

242 Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, Appendix G, Table D, p. 4 (Total of entries in column titled "Dry conditions").

reported to total approximately 126,000 acre-feet per year.[243] Consequently, Nebraska has underestimated the amounts by which it is likely to exceed its allocations during dry-year conditions by perhaps as much as 20,000 acre-feet to 30,000 acre-feet per year. As a result, the 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, are likely inadequate to ensure compact compliance during prolonged dry-year conditions, such as occurred from 2002 through 2006.

145. When a 20 percent reduction in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, is not sufficient to achieve compliance with the Compact and FSS, Nebraska then relies on the provisions in the IMPs that limit the net groundwater depletions for the URNRD, MRNRD, and LRNRD to 44 percent, 30 percent, and 26 percent, respectively, of Nebraska's allowable groundwater CBCU determined from using the RRCA Groundwater Model, as described in Finding 137. The difficulty in ensuring compliance with the Compact and FSS through these provisions of the IMPs is what is termed the "lag effect." That is, just as for groundwater withdrawals, where "there is [a] long time lag between the time when the pumping actually occurs and the time when it manifests itself on streamflows,"[244] depending on the location of the wells from which consumptive groundwater withdrawals are made, there is also a long time lag between the time when groundwater withdrawals are reduced or curtailed and the time when resulting increases in streamflow occur, again depending on the location of the wells from which pumping is reduced or ceases. Consequently, when it is determined that one or more of the URNRD, MRNRD, or LRNRD has exceeded their portion of Nebraska's allowable groundwater CBCU in the preceding year, as specified in the respective IMP, and further reductions are made to consumptive groundwater withdrawals in the respective NRD, it will be years before the effects of those reductions are expressed as increased streamflow, again depending on the location of the wells from which groundwater withdrawals are reduced or curtailed. If a particular NRD's exceedance of its portion of Nebraska's allowable groundwater CBCU occurs during a prolonged period of dry conditions, such as occurred from 2002 through 2006, it will likely not be possible for Nebraska to achieve compliance during the term of the current IMPs without focused curtailment of consumptive groundwater withdrawals in close proximity to surface water streams, which is not specifically required in any the IMPs for the URNRD, MRNRD, or LRNRD. As a result, the limitations on the average annual net streamflow depletions from consumptive groundwater withdrawals within the URNRD, MRNRD, and LRNRD are likely inadequate to ensure compliance with the Compact and FSS during prolonged dry-year conditions, such as occurred from 2002 through 2006.

146. Given Kansas' concerns that the IMPs for the NRDs are inadequate, Nebraska points out that in 2007 and 2008, Nebraska remained under its allocations by 30,000 acre-feet and 78,000 acre-feet, respectively.[245] The years 2007 and 2008, however, were wet years with the

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243 Transcript of Arbitration Proceedings, March 16, 2009, Volume VI at 1039:22-23 (Barfield).

244 Transcript of Arbitration Proceedings, March 16, 2009, Volume VI at 1006:13-15 (Larson).

245 *State of Nebraska's Post-Hearing Brief* at 3.

probability of non-exceedance for precipitation being 0.91 and 0.76, respectively,[246] and there were more than adequate surface water supplies. Because of the increased availability of surface water supplies in 2007 and 2008, Nebraska's Republican River allocations of 243,400 acre-feet and 332,400 acre-feet, respectively,[247] were the largest since accounting pursuant to the FSS was implemented.[248] This masks Nebraska's problem in complying with the Compact and FSS, which is groundwater CBCU, not surface water CBCU. Groundwater CBCU is by far the largest portion of Nebraska's total CBCU.[249] During dry-year conditions, such as occurred during 2002 through 2006, surface water CBCU varied, but groundwater CBCU did not vary significantly.[250] The provisions in the IMPs that if the 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD do not achieve compliance with the Compact and FSS, then the net groundwater depletions within the NRDs will be further reduced to the NRDs respective portions of Nebraska's allowable groundwater CBCU are not likely sufficient to achieve compliance with the Compact and FSS during prolonged dry-year conditions for the reasons set forth in the Finding 145.

147. Aside from seeking changes to the Accounting Procedures and seeking credit for any damages paid in calculating moving averages of its allocations less CBCU reduced by IWS, Nebraska and the Republican River NRDs intend to offset exceedances of Nebraska's future allocations with plans to continue clearing invasive riparian vegetation along the Republican River and its tributaries, plans to continue participation in incentive programs to retire irrigated acreage, and plans to implement streamflow augmentation projects.[251] However, the benefits from these plans remain largely unquantified.

148. The primary means that Nebraska and the Republican River NRDs have available to offset exceedances of Nebraska's future allocations is the leasing of surface water supplies for conveyance to Kansas, which one of Nebraska's experts referred to as "the lowest hanging fruit on the tree."[252] Although the Nebraska DNR and NRDs successfully leased 25,000 acre-feet, 53,500 acre-feet, and 15,000 acre-feet of surface water in 2006, 2007, and 2008,

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[246] Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, Figure 7.

[247] *State of Nebraska's Post-Hearing Brief* at 4.

[248] Kansas Exhibit 1, Expert Report of Dale Book, *Engineering Analysis of Losses to Kansas Water Users Resulting from Overuse of Republican River Supply in Nebraska*, January 20, 2009, Table 1.

[249] *Id.*

[250] *Id.*

[251] Nebraska Exhibit 15, Expert Report of James Schneider and James Williams, *Nebraska Compact Compliance*, February 17, 2009, pp. 10-15.

[252] Transcript of Arbitration Proceedings, March 12, 2009, Volume IV at 794:8 (Williams).

respectively, there is no evidence in the record that similar quantities of surface water could be leased during a prolonged dry period, such as occurred from 2002 through 2006. The probability of non-exceedance over the period of record (1918 – 2007) for precipitation in the Nebraska portion of the Republican River Basin during 2006, 2007, and 2008 was 0.63, 0.91, and 0.76, respectively,[234] which undoubtedly resulted in more surface water being available for lease than would be available during a prolonged dry period, particularly when the lessor can use groundwater as a substitute supply such as occurred in the Nebraska Bostwick Irrigation District during 2006.[253]

149. If Nebraska and the Republican River NRDs are going to rely on leasing surface water for conveyance to Kansas to offset exceedances of its future allocations and reduce future violations of the Compact and the FSS, then Nebraska and the Republican River NRDs should have permanent, interruptible supply contracts with surface water irrigators that subject to the call of Nebraska and the Republican River NRDs would provide certain amounts of surface water, if available. However, there apparently are no efforts underway to put in place such permanent, interruptible supply contracts.[254]

150. Because Nebraska has underestimated the amounts by which it is likely to exceed its allocations during dry-year conditions by perhaps as much as 20,000 acre-feet to 30,000 acre-feet per year,[255] the current IMPs adopted by Nebraska and the Republican River NRDs are inadequate to ensure compliance with the Compact and FSS during prolonged dry-year conditions, such as occurred from 2002 through 2006. Nebraska and the Republican River NRDs should make further reductions in consumptive groundwater withdrawals beyond what's required in the current IMPs, in addition to obtaining permanent, interruptible supply contracts with surface water irrigators, to ensure compliance with the Compact and FSS during prolonged dry-year conditions.

151. Neither the Compact nor the FSS require that Nebraska demonstrate in advance how it will be in compliance in the future. Nonetheless, Nebraska must maintain compliance as prescribed by the FSS during each 5-year period for normal administration and during each 2-year period for Water-Short Year Administration. While the Nebraska official responsible for ensuring compliance with the Compact and the FSS clearly understands non-compliance is not an option,[256] it is not clear that this same understanding exists within the NRDs. For example, in early 2007, the general manager for the MRNRD stated:

> As NRDs, we struggle in trying to help others understand that we have been active in the basin and that given time, our controls will have a positive benefit.
>
> …

[253] *See* Finding 85.

[254] Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 963:11-18 (Dunnigan).

[255] *See* Finding 144.

[256] *See* Finding 139.

> We are concerned on two points: 1) That the formula being used to measure water allocations for this lawsuit settlement are flawed and are not giving Nebraska irrigators appropriate credit for groundwater savings; and, 2) That the Nebraska DNR does not really know what needs to be done in order to bring Nebraska into compliance. We hesitate to subject the irrigators in the Republican Basin to such drastic reductions – and the entire region to such economic hardship – based on a guess or an assumption that may not be accurate or true.[257]

The fact is Nebraska has not been in compliance with the FSS since it was executed on December 15, 2002, until the 5-year normal administration period ending in 2008,[247] following the wet year of 2007 with wet-year conditions continuing through 2008, as described in Finding 146.

152. Even if Kansas' experts have not overestimated the amount of reduction in groundwater irrigated acreage that is necessary in Nebraska for Nebraska to comply with the FSS as described in Finding 135, it is not necessary to impose Kansas' proposed remedy to ensure that Nebraska complies with the Compact and FSS in the future.

153. To ensure Nebraska's future compliance with the provisions of the FSS, Kansas is entitled to injunctive relief enjoining Nebraska from exceeding its future allocations determined in accordance with the Accounting Procedures using the averaging provisions for normal administration and Water-Short Year Administration as set forth in the FSS.

154. Should Nebraska fail to comply with the injunction contemplated by Finding 153, sanctions may be appropriate in addition to the award of additional damages to Kansas. While such sanctions may be significant, those sanctions should be based on the specific circumstances of Nebraska's failure to comply, and hence it is not appropriate to recommend the pre-establishment of such sanctions in advance, as requested by Kansas.[258]

155. Contrary to the viewpoint expressed by one of Nebraska's experts,[259] the FSS does not provide that money can be exchanged for water in determining the 5-year averages of allocation less CBCU reduced by the IWS credit for normal administration periods or the 2-year averages for Water-Short Year Administration. Consistent with the express provisions of the FSS and as a sanction for violating the FSS by exceeding its allocations during Water-Short Year Administration in 2005 and 2006, Nebraska should not receive credit in subsequent 5-year averages for damages that may be paid to Kansas for those violations.

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[257] Kansas Exhibit 61, *An Open Letter To All Concerned About Nebraska Water Issues*, pp. 2, 3.

[258] Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, § III.b.vi.; *Kansas' Post-Trial Brief* at 38.

[259] Transcript of Arbitration Proceedings, March 12, 2009, Volume IV at 795:12-16 (Williams).

156. In addition to its proposed remedy, Kansas also seeks the appointment of a river master to administer future compliance with the FSS "on an annual basis until such time as Nebraska can demonstrate an independent ability to achieve compliance."[260] Acknowledging that the "Court rarely appoints a river master,"[261] Kansas cites three reasons why it believes the Court should appoint a river master: (1) Nebraska does not have a central authority or institutions that are capable of curtailing excessive consumptive groundwater withdrawals in Nebraska's portion of the Republican River Basin to achieve compliance with the FSS in the short term;[262] (2) there is no incentive for Nebraska to comply with the FSS, since Nebraska's gain from noncompliance with the FSS is considerably greater than Kansas' losses; and (3) there is a natural propensity for the states to disagree.

157. While Nebraska does not have a central authority that regulates groundwater withdrawals and although the Nebraska NRDs may not embrace the reductions in groundwater CBCU that may be necessary for compliance with the Compact and FSS during prolonged dry-year conditions, there is a central authority that can impose the necessary actions to ensure compliance: the State of Nebraska itself. The Nebraska NRDs operate pursuant to statutes enacted by the Nebraska legislature, and the Nebraska legislature can change those statutes to ensure that Nebraska complies with the Compact and FSS. As the director of the Nebraska DNR testified: "The State of the [*sic*] Nebraska has to live within its allocation."[263] With the injunctive relief suggested in Finding 153 enjoining Nebraska from exceeding its allocations in the future and sanctions for failure to comply, the cost to Nebraska for noncompliance should incentivize Nebraska to take whatever steps are necessary to ensure that it does stay within its allocations under the Compact pursuant to the FSS during all conditions including prolonged dry-year conditions.

158. Kansas cites to *Texas v. New Mexico*[264] as a precedent for the Court appointing a river master. In that case, as is the setting here, the Court recognized "the natural propensity of these two States to disagree."[265] But that was not the reason why the Special Master in that case made the recommendation, which the Court accepted, that a river master be appointed. In *Texas v. New Mexico*, the Court specifically noted the Special Master's recommendation as follows:

> … that because applying the approved apportionment formula is not entirely mechanical and involves a degree of judgment, an additional enforcement mechanism be supplied.

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260 Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, p. 1.

261 *Kansas' Post-Trial Brief* at 35.

262 *Id.*

263 Transcript of Arbitration Proceedings, March 13, 2009, Volume V at 954:7-8 (Dunnigan).

264 *Texas v. New* Mexico, No.65, Original, 482 U.S. 124, 107 S.Ct. 2279.

265 *Id.* at 134.

> We accept his recommendation and also his preferred solution: the appointment of a River Master to make the required periodic calculations.[266]

In this matter, a river master is not needed "to make the required periodic calculations" because pursuant to the FSS:

> The States will determine Virgin Water Supply, Computed Water Supply, Allocations, Imported Water Supply Credit, augmentation credit and Computed Beneficial Consumptive Use based on a methodology set forth in the RRCA Accounting Procedures, attached hereto as Appendix C.[267]

159. In *Texas v. New Mexico*, the river master appointed by the Court had the specific and limited duty "to make the required periodic calculations" in applying the approved apportionment formula. In this matter, Kansas has not identified what specific duties and authorities a Court-appointed river master could or should undertake. Kansas has only proposed the general duty "to administer Decree compliance on an annual basis"[268] Until such time as the duties and authorities of a river master for the Republican River Basin are specifically identified, appointment of a river master is not warranted.

CONCLUSIONS

Accounting Procedures

1. For the reasons set forth in the *Arbitrator's Final Decision on Legal Issues*, which is attached and incorporated herein, Nebraska's proposed changes to the Accounting Procedures are proper subjects for this arbitration.

Accounting Procedures – Estimating Computed Beneficial Consumptive Use for Groundwater and Imported Water Supply

2. The assertion made by Colorado and Kansas that the issue of estimating CBCU of groundwater and determining the IWS is not a proper subject for this arbitration, because Nebraska's expert report on this issue had not been submitted to the RRCA for its consideration, is not convincing. Nebraska's proposal to use 8 differences calculated using 16 runs of the RRCA Groundwater Model for each of 4 aquifer stresses is essentially the same as what was presented to the RRCA in August of 2008, even though the weighting coefficients used to combine the differences have changed. Neither Colorado nor Kansas timely made this assertion when they submitted their respective expert reports in response to

[266] *Id.*

[267] Final Settlement Stipulation, Volume 1 of 5, § IV.A., p. 17.

[268] Kansas Exhibit 6, Expert Report of David W. Barfield, *Ensuring Future Compliance by Nebraska*, January 20, 2009, § IV.3.

Nebraska's expert report on this issue, and neither timely raised this assertion during the hearing conducted as part of this arbitration.

3. Nebraska's proposed procedure for determining VWS, whereby what Nebraska terms VWS_G, determined as (θ – CKMN), is more consistent with the definition of VWS established in the Compact and adopted in the Accounting Procedures than is summing $CBCU_C$, $CBCU_K$, and $CBCU_N$, less IWS, each calculated in accordance with the existing Accounting Procedures, to compute VWS_G.

4. While Nebraska's proposal for determining what it terms VWS_G is consistent with the definition of VWS established in the Compact and adopted in the Accounting Procedures, Nebraska's proposed changes to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS, are problematic and adoption of Nebraska's proposed changes by the RRCA is not appropriate.

5. Although Nebraska's proposed changes to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS, should not be adopted by the RRCA, the RRCA should consider reconvening the Technical Groundwater Modeling Committee to thoroughly re-evaluate the nonlinear response of the RRCA Groundwater Model when simulated stream drying occurs, re-evaluate the existing procedures for determining CBCU and IWS, and document its conclusions and any recommendations in a report to the RRCA.

<u>Accounting Procedures – Haigler Canal</u>

6. During the period of years from 1995 through 2006, the annual amounts of water measured at the Haigler Canal Spillback gage exceeded the actual annual amounts of water measured at the Arikaree Gage in 2002, 2003, 2004, and 2005, indicating that a significant portion of the water measured at the Haigler Canal Spillback gage during these years does not remain in the Arikaree River as measurable surface water at the Arikaree Gage.

7. While some of the water measured at the Haigler Canal Spillback gage undoubtedly reaches the Arikaree Gage under certain conditions, there is insufficient information to justify changing the Accounting Procedures to reduce the diversions from the North Fork Republican River into the Haigler Canal by the amount of water measured at the Haigler Canal Spillback gage, as proposed by Nebraska.

8. Consequently, the changes to the Accounting Procedures proposed by Nebraska involving VWS calculations for the North Fork of the Republican River in Colorado and the Arikaree River are not justified.

9. During the period of years from 1995 through 2006, the annual amounts of water returning to the Arikaree River from irrigation using water from the Haigler Canal, as estimated in accordance with the change to the Accounting Procedures proposed by Nebraska to apportion 49 percent of the return flows to the Arikaree River at the Arikaree Gage, exceeded the actual annual amounts of water measured at the Arikaree Gage in 2001, 2002, 2003, and 2004.

Thus, only a small portion of the return flow from irrigation in Nebraska using water from the Haigler Canal returns to the Arikaree River, at least during the years since 2001.

10. The conclusion that since 2001 only a small portion of the return flow from irrigation in Nebraska using water from the Haigler Canal returns to the Arikaree River is supported by the observations that: (1) the lands irrigated with water from the Haigler Canal in the Arikaree drainage near Haigler are sandy; (2) many of the systems used to irrigate lands in Arikaree drainage near Haigler using water from the Hailger Canal have been converted to center pivot sprinklers reducing return flows comprised by overland flow; and (3) the direction of groundwater flow under the Arikaree drainage is north towards the Main Stem, not towards the Arikaree River.

11. While some of the water measured at the Arikaree Gage may be comprised of return flow from groundwater discharge under certain conditions, there is insufficient information to justify changing the Accounting Procedures to apportion any of the return flow from irrigating lands using water from the Haigler Canal to the Arikaree River, as proposed by Nebraska.

Accounting Procedures – Groundwater Model Accounting Points

12. The "equitable division" or "allocation" of the waters of the Republican River Basin set forth in Article IV of the Compact for a named "drainage basin" is derived from the "computed average annual virgin water supply" originating in that drainage basin, which ends at the confluence of the stream draining that basin and the "Main Stem" of the Republican River as "Main Stem" is defined in § II. of the Accounting Procedures. This definition of Main Stem is entirely consistent with Article III of the Compact.

13. The locations of the accounting points in the RRCA Groundwater Model that are used for calculating CBCU of groundwater for the "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," pursuant to § III.D.1. of the Accounting Procedures, are consistent with the allocations made by named drainage basin in Article IV of the Compact.

14. Changing the locations of the accounting points in the RRCA Groundwater Model that are used to determine CBCU of groundwater as proposed by Nebraska for the "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," such that the accounting point locations would correspond to the locations of the stream gages designated in § II. of the Accounting Procedures, would result in the CBCU of groundwater below the designated stream gages being included in the CBCU for the Main Stem rather than in the CBCU for the tributary drainage basins. These changes would be inconsistent with the definitions of these drainage basins implicit in Article III of the Compact and are not appropriate.

15. However, to the extent groundwater pumping causes depletions to streamflows downstream of the gages designated in § II. of the Accounting Procedures for the "Frenchman Creek

(River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," and upstream of the confluence of each associated stream with the Main Stem, the RRCA should modify the Accounting Procedures for these sub-basins to subtract the CBCU of groundwater below the designated gage for each Sub-basin and above the confluence of that Sub-basin's stream with the Main Stem from the VWS for that Sub-basin, to avoid a double-accounting of that quantity of water, and add that increment of groundwater CBCU in the VWS for the Main Stem, such as is currently done in accounting for the CBCU of surface water below the Sub-basin gages for Medicine Creek, Sappa Creek, Beaver Creek, and Prairie Dog Creek.

16. The accounting point currently used to determine the CBCU of groundwater in the "North Fork of the Republican River in Colorado drainage basin" is not located at the confluence with the Main Stem, as the Main Stem is defined in § II. of the Accounting Procedures. This is inconsistent with the explicit meaning of the "North Fork of the Republican River drainage basin in Colorado" in Article III of the Compact and results in CBCU of groundwater that should be included in the CBCU for the Main Stem being included instead in the CBCU for the "North Fork of the Republican River in Colorado drainage basin." The RRCA should move the location of this accounting point to the model cell in which the North Fork of the Republican River crosses the Colorado-Nebraska state line to provide for the appropriate determination of CBCU for the "North Fork of the Republican River in Colorado drainage basin" and CBCU for the Main Stem.

17. The changes to the Accounting Procedures described above should apply to all years for which the accounting of water use has not been finalized and approved by the RRCA.

Damages – Losses to Kansas Water Users from Overuse in Nebraska

18. Nebraska does not deny that it exceeded its basin-wide allocations in 2005 and 2006 and its Water-Short Year allocations above Guide Rock in 2005 and 2006.

19. Subsection V.B.2.e. of the FSS explicitly provides that for purposes of determining Nebraska's compliance during Water-Short Year Administration, Virgin Water Supply, Computed Water Supply, Allocations, and Nebraska's Computed Beneficial Consumptive Use, are to be calculated as two-year running averages. The FSS does not explicitly address the amount of the violation when Nebraska is not in compliance with the FSS during Water-Short Year Administration.

20. The two-year average of Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock for 2006 should not be used to determine the amount of Nebraska's violation for 2006 because the two-year average is greater than Nebraska's actual exceedance in 2006. Rather, the amount of Nebraska's violation for 2005 and 2006 should be equal to Nebraska's exceedance of its Water-Short Year Administration allocations above Guide Rock for each of those years.

21. Based on a document accepted as Kansas Exhibit 84 on the last day of hearing, irrigators in the Nebraska Bostwick Irrigation District chose to substitute water supply from Nebraska's allocation below Guide Rock for water supply from the Superior Canal in 2006. Given the explicit provision in § IV.A.e)(1) of the Accounting Procedures pertaining to use of substitute supplies for the Superior Canal from Nebraska's allocation below Guide Rock, a portion of the 2006 evaporation from Harlan County Lake should be assigned to Nebraska.

22. Adding half of the net evaporation from Harlan County Lake for 2006 to Nebraska's estimate of its 2006 allocation exceedance results in a revised estimate of the 2006 exceedance that is sufficiently close to Kansas' estimate of the 2006 exceedance to justify acceptance of Kansas' estimate, which allocated evaporation from Harlan County Lake "… based on long-term average uses."

23. Nebraska's exceedance of its Water-Short Year Administration allocation above Guide Rock is estimated to be 42,860 acre-feet for 2005 and 36,100 acre-feet for 2006, which are the amounts estimated by Kansas' expert.

24. To provide a basis for estimating the direct economic impacts to Kansas caused by Nebraska's exceedance of its Water-Short Year allocation above Guide Rock, the additional amount of water that should have been available for use in Kansas was routed in accounting simulations by the experts for Kansas and Nebraska to where the direct economic of impacts of the shortages occurred: the farm headgates in KBID and downstream of KBID. To perform these simulations the experts for both Kansas and Nebraska assumed that the additional amount of water that should have been available for use in Kansas was regulated through Harlan County Lake. After deducting for additional net evaporation from Harlan County Lake, the additional amounts of water that should have been available from Harlan County Lake were estimated to be 41,519 acre-feet for 2005 and 33,383 acre-feet, the amounts estimated by Kansas' expert.

25. The accounting simulations routing the additional water from Harlan County Lake performed by Kansas' expert results in estimated amounts of water that would have been available for delivery to KBID from the Courtland Canal at the Nebraska-Kansas state line of 40,551 acre-feet (rounded to 40,600 acre-feet) for 2005 and 32,605 acre-feet (rounded to 32,600 acre-feet) for 2006. These estimated amounts are overstated. Kansas' expert only subtracted the consumptive canal losses (losses that do not recharge computed as 18 percent of the total canal losses in accordance with RRCA accounting) from the Courtland Canal diversions in Nebraska, leaving the non-consumptive losses (losses that do recharge computed as 82 percent of the total canal losses in accordance with RRCA accounting) as part of the simulated additional supplies available to KBID from the Courtland Canal at the Nebraska-Kansas state line in 2005 and 2006. While some, if not all, of the non-consumptive losses from the Courtland Canal in Nebraska would reasonably be assumed to be available to Kansas irrigators as groundwater and as additional flow in the Republican River, the non-consumptive canal losses are losses from the canal and can not be part of the water supply available to KBID from the Courtland Canal at the Nebraska-Kansas state line.

26. There is insufficient information in the record to allow a reasonably reliable estimate of how the additional groundwater and flow in the Republican River from non-consumptive losses from the Courtland Canal in Nebraska might have been used by irrigators in Kansas.

27. The accounting simulations routing the additional water from Harlan County Lake performed by Nebraska's experts properly exclude all of the estimated canal losses from the Courtland Canal in Nebraska. However, Nebraska's experts made no attempt to estimate the amounts of canal losses that would have been available to Kansas as groundwater or as additional flow in the Republican River. Nebraska's experts have understated the additional amounts of water that would have available to Kansas irrigators below the Nebraska-Kansas state line in 2005 and 2006.

Damages – Direct Economic Impacts

28. The approach used by Kansas' experts to project irrigated crop yields that would have been realized, had overuse of water by Nebraska not occurred, is not materially the same as the approach used in *Kansas v. Colorado*, No. 105, Original, in several respects that are important. First, the crop response functions in *Kansas v. Colorado* were based on the response of crop yield to precipitation and irrigation only, whereas the version of IPYsim employed by Kansas' experts includes not only crop-yield response to precipitation and irrigation but also includes crop-yield response to total usable nitrogen. Second, the crop response functions in *Kansas v. Colorado* do not include economic considerations, whereas IPYsim incorporates costs for both nitrogen fertilizer and water. Third, Kansas' experts adjusted the IPYsim response functions first so that the economically optimal yields equaled trend yields and then secondly so that yields for fully irrigated crops (termed fully irrigated "expected yield" for an individual crop) equaled observed yields under actual irrigation multiplied by the ratios of simulated yield under full irrigation and simulated yield under actual irrigation, both simulated when the economically optimal yields equaled trend yields. This resulted in the fully irrigated "expected yield" for corn, which Kansas' experts identified as the most appropriate crop for their proposed yield modeling framework, of 206 bushel/acre. This fully irrigated "expected yield" is 10 percent higher than the historical maximum yield of 187 bushel/acre in KBID, which was observed in 2005. Kansas did not provide any information to verify the reasonableness of the resulting response functions that were then used to assess impacts, whereas the crop response functions in *Kansas v. Colorado* were based on empirical relationships; that is, relationships based on observations that can be verified or disproved by observation or experiment.

29. The experts for Colorado and Nebraska on the issue of economic impacts were both critical of the adjustment of the IPYsim crop response functions to estimate the crop-specific fully irrigated "expected yield."

30. Kansas did not sufficiently address variations in soil types and climate between western Kansas, where the crop-yield functions for precipitation and irrigation were developed and upon which the IPYsim crop response functions were based, and north-central Kansas

several hundred miles to the northeast, where KBID and the other impacted areas in Kansas are located.

31. There is no evidence in the record of an active water market in or adjacent to south-central Nebraska, where Nebraska leased surface water in 2006 that could be diverted by KBID at the Guide Rock Diversion Dam. Therefore, the unit cost that Nebraska paid to lease water in its attempt to comply with the FSS in 2006 is not the same as the unit value of water to Kansas from lost profits due to overuse by Nebraska in 2006.

32. In seeking damages, Kansas bears the burden of proof concerning the extent of such damages based upon a preponderance of the evidence[269, 270] and must show such damages to reasonable certainty.[271]

33. The preponderance of evidence at this juncture does not support the estimates of additional water that would have been available at the headgates of Kansas irrigators but for Nebraska's overuse of water in 2005 and 2006, the lack of significance of soil and climate variations assumed by Kansas' experts, the methodology used by Kansas's experts to project irrigated crop yields that would have been realized had overuse of water by Nebraska not occurred, or the estimates of the total direct economic impacts in 2005 and 2006 made by Kansas' experts with reasonable certainty. Kansas's estimates of the total direct economic impacts in 2005 and 2006 are not sufficiently reliable to form an appropriate recommendation for awarding damages to Kansas.

34. The alternative estimates of total direct economic impacts in 2005 and 2006 developed by experts for Colorado and Nebraska are also not sufficiently reliable to form an appropriate recommendation for awarding damages to Kansas.

35. Because this arbitration is non-binding, the legal principle *res judicata* is not applicable and Kansas may submit additional information to support or revise its estimates of actual damages caused by Nebraska's overuse of water in 2005 and 2006. Such additional information can be presented in arbitration supplemental to this present proceeding, before the same or a different arbitrator, or such information can be presented during a determination of damages by the Court.

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[269] "In a typical civil suit for money damages, plaintiffs must prove their case by a preponderance of the evidence." *Herman & MacLean v. Huddleston*, 459 U.S. 375, 103 S.Ct. 683 (1983), at 387.

[270] "The burden of showing something by a 'preponderance of the evidence,' the most common standard in the civil law, 'simply requires the trier of fact to believe that the existence of a fact is more probable than its nonexistence before [he] may find in favor of the party who has the burden to persuade the [judge] of the fact's existence.'" *Concrete Pipe & Products of California, In. v. Construction Laborers Pension Trust for Southern California*, 508 U.S. 602, 113 S.Ct. 2264, at 2279 (internal citations omitted).

[271] "It is well understood that such evidence must show damages to reasonable certainty. Mere 'plausible anticipation' does not merit consideration nor are flights into the realm of pure speculation entitled to be treated as evidence. *Connecticut RY. & Lighting Co. v. Palmer et al.*, 305 U.S. 493, 59 S.Ct. 316 (1939), at 505.

36. Clearly Kansas incurred damages resulting from Nebraska's overuse of water in 2005 and 2006 and those damages may well be in the range of one to several million dollars. However, until such time Kansas can demonstrate with a preponderance of evidence that its assumptions and methodology for estimating lost profits and establishing damages is reasonably reliable (either through independent peer review or with empirical data), during subsequent arbitration or before the Court, only an award of nominal damages should be made.

37. Nominal damages are "by definition, minimal monetary damages."[272] While nominal damages could be $ 1 or less,[273] given that Kansas has clearly been harmed by Nebraska's overuse of water but has not shown the extent of such harm with sufficient certainty, an award of nominal damages in the amount of $10,000 is recommended.

Damages – Indirect Economic Impacts

38. The gross indirect economic impacts, or "Value Added Impact" or "Indirect Value Added Loss" estimated by Kansas' experts for both 2005 and 2006 of 44 percent of the direct economic impacts (gross income loss), meaning that total economic impacts are estimated to be 1.44 times the estimated direct economic impacts, are reasonable.

39. Kansas' experts should have attempted to reasonably quantify the indirect benefits resulting from Nebraska's payments for actual damages. Also, there is no evidence in the record for this proceeding whether opportunity costs offsetting or reducing gross secondary impacts, as found to be appropriate by the Court in *Kansas v. Colorado*, No. 105, Original, were considered by Kansas' experts, or whether such offsets are even relevant in this instance.

40. Since an award of only nominal damages for direct economic impacts is recommended in this proceeding, no award of damages for indirect economic impacts should be made.

41. If Kansas seeks to demonstrate with a preponderance of evidence the amounts of additional water that would have been available at the headgates of Kansas irrigators, but for Nebraska's overuse of water in 2005 and 2006, and that its assumptions and methodology for estimating lost profits and establishing actual damages is reasonably reliable during subsequent arbitration or before the Court, Kansas should also attempt to reasonably quantify indirect benefits resulting from Nebraska's payment for actual damages and should also include any offsetting opportunity costs if such are relevant.

Future Compliance

42. To ensure future compliance with the FSS, Kansas has proposed that Nebraska reduce its groundwater-irrigated acreage in the Basin by approximately 515,000 acres. Kansas' experts

[272] 22 Am. Jur. 2d Damages § 8 (2008).

[273] *Colorado Investment Services v. Hager*, 685 P.2d 1371 (1984) at 1375.

estimate that this would reduce consumptive groundwater withdrawals by an average of 619,000 acre-feet per year.

43. Kansas has adequately demonstrated that its proposed remedy would result in Nebraska's compliance with the FSS, even during dry-year conditions similar to what occurred during the period 2002 through 2006. However, given the magnitude of the assumed increase in surface water CBCU from reductions in groundwater CBCU and the fact that Kansas' experts used datasets from years when precipitation was above average overall, Kansas' experts likely have overestimated the amount of reduction in groundwater irrigated acreage that is necessary in Nebraska for Nebraska to comply with the FSS. Therefore, Kansas has not adequately demonstrated that its proposed remedy is the "minimum remedy necessary for compliance" as it has asserted.

44. In its attempts to ensure future compliance with the Compact and FSS, Nebraska and the URNRD, MRNRD, and LRNRD have jointly developed revised IMPs for the 5-year term from 2008 through 2012. These revised IMPs first rely on 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD (intended to be achieved in the LRNRD through reduced allocations for individual irrigators), compared to the average withdrawals for 1998 through 2006. This would reduce consumptive groundwater withdrawals within the portion of the Republican River Basin in Nebraska by an average of 217,120 acre-feet per year from the 1998 – 2006 average of 1,083,530 acre-feet per year. An average reduction in consumptive groundwater withdrawals of 217,120 acre-feet per year is 35 percent of the average annual reduction of 619,000 acre-feet per year that Kansas estimates would result from its proposed remedy.

45. Simulations by Nebraska's experts of the performance of the IMPs, assuming 20 percent reductions in the average annual consumptive groundwater withdrawals within the URNRD, MRNRD, and LRNRD from the 1998 – 2006 average withdrawals, under a scenario of repeated dry conditions, during which compliance would be crucial, showed that Nebraska would be over its allocation under normal year administration by an average amount of 340 acre-feet per year, over the 5-year simulation period, and would be over by an average amount of 8,288 acre-feet per year under Water-Short Year Administration. However, Nebraska's basin-wide allocation from these simulations averaged 20,000 acre-feet per year more than the average basin-wide allocation of about 211,000 acre-feet per year that was determined by the RRCA for the actual dry-year period of 2002 through 2006, and Nebraska's allocation above Guide Rock from these simulations for Water-Short Year Administration averaged 32,000 acre-feet per year more than the actual average allocation above Guide Rock of 189,820 acre-feet per year that was determined by the RRCA for the Water-Short Year Administration in 2005 and 2006. Consequently, Nebraska has underestimated the amounts by which it is likely to exceed its allocations during dry-year conditions by perhaps as much as 20,000 acre-feet to 30,000 acre-feet per year. As a result, the 20 percent reductions in the average annual groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the average withdrawals for 1998 through 2006, are unlikely sufficient to ensure compact compliance during prolonged dry-year conditions, such as occurred from 2002 through 2006.

46. When a 20 percent reduction in the average annual consumptive groundwater withdrawals within the URNRD, MRNRD, and LRNRD, compared to the 1998 – 2006 average withdrawals, is not sufficient to achieve compliance with the Compact and FSS, Nebraska then relies on the provisions in the IMPs that limit the net groundwater depletions for the URNRD, MRNRD, and LRNRD to 44 percent, 30 percent, and 26 percent, respectively, of Nebraska's allowable groundwater. The difficulty in ensuring compliance with the Compact and FSS through these provisions of the IMPs is that just as for groundwater withdrawals where there is a long time lag between the time when the pumping actually occurs and the time when it manifests itself on streamflows, depending on the location of the wells from which consumptive groundwater withdrawals are made, there is also a long time lag between the time when groundwater withdrawals are reduced or curtailed and the time when resulting increases in streamflow occur.

47. When it is determined that one or more of the URNRD, MRNRD, or LRNRD has exceeded their portion of Nebraska's allowable groundwater CBCU in the preceding year, as specified in the respective IMP, and further reductions are made to consumptive groundwater withdrawals in the respective NRD, it will be years before the effects of those reductions are expressed as increased streamflow, depending on the location of the wells from which groundwater withdrawals are reduced or curtailed. If a particular NRD's exceedance of its portion of Nebraska's allowable groundwater CBCU occurs during a prolonged period of dry conditions, such as occurred from 2002 through 2006, it will likely not be possible for Nebraska to achieve compliance during the term of the current IMPs without focused curtailment of consumptive groundwater withdrawals in close proximity to surface water streams, which is not specifically required in any the IMPs for the URNRD, MRNRD, or LRNRD. As a result, the limitations on the average annual net streamflow depletions from consumptive groundwater withdrawals within the URNRD, MRNRD, and LRNRD are likely inadequate to ensure compliance with the Compact and FSS during prolonged dry-year conditions, such as occurred from 2002 through 2006.

48. Nebraska has not been in compliance with the FSS since it was executed on December 15, 2002, until the 5-year normal administration period ending in 2008, following the wet year of 2007 with wet-year conditions continuing through 2008. Although the IMPs for the Republican River NRDs are enforceable, the current IMPs adopted by Nebraska and the Republican River NRDs are inadequate to ensure compliance with the Compact and FSS during prolonged dry-year conditions, such as occurred from 2002 through 2006. Nebraska and the Republican River NRDs should make further reductions in consumptive groundwater withdrawals beyond what's required in the current IMPs, in addition to obtaining permanent, interruptible supply contracts with surface water irrigators, to ensure compliance with the Compact and FSS during prolonged dry-year conditions.

49. Neither the Compact nor the FSS require that Nebraska demonstrate in advance how it will be in compliance in the future. Nonetheless, Nebraska must maintain compliance as prescribed by the FSS during each 5-year period for normal administration and during each 2-year period for Water-Short Year Administration. To ensure Nebraska's compliance with the Compact and FSS into the future, it is not necessary to impose Kansas' proposed remedy. However, Kansas is entitled to injunctive relief enjoining Nebraska from exceeding its future

allocations determined in accordance with the Accounting Procedures using the averaging provisions for normal administration and Water-Short Year Administration as set forth in the FSS.

50. Should Nebraska fail to comply with an injunction, sanctions may be appropriate in addition to the award of additional damages to Kansas. While such sanctions may be significant, those sanctions should be based on the specific circumstances of Nebraska's failure to comply, and hence it is not appropriate to recommend the pre-establishment of such sanctions in advance, as requested by Kansas.

51. Consistent with the express provisions of the FSS, which do not provide that money can be exchanged for water in determining the 5-year averages of allocation less CBCU reduced by the IWS credit for normal administration periods or the 2-year averages for Water-Short Year Administration, and as a sanction for violating the FSS by exceeding its allocations during Water-Short Year Administration in 2005 and 2006, Nebraska should not receive credit in subsequent 5-year averages for damages that may be paid to Kansas for those violations.

52. With the injunctive relief enjoining Nebraska from exceeding its allocations in the future and sanctions for failure to comply, the cost to Nebraska for noncompliance should incentivize Nebraska to take whatever steps are necessary to ensure that it does stay within its allocations under the Compact pursuant to the FSS during all conditions including prolonged dry-year conditions.

53. In *Texas v. New Mexico*, the Court appointed a river master with the specific and limited duty "to make the required periodic calculations" in applying the approved apportionment formula.[274] Since the specific duties and authorities that a river master appointed by the Court could or should undertake in the Republican River Basin have not been specifically identified, appointment of a river master is not warranted at this time.

[274] *Texas v. New* Mexico, No.65, Original, 482 U.S. 124, 107 S.Ct. 2279, at 134.

RECOMMENDATIONS

1. As described in the *Arbitrator's Final Decision on Legal Issue*, Question 3, the Accounting Procedures should be modified so that evaporation from Harlan County Lake is allocated between Kansas and Nebraska in proportion to each state's use of water from Harlan County Lake for all purposes, including use to offset streamflow depletions from consumptive groundwater withdrawals.[275]

2. Nebraska's proposed changes to the Accounting Procedures to calculate $CBCU_C$, $CBCU_K$, $CBCU_N$, and IWS, should not be adopted. However, the RRCA should consider reconvening the Technical Groundwater Modeling Committee to thoroughly re-evaluate the nonlinear response of the RRCA Groundwater Model when simulated stream drying occurs, re-evaluate the existing procedures for determining CBCU and IWS, and document its conclusions and any recommendations in a report to the RRCA.

3. Nebraska's proposed changes to the Accounting Procedures involving calculation of VWS for the North Fork of the Republican River in Colorado and the Arikaree River should not be adopted.

4. Nebraska's proposed changes to the Accounting Procedures to apportion return flows from irrigation using water diverted through the Haigler Canal between the North Fork of the Republican River in Nebraska and the Arikaree River should not be adopted.

5. Nebraska's proposed changes to the Accounting Procedures to move the location of the accounting points in the RRCA Groundwater model to correspond to the location of the Sub-basin gages for "Frenchman Creek (River) drainage basin in Nebraska," "South Fork of the Republican River drainage basin," and "Driftwood Creek drainage basin," should not be adopted. However, to the extent groundwater pumping causes depletions to streamflows downstream of the gages in these sub-basins and upstream of the confluence of each associated stream with the Main Stem, the Accounting Procedures for these sub-basins should be modified to subtract the CBCU of groundwater below the designated gage for each Sub-basin and above the confluence of that Sub-basin's stream with the Main Stem from the VWS for that Sub-basin, to avoid a double-accounting of that quantity of water, and add that increment of groundwater CBCU in the VWS for the Main Stem.[275]

6. Nebraska's proposed change to the Accounting Procedures to move the location of the accounting point in the RRCA Groundwater model for the "North Fork of the Republican River in Colorado drainage basin" to the location where the North Fork of the Republican River crosses the Colorado-Nebraska state line should be adopted.[275]

7. Kansas should be awarded nominal damages of $10,000 for Nebraska's overuse of water in 2005 and 2006 until Kansas can correct its estimates of the amounts of water that would have been available to KBID from the Courtland Canal, but for Nebraska's overuse, and can

[275] Changes should apply to all years for which the accounting of water use has not been finalized and approved by the RRCA.

demonstrate that its assumptions and methodology for estimating lost profits and establishing damages is reasonably reliable, during subsequent arbitration or before the Court.

8. Nebraska's IMPs for the URNRD, MRNRD, and LRNRD are inadequate to ensure compliance with the Compact and FSS during prolonged dry-year conditions, such as occurred from 2002 though 2006. Nebraska and the Republican River NRDs should make further reductions in consumptive groundwater withdrawals beyond what's required in the current IMPs and should obtain permanent, interruptible supply contracts with surface water irrigators, to ensure compliance with the Compact and FSS during prolonged dry-year conditions.

9. To ensure Nebraska's compliance with the Compact and FSS into the future, it is not necessary to impose Kansas' proposed remedy. However, Kansas is entitled to injunctive relief enjoining Nebraska from exceeding its future allocations determined in accordance with the Accounting Procedures using the averaging provisions for normal administration and Water-Short Year Administration as set forth in the FSS.

10. Should Nebraska fail to comply with an injunction, sanctions may be appropriate in addition to the award of additional damages to Kansas. While such sanctions may be significant, those sanctions should be based on the specific circumstances of Nebraska's failure to comply.

11. Nebraska should not receive credit in subsequent 5-year averages for damages that may be paid to Kansas for Nebraska's violations of the FSS in 2005 and 2006.

12. A river master for the Republican River should not be appointed until the specific duties and authorities that a river master could or should undertake in the Republican River Basin have been specifically identified and determined to be necessary.

Dated: June 30, 2009

Karl J. Dreher
Arbitrator

CERTIFICATE OF SERVICE

I, Karl J. Dreher, hereby certify that I caused a copy of the foregoing Arbitrator's Final Decision to be placed in the U.S. Mail, postage paid, on this 30th day of June, 2009, addressed to each of the following:

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

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January 20, 2009

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LIST OF ACRONYMS

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

1.0 INTRODUCTION AND OVERVIEW

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

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

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

2.0 BACKGROUND

2.1 Overview of the Basin and Hydrologic Interactions

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

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

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

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

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

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

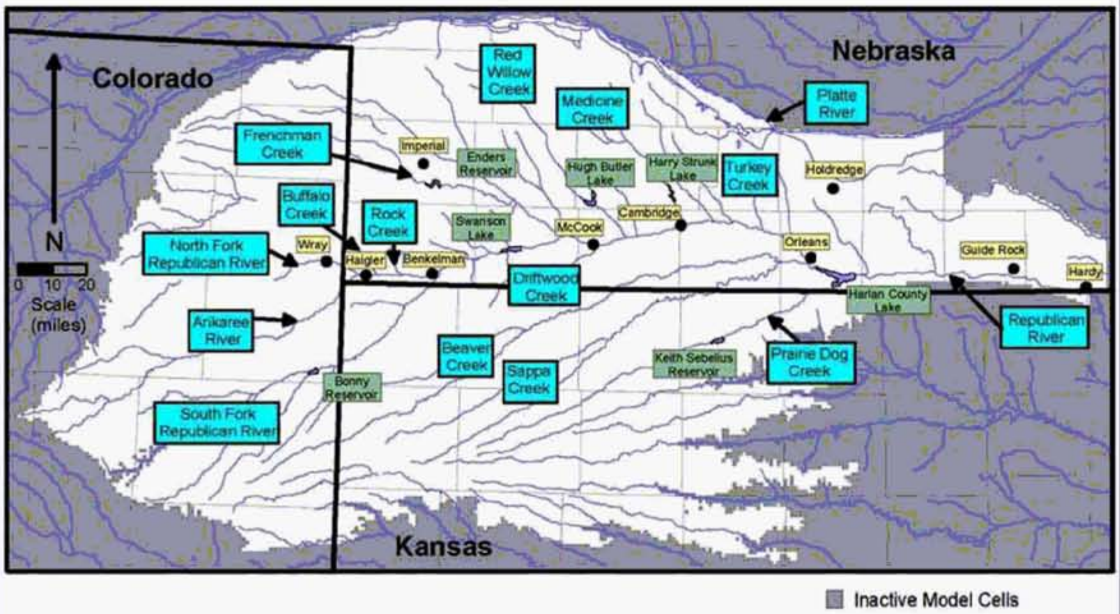

Figure 1. Map showing location of Republican River, tributaries, reservoirs and lakes, and selected towns.

McDonald Morrissey Associates, Inc.

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

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

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

2.2 Role of the RRCA Groundwater Model and Accounting Procedures

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

3.0 THE PROBLEM AND THE SOLUTION

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

3.1 The Problem: Errors in CBCU and IWS

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

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

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

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

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

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

3.1.1 Accounting for $CBCU_G$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.1.2 Hypothetical Example of Flow Components

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

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

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

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

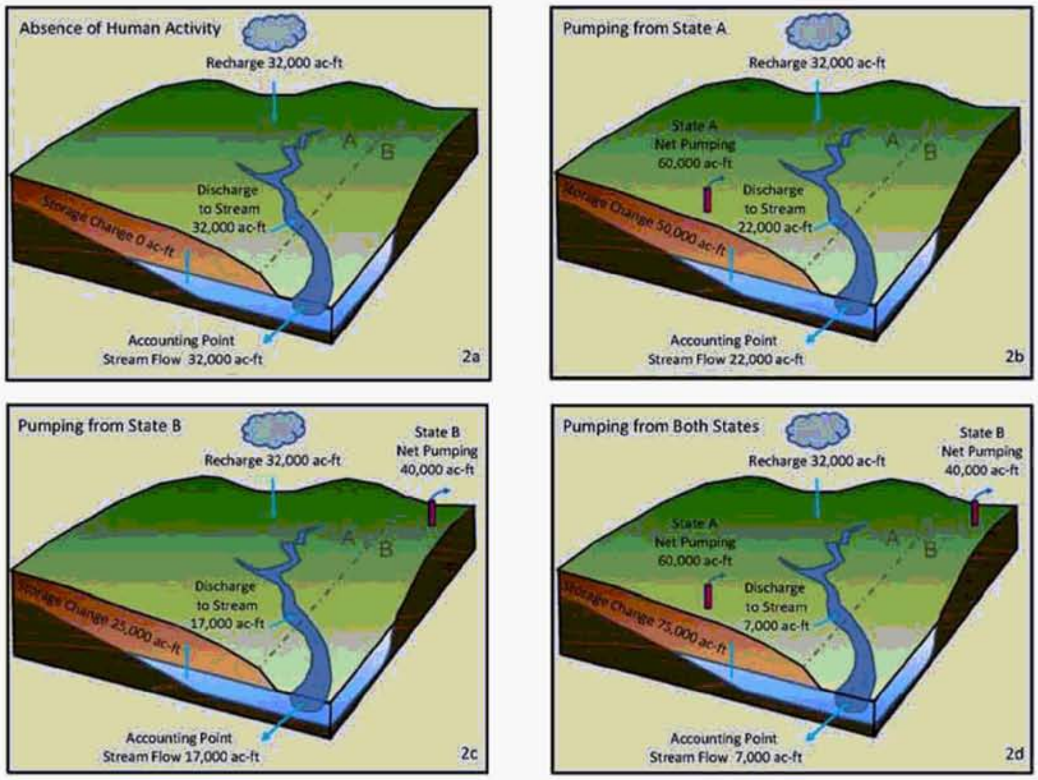

Figure 2. Block diagram showing annual flows in hypothetical sub-basin under different conditions of human activity.

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

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

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

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

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

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

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

3.1.3.1 Beaver Creek Baseflows and CBCU for 1965

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

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

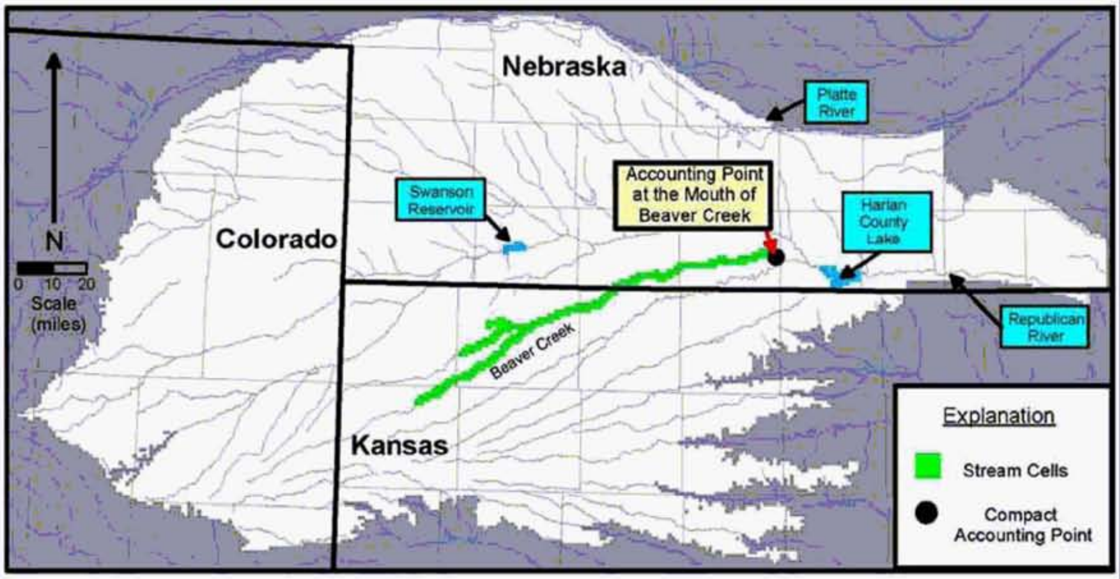

Figure 3. Map showing location of cells with stream boundary condition in Beaver Creek.

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

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

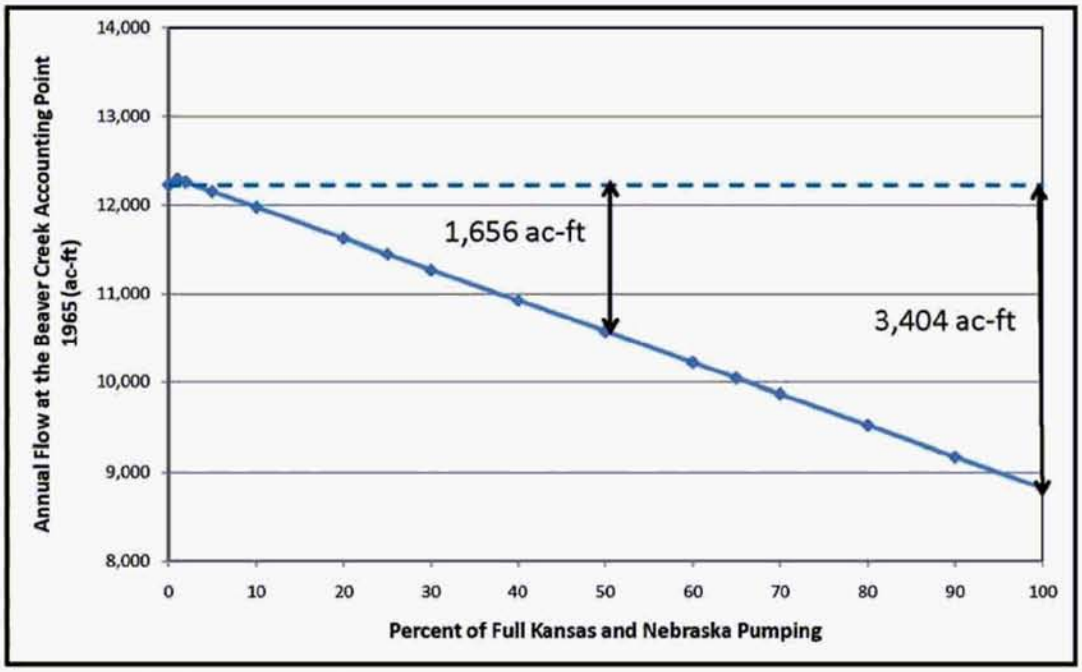

Figure 4. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

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

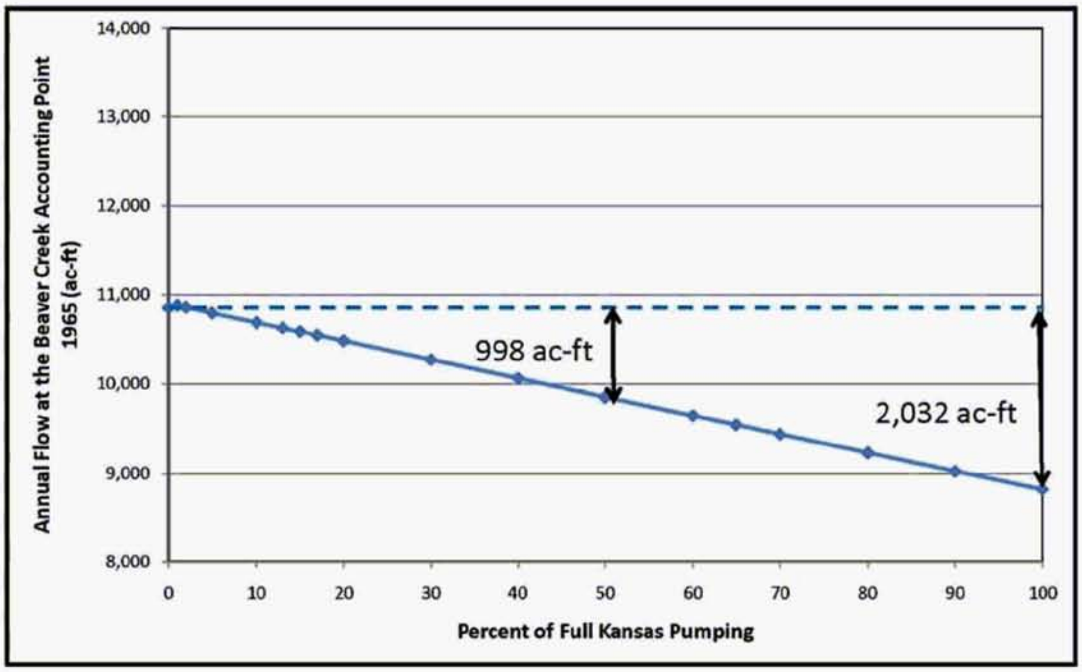

Figure 5. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

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

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

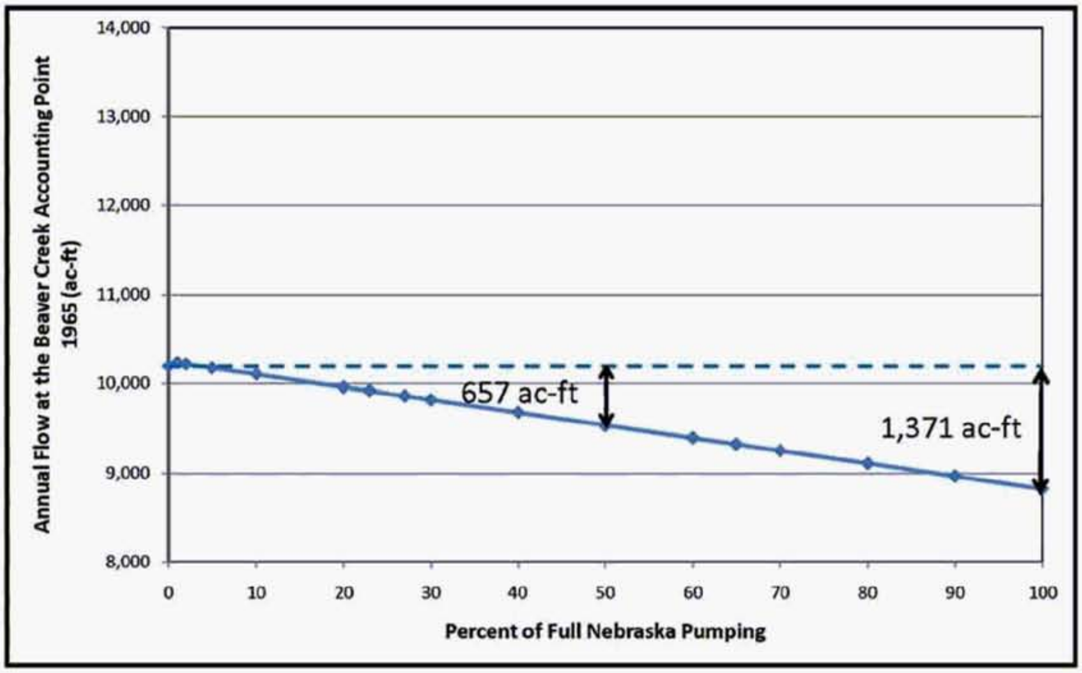

Figure 6. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 1965 with all other stresses active.

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

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

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

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

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

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

3.1.3.2 Beaver Creek Baseflows and CBCU for 2003

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

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

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

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

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

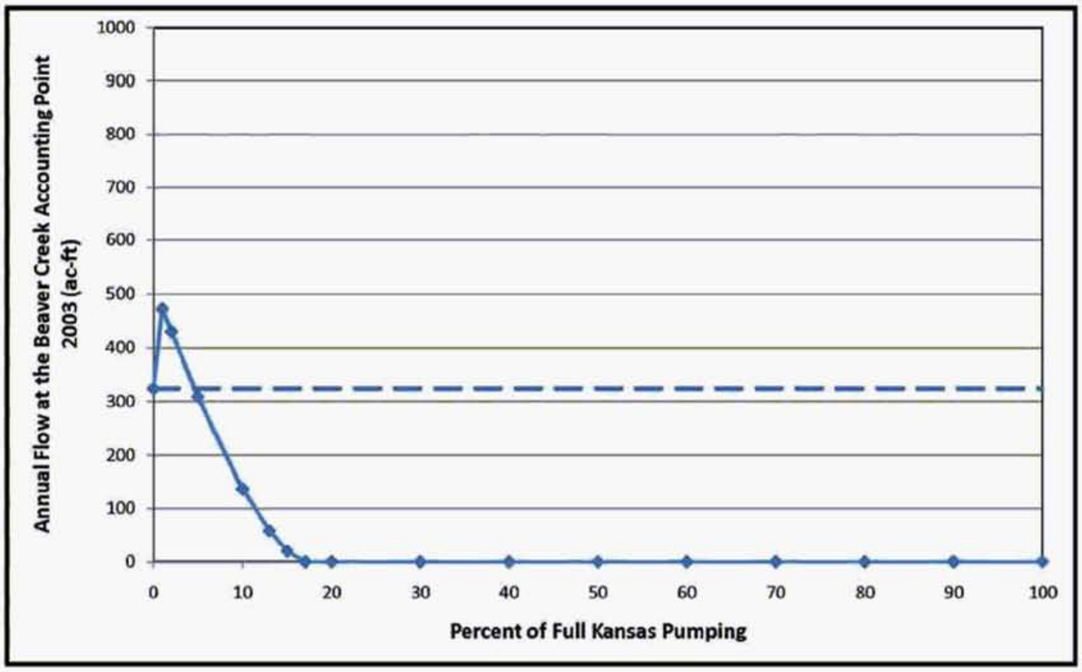

Figure 7. Graph showing percent of full pumping for Kansas versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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

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

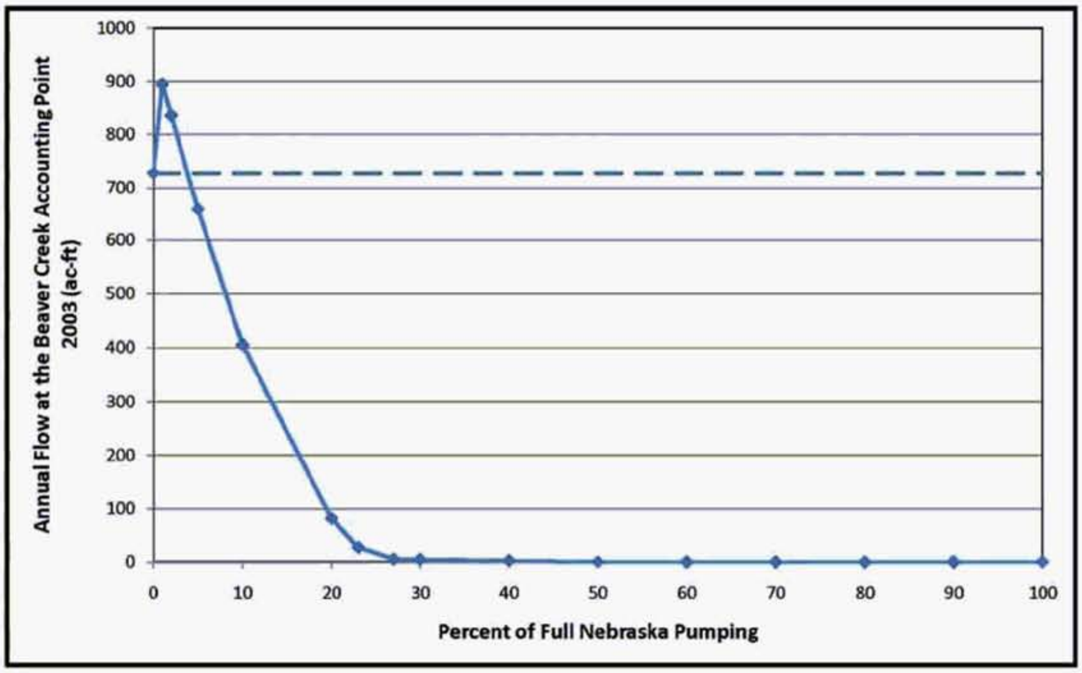

Figure 8. Graph showing percent of full pumping for Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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

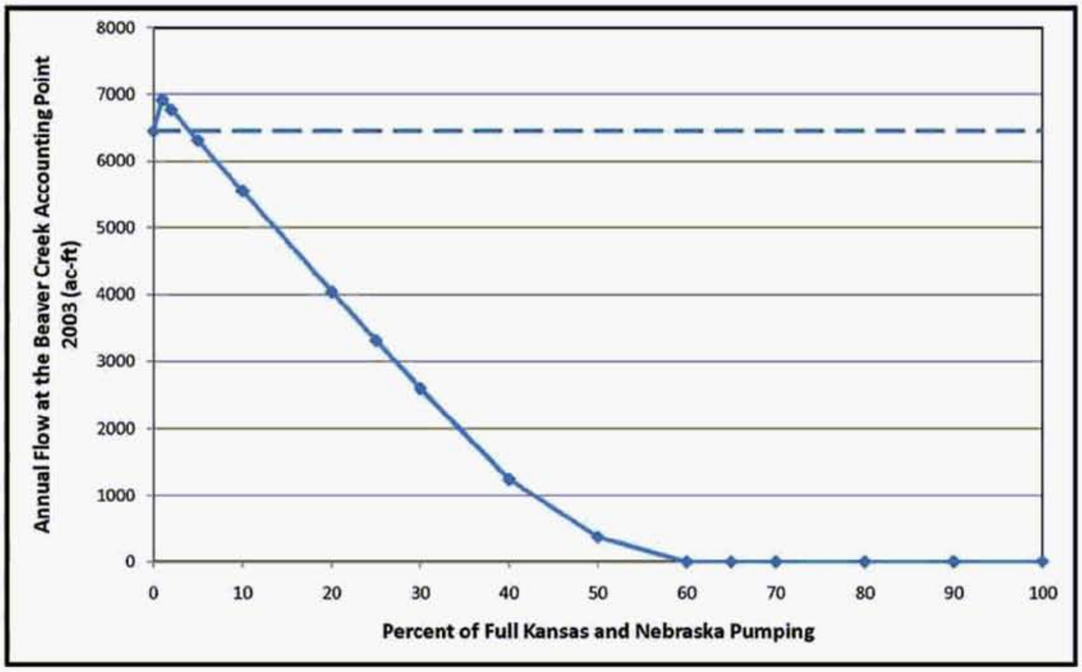

Figure 9. Graph showing percent of full pumping for Kansas and Nebraska versus annual stream flow at the Beaver Creek accounting point in 2003 with all other stresses active.

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3.1.3.3 Model Behavior When Baseflow is Zero

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

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

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

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

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

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

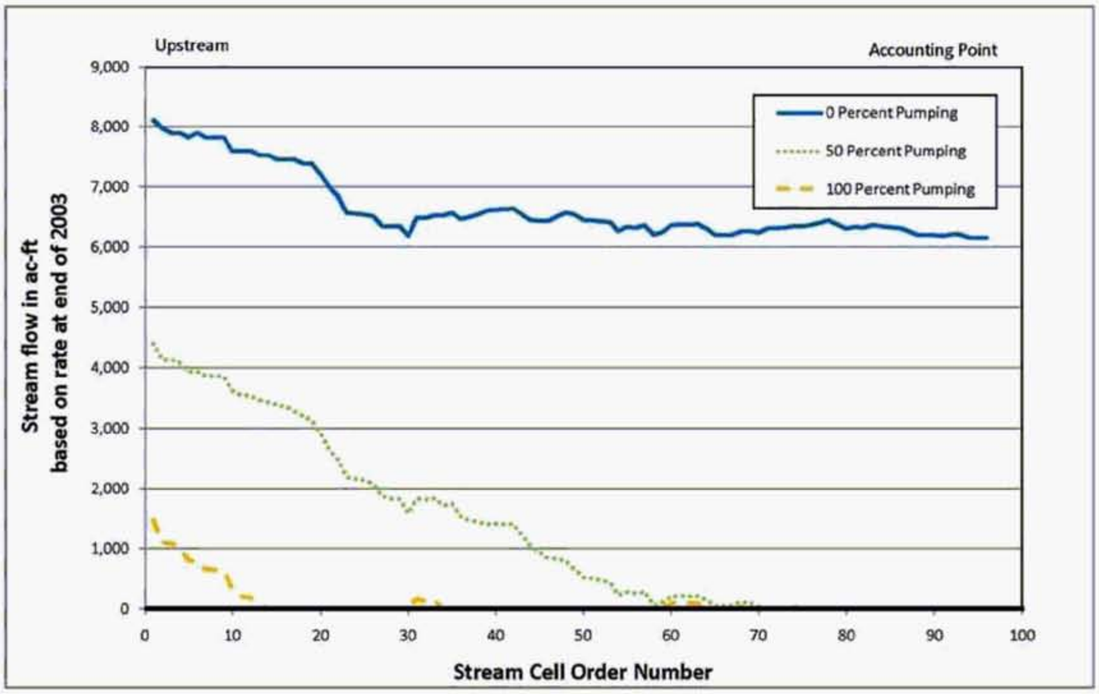

Figure 10. Graph showing stream cell order vs flow for various percents of full pumping for Kansas and Nebraska Pumping, Beaver Creek at the end of 2003.

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

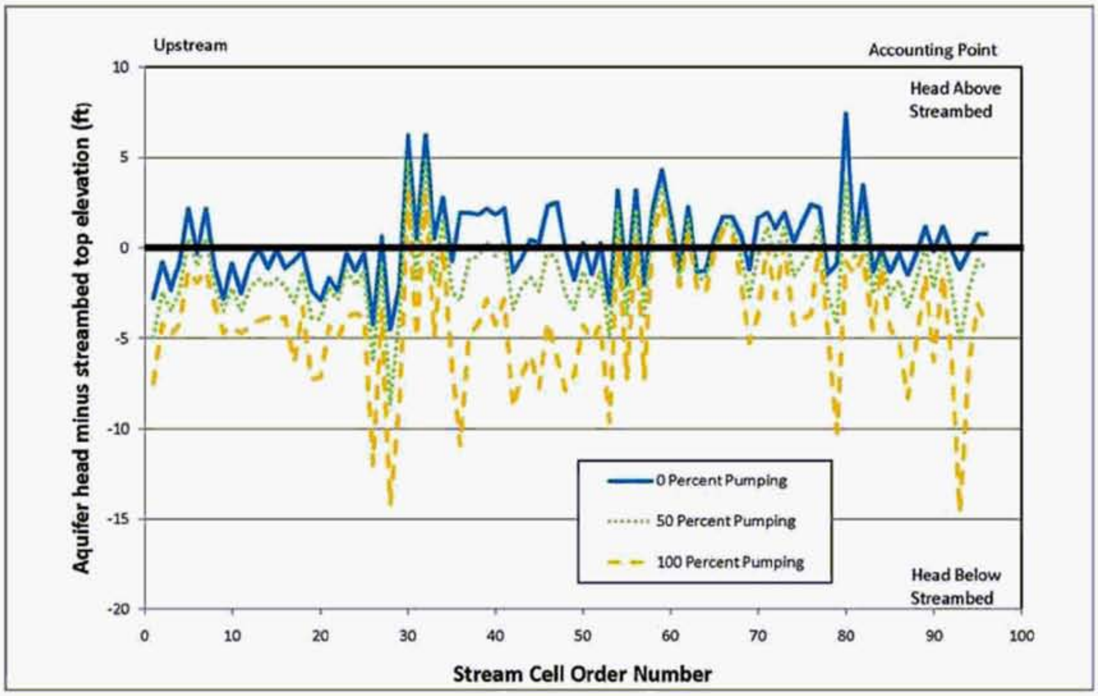

Figure 11. Graph showing stream cell order vs aquifer head minus stream top elevation for various percents of full pumping for Kansas and Nebraska Pumping, Beaver Creek at the end of 2003.

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

3.1.3.4 Storage Replenishment and Reestablishment of Baseflow

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

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

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

3.1.3.5 Conclusions for Beaver Creek

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

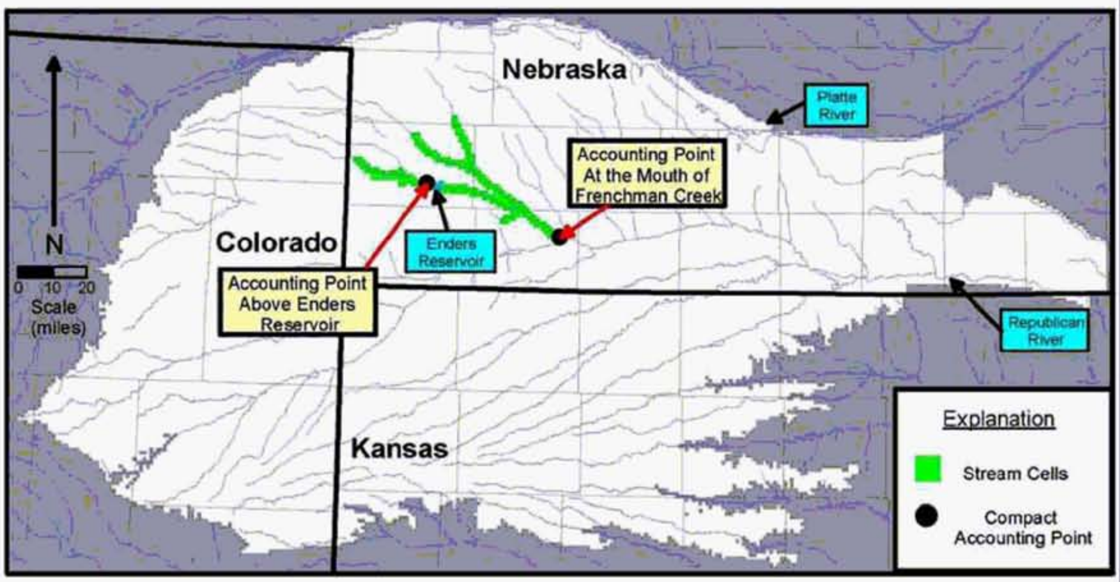

Figure 12. Map showing location of cells with stream boundary condition in Frenchman Creek.

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

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

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

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

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

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

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

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

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

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

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

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

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

3.1.5 Swanson-Harlan: IWS Estimation Failure

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

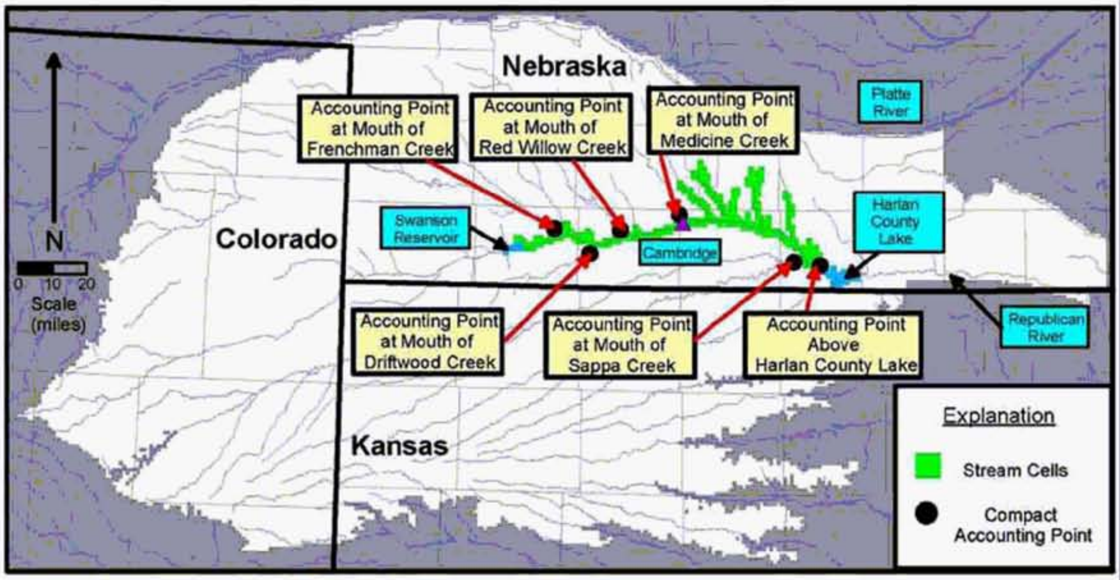

Figure 13. Map showing location of cells with stream boundary condition along the Main Stem of the Republican River from Swanson Reservoir to Harlan County Lake.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.1.7 Proposed Method for Determining CBCU and IWS

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

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

3.2 Importance of Base Condition

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

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

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

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

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

3.2.1 Criteria for Method to Compute CBCU and IWS Values

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

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

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

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

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

3.2.2 Proposed Method: Using Multiple Base Conditions

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

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

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

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

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

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

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

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

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

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

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

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

3.2.3 Characteristics of Proposed Method

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

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

3.2.4 Application to Beaver Creek

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

For this case, the following observations can be made:

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

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

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

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

The proposed impact equations can be simplified using these observations:

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

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

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

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

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

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

$R = VWS_G - (CBCU_K + CBCU_N)$ **(*Equation 14)***

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

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

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

3.2.5 Conclusion

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

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

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

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

4.1 Computed Water Supply

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

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

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

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

or,

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

where,

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

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

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

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

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

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

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

4.2 State Allocations and the Compact

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

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

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

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

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

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

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

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

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

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

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

4.3 State Impacts and IWS

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

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

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

4.4 Compliance Test

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

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

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

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

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

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

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

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

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

4.5 Conclusion

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

APPENDIX A: Current Calculations of $CBCU_g$ and IWS

A.1 Current Calculation of $CBCU_g$

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

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

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

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

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

A.2 Current Calculation of IWS

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

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

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

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

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

APPENDIX B: Alternate Calculation of Swanson Harlan Impacts

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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