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Subject: Kansas v. Nebraska and Colorado, No. 126 Original – Expert Opinion Report Prepared on Behalf of the State of Colorado

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Introduction

This letter documents my engineering opinions and the basis for those opinions on behalf of the State of Colorado. I have worked on groundwater issues concerning the Republican River basin since at least 2002 when I represented the State of Colorado on the groundwater modeling committee that was part of the settlement negotiations that led to the Final Settlement Stipulation in Kansas v. Nebraska and Colorado, No. 126, Original (December 15, 2002) (FSS). In the Republican River basin the principal aquifer is the Ogallala aquifer, which is also referred to as the High Plains Aquifer.

The Republican River Compact Administration (RRCA) Accounting Procedures require calculations of the Computed Beneficial Consumptive Use (CBCU) for each State. Some components of the CBCU can be determined or estimated from measured values. For example, CBCU associated with surface water diversions are computed from measured stream diversions. The amount of historical streamflow in a stream is also measured at key stream gages and is incorporated into the RRCA accounting.

The amount of streamflow that would have occurred in the absence of historical groundwater pumping cannot be directly measured as it can with a surface water diversion, but can only be predicted by estimating the amount streamflows that would have occurred in the absence of historical groundwater pumping. To estimate the streamflow depletions caused by groundwater pumping and the resulting beneficial consumptive use of groundwater for each State, the RRCA developed a numerical groundwater model in 2002-2003. This model was developed as part of a cooperative effort between Colorado, Nebraska, and Kansas, with assistance and input from Federal Agencies. One of the main purposes of the groundwater model was to provide information concerning the CBCU associated with groundwater pumping for use in the RRCA accounting.

Groundwater Model

The movement of water through a groundwater system is a complex and largely unseen phenomenon. In a surface water reservoir, the water that flows into a reservoir, out of a reservoir, or the amount of water in storage can be visually seen and in general directly measured. For a groundwater system, such as exists in the High Plains Aquifer which underlies the majority of the Republican River Basin, the amount, rate, and direction of groundwater flow can only be estimated. Engineers generally agree that the best way to estimate the movement of groundwater flow is through the use of a groundwater model.

A groundwater model uses a set of mathematical equations to approximate the physical system. It is based on the recognized principle of conservation of mass, which is the concept that water is neither created nor destroyed, but is only moved through the model in a representation of the real world. As is the case in all models, real world operations do not always fit neatly into a set of mathematical equations. As a result, any model is an approximation that results in model uncertainties.

The High Plains Aquifer, in a highly simplified sense, is a large underground reservoir. Water moves through the reservoir very slowly and the flow rates are typically measured in terms of feet per day. In a surface water system, flow rates are generally expressed in terms of feet per second which is a time scale 86,400 times greater than the time scale typically used to measure groundwater movement.

The movement of groundwater in the High Plains Aquifer is controlled by the inflows and outflows from the aquifer. Inflows into the aquifer consist of recharge from rainfall and recharge from surface and groundwater irrigation. Outflows from the aquifer are primarily the result of groundwater pumping, phreatophyte consumptive use, and groundwater flowing into the surface water streams. Modelers often refer to these outflows as “stresses”. It should be noted that generally the streams gain water from the aquifer but there are certain stretches where streams lose water to the aquifer as the result of hydrogeological conditions.

To attempt to determine how a State’s consumption of groundwater depletes the streamflow of the Republican River Basin, the RRCA groundwater model was developed to determine the change in baseflows. The term “baseflow” describes the portion of streamflow that results from groundwater flowing from the aquifer into the streams. The portion of the streamflow generated from surface runoff as the result of a precipitation is not included in the definition of baseflow.

To determine the difference in the amount of baseflow due to groundwater pumping, the RRCA groundwater model is applied by making two runs of the model. The difference in the baseflow estimates between the two runs is the result used in the RRCA Accounting as CBCU from groundwater pumping. The first model run is called the "base" run. In the RRCA groundwater model the "base" run simulates the amount of baseflow in the stream under historical conditions; that is with all groundwater pumping, groundwater recharge, and surface water recharge within the model study boundary for the period 1940 to the current accounting year turned "on".

The second model run is called the "no State pumping" run. The "no State pumping" run simulates the baseflow that would have occurred with the same model inputs as the "base" run with the exception that all groundwater pumping and pumping recharge of a State is turned "off." One of the outputs from the groundwater model in each run is the predicted baseflows in the streams. Changes in the baseflows predicted by the model for the "base" run versus the "no State pumping" run are assumed to be depletions to streamflow, i.e., the beneficial consumptive use of groundwater due to a particular State's groundwater pumping.

The level of confidence that modelers have in groundwater model results is principally developed by comparing model simulated results under historical conditions to observed data. The principal observed data is the historical groundwater level measurements and the historical baseflows. The simulated groundwater levels and baseflows in the groundwater model are compared against measured historical groundwater levels (also called "heads") and baseflows. How close the simulated results of a ground water model are to the historical measured values is a metric for how well the model is "calibrated". The better the "calibration," the more confidence modelers have in the reliability of the groundwater model results.

The above example describes how a groundwater model is used to assess impacts from groundwater pumping on streamflows. A similar procedure of taking the difference between two model runs is used in the RRCA Accounting Procedures to estimate the impacts on baseflow from groundwater water recharge resulting from importing water from the South Platte Basin into the Republican River Basin.

Nonlinear Problem

One of the issues that was considered in the RRCA Accounting Procedures is the non-linear behavior of the High Plains aquifer. The non-linear behavior of an aquifer is a difficult concept to explain and understand. A simple way to explain a non-linear system is that the sum of the parts is not necessarily equal to the whole. For example, in an aquifer system there is only a limited amount of baseflow that can be depleted by groundwater pumping. In a linear system it is assumed that amount of groundwater pumping is directly related to the amount of streamflow depletions. A doubling of the amount of groundwater pumping results in a doubling of the stream depletions. In a non-linear system, such as the High Plains Aquifer, the doubling of the groundwater pumping does not result in a doubling of the stream depletions.

As one example, assume that in the absence of groundwater pumping, there was a certain amount of baseflow in a stream because the groundwater levels were sloping towards the streams and conveying groundwater from the aquifer to the streams. Then, assume that as groundwater well pumping development begins, the groundwater level is lowered as the wells extract water from the aquifer. As the groundwater levels are lowered, the slope of the groundwater table towards the stream becomes less which results in less groundwater flowing towards the streams. A portion of the groundwater that is extracted by well pumping is groundwater from the aquifer that previously flowed into streams as baseflows. Thus the groundwater pumping reduced the baseflows in the stream. As additional groundwater pumping continues, the groundwater aquifer levels continue to decline and the baseflows continue to be reduced.

If groundwater development is great enough the groundwater levels will be drawn down until the groundwater levels drop below the bottom elevation of the streambed. This condition is often referred to as the aquifer being disconnected from the stream. When this occurs, the amount of loss from the stream is no longer a function of the groundwater levels in the aquifer, but remains at a constant rate no matter how much further the aquifer declines. As a result, additional pumping will further lower the groundwater levels in the aquifer but will not result in additional baseflow depletions to the streams.

In this example, the initial groundwater pumped from the aquifer has an effect on the amount of baseflow in the stream. But once the stream is disconnected from the aquifer, additional pumping will not impact the streamflows because the groundwater levels are below the bottom of the stream and the groundwater can no longer flow into the stream. The amount of water that would leak from a stream under this condition is not dependent on whether the groundwater level is five feet below the streambed or 50 feet below the streambed. Under these conditions the amount of water that can seep out of the stream bottom is limited by the streambed soil properties not by the groundwater level in the aquifer. It would be incorrect to assume that the streamflow impact from the first groundwater pumping is the same as the streamflow impact from additional pumping, especially once the stream is disconnected from the underlying aquifer. The above example illustrates how a stream that is disconnected from the aquifer can result in a non-linear behavior of the aquifer system.

It should be noted that the groundwater pumping when the aquifer is disconnected from the stream is not “free” water. The water pumped must come from somewhere, and that is from groundwater storage which is the amount of water contained in the aquifer. This is another reason that all groundwater pumping does not necessarily result in the same amount of stream depletions. Some of that water pumped comes from aquifer storage, not the stream, and the decline in aquifer storage results in the lowering of aquifer levels.

The RRCA groundwater model also reflects nonlinear behavior as the result of modeling phreatophyte consumptive use. Phreatophytes are species of plants that are capable of drawing water from the groundwater to meet the plants’ consumptive water requirements. There are many different plant types that fall into this category but common examples of phreatophytes are cottonwood trees and willows that are typically seen along streams channels in areas that also have high groundwater tables.

As groundwater flows through an aquifer toward a stream, a portion of the groundwater flow can be consumed by phreatophytes. A phreatophyte plant can only consume a limited amount of water. As long as the groundwater levels are high enough for the phreatophytes to be fully satisfied, any increase or decrease in groundwater levels will not result in an increase in phreatophyte consumptive use. Thus, if groundwater pumping affects the groundwater levels but the groundwater levels are high enough for the phreatophyte consumptive use to be fully satisfied, then the change in groundwater levels directly affects the baseflows in the streams.

However, as the groundwater levels drop with an increase in pumping, eventually the amount of groundwater consumed by the phreatophytes will decrease. The amount of groundwater a phreatophyte can consume declines as the groundwater levels decline. A phreatophytes' plants roots ability to pull water up to meet the plant consumptive use needs decreases as the groundwater level declines. If the groundwater pumping continues to increase and the groundwater levels continue to decline, the groundwater levels would eventually become low enough that the phreatophytes roots can no longer pull water from the groundwater table. In this latter instance, changes in groundwater pumping would have no effect on phreatophytes consumptive use, similar to an aquifer being disconnected from the stream, discussed previously.

The above example illustrates how different pumping levels can have different impacts on phreatophyte consumptive use. Groundwater pumping does not affect phreatophyte consumptive use by a constant percentage but the phreatophyte consumptive use varies depending on groundwater levels. As the result, the pumping effect on phreatophyte consumptive use can be nonlinear. Consumptive use by phreatophytes affect the rate and direction of groundwater flow in the aquifer which in turn effects the interaction between the aquifer and a stream and the resulting baseflows. As a result, this non-linear behavior of phreatophyte consumptive use results in a non-linear relationship between groundwater pumping and stream depletions when phreatophytes impact the groundwater flow like in the High Plains aquifer.

Groundwater Model Runs

The procedure to use the RRCA Groundwater Model to calculate the computed beneficial consumptive use of each State that was developed and agreed to by the three States is set forth in Subsection III.D.1 of the RRCA Accounting Procedures as follows:

D. Calculation of Annual Computed Beneficial Consumptive Use

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 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."

An output of the model is baseflows at selected stream cells. Changes in the baseflows 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 use of the RRCA Groundwater Model to determine the computed beneficial use of groundwater of each State was the result of extensive discussion and evaluation of various alternatives by the groundwater committee during the model development in 2002 and 2003. The groundwater committee was fully aware of the non-linear behavior of the aquifer system when the model was developed in 2002-2003 and agreed that the above described procedure to determine the computed beneficial consumptive use of groundwater of each State was the most reasonable and fair approach to estimate the depletions to streamflows due to each State's groundwater pumping.

Opinions

The following are my opinions and the basis for my opinions.

Opinion 1: The groundwater aquifer underlying the Republican River Basin responds in a non-linear manner to groundwater pumping and aquifer recharge.

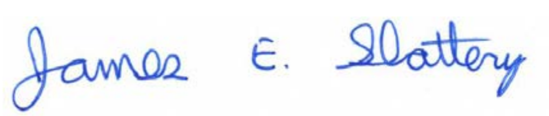
Basis for Opinion: As outlined in the previous sections of this report, there are various factors that result in the nonlinearity of the aquifer response to stresses as simulated by the RRCA groundwater model. These factors include situations where the streams become disconnected from the aquifer and the non-linear relationship between phreatophyte consumptive use and groundwater levels.

Opinion 2: The manner in which the RRCA accounting procedures apply the RRCA groundwater model is a reasonable application of the groundwater model that accounts for the nonlinearities of the system.

Basis for Opinion: The nonlinearity of the groundwater model results must be considered when using the model to determine the computed beneficial consumptive use of groundwater for each State to avoid double counting stream depletions from groundwater pumping and to fairly determine the computed beneficial use of groundwater of each State. The procedure using the groundwater model to determine the computed beneficial consumptive use for the purposes of each State as set forth in the RRCA Accounting Procedures was carefully considered by the Modeling Committee to account for the nonlinearity of the groundwater model results and is a reasonable procedure to address the nonlinearity issues.

Summary

This report summarizes my opinions and the basis for my opinions prepared on behalf of the State of Colorado. In developing these opinions I relied upon my experience as a member of the Modeling Committee who originally developed the groundwater model in 2002-2003 and the Final Settlement Stipulation including Appendices A-M.



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