Middle Arkansas River Subbasin: Second Opinion Water Budget Analysis

Prepared by:

Keller-Bliesner Engineering, LLC
78 East Center Street
Logan, UT 84321

Prepared for:

Water PACK
306-A North Main
St. John, KS 67576

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Introduction

The Kansas Department of Agriculture Division of Water Resources (Division) conducted a water budget analysis of the Middle Arkansas River Subbasin (Subbasin). This analysis was to assist the Middle Arkansas working group with the development of long-term management strategies to stabilize groundwater levels within the Subbasin and maintain baseflow of the Arkansas River. The Division has released draft water budgets, the most recent of which is dated November 12, 2004 and indicates groundwater outflows from the Middle Arkansas Subbasin exceed inflows by approximately 41,000 AF/y.

Water PACK, a member of the Middle Arkansas working group, retained the technical services of Keller-Bliesner Engineering (K-B) to conduct a second opinion groundwater budget analysis of the Subbasin. This report documents this second opinion study.

Methodology and Analysis

K-B conducted this second opinion groundwater budget analysis for the same Subbasin area (see Figure 1) and 13-year study period, 1988-2000 used by the Division. This was done to be consistent and directly comparable with the Division's analysis. No effort was made to evaluate the appropriateness[1] of the Subbasin boundaries or the representativeness of the 13-year study period. Use here of these boundaries and study period is not intended as an endorsement of either.

K-B's water budget analysis is intended to be an independent study rather than a critique of the Division's analysis. However, for expedience and to maximize the potential for acceptance, many of the procedures, assumptions, and basic data used in the Division's analysis were also used in K-B's study when and where K-B believed they were valid. Validation required review of the Division's latest draft water budget and in so doing K-B found what it believes to be some computational discrepancies and two significant conceptual errors in the Division's analysis. These apparent discrepancies and errors are discussed below.

[1] The hydrologic boundary of a basin in a water budget should be well defined. That is, all significant surface and groundwater flows into and out of the basin should be accurately measured or estimated where they cross the basin boundary. This suggests that basin boundaries should be coincidental with stream gaging points, watershed boundaries, and, to the degree possible, aquifer boundaries. Furthermore, to the extent that basins or subbasins are targets of specific management strategies and goals, boundaries should be drawn which are consistent with these strategies and take into consideration the hydrologic link among adjoining basins.

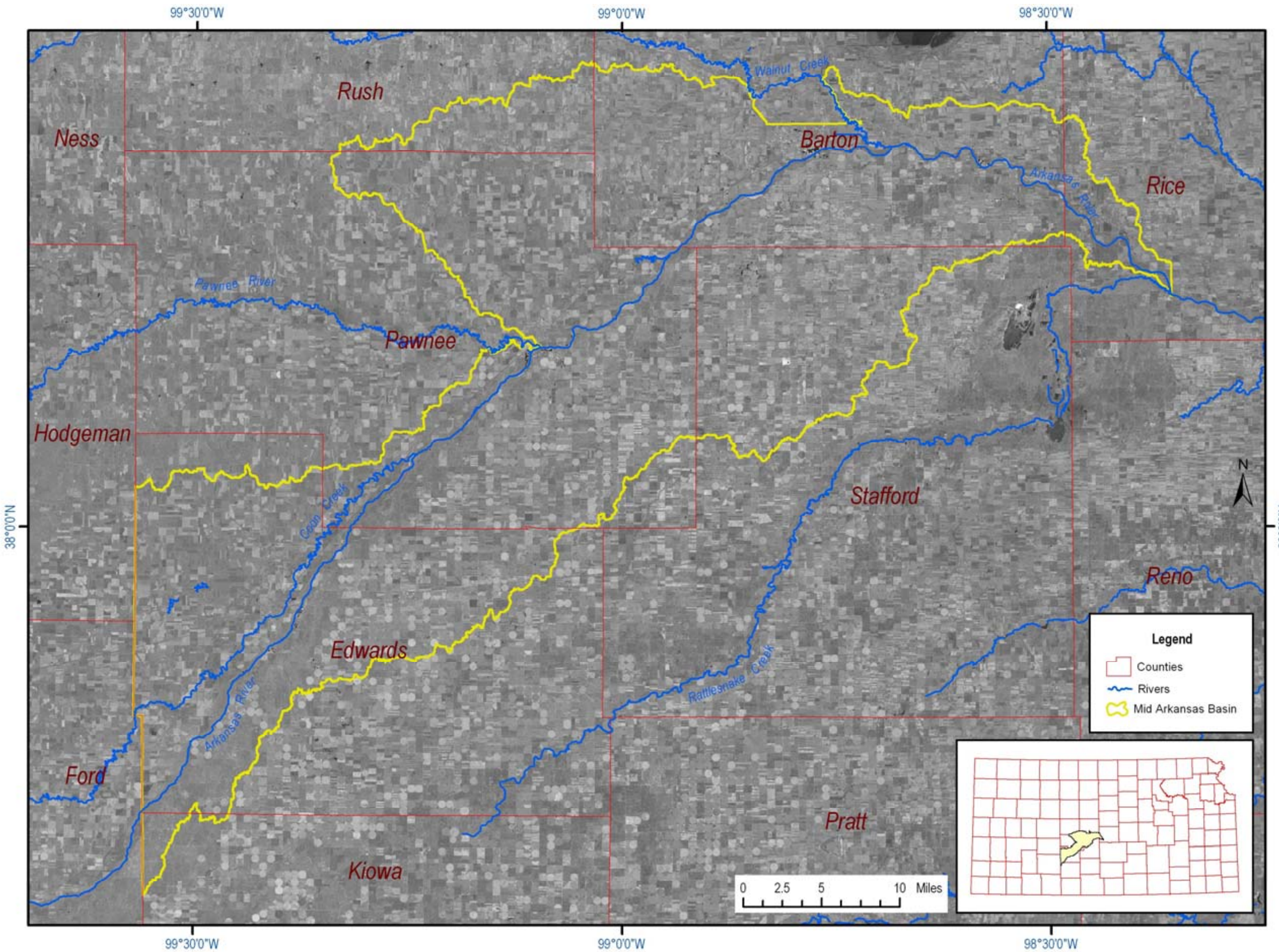

Figure 1. Middle Arkansas River Subbasin (background is panchromatic Landsat 7 satellite image)

Water Budget Formulation

A water budget is an accounting of the inflows and outflows of a hydrologic system such that the sum of inflows less outflows equals the change in storage.

$$\sum Inflows - \sum Outflows = \Delta Storage \qquad \textbf{Eq. 1}$$

The sign on the change in storage term, $\Delta Storage$, is negative when storage decreases due to outflows exceeding inflows and positive when storage increases as a result of inflows exceeding outflows. This is where K-B believes a conceptual error exists in the Division's water budget[2].

A water budget always has to balance. If a water budget does not balance it is a sign of errors in the measured and estimated values used in the analysis, and not an indication of overuse of the resource[3]. There is always some error in a water budget due to measurement errors, errors in estimated flows, spatial and temporal variability, and unaccounted flows. Thus there is always a degree of uncertainty, the magnitude of which is the confidence or lack there of in the budget. Accordingly, it is important to track the confidence interval associated with each water budget item so that in the end the validity of the budget analysis can be assessed. When a high degree of uncertainty exists, the budget variables contributing the most uncertainty can be targeted for improved accuracy with more detailed data collection and modeling. Optionally, the water budget can be expressed to close on the variable causing the most uncertainty. In other words, the water budget can be used to estimate the problem variable, provided reasonably accurate measurements and estimates can be made for the other significant components of the budget.

Groundwater budgets typically have relatively high degrees of uncertainty. This is due to the very nature of groundwater being below the ground surface where observations of its state and characteristics are confined to rather sparse measurement. Furthermore, flows into a groundwater system, particularly recharge from precipitation, are subject to a high degree of spatial and temporal variability.

Usually the most difficult hydrologic variable to accurately measure or estimate is groundwater recharge from precipitation. This is due to spatial variability of precipitation, spatial variability of infiltration characteristics (which change with land use and tillage practices and thus with time), temporal distribution of precipitation events and intensities, spatial and temporal variability of antecedent soil moisture, etc. Thus recharge from precipitation should generally be

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[2] The Division equated total outflow to total inflow **plus** change in storage, rather than **minus** change in storage. (See the equation on page one and Table 9 on page eleven of the Division's November 12, 2004 draft water budget analysis report.) Since, over the course of the 13-year study period, groundwater storage declined the change in storage is negative. Thus the sum of inflows minus negative change in storage should be equivalent to adding the absolute value of the change in storage. In the Division's budget the change in storage is subtracted from the inflows resulting in a double counting for the effect of declining groundwater levels.

[3] This is where K-B believes the second conceptual error exists in the Division's analysis. The Division associates imbalance in its water budget with overuse of the water resource rather than with errors inherent in its analysis.

a closure term in a groundwater budget analysis. Hence for K-B's study Eq. 1 was reformulated to close on average recharge from precipitation, the major component of groundwater inflow.

$$\sum Outflows + \Delta Storage - \sum Inflows\ (excluding\ Recharge) = Recharge \qquad \textbf{Eq. 2}$$

Groundwater outflows include: pumped diversions, baseflow discharge, phreatophyte consumption, and subsurface outflow. Groundwater inflows other than recharge from precipitation include: subsurface inflow, recharge from surface stream flows, and return flows from irrigation and uses. These inflows and outflows, the change in storage, and the resulting estimated recharge from precipitation are discussed and evaluated next for the Middle Arkansas River Subbasin groundwater system.

Pumped Groundwater Diversions

Average annual groundwater diversions for 1988 through 2000 were extracted from a Division spreadsheet[4] of Middle Arkansas River Subbasin points of diversions. The results are listed by use type (irrigation, industrial, municipal, recreation, stock water) in Table 1 and closely match the values used in the Division's 11/12/2004 draft water budget. Since nearly all of the water pumped is metered, we have a relatively high degree of confidence (95% confidence interval of ±10%) in the reported groundwater diversions.

Surface water diversions are not included in this groundwater budget analysis. This is consistent with the Division's approach. Our reason for excluding surface diversions from the analysis is that 92% of the surface diversion was by the Kansas Department of Wildlife and Parks, approximately 8 miles upstream of Great Bend on the Arkansas River, in close proximity to the riparian zone of the river where it would be reflected in the phreatophyte use calculation. Furthermore, it is unknown what portion of the diversion was from runoff, which does not figure into the groundwater budget, and what portion was from baseflow.

Table 1. Mean (1988-2000) Annual Groundwater Diversions and Recharge

Water Use	Diversion AF	Return Flow %	Recharge AF
Irrigation	145,197	10.6%	15,449
Industrial	1,750	50%	875
Municipal	4,267	25%	1,067
Recreation	451	50%	225
Stock Water	1,257	0%	0
Total	**152,922**		**17,616**

[4] *Middle_Arkansas_Points_of_Diversion revised by DLZ.xls* as provided by GMD#5 via email 1/26/2005. The spreadsheet is based on data extracted from the Division's Water Rights Information System (WRIS). Mean annual water use was extracted from spreadsheet column CK, "Avg WU 88 to 00."

Return Flows

For the Middle Arkansas River Subbasin the Division assumed groundwater recharge from irrigation return flows to be 5% of applied water for center pivots and 15% for flood irrigation. The groundwater irrigation recharge fractions submitted by the State of Kansas and adopted for the Republican River Basin (McKusick, 2003) are nearly double (see Table 2) those used by the Division.

The Division's values for the Subbasin appear low. Since they were attributed to KSU Department of Biological and Agricultural Engineering K-B contacted faculty at KSU for references to the associated studies. The engineering faculty contacted were not aware of any specific studies on irrigation return flows. However, they agreed 15% return flow to groundwater for flood irrigation was low and thought a better value would be 35%. For center pivot irrigation they felt 5% return flow to groundwater was a reasonable estimate when deficit irrigation is common (Rogers, 2004).

K-B decided to use an irrigation return flow to groundwater of 30% for surface irrigation and to base the return flow for center pivots on the extent of deficit irrigation in the Subbasin during the 13-year study period. Deficit irrigation occurs when the applied water is less than the net irrigation requirement divided by the irrigation efficiency. Using 2001 growing season data from the Division's spreadsheet (Zook, 2005), the computed mean center pivot gross depth of application on corn in Edwards County was 17.3 in[5]. Assuming an average center pivot application efficiency of between 85% and 90%, the computed net depth of application is 15.1 in. This is equal to the dry year (80% assured rainfall) NIR for corn in Edwards County (Rogers,

Table 2. Irrigation System Efficiencies, Spray Loss and runoff, and Deep Percolation Assumed by the State of Kansas for the Republican River Basin (McKusick, 2003)

System	Application Efficiency	Spray Loss Or Runoff	Deep Percolation
Flood	65%	8%	30%
Typical center pivot	85%	6%	9%
High efficiency center pivot	90%	3%	7%
Other sprinkler systems	75%	6%	19%

[5] There appear to be some discrepancies in some of the reported irrigated acreages, crop codes, and water use in the spreadsheet as computed gross application depths ranged from a low of 1.7 in to a high of 30.8 in. Only computed gross application values greater than 13.0 in were used to obtain the Edwards County average center pivot gross application rate of 17.3 in for corn in 2001.

2004). Thus it appears that on average corn, at least in the Edwards County portion of the Subbasin, is not deficit irrigated. Accordingly, K-B assumed a return flow to groundwater for center pivot irrigation of 8%, the Table 2 average for typical and high efficiency center pivots[6].

From the Division's spreadsheet (Zook, 2005) K-B calculated 12% of the groundwater irrigation diversion was for flood and 88% for center pivot[7]. Using this irrigation method split and irrigation returns to groundwater of 30% for flood and 8% for center pivots, results in a calculated average 10.6% of the groundwater diversion for irrigation returning to groundwater. See Table 1.

The Division did not include return flows from industrial, municipal, recreation, and stock water uses in its water budget. K-B assumed no return flow for stock water, 25% for municipal, and 50% for recreation uses[8]. Approximately one third of industrial groundwater use was assumed to be evaporation from sand and gravel pits. The remainder of industrial use was assumed to be largely non-consumptive with 75% return flow. This results in a weighted average return flow for industrial groundwater use of 50%.

Confidence in the groundwater return flow volumes is low at ±50% of the computed value for irrigation and ±100% of the return flow estimate for the non-irrigation uses. This results in a water volume weighted confidence interval of ±45%.

Baseflow

Baseflow is that portion of stream flow sustained by groundwater discharge. It is estimated by separating gaged stream flow hydrographs into baseflow and runoff components. K-B used a recursive digital filter[9] (Eckhardt, 2004) to obtain the baseflow estimates in Table 3.

[6] It should be noted that part of irrigation inefficiency is due to distribution uniformity, which results in variability in applied depth throughout the field. Even in a deficit irrigated field it is possible for some portions to receive excess applied water that results in deep percolation. Scheduling errors can also result in deep percolation on a seasonally under irrigated field.

[7] The irrigation system type codes in the spreadsheet only account for 85% of the average groundwater irrigation use. K-B assumed that the missing 15% would have a similar distribution of irrigation system types. The codes include "flood", "center pivot sprinkler", "center pivot", "sprinkler other than center pivot", and "other". Since K-B did not know the difference between the two center pivot types or what constituted the "other" type, the two pivot types were lumped together and the "other" type ignored.

[8] K-B assumed 75% of municipal water use is for outdoor watering and is consumptively used. The majority of the recreation uses of groundwater appear to be for gun clubs and fish ponds where it was assumed water would be lost equally to both seepage and evaporation.

[9] For the Arkansas River at Kinsley and Great Bend a maximum value of the long-term ratio of baseflow to total stream flow, BFI_{max}, of 0.80 (perennial stream with porous aquifers) was used and for the Pawnee River at Rozel a value of 0.50 (ephemeral streams with porous aquifers) was used.

Table 3. Average (1988-2000) Annual Flow and Estimated Runoff and Baseflow

Gaging Station	Flow	Runoff	Baseflow
Kinsley	59,563	15,567	43,996
Rozel	26,853	20,701	6,152
Great Bend	119,058	40,359	78,702
Net Baseflow Discharge			**28,555**

The estimated 1988-2000 annual average baseflow for the Arkansas River at Kinsley is very close to the Division's estimate. However, estimates for the Pawnee River at Rozel and the Arkansas River at Great Bend are considerably (50% and 20% respectively) higher than the Division's estimates. These differences are attributed to the somewhat subjective nature of hydrograph separation and the use of different hydrograph separation methods (digital filter versus local minimum).

Net baseflow discharge is the difference between baseflow leaving the Subbasin less baseflow entering. K-B used the sum of the baseflow estimates for the Arkansas River at Kinsley and the Pawnee River at Rozel for base inflow and the Arkansas River at Great Bend for base outflow. Confidence in the net baseflow discharge is relatively low at ±30%.

Stream Runoff Inflow

Some of the stream flow above baseflow (runoff) entering the Subbasin contributes to groundwater recharge. To estimate the volume of this recharge the runoff portion[10] of the daily stream flow hydrograph for the Arkansas River at Kinsley lagged by two days was added to the runoff component of the Pawnee River at Rozel lagged by one day[11]. The resulting sum of these lagged runoffs was then compared to the estimated runoff at Great Bend. Whenever the amount of the lagged Kinsley plus Rozel runoffs was greater than the estimated runoff at Great Bend, the excess was taken as groundwater recharge. Confidence in the resulting recharge from stream runoff inflow is the same as that for net baseflow discharge, ±30%.

Phreatophyte Consumption

The Division's estimate of 12,923 AF/y for the phreatophyte consumption was used in for this second opinion water budget analysis. Due to the limited information on phreatophyte consumption in the Subbasin, confidence in this assumed value is relatively low at ±30%.

Groundwater Inflow and Outflow

Groundwater inflow from the west and outflow to the east was estimated using the same hydraulic parameters as the Division; however, the resulting computed flows are different than the Division's (see Table 4). No effort was made to validate the hydraulic parameters as they appear reasonable and the net result of any changes would be relatively small. Confidence in the groundwater inflow and outflow estimates is relatively low at ±30%.

[10] The runoff component of stream flow is the gaged stream flow minus the estimated baseflow.

[11] The two-day and one-day lags were determined by autocorrelation of the flows at Kinsley and Rozel with the flow at Great Bend.

Table 4. Hydraulic Parameters and Resulting Estimated Mean Annual Groundwater Inflow and Outflow from the Subbasin

Groundwater Parameter	Inflow From West	Outflow to East
Hydraulic conductivity, K (ft/day	85	85
Groundwater gradient, i (ft/ft	0.0028	0.0025
Saturated thickness, b (ft)	46	39
Cross section width, w (ft)	134,376	37,646
Estimated flow (AF/y)	**12,336**	**6,616**

Change in Groundwater Storage

The Division used three-year rolling averages of winter water level measurements from 61 wells to estimate the annual change in water level throughout the Subbasin. K-B believes numeric averaging of water level measurements cannot adequately capture the spatial change in water levels occurring within the Subbasin unless the wells are uniformly distributed.

The Division estimated a basin average net groundwater level decline of 0.52 feet from 1989 to 2001. Using a specific yield of 0.15 and Subbasin area of 781,455 acres this results in an estimated net annual change in storage of -4,670 AF/y[12].

K-B used ordinary Kriging with parameters[13] reported by Olea and Davis (2003) for water level difference mapping of the High Plains Aquifer in Kansas to grid the difference between the minimum January 1988 and January 2001 water level measurements from 197 wells[14] in the Subbasin vicinity (56 were within the Subbasin). The resulting map of water level changes for 1988 to 2001 is presented in Figure 2. The changes range from a maximum decline of 7.5 ft in central Edwards County to a gain of 3.9 ft in Barton County with a Subbasin average decline over the study period of 1.21 ft. This average decline translates to a Subbasin average annual change in storage of -10,910 AF/y. This represents the Subbasin mean groundwater overdraft.

The standard error[15] for the gridded change in water levels was 1.11 ft. There appears to be a slight bias towards underestimating the water level decline. The 95% confidence interval for the change in water levels was estimated as two times the standard error divided by half the predicted value range (-7.5 to 3.9 ft) or ±39%. Assuming a 95% confidence interval of ±30% for

[12] This does not match the value reported and used in the Division's 11/12/2004 draft water budget. This discrepancy is presumably due to a computational error in the Division's analysis.

[13] The best-fit model to the omnidirectional semivariogram of differences in depth to water in the High Plains aquifer over the 5-year period 1998-2003, based on 1084 observations was spherical with a nugget of 9.6 ft2, range of 33 km, and a value of 16.9 ft2 for the sill minus the nugget. K-B used a 90 m^2 grid with 6 observations points per interpreted cell.

[14] The wells used were from a set reviewed by the Division and GMD #5 to correct location errors and use the appropriate well from nested sets. (Email from GMD #5 dated 5/5/2005.)

[15] Computed as sum of errors (observed – predicted) squared divided by the number of observation points (wells).

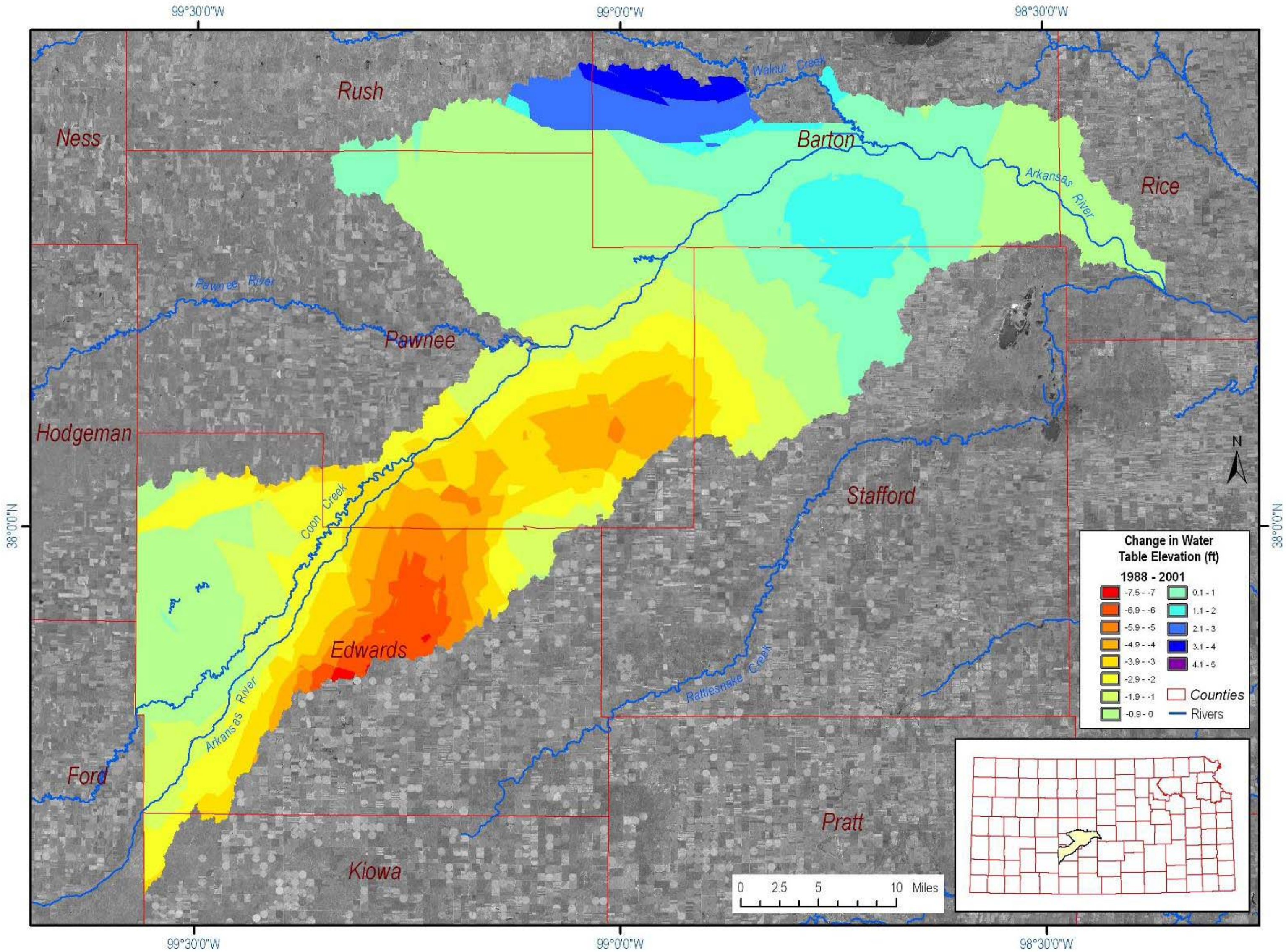

Figure 2. Change in Water Level Elevations from January 1988 to January 2001 in the Middle Arkansas River Subasin

the mean specific yield of the aquifer results in a combined 95% confidence interval of ±49% for the estimated change in storage volume. In other words, we are 95% confident that the mean annual groundwater decline (overdraft) is between 5,500 AF/y and 16,300 AF/y.

Results

The components of the groundwater budget are compiled and summarized in Table 5. The table is organized to close the water balance on the average annual recharge from precipitation following Eq. 2. The table tracks the 95% confidence interval for each component and lists the associated lower and upper bounds of the resulting range.

The average recharge estimated for the Subbasin is 146,242 AF/y with a 95% confidence interval of ±14%. This demonstrates the value of tracking the confidence in the water budget components and demonstrates that even when there is a low degree of confidence in some components of the balance, if their relative magnitude is small the computed confidence in the water balance closure term (recharge in this case) can still be relatively high.

The estimated recharge volume of 145,881 AF/y over a Subbasin area of 781,446 acres is equivalent to an average recharge rate of 2.24 in/y. This is identical to the working group's estimate of 2.25 in/y. The computed 95% confidence of ±14% gives a range for the average recharge rate of 1.92 in/y to 2.56 in/y, which captures the rate originally assumed by the Division.

Conclusion and Recommendations

A water budget can be a useful tool to understand water flow paths in a basin and develop management strategies for sustainable use of the water resource. To be effective the hydrologic boundaries of the basin being analyzed must be well defined and, with the exception of the closure term, the water inflows and outflows must be measured or estimated with confidence.

Table 5. Second Opinion Groundwater Budget for the Middle Arkansas River Subbasin including 95% Confidence Interval

Groundwater Budget Component	Volume AF	95% CI	Lower Bound	Upper Bound
Outflows				
Groundwater Diversions	152,922	10%	137,600	168,200
Net Baseflow Discharge	28,555	30%	20,000	37,100
Phreatophyte Consumption	12,923	30%	9,000	16,800
Groundwater Outflow	2,616	30%	1,800	3,400
Change in Storage	(10,910)	49%	(5,500)	(16,300)
Inflows				
Return Flows to Groundwater	17,616	45%	9,800	25,500
Groundwater Inflow	12,336	30%	8,600	16,000
Stream Runoff Inflow	10,272	30%	7,200	13,400
Average Recharge	145,881	14%	125,000	166,800

There are always uncertainties in data and computation techniques for a water balance, particularly for groundwater. Therefore, it is important to assign and track the confidence intervals throughout the budget. In the case of the Middle Arkansas River Subbasin, the groundwater budget components with the lowest degree of confidence are relatively small in magnitude and consequently do not significantly weaken confidence in the overall budget. However, there are some steps that could be taken to strengthen the water budget and enhance its usefulness as a management tool.

- A standalone water budget for a subbasin such as the Middle Arkansas River does not account for effects outside the subbasin boundaries. To some unknown degree water development upstream and up-gradient of the subbasin reduces surface and groundwater inflows to the subbasin. To evaluate upstream effects, a water budget analysis should be conducted for the entire Arkansas River Basin from the Colorado state line to Great Bend, with the Middle Arkansas River Subbasin and other areas as subbasins. The outflows from one subbasin would be inflows to another, thereby providing a hydrologic link and a cross check of the overall water budget.

- Confidence in the change in groundwater levels should be improved since this is the essential indicator of the degree of overdraft. Confidence could be improved by refining the geostatistical gridding (Kriging), refining the water level measurements used, and increasing the number of observation points used.

- While the 13-year study period is representative of hydro-climatic conditions in the vicinity of the Subbasin, a water budget analysis such as this, which averages across the study period, cannot be used to evaluate the individual effects of wet and dry periods. If the water budget analysis was conducted on an annual or seasonal (winter and summer) time-step, integrated trends in water use, stream flow, groundwater levels, and precipitation could be evaluated.

Changes in groundwater gradient with time from Dodge City to Kinsley should also be evaluated. This gradient appears to have flattened since predevelopment in the early 1970s. This is an indication that water development upstream and up-gradient of the Middle Arkansas River Subbasin may have affected groundwater and baseflow entering the Subbasin. Thus, it is important to evaluate upstream effects and the recommended trend analysis would help.

Regarding the estimated annual average overdraft in the Subbasin of 10,550 AF/y, the area of overdraft is concentrated in the upstream portion of the basin. It should be understood that reducing water use in the downstream portion of the basin will have little impact on reducing the overdraft. This points out a limitation of the water budget analysis, which implies a reduction of use anywhere in the basin would help stabilize water levels.

It should also be pointed out that to recover water levels in areas of decline will require reductions in pumping beyond the estimated overdraft. Furthermore, if minimum desired stream flows are to be realized through recovery of water levels, groundwater discharges to baseflow will increase. This will require even greater reductions in pumping to recover and achieve stable water levels.

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