Monitoring Changes in Groundwater Resources Due to Increased Surface Water Delivery Efficiencies in the Lower Republican River Basin

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ABSTRACT

Groundwater and surface water, including such engineered surface water bodies as irrigation canals and drainage ditches, are connected. As such, changes to the management of these surface water bodies will affect interconnected groundwater systems as well. In the Lower Republican River Basin in Kansas, United States, a regional irrigation district has converted several irrigation canals to buried pipe to reduce water lost to evapotranspiration and groundwater recharge, increasing the delivery efficiency of its system. The objective of this work was to investigate the change in local groundwater levels due to this conversion. Seven existing wells in the vicinity of converted or soon-to-be converted irrigation canals were equipped with pressure transducers, and hourly water-level measurements were collected over several years. Average water levels decreased in all wells post-conversion compared to measurements taken between 1970 and 2001. The water levels did not decrease equally, and in several wells, the water-level variance also changed from pre- to post-conversion. It is hypothesized that the observed changes are controlled by many factors, including those related to canal conversion (proximity to the converted canal and time since canal conversion), proximity to other surface water features such as the main stem of the canal and reservoir, and subsurface characteristics that influence the rate of infiltration from precipitation events. This research highlights the interconnectedness of surface and subsurface water resources and how water management decisions need to consider how these interactions may change to support sustainable water use.

INTRODUCTION

Groundwater and surface water are a single resource, connected by the natural and anthropogenic fluxes between them. Changes to surface waters affect groundwater, and vice versa. As such, surface water management decisions will affect groundwater, and vice versa (e.g., Winter et al., 1998; Fleckenstein et al., 2010; Conant et al., 2019; Lewandowski et al., 2020). For example, the construction of a reservoir can increase local groundwater levels due to increased infiltration and recharge (e.g., Zhang et al., 2012; Zhang et al., 2022), and groundwater pumping from aquifers can decrease baseflow to connected surface water systems (e.g., Barlow and Leake, 2012; Zipper et al., 2022). Water management decisions designed to prevent

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or minimize both flooding and water shortages as well as to ensure stable stream and riparian ecosystems alter the spatial and temporal distribution of water resources (Arnell, 1999; Rogers and Hall, 2003; Cosgrove and Loucks, 2015). Although historic water management policies considered only the part of the water system directly affected (e.g., impact of reservoirs on surface water systems), integrated water management plans now incorporate the entire terrestrial water system (i.e., groundwater and surface water) to better manage resources. For example, the compact governing the distribution of surface water to Colorado, Nebraska, and Kansas in the Republican River basin was amended in the early 2000s to account for depletion of the stream due to groundwater pumping in the adjacent alluvial aquifer (*State of Kansas v. State of Nebraska and State of Colorado*, 2002). Accounting for the full impact of water management decisions, including existing and new operations, is necessary to ensure water availability into the future.

Increased water demand is projected to occur due to population growth; concurrently, climate change is altering the hydrological cycle, affecting the timing and quantity of water availability around the world (Stewart et al., 2005; Vörösmarty et al., 2013a, 2013b). Changes to water management are required to ensure water availability now and into the future, and changes to one part of the terrestrial water system must not compromise the sustainability of other components. Research has demonstrated that the development and operation of dams and reservoirs have significant impacts on the local and downstream hydrology (Graf, 1999, 2006; Magilligan and Nislow, 2005). In addition, changes to water distribution systems, such as channelization, directly affect downstream hydrology (Simon and Rinaldi, 2006). The objective of this work is to monitor and assess the effects of modified water distribution, specifically the conversion from open canals to buried pipes, on local groundwater resources. This work demonstrates the importance of considering and monitoring the cascading effects of water management decisions throughout the terrestrial water cycle.

SITE DESCRIPTION

The Republican River basin encompasses approximately 24,540 square miles (63,500 km^2) of eastern Colorado, southern Nebraska, and northern Kansas that drain to the Republican River above the U.S. Geological Survey (USGS) gaging station at Clay Center, Kansas (fig. 1). The Republican River basin contains more than 2.7 million acres of irrigated agriculture served by a combination of surface and groundwater supplies. Of these, 1.6 million acres are in Nebraska, 435,000 acres are in Kansas, and 550,000 acres are in Colorado. In addition to irrigated agriculture, the water resources serve municipalities, industry, recreation, and wildlife.

The entire basin includes seven U.S. Bureau of Reclamation (USBR) storage reservoirs, one U.S. Army Corps of Engineers reservoir (Harlan County Reservoir), and several irrigation canal districts that supply water to agriculture. Much of the upper basin is underlain by the High Plains aquifer, which is used extensively for irrigation purposes. Alluvial aquifers are also present along the Republican River itself, and these aquifers are used for irrigation throughout the basin. Because of long-term imbalances between water supply and demand, Colorado, Nebraska, and Kansas ratified an interstate compact in 1943 to ensure equitable distribution of water within the basin. The compact also dictates that each state must efficiently manage its resources and should continuously try to improve efficiency measures to address current and future water supply issues. This study focuses on the Lower Republican River Basin (LRRB) region around Lovewell Reservoir, operated by USBR (fig. 1), which includes a portion of the Kansas Bostwick Irrigation District (KBID). KBID provides water from Harlan County and Lovewell reservoirs to irrigators between June and September of each year through a series of canals. The LRRB in Kansas is not underlain by the High Plains aquifer; subsurface resources are derived almost entirely from the alluvial aquifer along the Republican River channel. The dominant use of water in the study region is irrigation, representing more than 95% of water use overall and 75% of groundwater use (KGS, 2023a). Municipal water

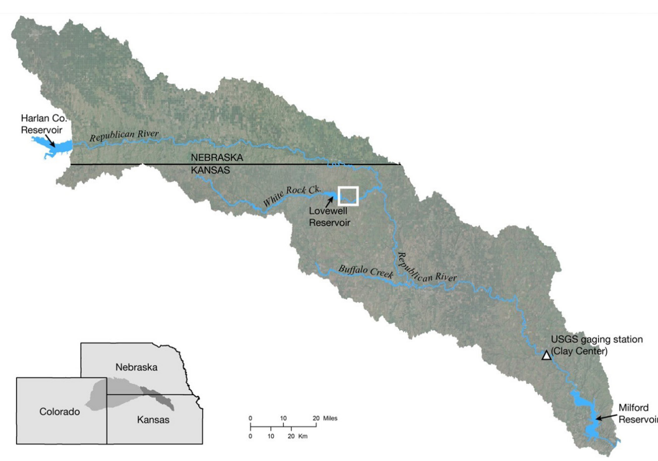

Figure 1. Map of the Lower Republican River Basin. Inset depicts the entire Republican River Basin. White box depicts study area (see fig. 2).

supply is the other significant groundwater use in the region, with lesser amounts used for industry, stockwater, and recreation (KGS, 2023a). KBID used restitution funds from a U.S. Supreme Court decision in 2016 to improve its water delivery efficiency by replacing some open irrigation canals with buried pipes to reduce water lost to evapotranspiration and groundwater recharge.

The LRRB lies within the High Plains and Plains Border sections of the Great Plains physiographic province. Topographically, the region comprises a series of rolling hills formed by the erosion of alternating beds of Cretaceous limestone, chalk, shale, and sandstone, which trend progressively younger from east to west. The bedrock uplands are mantled by 1–5 m of Quaternary loess. Bedrock in the study area east of Lovewell Reservoir mostly comprises the Carlile Shale. Basal deposits of alluvial sand and gravel found in river valleys are the primary sources of groundwater in this region (Sophocleous and Sawin, 1998).

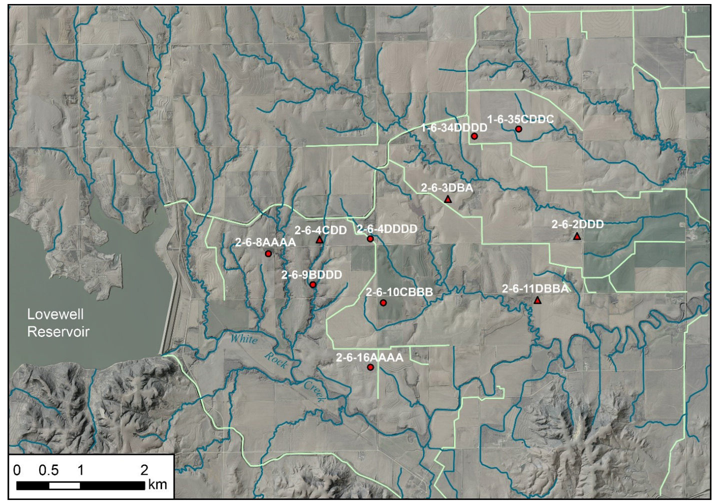

Figure 2. Location of 11 USBR wells in the vicinity of the project. Red circles denote wells located and equipped with pressure transducers for this work. Red triangles denote recorded locations of wells that were not found. Green lines indicate irrigation canals operated by KBID.

DATA

The USBR installed more than 200 monitoring wells in the vicinity of the KBID irrigation canal system in the mid-1950s. Water levels in these wells were monitored until 2001, predominantly by the USGS. KBID archived and stored water-level records on paper. Several of the existing monitoring wells installed by the USBR are in the vicinity of the pipes that were buried in the LRRB. As part of this work, in July 2017 we attempted to find these wells to begin a new monitoring program to quantify the effect on groundwater levels of converting open canals to buried pipes.

Of the 11 USBR wells identified in the vicinity of canal conversion using their Public Land Survey System (PLSS) locations, seven were located in July 2017 (fig. 2), including two that required repairs before use. Two of the wells (1-6-34 and 1-6-35) are in the vicinity of irrigation canals that were converted to buried pipes in 2017–2018, and the remaining five are in the vicinity of irrigation canals that were converted in 2016–2017. In December 2017, these seven wells were equipped with pressure transducers that measure and record groundwater levels and temperature hourly. Measurements were regularly downloaded from the sensors and hand measurements were taken periodically for sensor calibration.

ANALYSIS METHODS

Groundwater levels in the instrumented wells are shallow and fluctuate significantly with factors such as climate, groundwater pumping, and canal operation. To evaluate changes to the groundwater levels due to canal conversion, long-term averages of groundwater levels (1970–2001; historic) were compared to the average of recent groundwater levels collected as part of this work (2017–2021; recent). The year 1970 was selected to start the historic period to ensure that the water levels had stabilized from the construction of Lovewell Reservoir in 1952. Statistical differences between the historic and recent water-level averages were evaluated using both a student's t-test (parametric) and Wilcoxon signed rank test (nonparametric). The variance between the historic and recent water levels was also calculated and evaluated statistically using both an F-test (parametric) and a Levene test (nonparametric).

RESULTS AND DISCUSSION

A comparison of historic and recent water levels indicates water levels declined in all wells (figs. 3, 4; table 1). Furthermore, all average water-level declines were statistically significant (table 1). The change in variance of water levels between historic and recent was mixed, with three wells having no significant change in variance, three having a statistically significant change under both tests, and one with differing results between the parametric and non-parametric tests (table 1).

When the average historic and recent water levels in the wells are plotted in order of distance from the closest converted canal, it appears that some of the factors controlling the change in groundwater levels are proximity to the converted canal and time since the canal was converted (fig. 5). This observation is consistent with foundational hydrogeologic knowledge that the influence of

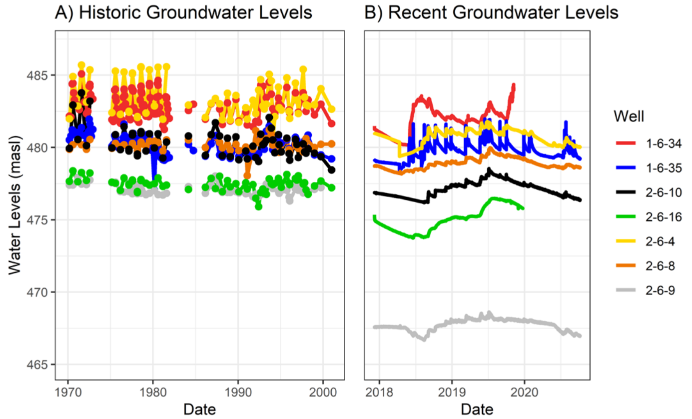

Figure 3. (A) Historic (1970–2021) water levels in the seven monitoring wells measured for this work. Measurements taken at approximately three-month intervals. (B) Recent (2017–2021) water levels in the seven wells measured every hour. Note difference in x-axis scaling between plots.

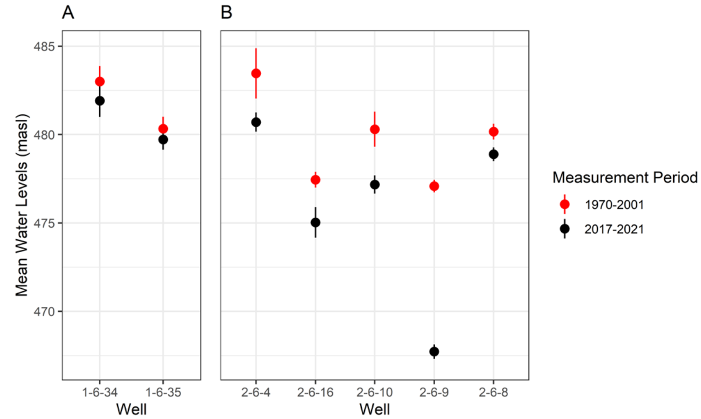

Figure 4. A comparison of mean water-level measurements between 1970–2001 and 2017–2021. Bars indicate standard deviation. Order along x-axis indicates distance from canals, from closest to farthest, grouped by timing of canal conversion: (A) wells near canals converted to underground pipes in 2017–2018 and (b) wells near canals converted in 2016–2017. X-axis distance is relative, in that well 2-6-4 is closest to canals converted first and well 2-6-8 is farthest from canals converted first. These results indicate that the conversion to underground pipes likely has a significant effect on groundwater levels in the monitored wells.

a stressor on the system will be greater closer to the stressor. For example, when groundwater is pumped from a well, it is expected that the groundwater level will decrease more closer to the well (e.g., Theis, 1935). Due to the low number of wells available for this work, the results are not definitive but do indicate that proximity to the converted canal plays a role in the influence the conversion has on groundwater levels. The largest change in water levels is observed in well 2-6-9. In this well, the observed decrease in average water level of 9.36 m is much larger than other wells nearby; wells 2-6-8 and 2-6-10, for example, had average decreases of 1.27 m and 3.12 m, respectively. We suspect that well 2-6-9 is damaged and is no longer in direct contact with the aquifer. This inference is supported by very slow recovery of this well after purging for water quality sampling that is not part of this paper. Whereas other wells recovered within minutes, this well did not fully recover between sampling periods. This leads us to believe that the water-level measurements do not reflect aquifer levels.

Discounting well 2-6-9, the well with the largest decrease in average groundwater levels is 2-6-10 with a 3.12 m decline. This well is located close to a converted canal, specifically the first canal converted to underground pipe. Although it is not the closest well to this canal (both 2-6-16 and 2-6-4 are closer [fig. 2]), local hydrogeologic conditions may have contributed to a larger change. These conditions include variability in subsurface properties, such as hydraulic conductivity, porosity, and specific yield, which would affect how quickly the water table would respond to changes in recharge. In addition, although groundwater and surface water use data for irrigation are available in Kansas, the exact location of irrigation application is often obfuscated by multiple points of diversion and points of use (MardonDoost et al., 2019). Also, volumes and locations of water delivered by irrigation districts, which are widely used in this region, are not publicly reported. Changes in irrigation strategies, volumes, and locations would alter groundwater recharge. Overall, the changes in average groundwater levels of wells 2-6-4, 2-6-10, and 2-6-16 are all quite consistent (fig. 5).

Water levels of each well, grouped by proximity to sections of converted canal, are discussed below. Quantile-quantile plots of both historic (1970–2001) and recent (2017–2021) data indicate that the data are approximately normal (figs. 6–7), although the recent data display a heavy tail, indicating increased occurrence of lower hydraulic head values, which indicate deeper water levels, than expected in a normal distribution (fig. 7). As a result of this divergence from normality, both parametric (t and F) and non-parametric (Wilcoxon and Levene) tests were conducted for each well, comparing the means (t-test and Wilcoxon test) and variances (F-test and Levene test) between the historic and recent water-level measurements (table 1).

Table 1: Mean water levels and variance for the historic (1970–2001) and recent (2017–2021) periods. Ratio of variance is given as historic-to-recent variances. Results from parametric (t and F) and nonparametric (Wilcoxon and Levene) tests indicate the differences between mean water levels (t and Wilcoxon) and water-level variance (F and Levene) between the historic and recent periods. Shaded boxes with bold, italicized values indicate differences are not statistically different (alpha level 0.01).

Well	Average Water Levels (masl)		Water Level Decrease (m)	Variance (m^2)		Ratio of Variance	p-value			
	1970–2001	2017–2021		1970–2001	2017–2021		t-test	Wilcoxon	F-test	Levene
1-6-34	483.00	481.92	1.08	0.765	0.848	0.902	1.04E-07	5.93E-22		
1-6-35	480.33	479.72	0.61	0.460	0.328	1.402	1.71E-03	5.54E-17		
2-6-10	480.30	477.18	3.12	0.989	0.262	3.775	2.20E-16	5.28E-12	8.70E-06	2.20E-16
2-6-16	477.45	475.03	2.42	0.195	0.749	0.260	2.20E-16	5.27E-12	1.05E-05	2.52E-11
2-6-4	483.46	480.71	2.75	2.032	0.293	6.939	3.70E-16	3.78E-12	5.10E-14	2.20E-16
2-6-8	480.16	478.89	1.27	0.198	0.152	1.302	1.44E-14	4.40E-11	1.15E-03	
2-6-9	477.08	467.72	9.36	0.126	0.165	0.764	2.20E-16	3.55E-11		

Wells in the Vicinity of Canals Converted in 2016–2017

Wells 2-6-4, 2-6-8, 2-6-10, and 2-6-16 are in the vicinity of irrigation canals that were converted to buried laterals in 2016–2017, the earliest canal conversions relevant to this study. All of these wells have statistically significant decreases in mean water levels from pre- to post-conversion. As discussed previously, well 2-6-9 is not considered further because it is suspected to no longer be connected to the aquifer.

Wells 2-6-4, 2-6-10, and 2-6-16 are all located within 400 m of the nearest converted canal and had similar decreases in mean water levels (from 2.42 m to 3.12 m). Well 2-6-8 is more than 1.5 km from the nearest converted canal and had a smaller, yet still statistically significant, water-level decrease (1.27 m). This provides evidence that proximity to the converted canals likely influences the response of the water level to the conversion.

Consistent with the small change in water levels in well 2-6-8, the change in variance of the water levels was minimal and not consistently significant between the Levene and F-tests. This suggests that the main drivers of water-level fluctuations may not have changed, meaning the irrigation canals were perhaps not a dominant cause of observed fluctuations in this location. Although wells 2-6-4, 2-6-10, and 2-6-16 had statistically significant changes to the variance of the water levels, these changes (increasing or decreasing variance) were not consistent among the three wells. For example, the variance in water levels for wells 2-6-4 and 2-6-10 decreased significantly. This indicates that the irrigation canals may have caused a significant amount of water-level fluctuations in these

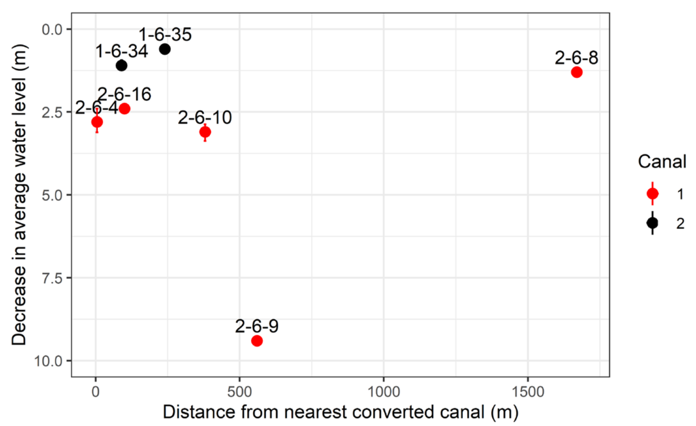

Figure 5. A comparison of the decrease in mean water-level measurements between 1970–2001 and 2017–2021. Bars indicate t-test confidence intervals. Canal 1 was converted prior to Canal 2. Mean water levels decreased more in wells closest to Canal 1 (red) than Canal 2 (black). Well 2-6-9 is included in this figure (decrease greater than 9 m) although it was not considered in the analysis as it is suspected to no longer be connected to the aquifer.

regions. Contrary to this, the variance for well 2-6-16 increased significantly since the canal conversion. The patterns of variance are difficult to compare due to the difference in temporal resolution between pre- and post-conversion water-level measurements. A possible reason for the increase in water-level variability in well 2-6-16 is that recharge from the canals was masking the signal from precipitation and other drivers of water-level change. It is also possible that there has been a change in water use, land use, or both in recent years, causing the water levels to vary significantly from historic levels. Future work should be conducted to better elucidate the reason variance has increased. Collecting data, ideally

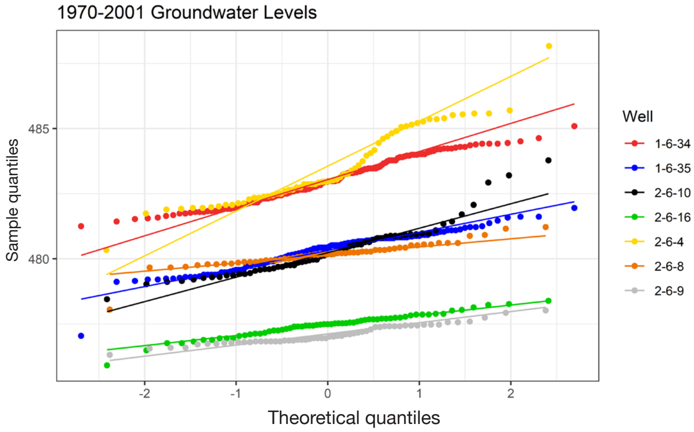

Figure 6. Quantile-quantile plot for water levels measured between 1970 and 2001.

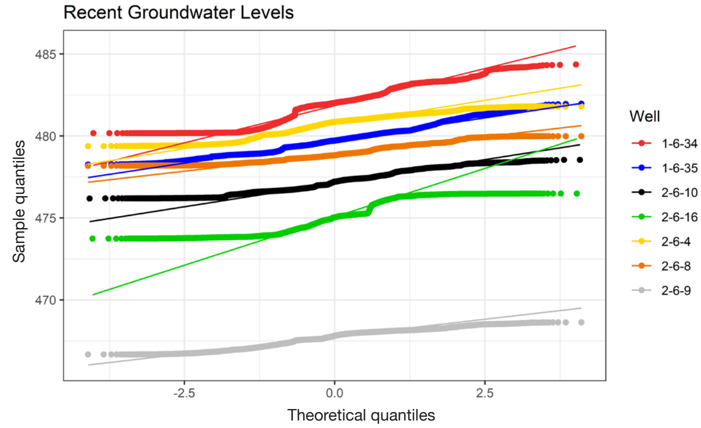

Figure 7. Quantile-quantile plot for water levels measured between 2017 and 2021.

in a location that has yet to undergo canal conversion, to support detailed water balances, quantifying water fluxes from specific sources such as precipitation, irrigation return-flow, and canal infiltration, would be useful in assessing these changes in variance. These water balances could be quantified using a variety of methods, including environmental tracers and hydrologic models.

Wells in the Vicinity of Canals Converted in 2017–2018

Of the wells studied, 1-6-34 and 1-6-35 are in the vicinity of the irrigation canals last converted to buried pipes. Although the pressure transducers were installed prior to the nearest canals being converted, the wells are close enough to other converted canals that would have exerted some influence on them. In these wells, the change in average groundwater levels between the pre- and post-conversion are the smallest at 1.08 m for 1-6-34 and 0.61 m for 1-6-35, although both are statistically significant, with $p < 0.01$ (table 1). Well 1-6-34 is located closer to the canals than 1-6-35, which likely accounts for the greater decline in groundwater level. It is anticipated that the decreases in groundwater levels will continue with time as the hydrogeologic system comes into equilibrium to the new hydrologic conditions.

The variances between pre- and post-conversion water levels for wells 1-6-34 and 1-6-35 are not statistically different ($p > 0.01$; table 1), indicating that what causes water levels to vary in these wells remains the same post-canal conversion as pre-conversion. Patterns of variability are difficult to discern between the two datasets as pre-conversion water levels were not continuously measured; however, fig. 3 indicates a change in seasonal signals between pre- and post-conversion, despite similarities in overall variance.

Relating to Aquifer Recharge

To understand the impact that canal conversions have on groundwater resources, it would be ideal to quantify the change in recharge. Currently, however, adequate data are not available to constrain the recharge estimates. Here, we discuss an approach to estimate change in aquifer recharge and highlight the additional data necessary to make this estimate.

Although drillers' logs indicate the presence of a confining layer in some of the wells used for this study (KGS, 2023b), the quick response to precipitation events indicates that the aquifer is likely responding as an unconfined system. In addition, other research in the Republican River basin has simulated the aquifers in this region as unconfined (Szilágyi, 2014). Further research is needed to better understand the nature of the aquifer in this region, specifically to understand whether it should be treated as a confined or unconfined system. If we assume that the groundwater system is unconfined, we can incorporate estimates of specific yield (Sy), which is the ratio of the volume of water that can drain by gravity to the total volume of the unit being drained, to convert the differences between the historic and recent water-level averages to estimates of changes in local groundwater recharge rates. If the aquifer is assumed to be confined, estimates of specific storage (Ss), which is the volume of water released by one unit volume under one unit decline in hydraulic head, could be used.

If we used a simple water balance approach that assumes that the observed change in water level (Δh) is due only to a change in recharge (ΔR) and that the aquifer is unconfined, expressed as $\Delta R = Sy^*\Delta h$, we could estimate the change in recharge due to canal conversion. In this case, the change in recharge would scale directly with the estimates of specific yield, making it a critical parameter.

Direct estimates of specific yield for this region are not available, and therefore future research should quantify the spatial variability of specific yield in this region.

The simple water balance approach described above has significant drawbacks, in addition to uncertainty associated with specific yield. For example, many other factors affect recharge in this area, including changes in precipitation, reservoir water levels, and local water use. Available data indicate stable water use; however, main stem canal discharge and lateral discharge data are not readily available. In addition, precipitation records indicate that the recent years were, on average, wetter than historic (2017–2021 average annual precipitation = 73.85 cm; 1980–2010 average annual precipitation = 66.5 cm), with most monthly precipitation totals close to or above the 1980–2010 climate norm (NOAA, 2023). This would cause precipitation-based recharge rates to be higher than historic, which means that the estimated change in recharge rates due to canal conversion from a simple water balance may be higher than actual values. Additional information about the spatial and temporal variability of water use and precipitation is necessary to adequately constrain estimates of change in recharge due to canal conversion.

CONCLUSIONS

The conversion of open canals to buried pipes is generally intended to increase the efficiency of water delivery to surface water users. Buried pipes reduce losses due to evaporation, seepage, and operational spills, ensuring that more of the water released is delivered to the end user (KDA, 2023). However, groundwater levels, which have come to a pseudo-equilibrium over the long timeframes that these canals have been in operation, will decline due to the loss of seepage water. In the KBID, water delivery through the canal system began in 1955 (KDA, 2023), so local groundwater levels have had several decades to come into equilibrium with the seepage from these canals. The results of this work indicate that the conversion from open canals to buried laterals does influence groundwater levels in the region. Although the proximity to the converted canal and time since canal conversion appear to have some control over the change in groundwater levels, quantifying their exact contribution is complicated by other factors, such as proximity to other surface water features and subsurface properties, which also control the timing and magnitude of these changes. The time it takes for the groundwater system to come into equilibrium with the new hydrologic conditions is yet unknown, but it is anticipated that water levels will continue to be monitored in several of the groundwater wells to further study this question. Although there were consistent decreases in water levels across all of the wells, changes in the variance of the water levels were not consistent. It is hypothesized that this is because of differences in local conditions, including proximity to other surface water features, such as the main stem of the canal; subsurface characteristics that alter infiltration from precipitation events; and changes in local land use.

It was not possible to quantify the change in recharge from canal conversion at this time because water levels in the wells have not yet equilibrated to the new hydrologic conditions. However, future work could include collecting additional data related to subsurface storage parameters in the region and canal discharge to convert the changes in measured water levels to changes in recharge. Alternatively, the measured water levels could be used to calibrate a hydrologic model of the area to estimate recharge loss.

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