Quantifying the impact of lagged hydrological responses on the effectiveness of groundwater conservation

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Key Points:

- The long-term effectiveness of pumping reduction-based groundwater conservation is dependent on lagged processes

Abstract

Many irrigated agricultural areas seek strategies to prolong the lifespan of their groundwater resources. However, it is unclear how lagged responses, such as reduced groundwater recharge caused by more efficient irrigation, may impact the ultimate effectiveness of these initiatives. Here, we use a variably saturated groundwater model to: 1) analyze aquifer responses to pumping reductions, 2) quantify time lags between reductions and water level responses, and 3) identify the physical controls on lagged responses. We explore a range of plausible model parameters for an area of the High Plains Aquifer (USA) where stakeholder-driven conservation has slowed groundwater depletion. We identify two types of lagged responses that reduce the long-term effectiveness of groundwater conservation. When vertical hydraulic conductivity (K_z) is > 3.5×10^{-3} m d^{-1}, more efficient irrigation reduces groundwater recharge on sub-decadal timescales (recharge-dominated response). By contrast, when K_z is < 3.5×10^{-3} m d^{-1}, changes in recharge are negligible, but pumping reductions alter the lateral flow between the groundwater conservation area and the surrounding regions over decadal timescales (lateral-flow-dominated response). For the modeled area, we found that a pumping reduction of 30% resulted in median usable lifetime extensions of 20 or 25 years, depending on the dominant lagged response mechanism (recharge- vs. lateral-flow-dominated). These estimates are far shorter than estimates made without accounting for the lagged responses. Our results indicate that conservation-based pumping reductions can extend aquifer lifespans, but lagged responses can create a sizable difference between the initial and long-term effectiveness of those conservation measures.

1. Introduction

Irrigation uses the majority (69%) of fresh groundwater withdrawals in the United States (DeSimone et al., 2015; Dieter et al., 2018). In many aquifers supporting irrigated agriculture, heavy pumping has resulted in unsustainable water-level declines, threatening the economy and environment (Aeschbach-Hertig & Gleeson, 2012; Deines et al., 2020; Scanlon et al., 2012). As groundwater is a limited resource, how to mitigate these declines to extend the usable lifetime of heavily stressed aquifers is a pressing question (Bierkens & Wada, 2019; Butler et al., 2020a; Castilla-Rho et al., 2019; Gleeson et al., 2020). In semi-arid environments with little access to surface water, groundwater conservation programs that seek to reduce pumping are one of the only viable options to decrease groundwater declines in the near to moderate term (Butler et al., 2020b; Deines et al., 2019; Hu et al., 2010).

One such program is Kansas' Local Enhanced Management Area (LEMA) program that was recently implemented in several areas of the state (Figure 1). LEMAs are a stakeholder-driven governance approach in which groundwater users (primarily irrigators) and groundwater management districts develop conservation plans that are subsequently approved and enforced by the state regulatory agency (Kansas Statutes Annotated 82a-1041, 2012). The state's first LEMA, referred to as Sheridan-6 (SD-6), was initiated in 2013 in a 256-km^2 area in northwest Kansas with the stated goal of reducing average annual pumping by 20% over a five-year period. During this period, irrigators exceeded their goal, reducing pumping by 31% on average and slowing water table decline rates while maintaining similar economic returns (Deines et al., 2019, 2021; Golden, 2018). This initial success led to an extension of the SD-6 LEMA for an additional five years, the 2018 formation of a much larger LEMA that encompasses most of the northwest Kansas portion of the High Plains aquifer (Groundwater Management District 4), and an additional 2021-initiated LEMA in west-central Kansas (Kansas Department of Agriculture, 2013, 2018, 2021) (Figure 1).

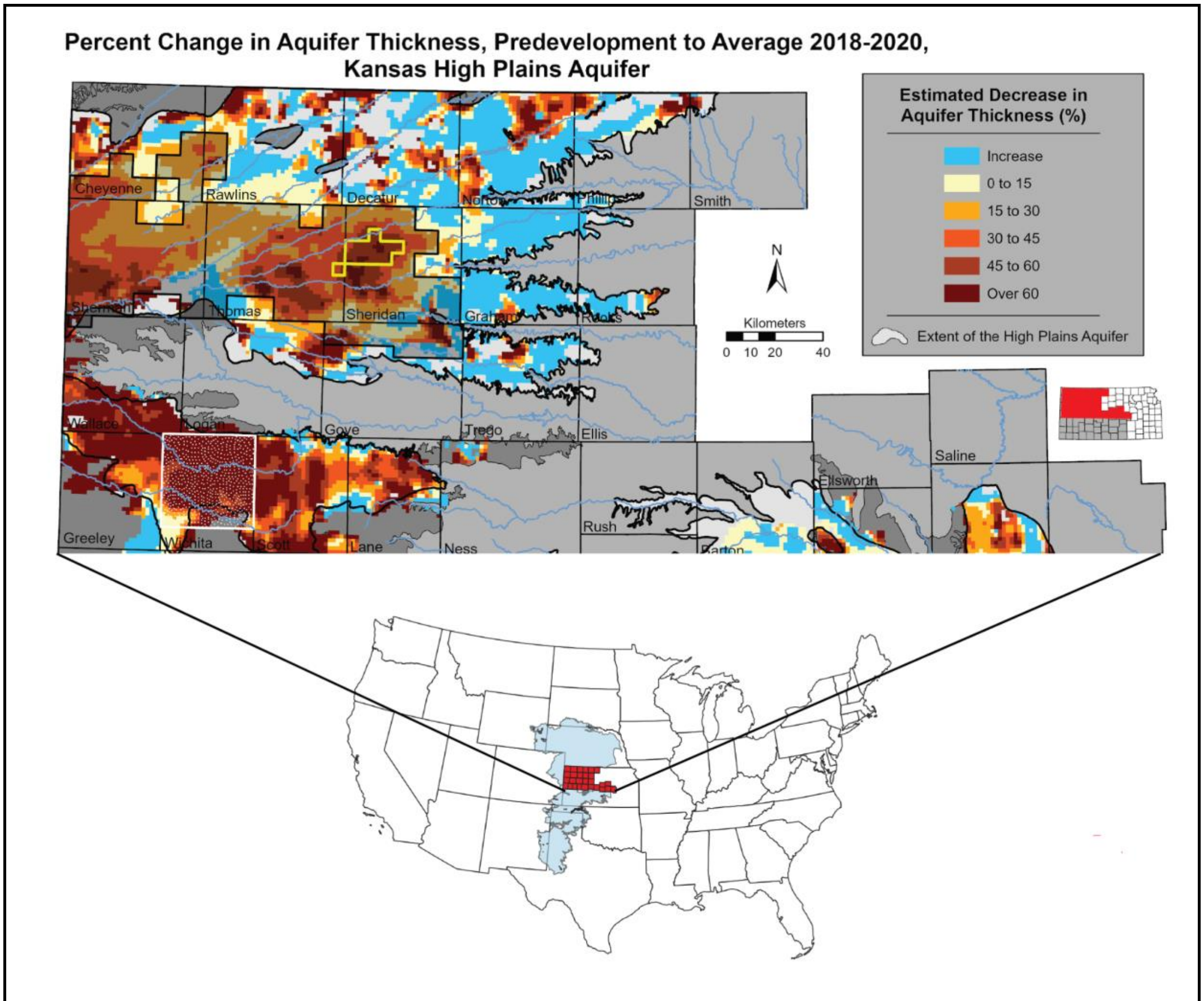

Figure 1: The large decrease in aquifer thickness from pre-development (~pre-1950) to present prompted the formation of the SD-6 LEMA (yellow outline). Initial success of the SD-6 LEMA led to the formation of a LEMA for all of Groundwater Management District 4 (shaded area) and an additional LEMA in Wichita County (white stippled area).

While initial results from the SD-6 LEMA are promising, it is not clear how the effectiveness of such conservation initiatives might change in the future as the hydrological system adjusts to the observed pumping reductions (Butler et al., 2020b; Deines et al., 2021;

Foster et al., 2017). The change in aquifer water levels in response to pumping is a function of the difference between pumping and net inflow, which is defined as total inflows (i.e., recharge, lateral inflows) minus all non-pumping outflows (i.e., discharge to streams, vegetation, lateral outflows), and is mediated by hydrostratigraphic characteristics (Butler et al., 2016). However, the relative contributions of vertical and lateral flows to net inflow are poorly understood (Butler et al., 2016, 2020b).While recent work has found that reductions in aquifer net inflow can decrease the effectiveness of groundwater conservation programs over time (Butler et al., 2020b), it is highly uncertain how the mechanisms, timescales, and magnitudes of lagged responses from different water balance components vary. For example, estimates of the magnitude and transit time for groundwater recharge vary dramatically over the HPA due to thick unsaturated zones (Gurdak et al., 2008; Katz et al., 2016; McMahon et al., 2006; Zell & Sanford, 2020). As a result, we do not know which lagged responses may impact overall groundwater sustainability, nor the timescales and controlling processes.

To address this knowledge gap, we seek to answer the question: *How do lagged responses to pumping reductions impact the effectiveness of groundwater conservation practices over time?* We hypothesize that when groundwater conservation initiatives, such as Kansas' LEMA program, are enacted, (i) the reduction in pumping causes an immediate change to the aquifer water balance, leading to a slowing of the water table decline rate (Figure 2a, light blue line); (ii) over time, inflows will diminish because the reduction in deep percolation (water that drains below the rooting zone) associated with more efficient irrigation (Deines et al., 2021) will eventually reduce recharge to the aquifer. Similarly, lateral inflow to the conservation area will diminish, as decreased pumping will reduce the hydraulic gradient driving water into the area. In both situations, the result will be an increase in water table declines to an intermediate rate between the pre-conservation decline rate and the immediate post-conservation rate (dark blue line in Figure 2a). To test these hypotheses, we developed a variably saturated groundwater flow model for the SD-6 LEMA based on historical observations and realistic conditions. We used this model to evaluate the long-term changes in the aquifer water balance associated with groundwater conservation, quantify the implications of lagged responses for estimates of usable aquifer lifetimes, and determine the physical controls on these lagged responses.

2. Methods

2.1 Model Overview

To test our hypotheses, we developed a representative variably saturated groundwater flow model of a north-south linear transect that passes through the SD-6 LEMA (Figure 2b). We elected to build a simplified model, rather than a fully-calibrated three-dimensional groundwater flow model, to better isolate the hydrological processes of interest, and more directly test our hypotheses by avoiding unnecessary site-specific complexity--an approach known as surrogate or archetypal modeling (Asher et al., 2015; Razavi et al., 2012; Voss, 2011a, 2011b; Zipper et al., 2018, 2019). Nevertheless, to ensure our model provided a reasonable simulation of the dominant processes in this region, we conducted an evaluation against field data from the SD-6 region.

2.2 Model Construction and Input Data

We used the United States Geological Survey's MODFLOW-NWT program and constructed the model using the Python package FloPy (Bakker et al., 2016). The 40 km long domain consists of a single layer of 50 grid cells, each 800 m by 800 m in size, covering a total area of 32 km^2. Each grid cell is roughly equivalent in area to an average quarter-section field (64.75 hectares [160 acres]) and cell dimensions were set based on the average distance between irrigation wells in the area. The model domain was split into two types of management practices (conservation and non-conservation; blue and orange areas, respectively, in Figure 2b), which were represented in the model using different pumping and deep percolation rates as described below. The conservation area was made up of 14 grid cells while the non-conservation areas each consisted of 18 grid cells to remove the influence of edge effects from the northern and southern no-flow boundaries. The single model layer is 72 m thick and starting pressure heads were set to 40 m; these values represent the average depth to bedrock and pressure heads, respectively, of the area for the pre-development period (~pre-1950) (Fross et al., 2012). The top of the model is assumed to be below the rooting zone to remove the influence of evapotranspiration, overland flow, and discharge to surface water bodies. Since regional groundwater flow is generally from west to east (perpendicular to our transect), we included a lateral flow boundary condition on the west side and a no-flow boundary on the east to represent the net lateral flow entering the SD-6 LEMA, which is distinct from the vertical inflow from groundwater recharge. We varied net lateral flows along with the model hydrostratigraphic properties as described in Section 2.3.

Pumping is simulated using MODFLOW's well (WEL) package. We estimated annual pumping volumes by establishing relationships between annual precipitation depth and measured pumping during the 2000-2018 period (Figure 3), when a large majority of irrigators had transitioned from traditional high pressure center pivot irrigation to more efficient center pivot with drop nozzle irrigation (Pfeiffer & Lin, 2010; Rogers & Lamm, 2012). We first estimated a relationship between precipitation and pumping for the "No Conservation" portions of the domain that included the period after the establishment of the SD-6 LEMA; observed pumping rates from the SD-6 LEMA were translated upward to account for the climate-adjusted average

27% reduction in pumped volume observed during the first four years of the LEMA (Whittemore et al., 2018). Using the "No Conservation" relationship as the baseline, two additional relationships were developed for the pumping scenarios modeled in this study (Figure 3a): (i) a 20% pumping reduction scenario based on the legal requirements for the SD-6 LEMA; and (ii) a 30% pumping reduction scenario that more closely reflects observed irrigator behavior. For each pumping scenario, we applied the estimated annual pumping volume uniformly over a 103-day period, which was the average time between the onset and cessation of irrigation pumping as observed in high temporal-resolution well observations (Butler et al., 2019). The applied pumping volume was computed as the area of a single grid cell times the irrigation depth from the statistical relationship established in Figure 3a. As discussed in Section 2.1, our surrogate modeling approach is not intended to precisely represent observed spatial pumping dynamics within the SD-6 LEMA, but rather the average aquifer response to typical regional pumping. To reflect that the estimated pumping volume is representative of the entire SD-6 area, which is heavily irrigated, we placed a pumping well in each individual grid cell both inside and outside the conservation area.

The model simulates flow through variably saturated porous media using the unsaturated zone flow (UZF) package, which uses a kinematic-wave approximation to solve the 1-D Richard's equation (Niswonger et al., 2006; Smith, 1983; Smith & Hebbert, 1983). While numerous models can simulate variably saturated flow, the UZF package for MODFLOW has several advantages for our purposes, including documented use in thick vadose zones (Hunt et al., 2008; Nazarieh et al., 2018), computational efficiency (Kennedy et al., 2016; Niswonger & Prudic, 2009), and widespread use (Bailey et al., 2013; Hou et al., 2020; Morway et al., 2013). Since the top of our model domain represents the bottom of the root zone, we provided UZF with annual values of deep percolation from a linear model fit between simulated deep percolation from a calibrated crop model for the SD-6 area with and without conservation (Deines et al., 2021), and the sum of annual precipitation and applied irrigation depth following Scanlon et al. (2006) (Figure 3b). Like pumping, annual deep percolation values were uniformly disaggregated to daily values over the 103-day pumping period. This assumption is justified because essentially all deep percolation in the area is the result of excess applied irrigation water (Ajaz et al., 2020). Unlike the separate relationships required for pumping under each conservation scenario, only one relationship is needed to estimate deep percolation because the effects of groundwater conservation are accounted for in the annual irrigation depth term. These relationships (Figures 3a and 3b) were used to generate deep percolation rate time series data for both the evaluation and projection periods and pumping rate time series for the projection period (Figure 3c).

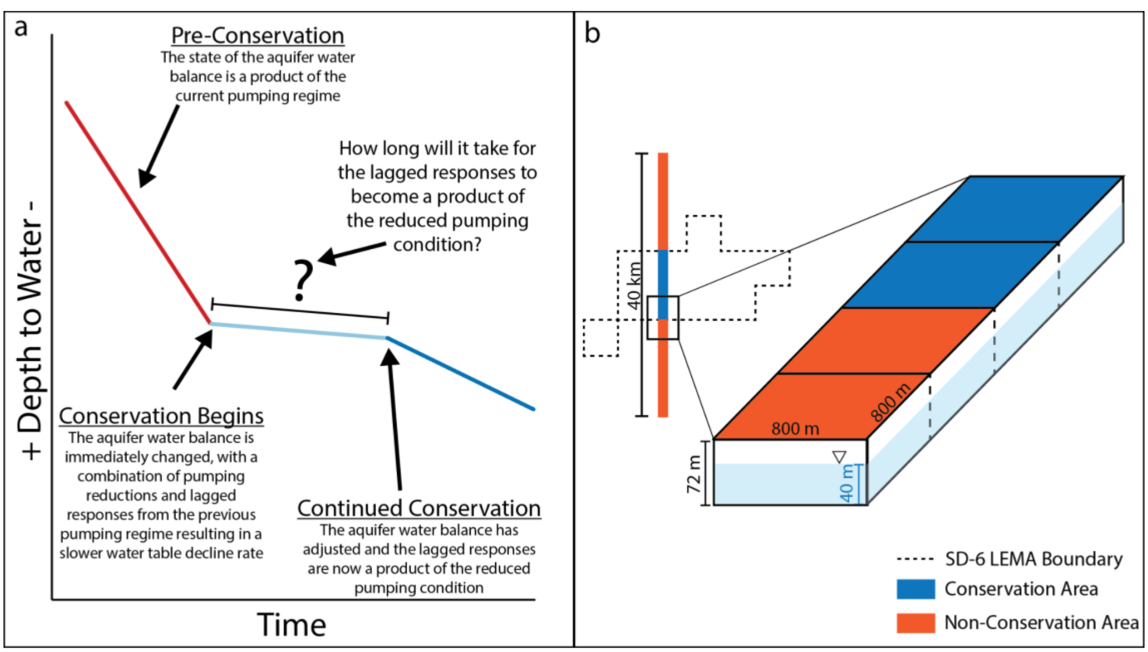

Figure 2: Conceptual diagrams. a) Graphical representation of how the aquifer water balance changes due to pumping reductions. The initial reduction in pumping causes an immediate change to the aquifer water balance, resulting from an initial period of high effectiveness (light blue line) that wanes in time as lagged responses, such as groundwater recharge and lateral flow, adjust to the new pumping regime (dark blue

line). b) Model overview, including the location of the transect relative to the SD-6 LEMA, the two separate areas (conservation and non-conservation), the grid cell dimensions, the domain depth, and the starting head value representative of the pre-development period.

Our simulations spanned 201 years (1900-2100), which can be divided into three periods: spin-up (1900-1954), historical (1955-2019), and projection (2020-2100). The 55 year spin-up period is prior to the onset of high capacity pumping in the region so the only fluxes in/out of the domain are deep percolation, which was applied at a rate of 5 x 10^{-4} m d^{-1} (~51 mm yr^{-1}) to approximate pre-development recharge in the area (Fross et al., 2012; Hansen, 1991), and the applied lateral inflows. To ensure that recharge and lateral inflow did not change the prescribed pre-development saturated zone pressure heads, a drain was placed at the pre-development water level (40 m) across the domain. This approximates the effect of the regional streams that drained the system during the pre-development period. After the spin up period, a mix of regression-estimated (1955 to 1992) (Wilson et al., 2005) and measured pumping volumes (1993 to 2019) for the SD-6 area was used to generate normalized pumping rates which were applied to the model (Figure 3c). As observed irrigator behavior within the LEMA was close to the 30% pumping reduction scenario, we used the 30% reduction pumping rates for 2013-2019. The projection period (2020-2100) allows us to evaluate the long-term implications of pumping with the baseline and the two reduction (20% and 30%) pumping scenarios. For the projection period, we randomly sampled annual precipitation from the historical precipitation record to estimate pumping and deep percolation for each year based on the relationships shown in Figure 3 since there are no consistent long-term historical (Lin et al., 2017) or projected (Figure S1) precipitation trends in this region, and historical precipitation patterns do not exhibit significant temporal autocorrelation (Butler et al., 2020).

2.3 Model Evaluation and Sensitivity Analysis

We used a Latin hypercube sampling scheme (McKay et al., 1979) to identify the model parameters that best reproduced observed hydrological data and evaluate the sensitivity of model output to each parameter and the interactions between parameters (Zipper et al., 2018). Our Latin hypercube sample consisted of 2,000 near-random, unique sets of hydrostratigraphic parameters (vertical saturated hydraulic conductivity, K_Z; specific yield, S_Y; Brooks and Corey epsilon, ε) and lateral inflow (LI), which were selected from a uniform distribution over the parameter space shown in Table 1. We ran one simulation using each parameter set to explore lagged responses to groundwater conservation across a range of hydrogeological settings and to reduce the risk of identifying a local optima as the best parameter set.

Table 1: Parameter space ranges for the Latin hypercube sampling scheme. As we are taking a surrogate modeling approach, ranges were extended outside of their observed values for the area to allow the parameter space to be fully explored. [1](Fross et al., 2012), [2](Butler et al., 2016), [3](Brooks & Corey, 1966)

Parameter	Lower Bound	Upper Bound
$\log_{10}$ Vertical Hydraulic Conductivity (m d^{-1})[1]	-6	1
Specific Yield (-)[2]	0.06	0.18
Brooks and Corey Epsilon (-)[3]	2	5
$\log_{10}$ Lateral Inflows (m d^{-1})[2]	-6	-3

Horizontal hydraulic conductivity and saturated water content were held constant at 20 m d^{-1} and 0.25, respectively, to reflect average values in the SD-6 LEMA area (Fross et al., 2012). The UZF package relies on the Brooks and Corey function to calculate unsaturated K_Z (Brooks

& Corey, 1966). This function requires residual water content, here approximated for each parameter set by taking the S_Y value for each set and subtracting it from the saturated water content (Niswonger et al., 2006). A value of 0.005 was added to the calculated residual water content to ensure that the unsaturated hydraulic conductivity value did not start at a value of zero.

We evaluated the performance of each of the 2000 simulations via comparison to the observed groundwater level data for the 1999-2019 period, which represents the longest continuous record of reliable observations within the SD-6 LEMA (KGS WIZARD Database; http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). The goal of this study is to ensure that the dominant processes (e.g., pumping reductions and lagged responses) are appropriately simulated while not overparameterizing the model since our focus is not on site-specific heterogeneity (Konikow & Bredehoeft, 1992).

We quantified model performance for each parameter set using a two-step approach. First, as the area has experienced significant drawdown, we eliminated model runs in which the head in the model domain at the end of the historical period (2019) was still at pre-development levels (Fross et al., 2012). For the remaining runs, we calculated the Kling-Gupta Efficiency (KGE; Kling et al., 2012) score for both the annual water table elevation and the interannual change in water table elevation, which are based on measurements taken each January in the LEMA area. We selected these two metrics to ensure that both the interannual and long-term dynamics were simulated reasonably, and used the minimum (lower-performing) of these two KGE values as the final KGE score for that parameter set. We then divided the model runs into four performance groups: poor (KGE < -0.41, which indicates that the model results are worse than the mean of the observations; Knoben et al., 2019), low (-0.41 < KGE < 0), medium (0 <

KGE < 0.5), and high (KGE > 0.5). A KGE score of 1 would indicate a perfect match between a simulation and observations. Only runs in the high performance group were analyzed for the projection period because those parameter sets were judged able to reasonably approximate historical hydrological conditions.

The models selected for projection were run to the year 2100 and the extension of the usable aquifer lifetime was quantified for the 20% and 30% pumping reduction scenarios. For each parameter combination and pumping scenario, the extension of the usable aquifer lifetime is calculated as the number of years that water levels in the aquifer remain above a minimum threshold relative to the baseline "No Conservation" scenario. For this region, we assumed that a minimum saturated thickness of eight meters is required for large-scale irrigation to allow for sufficient transmissivity, and therefore well yield, along with pumping-induced drawdown in the well (Butler et al., 2020b).

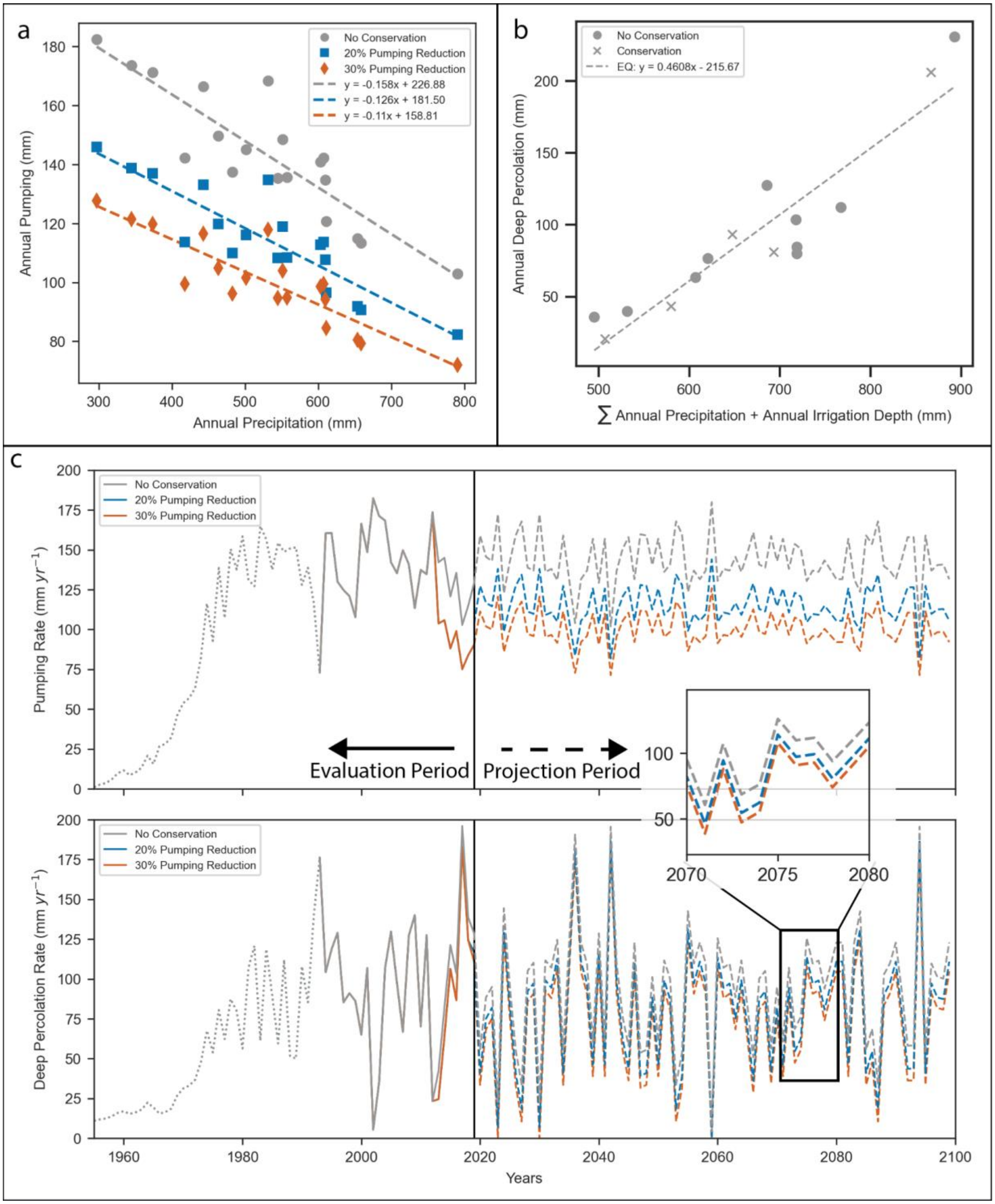

Figure 3: Annual statistical relationships for: a) pumping depth, b) deep percolation depth, and resulting applied c) pumping rate and d) deep percolation from the statistical relationships. For three very dry years in the prediction period, the statistical relationship in panel b produced negative deep percolation rates; these years were assigned a rate of 0 m d^{-1}. For the historical

period, pumping rate and deep percolation are shown only for the 30% pumping reduction scenario (orange) as this best represents observed irrigator behavior.

3. Results and Discussion

3.1 Recharge and lateral flow-dominated inflows

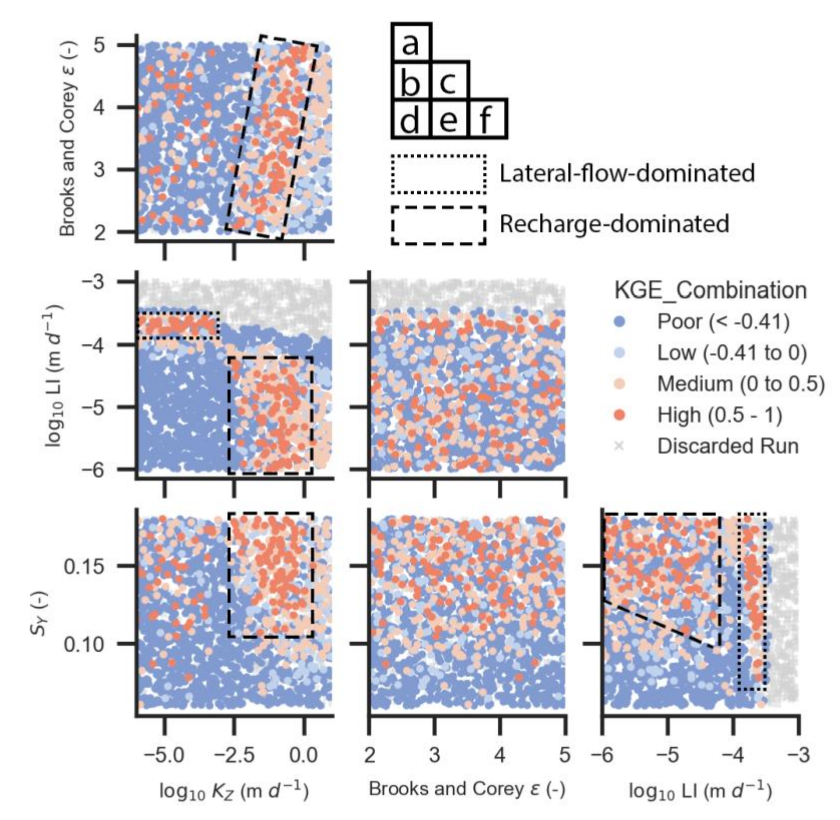

Figure 4: Model fit for each pairwise combination of parameters for the 30% pumping reduction scenario. Each point shows one simulation, colored by the KGE score for the model evaluation period. The dotted and dashed inset rectangles indicate grouping clusters for the lateral-flow- and recharge-dominated cases.

We found that many parameter combinations were able to reproduce the historical head and head change observations (Figure 4). Of the 2,000 parameter combinations tested, there were 121 simulations with high performance (Figure 4, dark red circles, KGE > 0.5). An additional 206 were rated as medium, 127 as low, 1,098 as poor, and 448 were discarded due to no simulated drawdown (Figure 4). Within parameter pairs, there are several clusters that occur throughout the parameter space (Figure 4b), the most evident occurring between lateral inflow (LI) and vertical hydraulic conductivity (K_Z). In parameter space, these two clusters correspond to a high LI/low K_Z zone, in which lateral groundwater flow is the dominant inflow to the aquifer, and a low LI/high K_Z zone, in which vertical groundwater recharge is the dominant inflow to the aquifer .

For the lateral-flow-dominated case, the parameter sets that yield high KGE scores have LI values between 1.6 x 10^{-4} and 2.5 x 10^{-4} m d^{-1} and K_Z values between 1 x 10^{-6} (the lower bound of the parameter space tested) and 5 x 10^{-4} m d^{-1}. However, for the Brooks and Corey ε and S_Y there are no clear thresholds, indicating that the rate of lateral flow is the controlling factor. The ranges of K_Z and LI values with good fits in the recharge-dominated case are opposite of the lateral-flow-dominated case, with higher K_Z values (from 3.5 x 10^{-3} to 1 m d^{-1}) and lower LI values (from 5 x 10^{-5} m d^{-1} to the lower bound of the parameter space tested, 1 x 10^{-6} m d^{-1}) (Figure 4b). In contrast to the lateral-flow-dominated case, the recharge-dominated case is also sensitive to the Brooks and Corey ε and S_Y. As K_Z approaches 1 m d^{-1}, the value of ε steadily increases from 2 to 5 (Figure 4a). The range of S_Y is also limited based on K_Z, with S_Y values between 0.1 and 0.18 necessary to generate KGE scores of >= 0.5 (Figure 4d). Vertical hydraulic conductivity is not the only controlling factor in the recharge-dominated case. As the value of LI increases towards its upper limit of 5 x 10^{-5} m d^{-1}, the range of S_Y also expands with its lower limit dropping from 0.13 to 0.1 (Figure 4f). The interplay between hydrostratigraphic parameters plays a more prominent role in the recharge-dominated scenario. Along with K_Z, the Brooks and Corey ε and S_Y influence the rate and volume of vertical water movement through the thick vadose zone, respectively, and therefore influence the performance of the model.

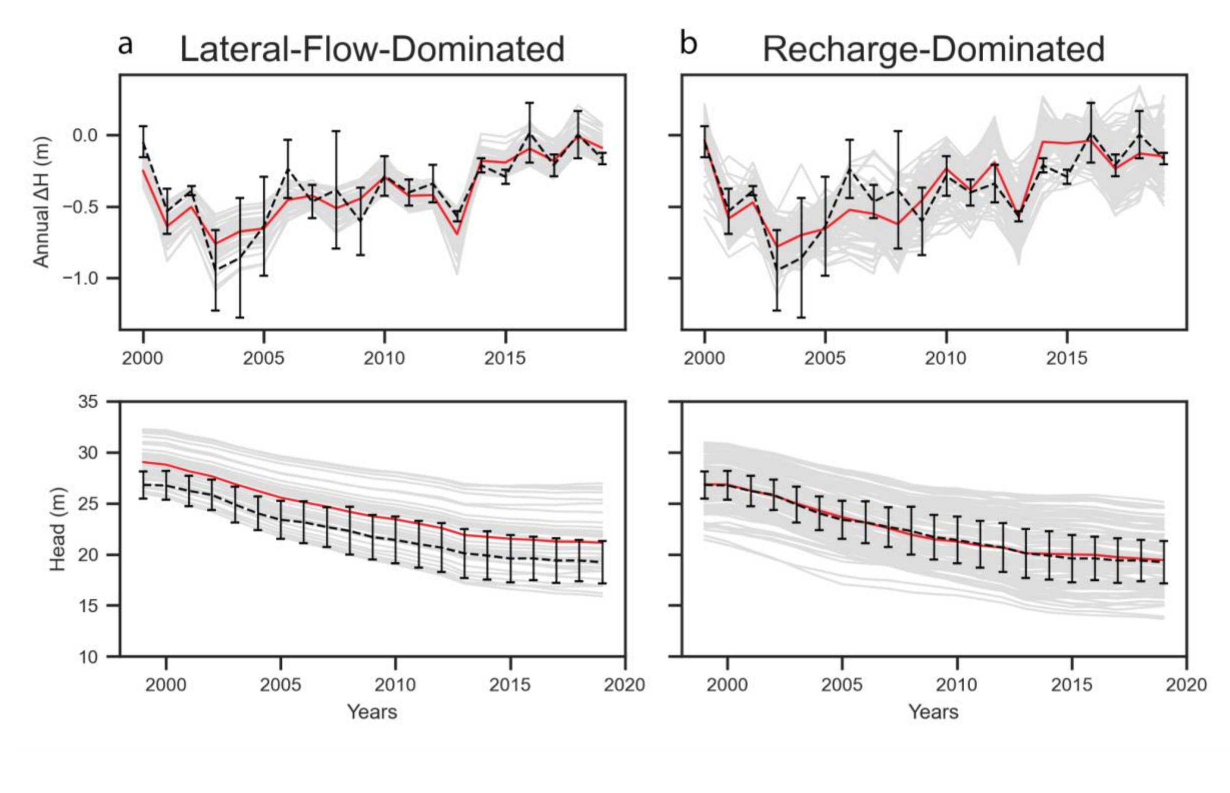

Figure 5: Results for the 30% pumping reduction scenario of observed (black, dashed line), simulated (light gray, solid lines), and average simulated (red lines) interannual change in pressure head and annual pressure head values for the a) lateral-flow-dominated and b) recharge-dominated cases. Simulation results presented for the center cell in the conservation area, the error bars show one standard deviation about the mean of the observed data.

For both the lateral-flow-dominated and recharge-dominated cases, the average simulated interannual change in pressure head and annual pressure head values (Figure 5a, b, red lines) closely align to the average observed value (Figure 5a, b, dashed lines). The individual components of the KGE score (mean Pearson correlation coefficient, variability ratio, and bias ratio; (Kling et al., 2012)), KGE score, and root mean square error (RMSE) for all high-performing recharge- and lateral-flow-dominated cases are given in Table 2 for the 1999-2019 evaluation period. The average simulated values also fell within or close to the standard deviation of the observed measurements, indicating that the model is reasonably capturing the annual and interannual dynamics of the natural system.

Table 2: Average model statistics for interannual and annual heads for the lateral-flow-dominated and recharge-dominated cases.

Statistic	Lateral-Flow-Dominated		Recharge-Dominated	
	Interannual Change in Head	Annual Head	Interannual Change in Head	Annual Head
Pearson Correlation Coefficient (r)	0.887	0.998	0.732	0.993
Variability Ratio (γ)	0.838	0.999	1.139	1.042
Bias Ratio (β)	1.044	1.056	0.982	0.973
Kling Gupta Efficiency Score (KGE)	0.685	0.765	0.643	0.762
Root Mean Square Error (m) (RMSE)	0.142	2.269	0.204	2.529

The wide variety of parameters that lead to reasonable agreement with the observed data indicates that multiple interpretations of the underlying processes that dictate groundwater recharge in areas with thick vadose zones are equally valid, following the principle of equifinality (Beven, 2006). In groundwater modeling, parameter estimation often seeks to find a local or global optimum to match limited observations while minimizing an objective function using software such as PEST (Doherty, 2015) or UCODE (Poeter & Hill, 1999). However, the hunt for an ideal parameter set that results in simulated values closely matching observed values can ignore other possible parameter sets that perform nearly equally well (Savenije, 2001). This is true for our surrogate model of the SD-6 area as the lack of vadose zone observation data paired with an exploration of a wide parameter space resulted in two possible and equally valid mechanisms that affect the long term performance of pumping reduction-based groundwater conservation initiatives.

3.2 Lagged responses to conservation in recharge- and lateral flow-dominated conditions

Due to differences in their underlying hydrological processes, recharge-dominated and lateral-flow-dominated cases exhibit different long-term hydrological responses to groundwater conservation. In lateral-flow-dominated settings, changes in deep percolation caused by pumping reductions do not significantly impact recharge rates within the 80-year projection period because recharge rates are low to begin with and changes in deep percolation take a long time to propagate down to the water table (Figure 6a). Following reductions in pumping, water table decline rates are initially sizably reduced then increase through time, consistent with our hypothesis (Figure 2a). The increase occurs because the initial reduction within the conservation area creates a lateral hydraulic gradient that drives lateral flow into the surrounding non-conservation area; this phenomenon is further discussed in Section 3.3. The lateral flow-dominated case relies on high fluxes of net lateral inflow to compensate for the lack of recharge. This case only applies when K_Z values are low as any increase in recharge would add too much water to the aquifer, resulting in unrealistic rises in the water table. When LI is the controlling mechanism, the vadose zone properties have a negligible impact on the effectiveness of the pumping reductions.

In recharge-dominated cases, the rate of deep percolation eventually controls the rate of groundwater recharge. Reductions in pumping decrease the amount of water that is applied in excess of crop water demands, and thus reduce the rate of deep percolation (Figure 3b). Unlike the lateral flow-dominated case where there is no difference in recharge between the conservation and non-conservation areas, the effects of changing deep percolation lead to a reduction in groundwater recharge within the conservation area relative to the non-conservation area (Figure 6b). Once the lagged response of recharge adjusts to the reduced pumping condition, water table decline rates increase, consistent with our hypothesis. However, even in recharge-dominated settings, the effects of changing lateral outflows still play an important role. Lateral outflows across the border of the conservation area reach up to ~25 mm yr^{-1}, which is comparable to the difference in recharge between the conservation and non-conservation areas (Figure 6b).

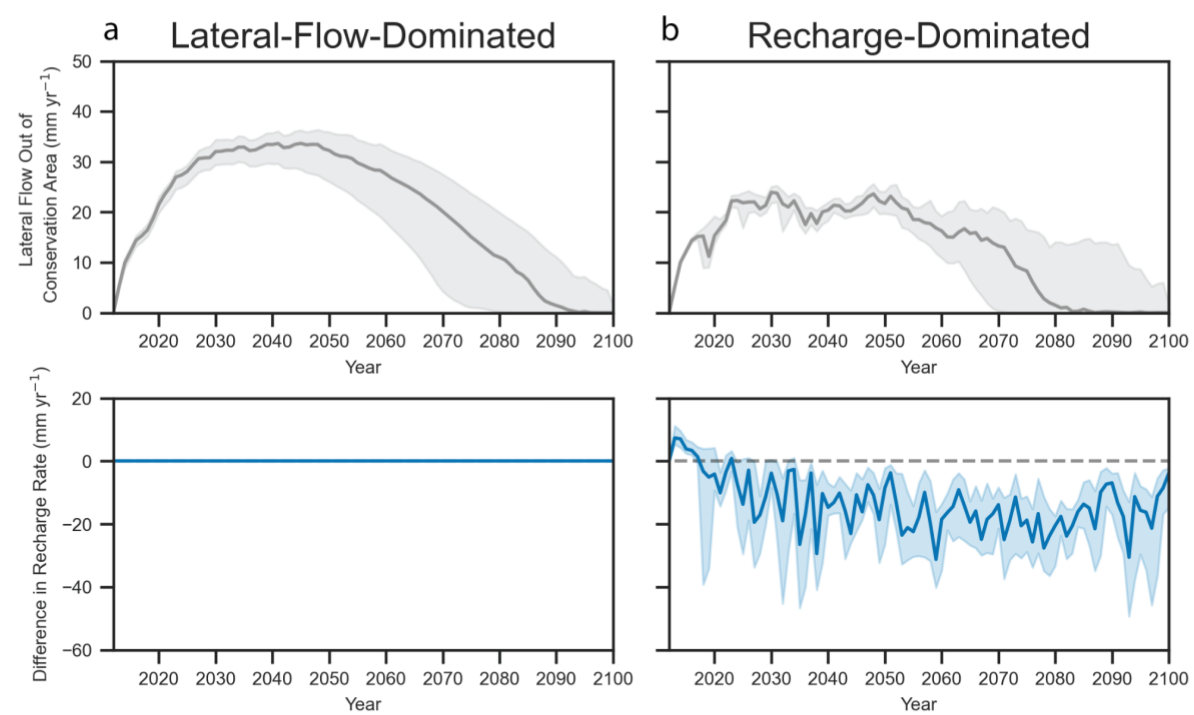

Figure 6: Average time series of simulated lateral outflow from the conservation area to the non-conservation area (upper plots) and difference in recharge rate between the conservation area and the non-conservation area (lower plots) for a) the lateral-flow-dominated and b) recharge-dominated cases.Thick lines represent average values across all model runs used for the projections and the shading indicates the interquartile range.

These two processes have distinct time lags from the onset of groundwater conservation measures. For the lateral-flow-dominated cases, flow out of the conservation area begins with the start of pumping reductions and increases quickly with the development of a head gradient between the conservation and non-conservation areas. Eventually, lateral outflow peaks at a rate of ~34 mm yr^{-1} from 2030 to 2050, or ~17 to ~37 years after the onset of conservation (Figure 6a). After 2050, lateral outflow gradually decreases due to a decline in the head gradient between the conservation and non-conservation areas, typically reaching 0 mm yr^{-1} between 2080 and 2100 depending on the case. In the recharge-dominated cases (Figure 6b), lateral flow out of the conservation area follows a similar pattern, though with a lower peak (~24 mm yr^{-1}) and more interannual variability. The interannual variability in lateral outflows in the recharge-dominated cases is due to differences in recharge rates between the conservation and non-conservation areas, with larger lateral outflows when the recharge differences between the conservation and non-conservation areas are greater because this induces a larger hydraulic gradient between the two areas. For the recharge-dominated cases, there is an immediate short lived-period of positive differences in recharge rates, with recharge into the conservation area greater than into the non-conservation area because the reduction in water table decline rates allows more recharge to reach the water table than at higher decline rates. After five years, recharge rates in the groundwater conservation area adjust to the lower deep percolation rates associated with the reduced pumping condition, resulting in a negative difference for the rest of the simulation.

These differences between the lateral- and recharge-dominated cases indicate that, in settings with higher values of K_Z (> 0.0035 m d^{-1}; Figure 4), excess applied irrigation water can traverse the thick vadose zone that is present in western Kansas and ultimately recharge the water table. However, vertical hydraulic conductivity is not the only controlling factor in the recharge-dominated cases, as LI, S_Y, and Brooks and Corey ε also play important roles in the long-term effectiveness (see Figure 4). In cases where S_Y is low, high-performing parameter sets tend to have a greater LI to compensate for the low drainable pore space. When K_Z values are low, Brooks and Corey ε values must be low as well to allow for the calculated unsaturated hydraulic conductivity value to be high enough to transmit water through the vadose zone at a rapid enough rate to initiate groundwater recharge. As K_Z increases, so must the Brooks and Corey ε, limiting the value of unsaturated hydraulic conductivity and preventing the aquifer from becoming inundated with excess water.

3.3 Effects of lagged responses on aquifer usable lifespan

These lagged responses to groundwater conservation lead to different estimates of the degree to which conservation extends the usable aquifer lifetime. The lateral-flow-dominated cases had an average extension of 15 years for a 20% pumping reduction and an average extension of 25 years for a 30% reduction (Figure 7a, c). Results were similar for the recharge-dominated cases, where the average extension was 12 years with a reduction in pumping of 20% and 20 years for a pumping reduction of 30% (Figure 7b, d). Using the start of the initial SD-6 LEMA in 2013, the remaining usable lifetime can be quantified. For the recharge-dominated cases, if no pumping reductions are applied, the water table will fall below eight meters of saturated thickness (the minimum thickness capable of supporting irrigated agriculture (Butler et al., 2020b) in 2047. If pumping is reduced by 20% or 30%, this usable expiration date changes to 2059 and 2067, respectively. In the lateral-flow-dominated cases, enacting no pumping reductions sets the usable aquifer expiration date at 2045. With a 20% and 30% pumping reduction, this date is extended to 2060 and 2070, respectively. The numbers found in this study are within the envelope found by Butler et al. (2020b) who used a data-driven approach to quantify the extension of usable lifetime under various exploratory scenarios. Our analysis extends this previous work by quantifying the relative importance of lateral flow and recharge as drivers of long-term change in net inflows.

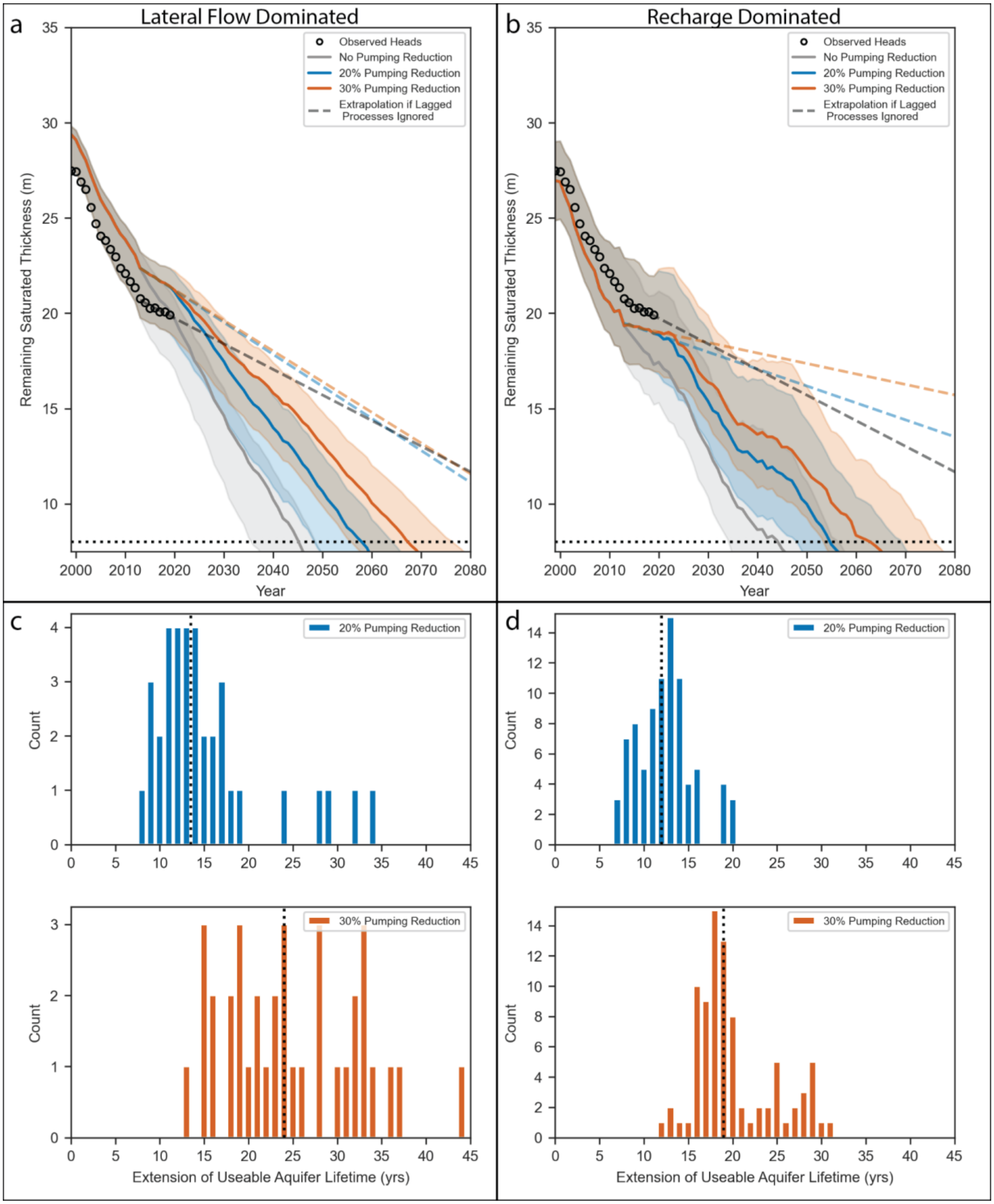

Figure 7: a) and b):Median simulated saturated thickness for the three pumping scenarios for a) lateral-flow-dominated and b) recharge-dominated cases. Dashed lines represent extrapolated remaining saturated thickness if the impact of lagged responses is ignored. The horizontal dotted line represents the minimum saturated thickness (eight meters) needed for large-scale

irrigated agriculture. c) and d): Median extension of usable lifetime (vertical black dotted line) and histogram of model outcomes for the 20% and 30% pumping reduction scenarios for c) lateral-flow-dominated and d) recharge-dominated cases. Shaded areas in panels a) and b) represent the interquartile range of the simulated projections.

In general, these results indicate that the effectiveness of groundwater conservation could be overestimated if only using data from the period between initiation of pumping reductions and the onset of the lagged responses. Using the observed heads from 2013 to 2019 and extrapolating until the aquifer thickness drops below eight meters, the usable lifespan extends to 2107 (Figure 7a,b black dashed line). For the lateral flow-dominated cases, this value drops to 2098 for the 20% pumping reduction scenario and 2102 for the 30% pumping reduction scenario (Figure 7a, blue and orange dashed lines). The recharge-dominated cases result in a much greater duration with the usable lifetime extending to 2142 for the 20% pumping reduction case and 2220 for the 30% pumping reduction case (Figure 7b, blue and orange dashed lines). Using only the initial appearance of pumping reduction effectiveness and ignoring the impacts of lagged responses leads to drastically different interpretations of the effectiveness of these conservation methods. The subsequent rebound in the water table decline rate dictates the long term effectiveness of groundwater conservation strategies. Understanding the mechanisms that control these lagged responses can manage stakeholder expectations and lead to the design of more effective conservation strategies that can further extend the usable lifetime of stressed aquifers. For example, as the effectiveness of initial conservation measures wanes and a return to increased water table decline rates begin to be observed, Butler et al. (2020b) have shown that additional pumping reductions can further extend usable aquifer lifetimes.

3.4 Implications of isolated conservation areas within heavily stressed regional aquifers

Conservation strategies are most likely to be enacted in the most heavily stressed aquifers. In the United States, these are located in the west where the doctrine of prior appropriation, or colloquially "*first in time - first in right*", is the guiding principle for water rights (Johnson & DuMars, 1989). This has led to extensive litigation that will likely increase as water resources are diminished through time (Griggs, 2013). We found that lateral flow out of the conservation area (Figure 6) means that some of the water savings are transferred to non-conservation areas (Figure 8), effectively subsidizing those outside the conservation area. As our modeling setup is symmetric, the largest extension of usable lifetime occurs in the center of the conservation area (values plotted in Figure 7) and decreases towards and across the boundary between the conservation and non-conservation areas. This pattern is greater under the lateral flow-dominated cases but also occurs in recharge-dominated cases due to the reduction-induced gradient changes discussed above. The activities in the conservation area will affect the usable aquifer lifetime in the nearby non-conservation area. Without any reductions in pumping, this area achieves an extension of at least 5 years at distances of approximately 2 km from the boundary for the 20% pumping reduction case and between 3.5 and 4 km for the 30% pumping reduction case. Extensions of the usable aquifer lifetime at 7 km from the boundary range between about 0.75 and 2 years. However, the magnitude of this effect is dependent on the horizontal conductivity value. The lateral flow subsidy would also be smaller (relative to the volume of water conserved within the conservation area) as the size of the conservation area increases.

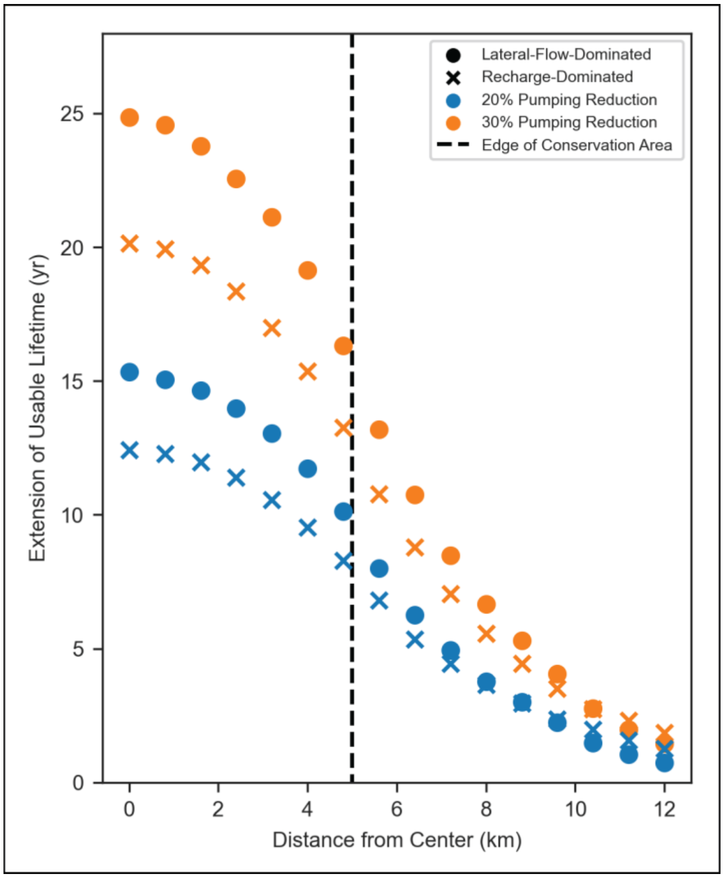

Figure 8: Average extension of usable aquifer lifetime for the lateral-flow-dominated (circles) and recharge-dominated (Xs) compared to distance from the center of the conservation area.

While our surrogate model simulations found net outflow across the LEMA boundary, in practice many overexploited areas where groundwater conservation measures may be implemented are closed basins and therefore this may manifest through other impacts such as a reduction in cross-boundary inflows to the conservation area (Pauloo et al., 2021). In either case, this indicates that the benefits of pumping reductions can extend beyond the boundaries of the areas with groundwater conservation initiatives, with potential socio-political impacts. For instance, if pumping reductions are implemented in trans-boundary aquifers, lagged responses should be accounted for to ensure that water resources are shared equitably, not just within the

United States but across the globe (Callegary et al., 2018; Lee et al., 2018; Lipponen & Chilton, 2018; Sindico et al., 2018).

3.5 Limitations and future research needs

Although the modeling framework presented here represented the interannual and annual dynamics of the observed natural system (Figure 5), there are several limitations to our approach that may affect the results. First, aquifers are inherently complex, spatially heterogeneous, and frequently lack sufficient observation data. Our analysis deliberately simplified this complexity into a homogeneous surrogate model in order to isolate the lagged hydrological responses to groundwater conservation, and therefore does not capture the intricacies of the natural world, such as spatial changes in depth to bedrock, strata discontinuity, or incorporation of regional groundwater gradients. Additionally, although Kansas has the most robust groundwater well metering data across the United States (Foster et al., 2020; USDA National Agricultural Statistics Service, 2019), the spatial distribution of wells used for pumping and observation data is not captured in our study as we evenly distributed pumping across the conservation and non-conservation areas to investigate average processes within the LEMA.

Second, the applied pumping and deep percolation rates are based on statistical relationships using limited data. Pumping rates for the period from 1955 to 1992 are based on a regression model while rates from 1993 to 2018 are based on observed data. Additionally, when developing the projected pumping rates, we assumed that irrigation efficiency does not change, which may not be the case as new technologies are adopted by the agricultural community. Applied deep percolation rates were developed using ten years of modeled data and extrapolated to fill the historical record, which may have resulted in deep percolation rates that are too high. We also assumed that the east-to-west lateral inflows to the system are constant through time.

These issues point to a critical need to better monitor vertical fluxes of water in deep vadose zones and lateral fluxes in aquifers to inform future modeling efforts and conservation program evaluations.

Third, the use of the UZF package to simulate variably saturated flow is limited in several aspects. If applied deep percolation rates are greater than the prescribed saturated hydraulic conductivity, excess water is removed from the system, as low hydraulic conductivity conditions typical of lateral-flow-dominated cases are limited not just by the rate at which water percolates through the unsaturated zone, but also by the supply of water able to infiltrate into the root zone. Applying heterogeneity to the model domain was not possible with the UZF package as it can only be applied to one active layer, further simplifying the representation. We had attempted to address this limitation by using another MODFLOW-based variably-saturated flow solution, HYDRUS Package for MODFLOW (Beegum et al., 2018; Seo et al., 2007), which solves a 1-D unsaturated Richards Equation for each cell column, but experienced both instability and anomalous results that prevented its application here. Finally, all projection results are based on randomly sampling the historical record of precipitation to generate time series for deep percolation and pumping, which provides realistic daily meteorological dynamics but inherently ignores climate change impacts and implications.

Although our modeling approach may disregard some locally important heterogeneity, our objective was to analyze the major factors controlling the long-term effectiveness of groundwater conservation initiatives. Our simplified surrogate modeling approach allows for the fundamental processes to be investigated while removing the impact of site specific phenomena, ultimately allowing for a more generalized understanding of system dynamics. Applying these assumptions, we were able to investigate the interplay between hydraulic properties and recharge, the long-term effectiveness of pumping reduction based groundwater conservation strategies, and estimate the extension of the usable aquifer lifetime for both the lateral-flow- and recharge-dominated cases.

4. Conclusions

In this study, we demonstrate that groundwater conservation strategies based on pumping reductions are an effective method for conserving groundwater over a period of decades. Our results indicate that there are two possible controlling mechanisms, lateral groundwater inflow and recharge, that ultimately govern the long-term effectiveness of such conservation initiatives. We found that larger reductions in pumping result in a longer extension of the usable aquifer lifetime, and that this impact wanes toward the edges of the conservation area. However, we also found that reductions in pumping result in a groundwater mound relative to the surroundings that alters the regional hydraulic gradient, so that the benefits of groundwater conservation programs may extend beyond the areas implementing conservation practices. These results show that initial water table data might overestimate the long-term effectiveness of pumping reduction-based groundwater conservation , and that a robust understanding of the local geology and groundwater flow are imperative for designing resource conservation programs and communicating their likely future path to the stakeholder community.

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Supplemental Information

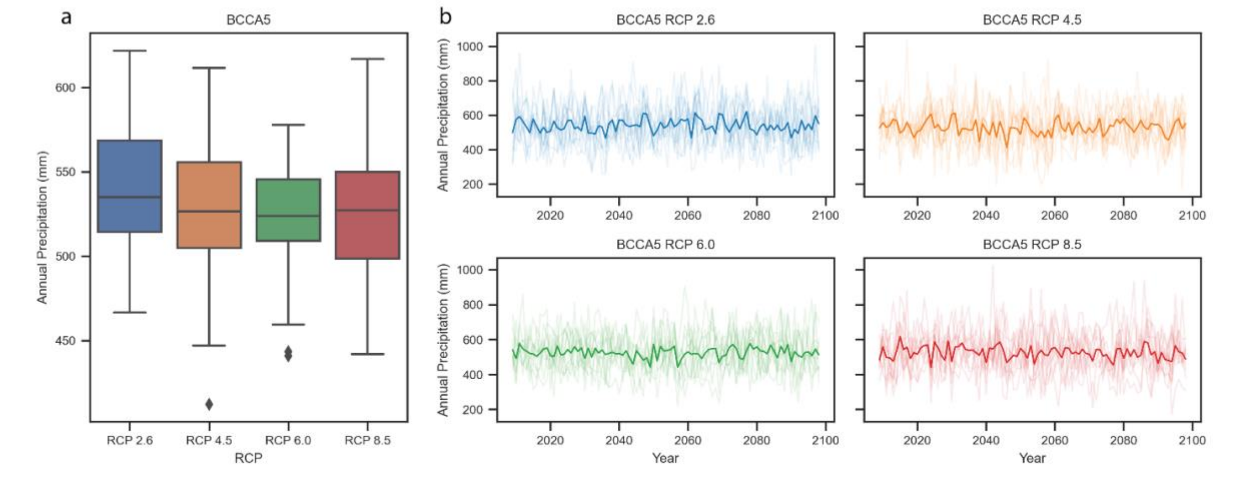

Figure S1: We used aggregated daily bias correction constructed analogs (BCCAs) for precipitation data from downscaled Coupled Model Intercomparison Project 5 (CMIP5) data in the area of the Sheridan-6 Local Enhanced Management Area to assess if there were any long-term trends in precipitation that needed to be considered. From the a.) boxplot displaying the ensemble mean and the b.) individual time series (lighter color) and ensemble mean (dark line) for each representative concentration pathway it is clear that there are no long-term trends in forecasted precipitation for this area.