An Overview of the Q-Stable Analysis

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1. Introduction

The High Plains aquifer (HPA) has been stressed by decades of large-scale irrigation pumping, leading to significant declines in groundwater levels that threaten the livelihood of the region. In portions of the HPA in Kansas, water levels have declined by more than 60% since the onset of large-scale pumping for irrigated agriculture (Whittemore et al., 2023a), and the aquifer is already nearing the end of its usable lifetime in some locations (Buchanan et al., 2023). Because of the large imbalance between pumping and recharge, the only viable means to reduce water-level declines in the near term is to decrease pumping. Butler et al. (2016) presented a method, called Q-stable, for estimating a level of pumping that would lead to approximately stable water levels at the timescale of several years to decades. This document summarizes the key considerations involved in the implementation of the Q-stable analysis in the Kansas HPA.

2. Key Considerations

Estimation of Q-stable

Throughout the HPA, irrigation pumping is the dominant driver of annual water-level changes, especially in the western third of Kansas, where surface water is almost nonexistent and water table depths are great enough to preclude rapid recharge. Under these conditions, analysis of the annual aquifer water budget for an area leads to a linear relationship between the average annual water-level changes and total annual pumping (Figure 1). Q-stable, the annual pumping value that would lead to a water-level change of zero, is computed from the best-line fit to the observed data as shown in Figure 1a. Stabilized water levels occur when pumping equals the net inflow to the aquifer, where net inflow represents the sum of all inflows to the aquifer minus the sum of all outflows other than pumping (Figure 2). As a result of the decades-long annual water-level measurement program and the required metering of non-domestic pumping wells, the Kansas HPA region has excellent data for estimating Q-stable and the method has been successfully applied to areas ranging in size from groundwater management districts down to several townships (Butler et al., 2018).

Assessment of Data Quality

Assessment of data quality is an important component of the Q-stable estimation procedure, because outlying or unusual data points can have a significant effect on the estimate (Butler et al., 2023a). Although outright errors in water-level measurements may contribute to outlying values of average water-level change (particularly in smaller areas with fewer monitoring wells), significant outliers are often due to more systematic factors, such as late-season pumping (resulting in lower than normal water levels in January, when annual water-level measurements are taken). Thus, although outliers can be identified using statistical criteria, human review is required to determine the best way to handle outlying data to obtain a representative Q-stable estimate. For example, heavy snows significantly delayed the

2007 water-level measurements in northwestern Kansas, leading to an abnormally long time between the 2006 and 2007 measurements and an abnormally short one between the 2007 and 2008 measurements. Consequently, after review, we averaged the 2006 and 2007 water-level change and pumping values and represented them as a single point (2006-7) in Figure 1. Figure 1b illustrates how we compute the uncertainty in the Q-stable estimate to convey the confidence in that estimate.

Assessment of Impact of Pumping Reductions and Monitoring Changes in Net Inflow

The Q-stable analysis can be used to both project and measure the aquifer's response to pumping. We have developed simple approaches to assess the effect of pumping reductions using pumping, water-level, and precipitation data (Figure 3; Whittemore et al., 2023b; Butler et al., 2023b). These approaches, which have been demonstrated at the groundwater management district and local enhanced management area levels, could be applied on an annual basis to provide ongoing assessment of reduction impacts.

The Q-stable approach assumes that net inflow is approximately constant over the period of analysis, a condition that appears to have held throughout the HPA for the past few decades and that we anticipate will hold for the near future. However, in groundwater conservation areas, we expect net inflow to eventually start decreasing due to reduction of irrigation return flows (due to less water being applied on the land surface) and other components of the aquifer water budget. Reduction in net inflow will lead to a shift of the water-level change versus pumping relationship (Butler et al., 2016), so these plots should be updated annually to monitor for such changes (Figure 3b). If changes are detected, further pumping reductions will be needed to achieve stable water levels under future conditions. Simulation of plausible future net inflow reductions could be used to estimate remaining aquifer lifetimes under different pumping management scenarios (Butler et al., 2020).

3. County Scale Application

We applied Q-stable analysis at the county scale across the HPA using data for 2010 to 2023. Figure 4 shows the computed net inflows as the total amount of water that enters the aquifer each year in acre-feet and, in parentheses, inches per acre. Figure 5 plots the percent reduction in the annual average groundwater pumping needed to match the net inflow volumes (i.e., stable water levels).

Several components that make up the net inflow (Figure 2) are tied to pumping, such as irrigation return flows and continued drainage from de-watered aquifer units. Because of this, counties that have higher levels of water usage tend to have higher net inflows. However, they also have relatively higher estimated percent reductions in pumping due to greater water-level declines. In south-central Kansas, increasing precipitation rates from west to east in combination with shallower depths to water, and sandy soils, allow for higher rates of precipitation recharge, in contrast with western Kansas inflows, which are more pumping-induced and transitory in nature. As a result, the counties in south-central Kansas generally have higher net inflows relative to pumping and thus lower pumping reduction percentages.

Each county area in Figures 4 and 5 is shaded based on the R-squared value, representing the percentage of variations in water level changes explained statistically by the variations in pumping. Counties with low

R-squared values (rose-shaded on the maps) denote areas of potentially high uncertainties. As mentioned earlier, this uncertainty in the relationships between water-level change and pumping often originates from sparse or incomplete measurement histories or non-representative depth-to-water measurements. These shortfalls can be overcome in part by identifying areas with relatively uniform aquifer conditions and irrigation practices. Current projects at the KGS (e.g., airborne electromagnetic surveys) will help to identify such areas for future Q-stable analyses.

4. Final Thoughts

Experience in western Kansas has shown that we can compute Q-stable with confidence on the scale of areas of two to three townships or larger. The plotting approach shown in Figure 1 also allows us to estimate the uncertainty. The major unknown is when net inflow, and thus Q-stable, will start to decrease in response to pumping reductions. Monitoring over time will eventually clarify that issue. In the Sheridan-6 LEMA, now 11 years after implementation of pumping reductions (Figure 3b), we have not yet detected significant changes in net inflow. At the Kansas Geological Survey, we are continuing to pursue research on net inflow to develop a better understanding of when such changes will occur.

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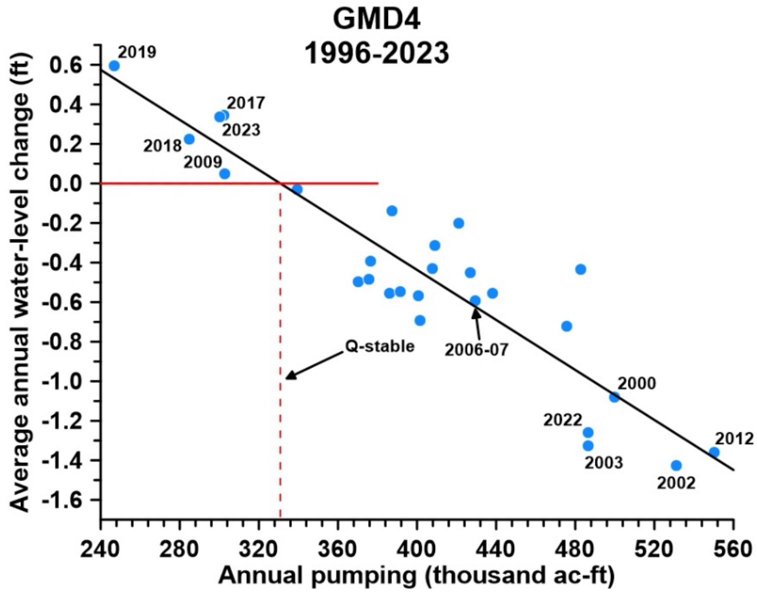
(a)



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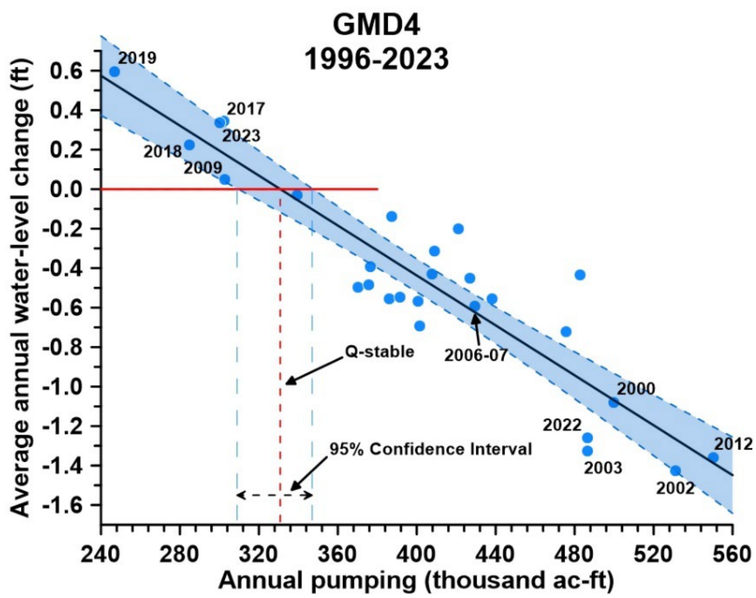


Figure 1. a) Average annual water-level change versus total pumping in Groundwater Management District 4 from 1996 to 2023 with best-fit line (solid line, R^2=0.84). Data values for 2006 and 2007 have been averaged and represented as a single point (2006-7, see text). The red vertical dashed line represents Q-stable, the annual pumping (331 thousand acre-ft) that results in a water-level change of 0 on the best-fit line. Dates represent the five years with the most and the least annual pumping during this period. b) Plot illustrating method to estimate the uncertainty in the Q-stable estimate. The shaded blue area represents the 95% confidence interval about the best-fit line. The intersection of the horizontal red line with the boundaries of the confidence intervals defines the 95% confidence interval for the Q-stable estimate (horizontal black line with arrows, 294 to 354 thousand acre-feet).

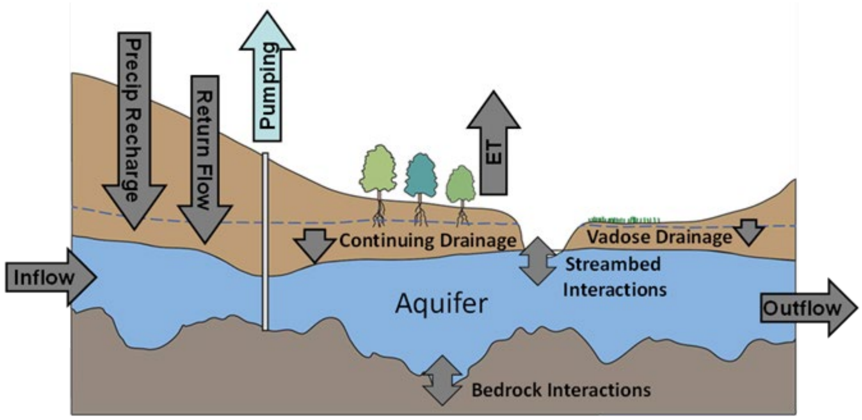
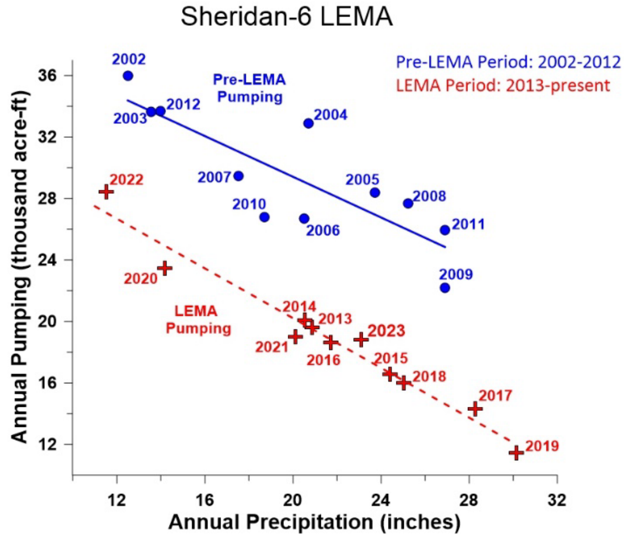


Figure 2. Typical aquifer water budget. In the Q-stable approach, all inflows and outflows other than pumping are lumped together as net inflow (ET stands for evapotranspiration).

(a)



(b)

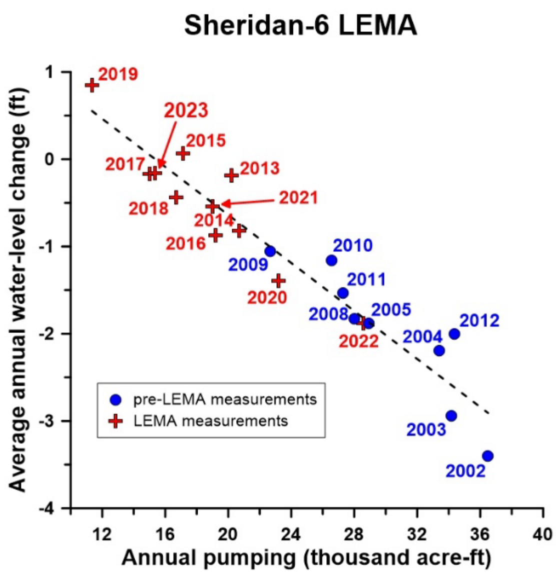


Figure 3. a) Total annual pumping versus annual precipitation in the Sheridan-6 Local Enhanced Management Area (LEMA) before (2002–2012) and after (2013–2022) establishment of the LEMA, demonstrating a significant reduction in pumping (LEMA vs. pre-LEMA) for comparable precipitation conditions (after Whittemore et al., 2023a). b) Average annual water-level change versus annual pumping in the Sheridan-6 LEMA demonstrating a significant reduction in the water-level decline rate and pumping after the establishment of the LEMA. The linear relationship (R^2 of best-fit line is 0.92) exhibited by the pre-LEMA and LEMA data in the lower figure indicate that net inflow, and thus Q-stable, has changed little since 2002. If the net inflow begins to decrease, values will fall below the current linear plot (after Butler et al., 2023b).

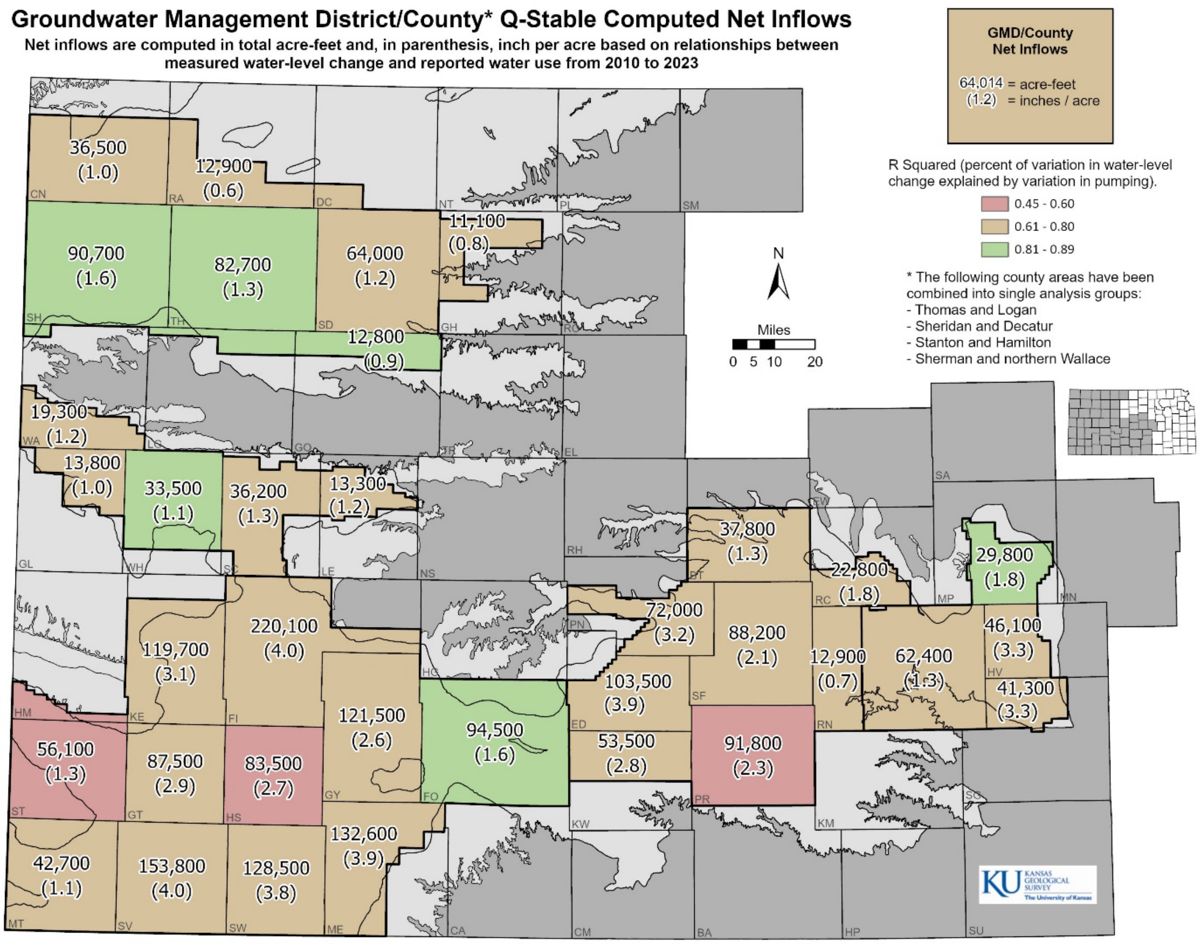


Figure 4. Computed net inflows, based on water-level change and reported groundwater usage from 2010 to 2023, by county areas within groundwater management districts. Confidence intervals, not shown, have been calculated for all Q-stable estimates.

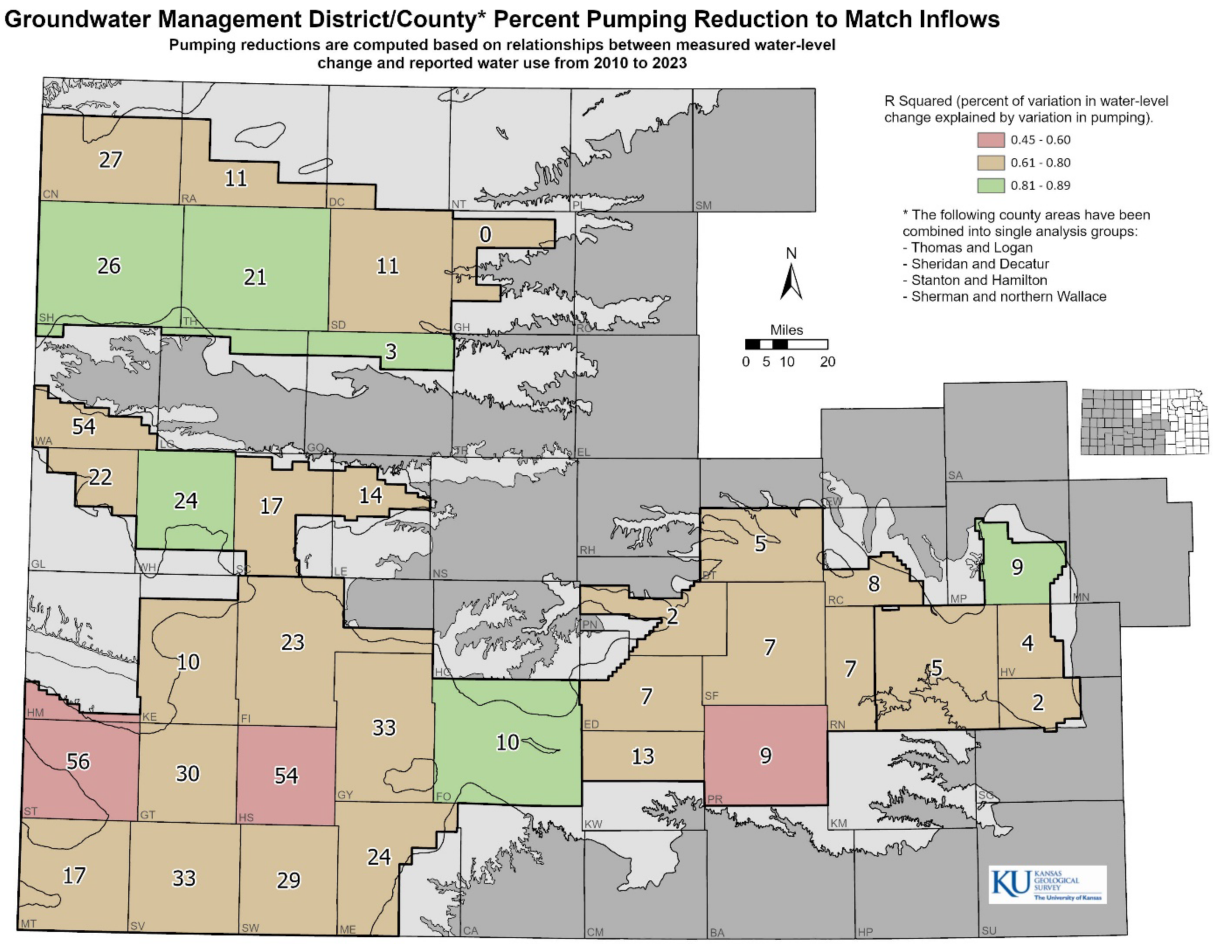


Figure 5. Computed percent reduction in average use to achieve stable water levels, based on water-level change and reported groundwater usage from 2010 to 2023, by county areas within groundwater management districts.

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