Groundwater

Net Inflow: An Important Target on the Path to Aquifer Sustainability

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Abstract

Aquifers supporting irrigated agriculture are a resource of global importance. Many of these systems, however, are experiencing significant pumping-induced stress that threatens their continued viability as a water source for irrigation. Reductions in pumping are often the only option to extend the lifespans of these aquifers and the agricultural production they support. The impact of reductions depends on a quantity known as "net inflow" or "capture." We use data from a network of wells in the western Kansas portions of the High Plains aquifer in the central United States to demonstrate the importance of net inflow, how it can be estimated in the field, how it might vary in response to pumping reductions, and why use of "net inflow" may be preferred over "capture" in certain contexts. Net inflow has remained approximately constant over much of western Kansas for at least the last 15 to 25 years, thereby allowing it to serve as a target for sustainability efforts. The percent pumping reduction required to reach net inflow (i.e., stabilize water levels for the near term [years to a few decades]) can vary greatly over this region, which has important implications for groundwater management. However, the reduction does appear practically achievable (less than 30%) in many areas. The field-determined net inflow can play an important role in calibration of regional groundwater models; failure to reproduce its magnitude and temporal variations should prompt further calibration. Although net inflow is a universally applicable concept, the reliability of field estimates is greatest in seasonally pumped aquifers.

Introduction

Irrigated agriculture is the largest user of groundwater globally (Siebert et al. 2010). That intensive use has come at a price, as many aquifers supporting irrigated agriculture are under stress and face a highly uncertain future (Alley and Alley 2017). Extending the lifespan of these aquifers and the food production and regional economies that they support have thus become issues of worldwide importance.

Groundwater-based irrigation is common in many semi-arid areas. There is often little surface water to substitute for groundwater, so reductions in pumping, which are typically accompanied by modifications of agricultural practices, are often the only option to diminish decline rates and extend aquifer lifespans (Hu et al. 2010; Deines et al. 2019; Butler et al. 2020a, 2020b). The critical questions then become (1) how much should pumping be reduced to have a significant impact on water-level decline rates, and (2) is there a possibility of stabilizing water levels for at least the short to medium term?

Data from the High Plains aquifer (HPA) in western Kansas can provide insights into how these questions can be addressed. This portion of the HPA has been heavily stressed for decades, producing large water-level declines that have called into question the continued viability of groundwater-supported irrigated agriculture and the rural communities that depend on it (Figure 1; Buchanan et al. 2015). In response to this condition, Kansas developed the Local Enhanced Management Area (LEMA) program in 2012. This is a grassroots-based initiative for pumping reductions that is supported by regulatory oversight (Kansas Statutes Annotated 82a-1041 2012). The first LEMA was established in 2013 in a 255 km^2 area in northwest Kansas, the Sheridan-6 Local Enhanced Management Area (SD-6 LEMA; yellow polygon in Figure 1), and has the goal of reducing average annual groundwater use by 20% (Northwest Kansas Groundwater Management District No. 4 2016). Figure 2a is a plot of annual water-level change (ΔWL) vs. annual pumping (Q) for the SD-6 area. The linearity of this plot of pre-LEMA (prior to the pumping reductions initiated in 2013) and LEMA (2013 and later) data is

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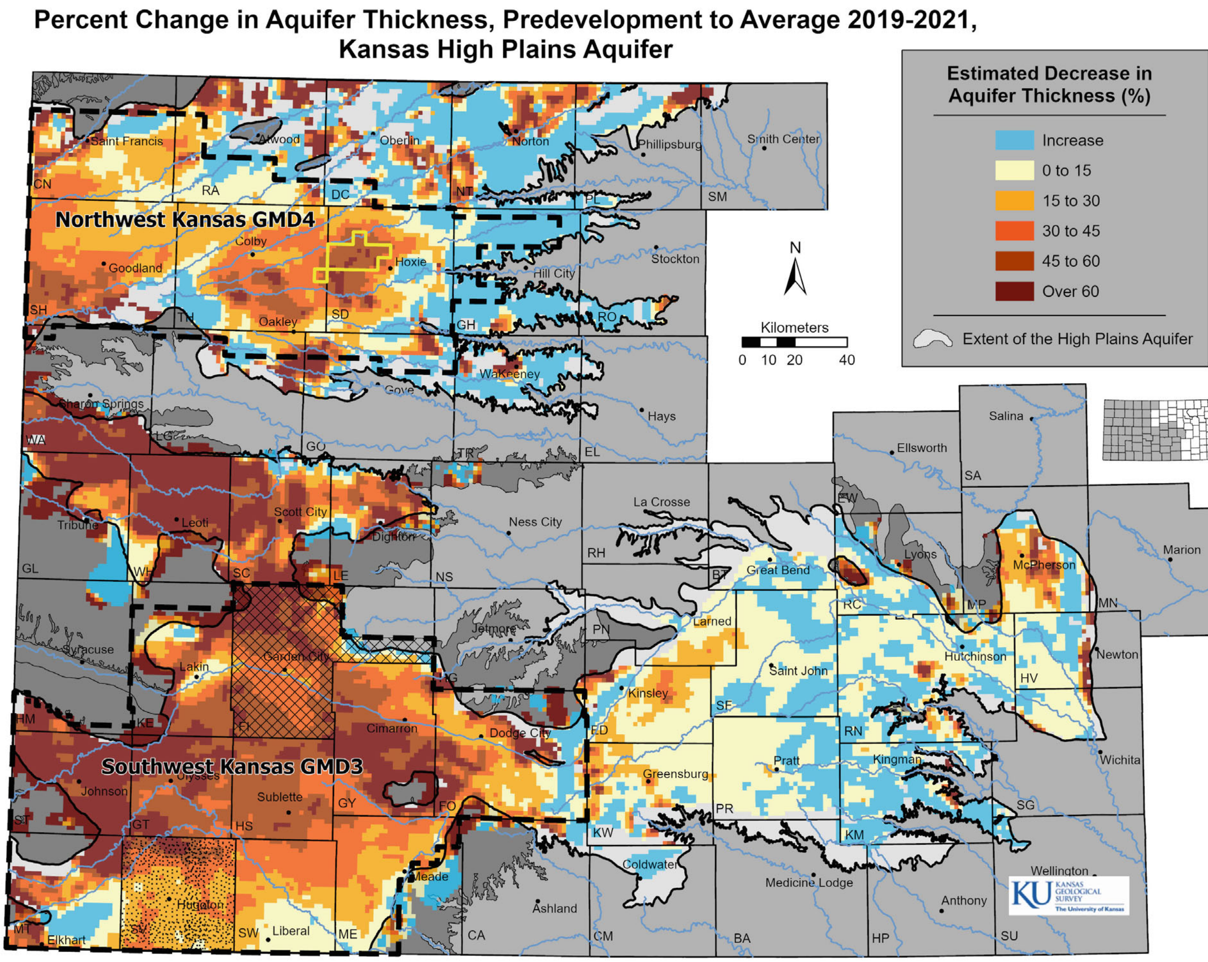

Figure 1. Map of the percent change in aquifer thickness from predevelopment to present for the HPA in Kansas (the inset on the right shows the portion of the state pictured here). Predevelopment is defined as period prior to onset of widespread pumping for irrigated agriculture, which occurred between 1940 and the late 1950s in most of the Kansas HPA; present is defined as average of 2019 to 2021 winter conditions. GMD3 and GMD4 are delineated by dashed black lines. The yellow polygon in GMD4 is the SD-6 LEMA; the crosshatched region in GMD3 marks the portions of Finney County lying within GMD3 and the county marked by the stippled pattern in southern GMD3 is Stevens County. The areas of aquifer increase in the western third of the figure are areas of thin aquifer that are of little practical importance.

striking, but is common in ΔWL vs. Q plots across the Kansas HPA (Whittemore et al. 2018). Butler et al. (2016, 2018) have shown that the intercept over the slope of the best-fit line to these plots yields a quantity that they term "net inflow." Figure 2b is a plot of annual pumping and cumulative water-level change vs. time for the SD-6 area; the horizontal dashed line is the net inflow calculated from Figure 2a. The decline rate moderates and then reverses as the annual pumping approaches and drops below, respectively, the net inflow. This indicates that net inflow is likely one of the primary determinants of how decline rates will be impacted by pumping reductions for at least the near term (several years to few decades). Thus, it appears that a key quantity needed to assess the near-term response to pumping reductions can be directly estimated from field data.

The purpose of this paper is to explore the net inflow concept and its practical utility. We begin by relating it to the well-known "capture" theory (Lohman et al. 1972; Bredehoeft 2002; Konikow and Leake 2014) and explain why use of "net inflow" may be preferred over "capture" in some contexts. We then demonstrate the utility of the field-calculated net inflow at a range of spatial scales through a series of applications in the HPA in western Kansas. Net inflow can change over time, so we also discuss the importance of monitoring those changes and their ramifications for the impact of pumping reductions on decline rates. We conclude with a brief discussion of the importance of the timing and quality of the water-level and pumping measurements used to estimate net inflow.

Net Inflow

Definition and Determination

The aquifer water balance can be written in its simplest form as:

$$\textit{Water volume change in aquifer} = \textit{Inflows} - \textit{Outflows} \tag{1}$$

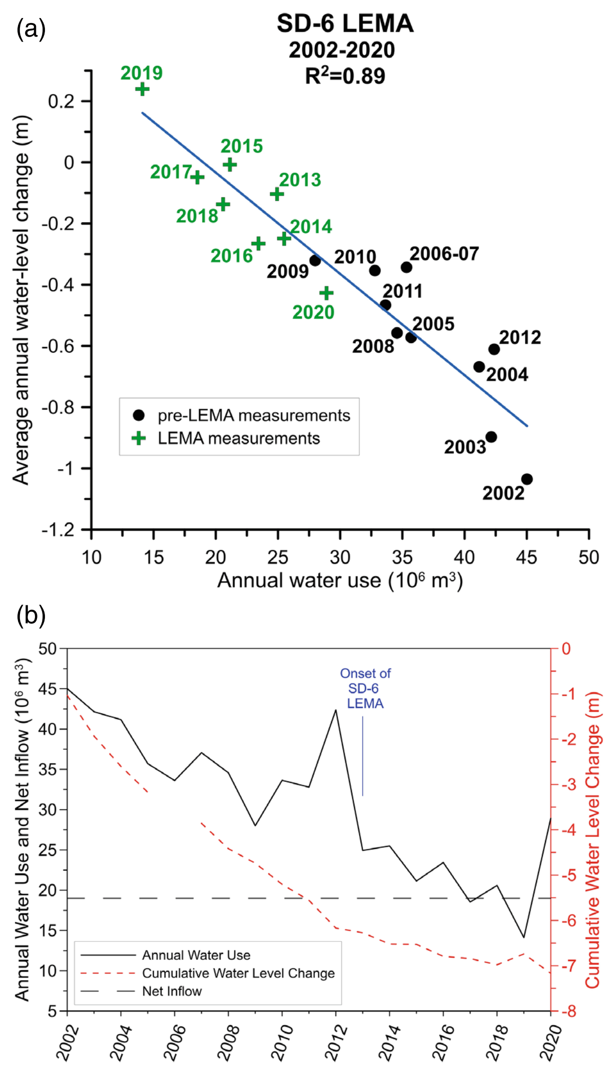

Figure 2. (a) Average annual water-level change (ΔWL) vs. annual water use (Q) plot for the SD-6 LEMA in GMD4. Solid line is the best fit to the 2002 to 2020 data ($\Delta WL = 0.6286 - 0.03310Q$, $p < 0.0001$). ΔWL for the circles is the average water-level change for the seven wells measured every year from 2002 to 2012 (pre-LEMA wells); ΔWL for the pluses is the average for the pre-LEMA wells with two, three, and four additional wells (2013, 2014 to 2015, and 2016 to 2020, respectively) that were drilled later (Butler et al. 2018). Heavy snows delayed 2007 water-level measurements from early January to late February through early April, so the average ΔWL value for 2006 and 2007 is used here. Annual water use is sum of reported use from a maximum of 195 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ± 0.19 m and that in Q is $\pm 0.4\%$ of plotted value (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). Data are provided in Table S1. (b) Annual water use (left y-axis) and cumulative water-level change (right y-axis) vs. time for the SD-6 LEMA in GMD4. Large dashed line is the average net inflow (left y-axis) calculated from (a); onset of LEMA pumping reductions (2013) is marked by vertical line and gap in the cumulative water-level change plot is due to the lack of the 2006 ΔWL value. The estimated uncertainty (one standard deviation) in net inflow is 1.3×10^6 m^3 (determined using methods described in Butler et al. 2016 and Bohling et al. 2021).

Although the quantification of the individual fluxes contributing to aquifer inflows and outflows has been a long-term objective of groundwater hydrology, it is still rarely achievable in practice beyond heavily instrumented research sites. As a result, Butler et al. (2016) proposed lumping all aquifer inflows and all outflows save pumping into a term they designated as "net inflow." Equation 1 can then be rewritten as:

$$\textit{Water volume change in aquifer} = \textit{Net Inflow} - \textit{Pumping} \tag{2}$$

Butler et al. (2016, 2018) show how Equation 2 can be rewritten for an area of an unconfined aquifer like the HPA in Kansas as:

$$\Delta WL = \frac{I}{Area \times S_Y} - \frac{Q}{Area \times S_Y} \approx b - aQ \tag{3}$$

where ΔWL is the average water-level change for the area (L), S_Y is the specific yield (–), I is net inflow (L^3), Q is pumping (L^3), and a and b are constants, with all quantities typically defined on an annual time frame. Equation 3 is consistent with the cumulative water-level plot in Figure 2b, as setting Q equal to or below I will result in stable or increasing water levels, respectively.

Linearity of a plot of ΔWL vs. Q indicates that I and S_Y are approximately constant, so that I can be estimated by dividing the intercept (b) by the slope (a), and S_Y can be estimated from the slope parameter. Butler et al. (2016) explain that a near-constant S_Y would be expected for the analysis of aquifer areas of a few hundred square kilometers or greater as heterogeneities would tend to be averaged out within the same aquifer unit. Net inflow could vary more, depending on the primary mechanisms contributing to it and the depth to water. However, as long as S_Y is nearly constant, the average I and its variations in time can be readily calculated. In all cases, a plot of ΔWL vs. Q will reveal if the assumptions underlying the approximation on the right-hand side of Equation 3 are appropriate.

The term "net inflow" was first proposed by Hill (1946) in a six-page discussion following a paper by Conkling (1946). Hill appears to have developed an approach similar to that described above by taking a method used in surface reservoir studies and applying it to aquifers. The term fell into disuse in the two decades following the Hill discussion and was independently proposed by Butler et al. (2016). Hill (1946) noted that net inflow would vary much less than typical hydrologic phenomena, consistent with our findings in the Kansas HPA (Butler et al. 2020a).

Relation to Capture

Theis (1940), in one of the fundamental papers underlying our discipline, pointed out that water pumped from a well must be "balanced by a loss of water somewhere." A portion of the discharged water from a well comes from a loss of aquifer storage (i.e., groundwater mining or aquifer depletion), while the rest comes from increased recharge and/or decreased discharge. This second portion was later labeled capture (Lohman et al. 1972) in the sense that the well has captured flow that otherwise would have gone elsewhere. The captured volume at any particular time can be calculated as the difference between the pumping volume and the change in aquifer storage (i.e., same as net inflow; Equation 2). This calculation is typically done with water-level data, the best available estimate of pumping, and an estimate of specific yield (Konikow 2013). Recent work, however, has shown that the common values used for specific yield in many modeling studies may not be representative of conditions in often highly heterogeneous aquifers (Butler et al. 2020a; Liu et al. 2022). Under certain conditions, stream depletion, a major component of capture in interconnected stream-aquifer systems, can be estimated directly (Barlow and Leake 2012).

The definition of capture stresses the role of head-dependent boundary conditions, and the primary examples used to illustrate the concept, hypothetical aquifers in arid basins or on circular islands, aptly illustrate that role and the appropriateness of the term "capture" (Bredehoeft 2002). However, the term may be less intuitive when applied to the budget of an area within a much larger aquifer, such as the SD-6 LEMA (Figure 1). Furthermore, Barlow et al. (2018) point out the confusion that can arise between the "capture" and "capture zone" terminology and state that the "capture zone" concept appears to be better understood by the groundwater community.

Net Inflow or Capture?

Net inflow and capture describe the same phenomenon, but use of net inflow may have advantages over capture in certain contexts. First, the term encapsulates the budget-based definition. Second, as shown in the Introduction, it can be directly estimated from field data and is a clear target quantity for groundwater conservation efforts, particularly in areas such as the Kansas HPA where data have shown that net inflow has been near stable for the last quarter of a century (Butler et al. 2018). Third, it is more accessible to stakeholders who can readily grasp the budget-based definition. Finally, the confusion between "capture" and "capture zones" discussed by Barlow et al. (2018) can be avoided.

Western Kansas Demonstrations

Water use in Kansas is regulated by the Division of Water Resources of the Kansas Department of Agriculture. In the Kansas HPA, the Division works in conjunction with five groundwater management districts (GMDs), which were established to allow local input into the management of the water resources in their areas (Buchanan et al. 2015). In the following paragraphs, we examine how net inflow changes between and within two western Kansas GMDs.

Northwest Kansas Groundwater Management District No. 4 (GMD4) is a 12,623 km^2 area in northwestern Kansas (Figure 1). Figure 3 is a plot of annual pumping

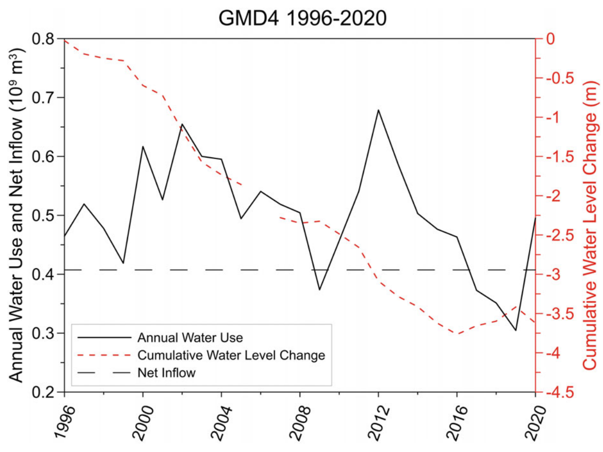

Figure 3. Annual water use (left *y*-axis) and cumulative water-level change (right *y*-axis) vs. time for GMD4. Large dashed line is the average net inflow (left *y*-axis) calculated from Figure S1; gap in the cumulative water-level change plot is due to the lack of the 2006 ΔWL value (see further explanation in Figure S1). The estimated uncertainty (one standard deviation) in net inflow is 0.012×10^9 m^3 (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). Data are provided in Table S2.

and cumulative water level change vs. time for the GMD4 area from 1996 to 2020; the horizontal dashed line is the net inflow calculated from a plot of water-level change vs. annual pumping (Figure S1, supporting information). In the four wettest years during this period (2009, 2017 to 2019), annual pumping was below net inflow and water levels increased. In all other years, water levels decreased with the largest declines occurring in the four driest years (2000, 2002 to 2003, and 2012). Although water levels rose in the wettest years, that rise was not produced by same-year recharge, as the thick (January 2021 average of 42.7 m) and heterogeneous vadose zone in GMD4 prevents rapid downward movement of surficial recharge (Butler et al. 2021a). Instead, the rise in water levels was produced by an annual pumping that was below the relatively constant net inflow because of the large amount of precipitation during the irrigation season in those years. The pumping reduction that would be required to reach net inflow each year, on average, across the region is 19% when calculated using the 1996 to 2020 data; this estimate is consistent with the 23% reduction calculated by Butler et al. (2018) using the 1996 to 2016 data. The percent pumping reduction, in this case 19%, is also the percent of the average annual pumping that is supplied by aquifer depletion. In other words, 81% of the average annual pumping is supplied by net inflow. Although the success of the SD-6 LEMA (2% of the GMD4 area) led to the establishment of a LEMA across the entire district in 2018, the initial reduction goals for the district-wide LEMA are modest and have yet to have a discernible impact on decline rates.

A fundamental assumption of this approach to estimate net inflow is that the measured average annual water-level change is representative of the actual average annual change over the area. Although that cannot be checked rigorously in the field, it can be checked with a recently completed groundwater model of GMD4 (Wilson et al. 2021). The average water-level change calculated from the 19,211 model cells in the active area in GMD4 can be compared to the average change calculated from the 174 cells at the locations of wells measured every year from 1996 to 2021 (cells ≈ 804 m by 804 m [0.5 miles on a side]). The comparison shows that the average from the 174 wells is in good agreement with the average from all the active cells in GMD4 (Figure S2); the net inflow estimates are within 0.65% of each other. Thus, the assumption appears reasonable for assessments at the scales considered here.

Southwest Kansas Groundwater Management District No. 3 (GMD3) is a 21,605 km^2 area in southwestern Kansas (Figure 1). Pumping data prior to 2005 appear suspect (Butler et al. 2018), so net inflow calculations are based on the 2005 to 2020 data. Figure 4a is a plot of annual water-level change vs. annual pumping for GMD3 (see later discussion of data noise). Figure 4b is a plot of annual pumping and cumulative water-level change vs. time for the GMD3 area; the horizontal dashed line is the net inflow calculated from Figure 4a. The pumping reduction that would be required to reach net inflow each year, on average, across the district is 18% (82% of the average annual pumping is supplied by net inflow). This is consistent with the 23% reduction from a reanalysis of the Butler et al. (2018) calculations using the 2005 to 2016 data (Text S1). Despite the large declines experienced in the district, no LEMAs have been established in GMD3. The observed stabilization of water levels from 2017 to 2019 (Figure 4b) was produced by a series of wetter-than-average years (labeled on Figure 4a) that reduced the need for pumping rather than by the establishment of a LEMA or similar conservation program.

The above estimates of required pumping reductions are averages across each district. However, there can be a great deal of variability within districts. Finney County (2691 km^2 in GMD3; cross-hatched area in Figure 1) on the northern boundary of GMD3 illustrates similar behavior to the district-level evaluation (Figures S3a and S3b). In this case, the pumping reduction that would be required to reach net inflow is 18%, consistent with the district-wide results. In contrast, Figure 5a is a plot of annual pumping and cumulative water-level change vs. time for Stevens County (1884 km^2; stippled area in Figure 1) on the southern boundary of GMD3. The two pairs of dashed lines are the results of two interpretations of a noisy plot of water-level change vs. annual pumping (Figure 5b, see later discussion). These interpretations lead to two estimates of the percent reduction required to reach stable water levels (37 and 40%), both of which are over twice that required in Finney County. Similar differences to those between Finney and Stevens counties have been observed at the county and subcounty level in all three GMDs in western Kansas. These differences

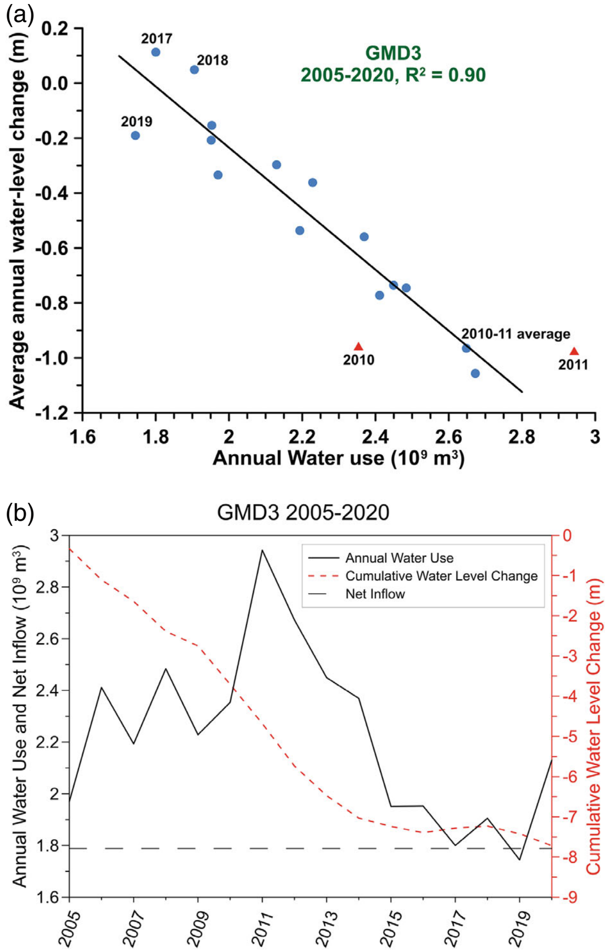

Figure 4. (a) Average annual water-level change (ΔWL) vs. annual water use (Q) plot for GMD3. Solid line is the best fit to the 2005 to 2020 data ($\Delta WL = 1.9886 - 1.1116Q$, $p < 0.0001$) using the average ΔWL and Q values for 2010 to 2011 (see Text S2). ΔWL is the average computed using the 251 wells measured every year from 2005 to 2021. Q is the sum of reported use from a maximum of 15,175 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.070 m and that in Q is ±0.05% of plotted value (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). Data are provided in Table S3. (b) Annual water use (left y-axis) and cumulative water-level change (right y-axis) vs. time for GMD3. Large dashed line is the average net inflow (left y-axis) calculated from (a). The estimated uncertainty (one standard deviation) in net inflow is 0.076 x 10^9 m^3 (determined using methods described in Butler et al. 2016 and Bohling et al. 2021).

reveal the importance of the areal scale of the analysis for determining the needed pumping reductions. Zwickle et al. (2021) in an interdisciplinary evaluation of the SD-6 LEMA stress the need to focus on establishing LEMAs and similar management structures in relatively small areas in which aquifer conditions and producer practices do not vary greatly. They state that efforts to establish LEMAs over larger areas could encounter greater problems with adoption because of the lack of homogeneity in terms of aquifer conditions and producer practices and attitudes.

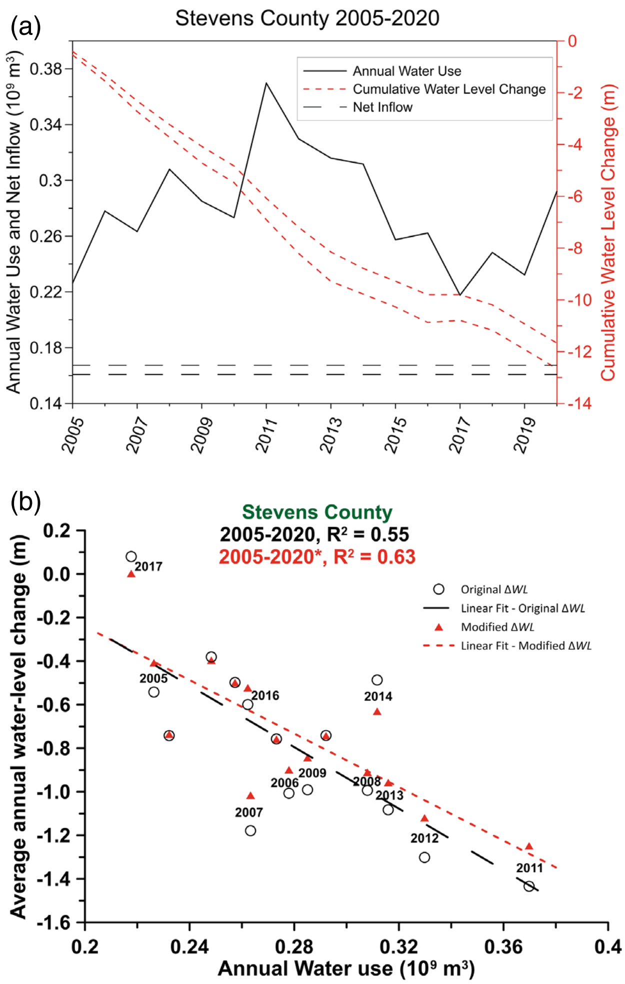

Figure 5. (a) Annual water use (left y-axis) and cumulative water-level change (right y-axis) vs. time for Stevens County in GMD3. Large dashed lines are the average net inflow (left y-axis) calculated from (b). The lower cumulative ΔWL line and the upper net inflow line are based on the solid circles in (b), while the upper cumulative ΔWL line and the lower net inflow line are based on the modified ΔWL values (triangles in (b)). The estimated uncertainty (one standard deviation) in net inflow is 0.032×10^9 m^3 for lower line and 0.12×10^9 m^3 for upper line (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). (b) Average annual water-level change (ΔWL) vs. annual water use (Q) plot for Stevens County in GMD3. Large dashed line is the best fit to the 2005 to 2020 data ($\Delta WL = 1.1825 - 7.0623Q$, $p = 0.00094$) with ΔWL being the average computed using the 21 wells measured every year from 2005 to 2021. Small dashed line is the best fit to the modified 2005 to 2020 data ($\Delta WL = 0.9879 - 6.1453Q, p = 0.00022$) with ΔWL being the modified average described in the text (triangles represent the modified values). In both cases, Q is the sum of reported use from a maximum of 1214 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ± 0.18 m and ± 0.14 m for the original and modified data, respectively, and that in Q is $\pm 0.2\%$ of plotted value (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). The years with sizable differences between the two quantities are labeled; data are provided in Table S4.

Temporal Variations in Net Inflow

The above analyses have resulted in an average value for net inflow. However, net inflow would be expected to vary somewhat with time. One approach to assess temporal trends would be to perform the analysis over segments of the ΔWL vs. Q plot. Figure 6a presents a plot of water-level change vs. annual pumping for the first and last halves of the GMD4 data series. This plot reveals the problems associated with such an approach; the four wettest years in the 1996 to 2020 period were after 2008 so, despite the good fit to the first half of the data series, the lack of data during wet years limits confidence in the results. Thus, trend detection using such plots requires that the individual segments sample the full range of climatic conditions expected in the area.

An alternative approach is to calculate the net inflow each year and assess trends in that time series. This is done by assuming the S_Y estimated from the ΔWL vs. Q plot remains constant over the entire period and substituting it, along with the annual ΔWL and Q values, into Equation 3 to calculate I for each year. This is admittedly a worst-case analysis, as we are assuming that all of the regression residual is attributable to annual variations in I, but it is useful for a first-order assessment of temporal trends. Figure 6b is an example of this approach for the GMD4 data series. Net inflow varies from year to year but the variations are relatively small (Coef. of Variation = 0.10), consistent with the findings of Butler et al. (2020a). Visually, there appears to be a slight decreasing trend over the 25-year period (0.27%/year) but it is not statistically significant ($R^2 = 0.04$, p = 0.30); moreover, removal of 1 year on either end of the time series results in an even more negligible trend (0.11%/year; $R^2 = 0.01$, $p = 0.70$). Thus, the assumption of a near-constant I appears reasonable for this period.

The variations in Figure 6b are related to a variety of factors including errors in water-level measurements and reported pumping data, pumping shortly before the annual measurements, small fluctuations in S_Y, and climatic forcings. Given that the majority of the annual water-level measurements are completed within a few days in each area and that wells in the unconfined western Kansas HPA display atmospheric-pressure-driven water-level fluctuations that can be up to 0.3 m in magnitude (Butler et al. 2021b), year-to-year variations in atmospheric pressure can be an important climatic contributor to the apparent temporal variations in net inflow.

The data plots presented here indicate that net inflow has remained approximately constant across GMDs 3 and 4 for the last 15 to 25 years. However, trends in net inflow should eventually arise from both natural (e.g., climate-induced changes in recharge) and anthropogenic (e.g., changes in pumping) forcings. Although we have not observed net inflow trends in the SD-6 LEMA (Figure 2a), we expect that the pumping reductions will eventually lead to a decrease in I as a result of reductions in irrigation return flow, changes in lateral hydraulic gradients, and so on (Butler et al. 2020b; Glose

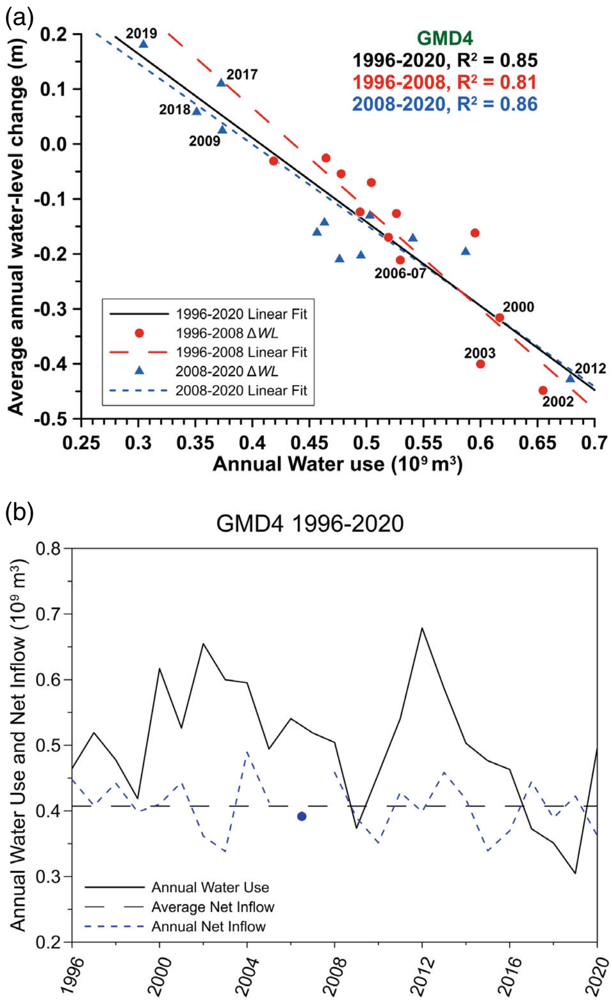

Figure 6. (a) Average annual water-level change (ΔWL) vs. annual water use (Q) plot for GMD4. Solid line is the best fit to the 1996 to 2020 data, large dashed line is the best fit to the 1996 to 2008 data, and small dashed line is the best fit to the 2008 to 2020 data. The average ΔWL and Q values for 2006 to 2007 are used in the 1996 to 2020 and 1996 to 2008 plots. Years with the highest and lowest water use during the period and 2006 to 2007 are labeled; data are provided in Table S2. See caption in Figure S1 for further information. (b) Annual water use and average and annual net inflow vs. time for GMD4. The large dashed line is the average net inflow calculated from the solid line in (a), while the small dashed line is the annual net inflow calculated as described in text; the circle is the average annual net inflow for 2006 and 2007. Uncertainty estimates (one standard deviation) in annual water use, average net inflow, and annual net inflow are ±0.09% of plotted value, 0.012×10^9 m^3, and 0.041×10^9 m^3, respectively (determined using methods described in Butler et al. 2016 and Bohling et al. 2021). Data are provided in Table S2.

et al. 2022). The reductions in I would be revealed on ΔWL vs. Q plots by a downward shift in the data points (i.e., the same pumping would produce a greater water-level decline). The slope of the plot should not change because S_Y will vary little at this spatial scale if water levels remain in the same hydrogeologic unit. Similarly, increases in I would be revealed by an upward shift in the data points.

Many of the literature examples of capture illustrate a quantity that increases for many decades to centuries prior to stabilizing (Bredehoeft 2002; Konikow and Leake 2014). Widespread pumping for irrigated agriculture began in GMD4 in the early 1960s; the number of water rights increased sharply before gradually leveling out in the mid-1970s to early 1980s (Wilson et al. 2021). By 1996, if not earlier, net inflow appears to have stabilized over the district. This relatively short time to stabilization, which is likely a result of the distribution of the large number of pumping wells, aquifer heterogeneity, and the rapid drying up of the vast majority of streams in the district (there is essentially no baseflow into stream channels in western Kansas), may be a characteristic of many heavily stressed aquifers in semi-arid areas. In aquifers where net inflow is still increasing, the pumping reductions based on the estimated net inflow will be overly conservative as not all the mechanisms contributing to the net inflow would have fully come into play.

Data Quality

The field calculation of net inflow discussed in the earlier sections is dependent on reliable measurements of water levels and pumping.

Water Levels

For decades in Kansas, annual water-level measurements have been taken in a network of wells (about 1400) distributed approximately uniformly (every ≈ 40 km^2) over the HPA (Miller et al. 1998; Bohling and Wilson 2012). The guiding principles for the program have been to minimize measurement error, take measurements at a time when pumping activity is at a minimum, and be consistent with the timing of measurements from year to year. In the Kansas HPA, the preferred time for measurements is January, typically three to four months after cessation of irrigation pumping. As a result, year-to-year variations in the timing of the end of the irrigation season have relatively little influence on the measurements and thus the ΔWL values. However, in some years, particularly in southwestern Kansas, pumping late in the year can have a sizable impact on the ΔWL values. The small difference in ΔWL but the large difference in Q for 2010 and 2011 in Figure 4a is an example of the impact of December pumping activity on the annual measurements (see Text S2 for further discussion). The noise introduced into the ΔWL data by the late-year pumping made little difference in this case as the I values differed by less than 3% between estimates made using the original values or the average of the two as in Figure 4a. In other cases, pumping activity prior to the measurements can introduce so much noise that the calculation is of little value. Thus, estimation of net inflow from a ΔWL vs. Q plot is most effective in a seasonally pumped aquifer using water-level measurements taken three to four months after the end of the pumping season.

Measurement errors may have little influence on net inflow calculations over a large area, such as GMDs 3 and 4 where the ΔWL values are averages of 251 and 174 values, respectively, but their impact can be larger when the number of wells is relatively small. Although the impact on the net inflow calculation may still be small, the confidence in the results can be lessened. Figure 5b shows the influence of suspected measurement errors on the ΔWL values in Stevens County. The ΔWL values are the annual averages of measurements taken at 21 wells. In 13 of the 16 years, one or two of the 21 wells (six wells total) had water-level changes that were significantly different from the other 19 to 20 (see Text S3). When those wells are removed from the averages, the ΔWL values change from the circles to the triangles in Figure 5b. Although the R^2 increased by 15% and the p value decreased by 77%, I changed by less than 4%. However, as the number of wells gets smaller (i.e., in the single digits), such apparent measurement errors could have a much larger impact.

Annual Pumping

Every non-domestic pumping well is required to have a totalizing flowmeter in the Kansas HPA; the recorded pumping volumes must be reported annually and are subject to regulatory verification (Butler et al. 2016). Direct measurements of pumping allow important insights to be gleaned about aquifer behavior, but may not be available in many aquifers (Foster et al. 2020). Bohling et al. (2021) have shown that a random subset of metered wells as small as 10 to 20% can be used to obtain excellent estimates of the pumping in an area if the total number of pumping wells is known. Even when the number of wells may be uncertain, working with bounding values can provide a likely range for the pumping and thus a range for net inflow. Reliable estimates of net inflow become more problematic in the absence of direct measurements of pumping.

Discussion and Conclusions

Groundwater depletion in aquifers supporting irrigated agriculture has become an issue of global concern (Alley and Alley 2017). The major purpose of this paper is to draw more attention to the net inflow concept and its practical utility. Through a series of demonstrations at scales of relevance for many practical applications, we have shown how estimates of net inflow from field data can be used to help redirect these heavily stressed systems onto more sustainable paths. We also have explored the impact of the quality, quantity, and timing of the water-level and pumping data on the resulting estimates of net inflow, and found that the estimation process should be most effective in seasonally pumped aquifers.

The net inflow concept is nothing new. It was originally proposed over 75 years ago, a few years after Theis' seminal 1940 paper that introduced the concept later named capture. Net inflow and capture are equivalent but each may have a context where its use is preferred. For example, in discussions with stakeholders in the Kansas portion of the HPA, the concept of net inflow has been readily grasped and accepted. The pairing of the ΔWL vs. Q plot with the Q and cumulative ΔWL vs. time plot has proven to be a convincing demonstration of the concept and its relationship to field data.

The reductions in pumping required to diminish decline rates in these heavily stressed systems will likely lead to decreases in net inflow and thus further pumping reductions in the future (Butler et al. 2020b). The decreases in net inflow will be a function of the major fluxes that are contributing to it, so the quantification of those fluxes is critical. This will require more attention to long-term monitoring of the aquifers of interest. This monitoring must move beyond annual water-level measurements and limited-term, campaign-style projects. In particular, more attention must be paid to the major stress on these aquifers, pumping. Direct measurement of pumping at a subset of wells in an area should become the rule, and not the exception, if we are to develop the insights into an aquifer's functioning that are needed to reliably assess its future prospects. Pumping estimates based on utility records, evapotranspiration estimates, various remote sensing platforms, and machine-learning approaches will be most effective if integrated with direct measurements.

Net inflow appears to have been near constant over much of the western Kansas HPA for the last quarter of a century. The thick vadose zone is likely primarily responsible for this condition, as the temporal variability in infiltration at the land surface is greatly damped with depth (Dickinson et al. 2014; Dickinson and Ferré 2018). Reductions in pumping for irrigated agriculture may therefore take years to decades to result in decreases in net inflow. Although the impact may be delayed for an extended period of time, it will eventually occur. As we have discussed elsewhere (Butler et al. 2020b), this delay may give rise to a period of apparent sustainability (water levels, on average, changing little or even increasing with time) when pumping is reduced to or below net inflow. The agencies that are responsible for groundwater management will need to educate water users in their areas so that this apparent sustainability does not result in increased pumping, which would lead to further water-level declines that would be accelerated once the reductions in net inflow begin. When they do occur, the decreases in net inflow will be evident on ΔWL vs. Q plots, so that groundwater management practices can be modified.

The estimates of net inflow and percent pumping reductions given here can vary with the period of analysis because of the strong correlation between precipitation and pumping in the Kansas HPA (Whittemore et al. 2016; Butler et al. 2021b). The variation in these estimates, however, will be small once the full range of climatic conditions in an area has been experienced.

Groundwater models of seasonally pumped aquifers should be able to exploit certain aspects of the approach described here. The net inflow estimate obtained from a ΔWL vs. Q plot could serve as an important constraint for regional groundwater models. If a model cannot reproduce the magnitude and temporal behavior of the field-calculated net inflow, then further calibration should be considered. As we have shown elsewhere, the specific yield estimate obtained from this plot can also serve as an important model constraint (Butler et al. 2020a; Liu et al. 2022).

The findings presented here should be representative of conditions in seasonally pumped aquifers in semi-arid areas with relatively thick vadose zones. However, the approach described in this paper is not limited to that setting. Butler et al. (2016, 2017) examined its applicability in Equus Beds Groundwater Management District No. 2 (GMD2), the easternmost Kansas GMD, which is located in a subhumid area with perennial streams and relatively shallow water tables. As shown in Figure 4 in Butler et al. (2016), similar linear relationships are observed in that setting, although the data spread about the best-fit line is often larger as a result of greater interannual variability driven by stream-aquifer interactions and rapid recharge. Given our experience in GMD2, we expect that reliable estimates of net inflow will be attainable in many seasonally pumped aquifers with relatively shallow depths to water and perennial streams. Further assessments are required to determine the response of net inflow to changes in natural and anthropogenic forcings in other settings. We anticipate that linear relationships will be difficult to obtain from once-a-year measurements in aquifers that are dominated by year-round industrial and municipal pumping. Use of annual average water levels, however, may enable linear relationships to be obtained under those conditions.

Our discipline faces many challenges as we strive to meet societal expectations and provide reliable estimates of what the future holds for aquifers supporting critically needed agricultural production. Hopefully, the concepts discussed here can play a role in helping us meet those expectations and better prepare the world for what lies ahead.

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Authors' Note

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1 Supporting information.

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