Groundwater

Water Well Hydrographs: An Underutilized Resource for Characterizing Subsurface Conditions

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Abstract

Many of the world's major aquifers are under severe stress as a result of intensive pumping to support irrigated agriculture and provide drinking water supplies for millions. The question of what the future holds for these aquifers is one of global importance. Without better information about subsurface conditions, it will be difficult to reliably assess an aquifer's response to management actions and climatic stresses. One important but underutilized source of information is the data from monitoring well networks that provide near-continuous records of water levels through time. Most organizations running these networks are, by necessity, primarily focused on network maintenance. The result is that relatively little attention is given to interpretation of the acquired hydrographs. However, embedded in those hydrographs is valuable information about subsurface conditions and aquifer responses to natural and anthropogenic stresses. We demonstrate the range of insights that can be gleaned from such hydrographs using data from the High Plains aquifer index well network of the Kansas Geological Survey. We show how information about an aquifer's hydraulic state and lateral extent, the nature of recharge, the hydraulic connection to the aquifer and nearby pumping wells, and the expected response to conservation-based pumping reductions can be extracted from these hydrographs. The value of this information is dependent on accurate water-level measurements; errors in those measurements can make it difficult to fully exploit the insights that water-well hydrographs can provide. We therefore conclude by presenting measures that can help reduce the potential for such errors.

Introduction

Aquifers across the globe are under stress to meet the ever-increasing demand to support irrigated agriculture and provide drinking water for millions (Alley and Alley 2017). The question of what the future holds for these highly stressed systems is one of global importance. Defining paths forward, however, is fraught with uncertainty. Without better information about subsurface conditions, it will be difficult to reliably assess the aquifer response to management actions, regardless of the impacts of a changing climate (Butler et al. 2020a, 2020b).

One source of data that has not been fully utilized is that from networks of monitoring wells that provide near-continuous records of water levels through time. Most organizations running these networks have to expend most, if not all, of their funding and energy on network maintenance, which is a far from trivial task. The result is that relatively little attention is given to interpretation of the acquired well hydrographs. However, embedded in those hydrographs is valuable information about subsurface conditions and aquifer responses to natural and anthropogenic stresses. That information could significantly enhance the reliability of assessments of future prospects for many systems. Although the value of that information has been recognized for over a century (e.g., Veatch 1906; Robinson 1958), it has received relatively little recent attention beyond work on water-level responses to various natural forcings (e.g., Healy and Cook 2002; Butler et al. 2007; McMillan et al. 2019). The one area in which there has been a considerable amount of recent activity is time series modeling of hydrographs from near-surface aquifers using predefined transform functions (e.g., von Asmuth et al. 2002; Collenteur et al. 2019). Hydrograph interpretation will be an important element of efforts to help clarify appropriate transform functions and inform and extend that modeling process.

The purpose of this paper is to explore the insights that can be gleaned from the interpretation of hydrographs from continuously monitored wells. Previously, we have

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provided interpretations of hydrographs from wells at three sites in the High Plains aquifer (HPA) in Kansas (Butler et al. 2011, 2013). This paper greatly expands on those earlier analyses in terms of both areal extent and topical coverage. We begin with an overview of the HPA monitoring network of the Kansas Geological Survey (KGS). Following that, we demonstrate how information about an aquifer's hydraulic state and lateral extent, the nature of recharge, the hydraulic connection to the aquifer and nearby pumping wells, and the expected response to conservation-based pumping reductions can be extracted from hydrographs of network wells. We then discuss some of the sources of error in water-level data and present some measures to help reduce the potential for such errors. The paper concludes with a summary of the major findings.

The KGS Index Well Network

The index well network was initiated in the summer of 2007 to enhance understanding of conditions in the HPA in western and south-central Kansas. The network began with the installation of three monitoring wells, each of which had an integrated pressure transducer-datalogger unit (hourly acquisition rate) connected to telemetry equipment that enabled near real-time viewing of water levels on the KGS website. As a result of the insights acquired from the original three wells (Butler et al. 2013), the program expanded into its current state of 20 wells equipped with telemetry and another seven with sensors that are periodically downloaded (Figure 1; Butler et al. 2020c). One of the objectives of the program is to maintain the network for the long term, so most wells are screened at or near the bottom of the aquifer. Sites are visited approximately quarterly for downloading, manual measurements, and equipment maintenance. Vented transducers are used at all sites and a number of sites have barometers to allow assessment of water-level responses to fluctuations in barometric pressure.

Figure 2 is the water-level record from one of the original three wells, the Thomas County index well in northwest Kansas, that displays features that are

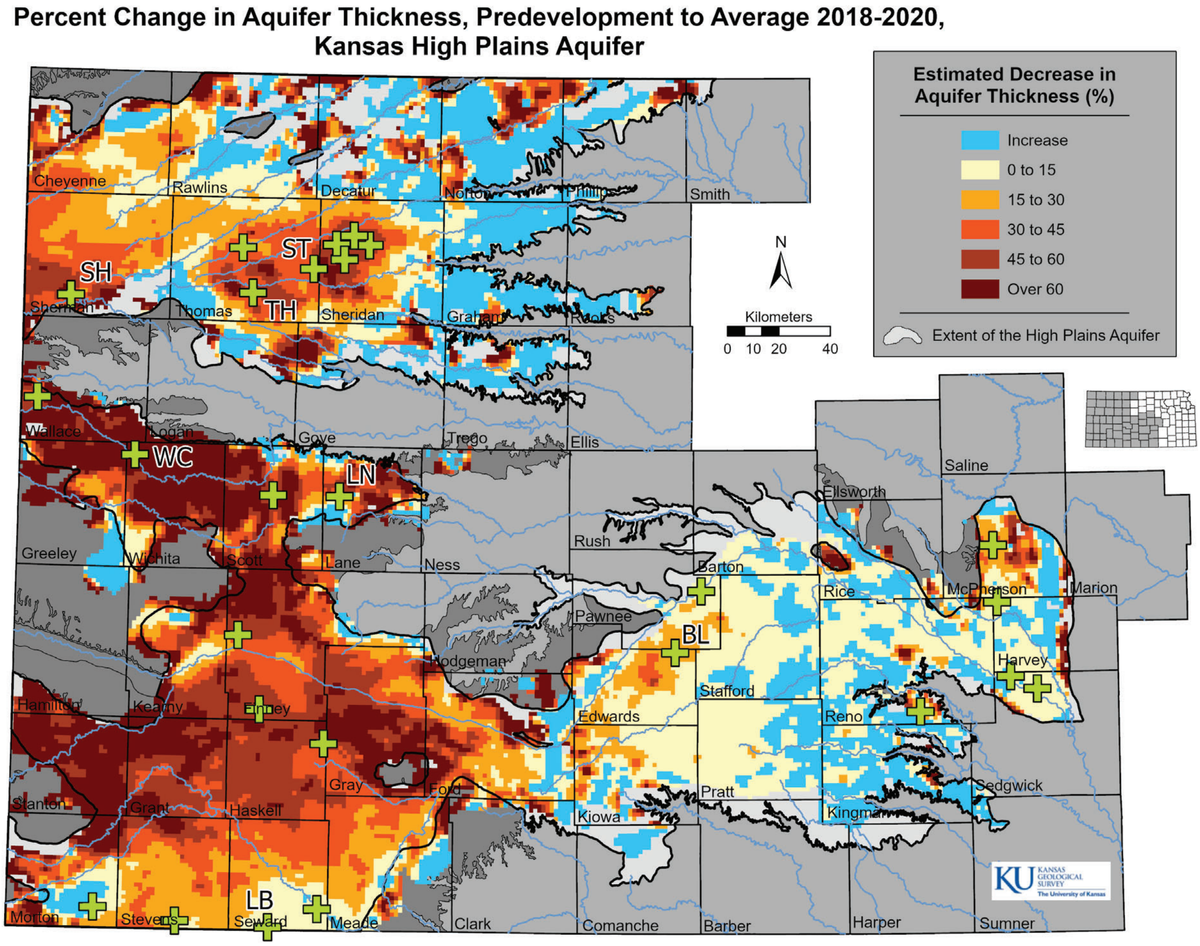

Figure 1. Map of the percent change in aquifer thickness from predevelopment to present for the High Plains aquifer (HPA) in Kansas (the inset on the right shows the portion of the state pictured here). Wells of the Kansas Geological Survey Index Well Network are indicated with plus signs and those discussed in the paper are labeled (labels defined in text). Predevelopment is defined as period prior to onset of widespread pumping for irrigated agriculture, which occurred between 1940 and the mid-1950s in most of the Kansas HPA; present is defined as average of 2018 to 2020 winter conditions. The areas of increase in the western third of the figure are areas of thin saturated thickness that are of little practical importance.

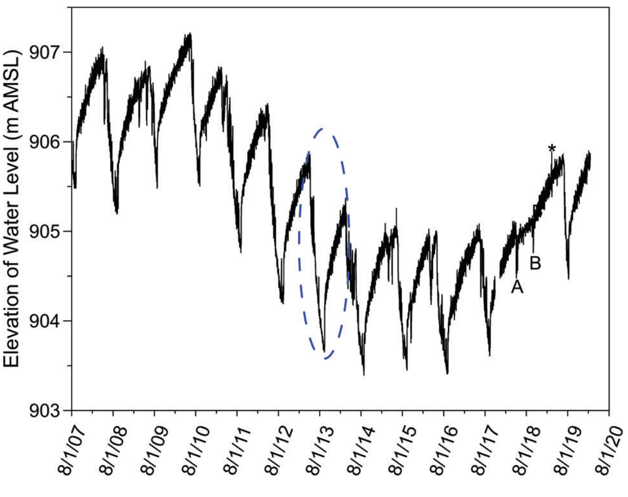

Figure 2. Elevation of water level versus time for the Thomas County index well in northwest Kansas (TH in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 905 m corresponds to a depth to water below land surface of 66.5 m. The well is screened over 3.05 m at the bottom of the aquifer, which is at an elevation of 885.03 m. Dashed ellipsoid indicates period expanded in Figure 3; A, B, and * defined in text.

characteristic of the majority of the network wells. The most prominent of these are a strong seasonal pumping signal, continued water-level recovery until the start of the next pumping season, and a clear water-level response to barometric pressure fluctuations (water-level "band"). In the following section, we show how water level records from this and other network wells can be used to develop insights of considerable practical value.

Interpretation of Water Well Hydrographs

Hydraulic Conditions

The hydraulic state (confined to unconfined) is a key aquifer characteristic that often may not be known. However, passive monitoring of responses to pumping or natural forcings can clarify the condition in the monitored interval.

Response to pumping: The water-level response to nearby pumping can be a diagnostic indicator of the hydraulic state of the aquifer (in this case, confined versus unconfined). Figure 3a depicts a 7-month period spanning the 2013 irrigation season at the Thomas County index well (dashed ellipsoid in Figure 2). The commencement or cessation of pumping produces a rapid change in water level that quickly transitions to a much more gradual change over time. In an unconsolidated aquifer like the HPA, this behavior, which is most noticeable at the start and end of the irrigation season as in Figure 3a, is simply the hydrograph expression of the two-stage response to pumping observed in unconfined aquifers (Neuman 1972, 1975). The rapid change in water level occurs during the period when changes are controlled by compressive storage; this is followed by a transition to the period in which changes are controlled by drainable porosity. In contrast, the hydrograph expression of a confined response is much smoother in time (Liberal 436 index well - Figure 3b) as the result of compressive storage being a dominant control on water-level changes at all times in the absence of boundary effects (Theis 1935; Hantush 1964). Thus, the hydraulic state of a monitored interval in the HPA can often be recognized through visual inspection of a hydrograph, even when spanning multiple years (Figure 2). The above statements pertain to an

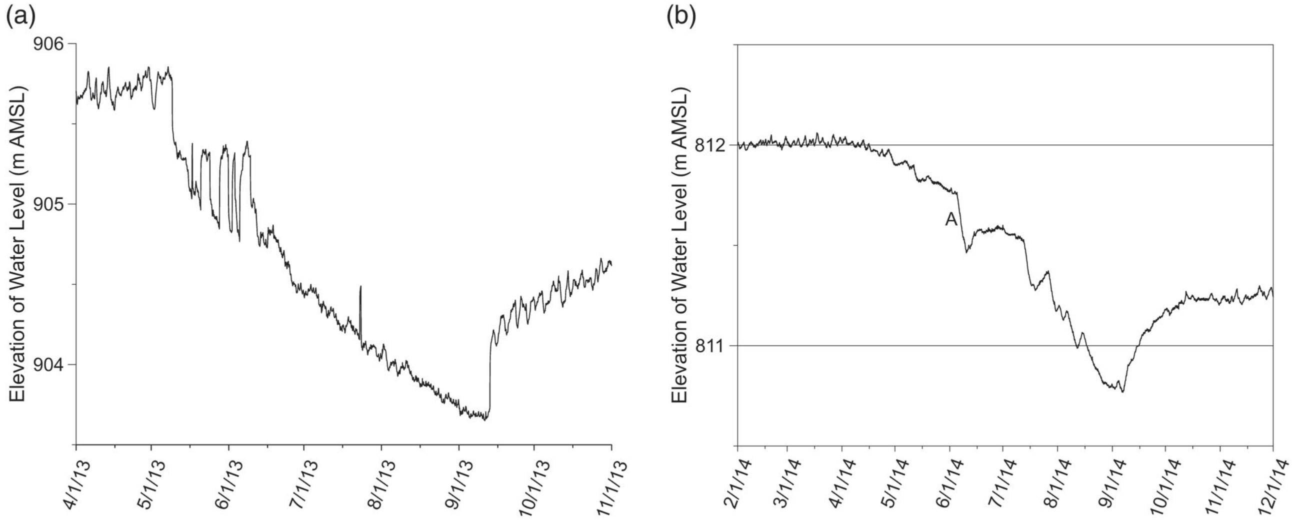

Figure 3. (a) Expanded view of the 2013 pumping season (marked by dashed ellipsoid in Figure 2) at the Thomas County index well (see Figure 2 caption for further details about well). (b) Elevation of water level versus time for the February through November 2014 period at the Liberal 436 index well in southwest Kansas (LB in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 811 m corresponds to a depth to water below land surface of 48.85 m. The well is screened for 3.05 m with the lower end at an elevation of 726.96 m. The bottom of the aquifer is at an elevation of 684.28 m but the lower portions of the aquifer have higher salinity water of little use for irrigated agriculture; A defined in text.

unconsolidated formation. In a consolidated formation, a two-phase response similar to Figure 3a could be observed in a double-porosity aquifer where the fractures are the major conduit for flow with the matrix serving as the storage source. Thus, some knowledge of the geology is required for reliable interpretations.

Response to natural forcing: In cases where the pumping-induced response is not clear because of the absence of nearby pumping wells or of a strong hydraulic connection to them, the water-level response to barometric pressure fluctuations will reveal the hydraulic state of the monitored interval (in this case, the full range of confined to unconfined). Although visual inspection of the hydrograph-recorded responses to variations in barometric pressure can often reveal the hydraulic state (e.g., relatively large fluctuations in an unconsolidated aquifer such as in Figure 2), a time- or frequency-domain analysis is required in the general case. The time-domain regression convolution approach yields barometric response functions (BRFs) that have diagnostic forms for unconfined, confined, and semi-confined aquifers (Rasmussen and Crawford 1997; Spane 2002; Butler et al. 2011) and can be calculated using public-domain software (e.g., Toll and Rasmussen 2007; Bohling et al. 2011). Figure 4 shows the BRF responses for the Thomas County and Liberal 436 index wells, which are consistent with the interpretation based on the visual inspection of the pumping-induced responses. The Thomas County BRF is an example of the response in an unconfined aquifer with a deep water table (Weeks 1979; Spane 2002); in the case of a shallow water table, there may not be a measureable response to barometric pressure changes or the response can change over time due to varying conditions in the vadose zone (Butler et al. 2011). The Liberal 436 index well is an example of a confined aquifer response in which the BRF stabilizes at larger lags. In a semi-confined setting, the BRF will initially resemble that of a confined system, but then will deviate from it at larger lags (Butler et al. 2011). Frequency-domain methods have been implemented in public-domain software (Schweizer et al. 2021), but are not fully developed for the general assessment of the hydraulic state of a monitored interval (Rau et al. 2020).

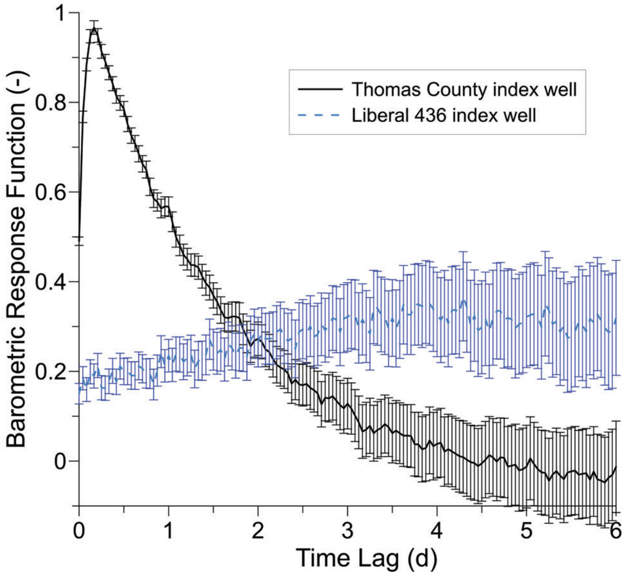

Figure 4. Six-day barometric response functions (BRFs) for Thomas County and Liberal 436 index wells. Period of analysis is October 30, 2019 to December 30, 2019 for Thomas County well and December 7, 2013 to January 6, 2014 for Liberal well. Given these and analyses of other periods, the BRFs for both wells appear to have changed little from the onset of monitoring (2007 and 2012 for Thomas and Liberal wells, respectively) to present. Error bars indicate one standard error about the estimated functions; linear trend removed from data series prior to BRF calculation. A BRF characterizes the water-level response to a step change in barometric pressure; the time lag is the time since the imposition of that change. The BRFs and their error bars were calculated using Bohling et al. (2011).

Lateral Extent

The lateral extent of an aquifer interval is rarely known. Although regional numerical models routinely assume a continuous unit, that often may not be the case. Hydrographs can provide some insight into the lateral extent of the aquifer interval in which the well is screened. Figure 3b depicts a characteristic hydrograph form in a laterally bounded aquifer (the permeable interval in which the pumping and monitoring wells are located is surrounded by units of much lower permeability). The rapid recovery relative to the duration of pumping, the step change across the pumping period, and the stabilization of water levels are diagnostic hydrograph features of a bounded aquifer; Butler et al. (2013) describe the theoretical basis for these features.

A hydrograph in which water levels continue to recover until the start of the next pumping season (Figure 2) can be an indication of a relatively unbounded system. However, it is not necessarily so, as continuing vertical inflow can obscure the bounded hydrograph form of Figure 3b. In that case, the water-level response to pumping can be helpful in clarifying the lateral extent. Linear water level versus time segments during periods of pumping, such as the 5-day period marked by A and similar segments in Figure 3b, are an indication that the aquifer is at least partially bounded laterally. However, a longer time interval is needed to establish the extent of the isolation (Butler et al. 2013). Identification of linear intervals in the presence of multiple pumping wells can be difficult because of wells cutting on and off, particularly in the latter stages of the irrigation season. Furthermore, a linear response may be produced by interacting cones of depression, and not the geology. Thus, some knowledge of the area is required for reliable interpretation.

Recharge

Recharge is an important component of an aquifer's water budget. However, characterizing the nature of that recharge (i.e., the recharge regime), much less quantifying it, has proven challenging (Healy 2010). Although episodic recharge (correlated with precipitation and often with large interannual variations) is commonly assumed in regional models, steady recharge (small interannual variations) may often be the rule in aquifers with deep water tables. For example, there are few indications of episodic recharge in the hydrographs from wells in semi-arid western Kansas; in most cases, the hydrographs resemble that in Figure 2 without any of the features that typically would be associated with episodic recharge. Moreover, Butler et al. (2016) use a water-balance approach to show that net inflow (everything flowing into the area minus everything flowing out except pumping) has remained approximately constant in time across the Kansas HPA for close to a quarter of a century. Although recharge is just one component of net inflow, the fact that net inflow changes little from year to year is a strong indication that recharge likely does the same (i.e., steady recharge). Butler et al. (2020c) use the same water-balance approach to show that near-constant net inflow has been observed at the Thomas County index well since monitoring began in 2007. This is not unexpected as a thick vadose zone should act as a low-pass filter on surficial recharge (Stephens 1996).

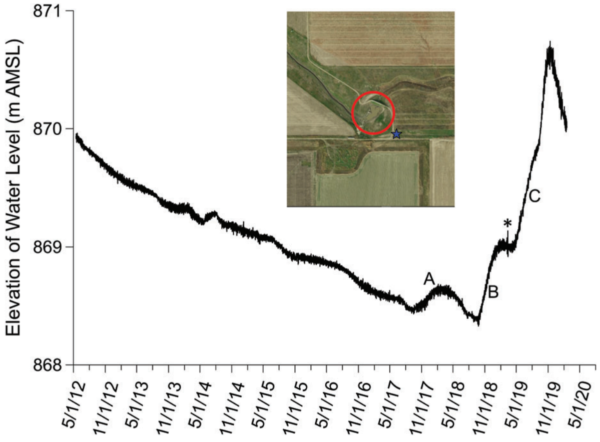

Figure 5. Elevation of water level versus time for the Steiger index well in northwest Kansas (ST in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 869 m corresponds to a depth to water below land surface of 34.74 m. The well is screened over 9.75 m at the bottom of the aquifer (elevation of 849.79 m), an additional 2.44 m of screen is in the underlying shale and serves as a sump. Inset is an aerial photo of well (star) and nearby impoundment (within circle [radius approximately 76 m]); A to C and * defined in text.

In aquifers with deep water tables, episodic recharge should primarily be limited to areas where the recharge has been focused via a variety of mechanisms. That is in the case in western Kansas where episodic recharge has only been observed at sites of focused recharge. The hydrograph from the Steiger index well in northwest Kansas (Figure 5) displays a series of focused episodic recharge events (marked by A to C). The local nature of the recharge events is revealed by the relatively rapid decrease in water level following each peak as water flows laterally to areas that did not receive the vertical recharge. The Steiger well (star in Figure 5 inset) is located near an impoundment behind a small dam over an ephemeral stream channel (circle in Figure 5 inset). The most likely cause of the substantial rises in water level is recharge from the impoundment during the three wetter than normal years from 2017 to 2019. Aerial photos taken intermittently over the last two decades reveal that the impoundment is typically dry or nearly so. However, the succession of wetter than normal years filled the impoundment and produced a water-level rise at the Steiger well of over 2.2 m; comparison of the substantial rise in water level with area rainfall indicates that the recharge pulse appears to have taken a little over a year to reach the water table. In areas of varied topography, such as northwestern Kansas, where ephemeral stream channels are common, impoundments would likely produce similar focused recharge in wet years. Such impoundments may prove to be one of the only potential avenues for managed aquifer recharge in many semi-arid areas where access to surface water is limited.

Episodic recharge events are commonly observed on hydrographs from wells in areas with relatively shallow depths to water (e.g., Healy and Cook 2002; Eaton 2020). For example, recharge events in response to precipitation at different temporal scales are observed in HPA hydrographs in sub-humid south-central Kansas where the water table is much shallower than in areas to the west (average depth to water in northwestern Kansas is over four times that in south-central Kansas; Butler et al. 2016). The hydrograph from the Belpre index well (Figure 6) illustrates recharge events associated with periods of precipitation ranging from hours to months in duration. The event marked A on Figure 6 and expanded in the inset is an example of the former; a rapid rise in water level in response to rainfall (D) is followed by a recovery (recession) curve (E) as the water is redistributed in the aquifer as described by Healy and Cook (2002) and others (in this case, the well is screened near the center, and not the bottom, of the aquifer). Periods of precipitation lasting weeks (B) and months (C) reveal the recharge response to longer-term events. Water-level responses to wet periods of several months in duration, such as that beginning at C in Figure 6, have been observed in hydrographs across south-central Kansas (e.g., Figure 3 in Butler et al. 2011). As we have shown earlier (Butler et al. 2018), recharge during these infrequent seasonal wet periods plays a critical role in keeping the water levels in the south-central Kansas HPA close to a stable condition. If changing climatic conditions result in a decreasing frequency of such events, the depletion of the aquifer in this area could significantly increase, a situation that is likely true for many other areas as well.

Hydraulic Connection

The response of water levels to pumping at nearby wells is affected by the nature of the hydraulic connection between the monitored and pumped intervals. At the Thomas County index well (Figures 2 and 3), the monitored interval appears to be in direct hydraulic

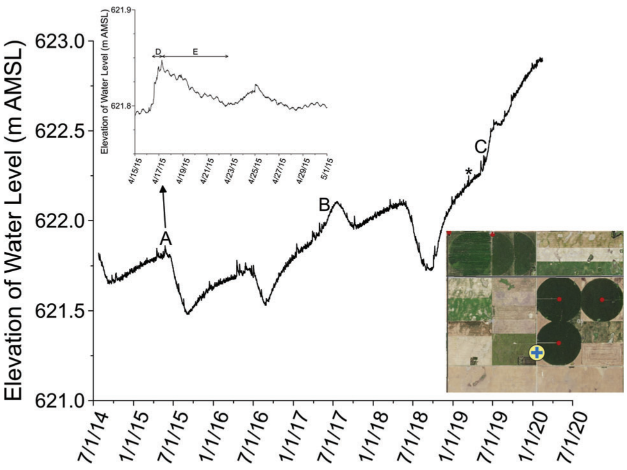

Figure 6. Elevation of water level versus time for the Belpre index well in south-central Kansas (BL in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 622.0 m corresponds to a depth to water below land surface of 11.99 m. The well is screened over 6.10 m near the center of the aquifer (bottom of the screen is at an elevation of 600.77 m); elevation of the aquifer bottom is estimated to be between 573 and 581 m. Inset plot is an expansion of the water-level record in the vicinity of A; inset aerial photo is of the index well (blue plus sign in yellow circle) and nearby pumping wells (red circles), the irrigation circles are approximately 800 m in diameter; B to E and * defined in text.

connection with the nearby pumped intervals as shown by the two-stage response discussed earlier and the water-level changes associated with cutting on and off nearby irrigation wells (Figure 3). In contrast, at the Belpre index well (Figure 6), the smooth and relatively small water-level changes during the pumping season indicate that the monitored interval is not in direct hydraulic connection with nearby pumping wells. The small spikes observed during periods of pumping at the Belpre well are all associated with precipitation events, and not the cutting on and off of nearby wells. The average (2014–2017) annual pumping over a circle of 3.22 km (2 mi) in radius centered on the Belpre well was 86% of that for the Thomas well. Thus, despite the density of nearby pumping wells (see photo in Figure 6), the hydrograph indicates that the monitored interval is likely separated from the pumped intervals by units of lower permeability; the Belpre well does appear to be in good hydraulic connection with the monitored interval.

The hydraulic connection between the well and the aquifer can change with time. These changes are typically associated with the buildup of products of biochemical reactions and/or the silting up of the screened interval. Monitoring of water-level responses to barometric pressure fluctuations is a convenient means of identifying when such changes are occurring. The hydrograph from the Sherman County index well in northwest Kansas provides an example of water-level responses to the silting up of the screened interval, which most likely resulted from not developing the well after installation (Figure 7).

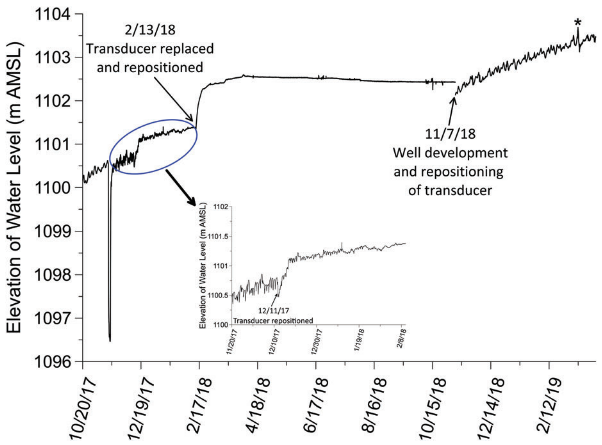

Figure 7. Elevation of water level versus time for the Sherman County index well in northwest Kansas (SH in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 1103 m corresponds to a depth to water below land surface of 53.43 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 1058.89, 0.92 m above the aquifer bottom). Inset is an expansion of the water-level record within the ellipse; * defined in text.

The inset shows the dampening responses to barometric pressure changes as the upper portions of the screened interval fill with silt and reduce the connection between the well and the aquifer. On December 11, 2017, we discovered that the transducer was being submerged by silt, so we moved it up 0.53 m, producing a 6-day period of enhanced water flow into the well. On February 13, 2018, we removed the transducer from the well and found it was completely plugged with silt. We replaced the transducer and positioned it 4.95 m above the original position. Removing and replacing the transducer appeared to disturb the silt column, allowing water to flow into the well for close to 2 months. After that, water levels remained nearly stable, with minimal response to barometric pressure changes, for the next 7 months. This period included the 2018 pumping season during which the water level gradually declined 13 cm; the typical water-level change during the irrigation season at this well is approximately 10 m. Immediately after the well was thoroughly developed on November 7, 2018, the water-level recovery from the previous pumping season and the fluctuations produced by changes in barometric pressure resumed. Although the near-complete deterioration of the hydraulic connection was apparent from a visual inspection of the hydrograph, smaller changes may not be as easily identified. Thus, in the general case, periodic calculation of the well BRF, or the frequency-domain equivalent, should be used to assess changes in the hydraulic connection and the need for well development. Periodic slug tests are also an effective tool for this purpose, but BRF or frequency-domain calculations are more convenient because identification of deteriorating conditions can be done remotely for wells with telemetry.

Response to Meteorologic Conditions

Water-level responses to large changes in meteorologic conditions, whether they be seasonal variations or extreme events, can provide insights of practical value.

Seasonal variations in barometric pressure: The range over which barometric pressure varies is not constant through the year, as the range in summer is considerably smaller than that in fall and winter in the United States (Herron et al. 1969; Houck et al. 2005). The result is that the magnitude of water-level responses to barometric pressure changes can vary through the year. This seasonal variation is most evident in hydrographs that show little response to pumping, such as that from the Wichita County index well in west-central Kansas (Figure 8). The diminishing water-level fluctuations observed when moving into summer should not be confused with the deterioration of the hydraulic connection between the well and the aquifer.

Hailstorms: A hailstorm can be extremely damaging in agricultural areas as a field can be decimated in a matter of minutes. In areas of groundwater-supported irrigated agriculture, a hailstorm can lead to an abrupt cessation of pumping. In May 2018, a hailstorm hit the fields in the vicinity of the Thomas County index well. The storm ended the pumping season in the immediate vicinity of the well but pumping continued in nearby areas; the 2018 pumping for a circle of 1.6 km (1 mi) centered on the Thomas County index well was 23% of the 2014 to 2017 average, while the 2018 pumping for a circle of 8.0 km (5 mi) centered on the well was 56% of the 2014 to 2017 average. The water-level response provides insights into how the aquifer would respond to conservation-based pumping reductions. After the hail-induced cessation of nearby pumping (A on Figure 2), water levels rose at a smaller rate than during the winter recovery period because of pumping continuing in adjacent areas. The pumping in the general area ceased in early October (B on Figure 2), after which the water level rose at a rate similar to that observed during the previous winter recovery. This rise was not produced by enhanced recharge in 2018; it resulted from the steady net inflow to the area. Butler et al. (2020c) have shown (in their Figure 47) that the net inflow in the vicinity of the Thomas County index well during 2018 was approximately the same as each year since monitoring began in 2007. In agricultural areas such as this with deep water tables and a history of near-constant net inflow, the near-term impact of conservation-based pumping reductions should be predictable using the net inflow calculated from the monitoring history (i.e., assuming that the net inflow of the recent past will be the net inflow of the near future). However, what exactly is meant by "near-term" or "near future" has yet to be determined; it could be several years to a few decades or more (Butler et al. 2020b).

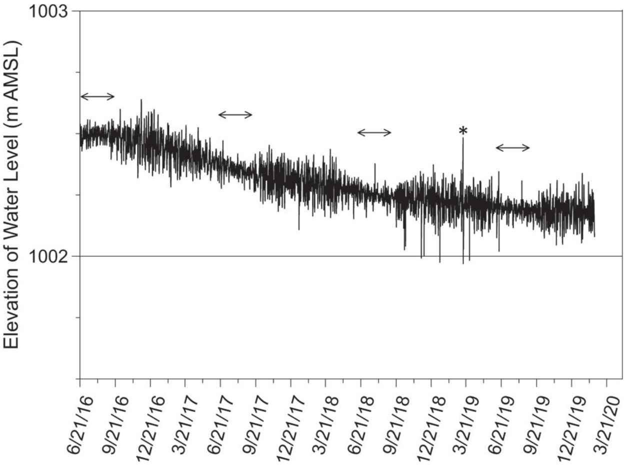

Figure 8. Elevation of water level versus time for the Wichita County index well in west-central Kansas (WC in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 1002.5 m corresponds to a depth to water below land surface of 48.46 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 994.57, 1.52 m above the aquifer bottom). The double-headed arrows indicate the summer period (June 21st to September 21st); * defined in text. Some of the larger spikes are likely spurious readings produced by insolation of the transducer vent tube (Figure 9 and associated discussion).

Bomb cyclones: A bomb cyclone is a large rapidly deepening extratropical cyclone that typically occurs from autumn to spring in the Northern Hemisphere (Sanders and Gyakum 1980). The center of the system is at a lower pressure than usual so the movement of the system can cause very rapid and large drops in atmospheric pressure (hence, the term "bomb"). On March 13, 2019, a bomb cyclone formed over Colorado and produced the lowest pressure ever recorded in Colorado (Eagleman 2021). The storm moved eastward through western Kansas producing a large drop in barometric pressure head across the region. As a result, water levels in wells in the Kansas HPA spiked upward. The * in Figures 2 and 5–9 indicate the upward spikes observed at those wells. The water-level response to a bomb cyclone can be a useful first-order assessment of the hydraulic connection between the well and the aquifer; the lack of a spike or one in the opposite direction than expected would likely be an indication of a poor connection between the well and the aquifer.

Measurement Error

Gleaning insights into subsurface conditions from water-well hydrographs is dependent on accurate water-level measurements (Rau et al. 2019). Error in those measurements or their timing can make it difficult to fully exploit the information embedded in the hydrographs.

Manual measurement errors: Except in cases of difficult-to-access locations, transducer measurements should not be the sole data source. Sensor performance should be checked with manual measurements on a regular interval, approximately every 3 months in our case, to ensure the sensor is operating according to specifications. Errors in those manual measurements, however, can make it difficult to assess transducer performance. The Lane County index well in west-central Kansas is measured once a year with a chalked steel tape as part of

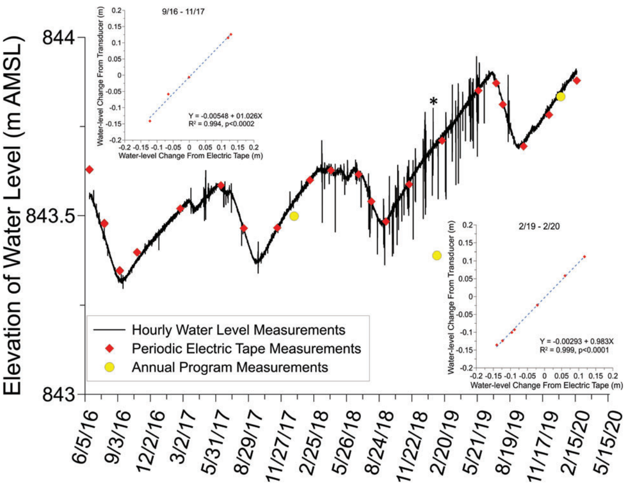

Figure 9. Elevation of water level versus time for the Lane County index well in west-central Kansas (LN in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 843.5 m corresponds to a depth to water below land surface of 25.80 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 834.25, 0.92 m above the aquifer bottom). The two insets display the in-field calibration results using measurements from the given periods; * defined in text.

the annual winter water-level measurement program in the Kansas HPA (Miller et al. 1998), and then more frequently with an electric tape (etape) as part of periodic site visits; the steel tape values are reported to the nearest hundredth of a foot (0.003 m) while the etape values to the nearest millimeter. The well hydrograph (Figure 9) shows that steel tape measurements have proven problematic at this well (average [2017–2020] absolute difference between steel tape and transducer values is 0.238 m). The agreement became much better (2020 deviation <3 cm) with the assistance of an experienced operator. The etape measurements, which are easier to make and less prone to error in the absence of an experienced operator, are in much better agreement (same etape and same reference point on the casing top used for all measurements).

Transducer drift: Transducers are subject to long-term drift as a result of strain hardening of the diaphragm, bonding deterioration, aging of circuitry, and other factors. The Lane County hydrograph illustrates such a drift; the transducer measurements are below manual measurements in 2016, but then gradually change to be above manual measurements in the second half of 2019 and early 2020 (Figure 9). We see such drift in virtually all of the wells in the HPA network. Transducer manufacturers recommend periodically sending the sensors back for calibration in a controlled setting. Oftentimes, however, an in-field running calibration is a cost-effective means of compensating for the drift if manual measurements are taken carefully. Plots of water-level change from etape measurements versus water-level change from transducer measurements can characterize the relationship between the manual and transducer measurements for different calibration periods (insets in Figure 9). In the case of the Lane County well, there was a systematic decrease in the slope parameter and a smaller increase in the intercept parameter from 2016 to 2020. This drift can largely be compensated for by applying the calibration equations from the different periods (two of which are shown in the insets in Figure 9) either by periodic adjustments or continuous interpolation (to avoid introducing small steps into the record). A minimum of four to five etape measurements is recommended for each calibration period to reduce errors produced by mismeasurements; the same etape should be used for all measurements at a well.

Impact of solar insolation: Gauge (relative to atmospheric pressure) transducers are commonly used in monitoring networks like that of the KGS. A transducer provides a measurement that is relative to conditions in the chamber behind the pressure-sensitive diaphragm; in the case of a gauge (vented) sensor, the chamber is kept at atmospheric pressure by a small-diameter vent tube that runs the length of the cable. If the cable or the bare vent tube is exposed to direct sunlight, as a result of the setup of the telemetry system, desiccant chamber, etc., then variations in solar insolation can introduce noise (spikes) into the transducer measurements as a result of the heating and cooling of the air in the vent tube producing anomalous back pressures on the pressure-sensitive diaphragm (Cain et al. 2004). The Lane County well (Figure 9) shows a large number of such spikes, particularly during the 2018 to 2019 recovery period; some similar spikes were observed at the Wichita County well (Figure 8). The frequency of spikes at the Lane County well was greatly reduced beginning on May 24, 2019 by attaching loose white fabric to the outside of the exposed section of vent tube. The surface setup at the Lane, Sherman, and Wichita County index wells was recently reconfigured to eliminate the possibility of solar insolation impacting sensor measurements; the original setup at the Thomas County, Liberal 436, Steiger, and Belpre index wells did not expose the cable or vent tube to direct sunlight.

Clock drift: The integrated transducer/datalogger units used for water-level measurements have internal clocks that will slowly drift in time. Traditionally, we have reset the internal clock of a unit during quarterly visits if the clock drifted by more than a few minutes. As indicated in the previous paragraph, we have started reconfiguring the surface setup at the well sites. In addition to removing the spikes produced by solar insolation, the new setup enables us to reset the unit clock to a reference clock every 24 h. We do not adjust the clock for daylight savings time.

Discussion and Conclusions

The primary purpose of this paper was to demonstrate the range of insights that can be gleaned from hydrographs from long-term monitoring well networks. This work should thus be considered as a follow-up to a long line of earlier contributions that demonstrated and/or emphasized the importance of long-term monitoring to enhance understanding of hydrologic processes (e.g., Fishel 1956; Alley et al. 2002; Alley and Alley 2017). Although the examples discussed here were all drawn from the High Plains aquifer in the state of Kansas, the focus was on general principles that should be widely applicable. The ultimate objective was to show that much information of practical importance is embedded in hydrographs from continuously monitored wells (acquisition intervals of several hours or less). This information can be lumped into two general categories: subsurface conditions (outside of the well) and well conditions.

Subsurface conditions: The hydraulic state of a monitored interval can virtually always be ascertained from the water-level response to nearby pumping or to fluctuations in barometric pressure. In some cases, the bounded nature of the monitored interval can be revealed from the form of the hydrograph or the water-level response during extended periods of pumping. Hints about the heterogeneity in the vicinity of the monitored interval can be gleaned from the response to nearby pumping, while insights into the nature of recharge (steady vs. episodic) and the near-term response to proposed pumping reductions can be obtained through visual inspection of hydrographs and calculation of net inflow.

Well conditions: The state of the hydraulic connection between the well and the monitored interval can be assessed from the water-level response to nearby pumping or to fluctuations in barometric pressure. Most importantly, the changes in that connection can be monitored over time using the response to variations in barometric pressure. In wells with telemetry capabilities, this monitoring becomes a convenient means of identifying when well development is needed.

The information obtained from individual wells pertains to conditions in the immediate vicinity of those wells. However, more widely applicable insights can be justified when the same information is obtained from multiple wells. For example, in semi-arid western Kansas, only one well (the Steiger index well—Figure 5) of the 19 sites monitored in that region has a hydrograph that displays episodic recharge. Similarly, only three of the 19 sites have hydrographs that indicate confined conditions. Thus, one can conclude that much of the aquifer in that area is under unconfined conditions with relatively steady recharge that has been significantly smoothed by the lengthy transit through the vadose zone.

Although not emphasized here, there is a rich history of estimating subsurface properties from water-level responses to natural forcings (e.g., Jacob 1940; Bredehoeft 1967; Hsieh et al. 1987; McMillan et al. 2019). Many of these methods use water-level responses to earth tides, which are an important natural forcing in consolidated formations, but are more difficult to detect in wells in unconsolidated formations. Xue et al. (2013) demonstrate the potential of these methods for monitoring changes in formation conditions over time. However, deterioration of the connection between the well and the monitored interval can introduce significant error into the parameter estimates determined with these methods.

The secondary purpose of this paper was to emphasize that the insights obtained from well hydrographs depend on high-quality water-level data. As shown here, periodic manual measurements are an essential element of a monitoring program; they are used to ensure that the instrumentation is producing reliable data and to perform running in-field calibrations. Although other instrumentation (depth sounders, capacitance sensors, floats, etc.) can be used, the pressure transducer is the primary instrument of choice for water-level monitoring. Each transducer has a defined pressure range over which it can be used. The resolution, repeatability, and accuracy of the device is a function of that range; sub-millimeter resolutions are common but the repeatability and accuracy specifications (often given in the form of a standard error) are typically on the order of several millimeters to a few centimeters for the transducer ranges commonly used in practice. Ideally, the selection of a transducer range would be based on the expected water-level changes at the well, but pragmatic considerations, such as the need to have transducers with ranges that are appropriate for most wells in the network, may lead to larger-than-needed ranges and, as a result, an increased noise level. The noise level can also be a function of the measurement process; some transducer-datalogger units take the average of a series of measurements over a small time window to reduce noise, while others just take one or very few measurements to maximize battery life. As expected, the noise level is smaller when the measurement is averaged over a time window.

We have discussed the insights that can be gleaned from the calculation of net inflow at several points in this paper. However, the results of that calculation may be questionable outside of mature, seasonally pumped aquifers with high-quality water-level and water-use data. In terms of water-level data, measurements taken three or more months after cessation of irrigation pumping are needed, so that the year-to-year variations in the timing of the end of the irrigation season have a minimal impact. In addition, the measurements should be taken at approximately the same time each year. As we and others have learned, water-level data acquired during the pumping season, shortly after the cessation of pumping, or at greatly varying times from year to year can introduce so much noise into the net inflow calculation that the results are of little use. Ideally, as in the Kansas HPA, all nondomestic pumping wells have totalizing flowmeters and the annual pumping volumes are reported each year and subject to regulatory verification. However, we recognize that Kansas is an outlier in this regard, and in earlier papers (Butler et al. 2016, 2018) have emphasized that greater attention should be paid to the acquisition of high-quality pumping data so that deeper insights can be gleaned into an aquifer's future.

Multi-year datasets from a network of continuously monitored wells operating at acquisition intervals of several hours or less are an example of what is now termed "Big Data." Visual inspection and manual exploration of hydrographs are possible when the network is relatively small and resources for such activities are available, but that will not be the general case. Artificial intelligence could play a valuable role in this regard. Although various approaches have been used to identify groups of hydrographs with similar characteristics (e.g., Winter et al. 2000; Giese et al. 2020), the power of hydrograph interpretation has yet to be fully explored. Machine learning approaches could be developed to scan data from monitoring well networks to identify the hydraulic state and lateral extent of the monitored interval, the primary recharge regime, the deterioration of the connection between the well and the formation, and even estimate some subsurface parameters using the principles discussed here. Such approaches could provide valuable information for modeling investigations and begin to narrow the often sizable gap between the model conceptualization and reality.

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