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Seasonal water-level perturbations beneath the high plains of the Llano Estacado

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ABSTRACT

Study region: The Llano Estacado is a vast elevated plain located at the southern end of the Great Plains of North America. The Llano Estacado region is favorably situated above the southernmost extension of the Ogallala Aquifer, which provides groundwater for a highly productive irrigated agricultural system.
Study focus: A method was developed to compute the average deviation of the groundwater level from a nonstationary annual-average water level.
New hydrological insights for the region: Groundwater is pumped from the Ogallala Aquifer during each growing season, which induces seasonal and long-term changes in observed groundwater levels. Recorder wells, maintained by the Texas Water Development Board, track these changes and provide a wealth of hydrologic data. Of special interest here are seasonal water-level perturbations induced by nearby actively pumped wells. Groundwater levels are observed to follow a regular pattern of declining water levels during the growing season followed by a recovery after irrigation systems are shut down. In areas with limited groundwater, farmers may shut off irrigation systems when soil moisture is adequate or when the supply of available water becomes critically low. As a result, one can often detect periods during the growing season when irrigation is paused and the water table is allowed time to partially recover. Such hydrographic deviations appear to correlate closely with periods of abundant rainfall. In areas where groundwater supplies are more plentiful, irrigation breaks are less evident. This suggests that farmers with adequate groundwater may be less inclined to shutdown irrigation systems to conserve water despite adequate rainfall.

1. Introduction

The Llano Estacado of western Texas and eastern New Mexico is a physiographic region located at the southern end of the Great Plains of North America (Shumard, 1892; Johnson, 1901). This vast elevated plain has long been recognized as a distinct region (Fenneman, 1931; Cummins, 1892). The key distinguishing feature is its exceptionally level surface; a surface that generally lacks flowing streams or other reliable sources of surface water (Germond, 1940). Beneath this low-relief tableland lies the southernmost extension of the Ogallala Aquifer – a vast freshwater aquifer that underlies portions of eight states with the bulk of its volume beneath Texas, Oklahoma, Kansas, and Nebraska (Lewis, 1990; Opie, 2000). The Ogallala Aquifer provides a source of groundwater that is key to a productive irrigated agricultural system (Terrell, 1998).

Unlike other states where groundwater is more strictly managed, farmers and ranchers of Texas operate under the rule of capture, which grants landowners the right to capture groundwater beneath their property (Cronin, 1969; Brune, 1981; Kaiser, 1987).

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Landowners do not necessarily own the water but have the right to pump and capture whatever water is available, regardless of the effects of that pumping on neighboring landowners (Kaiser, 2005). Unrestricted pumping has led to a significant depletion of groundwater resources in the Texas portion of the Llano Estacado (Musick et al., 1990; Postel, 1992; Alley, 2006).

In an attempt to monitor groundwater conditions, the Texas Water Development Board (TWDB), in partnership with local groundwater districts, maintains a network of automated water level recorders in observation wells throughout the state (Hopkins, 1994). These instrumented wells, referred to as "recorder wells", are equipped with sensors that provide hourly or daily information with regard to water levels (Finnell, 2009). Of special interest here are seasonal fluctuations that result from the extraction of groundwater during the growing season. Although recorder wells are not pumped, neighboring actively pumped wells can induce a seasonal depression of the water table within the observation well and this perturbation can be observed and recorded (Hopkins and Anderson, 2016).

Seasonal perturbations detected in an observation well are not a result of natural phenomenon; rather they are driven by human decisions to switch nearby irrigation pumps on or off (Conover and Akin, 1942; Merriam, 1942; Land and Newton, 2008). Each year, farmers assess climatic and soil moisture conditions and make rational decisions as to when to start and stop irrigation. Farmers make independent decisions to ensure the success of their chosen crop, however, they are guided by an understanding of local conditions and the need to raise a crop during a well-defined growing season. Thus, the collective actions of numerous farmers acting independently produce seasonal perturbations that typically follow regular patterns that tend to repeat each year.

That is not to say that seasonal patterns are identical from one year to the next. Variations in rainfall can indirectly modify seasonal patterns of groundwater extraction. Producers may switch off irrigation pumps during periods of adequate rainfall whereas periods of drought may lead to more vigorous pumping. The supply of available groundwater can also influence the amount of water extracted for irrigation. As the available water supply is reduced to an unusable level, irrigation pumps may be shutoff to allow groundwater to refill cones of depression. Thus, random climatic shifts and supply problems can lead to changes in irrigation patterns and the water table will respond accordingly.

The focus of this paper is on seasonal fluctuations of the water table observed in agricultural regions on the high plains of the Llano Estacado.

2. Methods

Water levels in an aquifer respond to changes in the balance between recharge and discharge. In the case of groundwater beneath the Llano Estacado, recharge is negligible and water levels are driven primarily by extraction of water for irrigation or other purposes. Since a recorder well is not pumped, the observed water-level perturbations are induced by overlapping cones of depression that radiate outward from nearby actively pumped wells. Typically, seasonal perturbations detected in a recorder well are cyclical such that the water table is depressed during the growing season then recovers as pumping is curtailed. Thus, the frequency of an oscillation is roughly one cycle per year or one cycle every 365 days.

The Ogallala Aquifer is a non-stationary system such that, after each annual cycle, water levels do not necessarily return to the undisturbed level of the previous year. In most cases, aquifer depletion causes the mean water level to drop relative to the land surface so that after each annual cycle the depth to water has increased somewhat. In a few rare cases, water levels in an observation well may appear to rise for a few years as nearby active wells are abandoned and cones of depression are allowed time to recover. Nevertheless, whether the water table rises or falls, the mean water level is slowly but constantly changing over time.

One can define a mean annual water level $\overline{D}_n$ for any given day n by simply averaging daily water levels over a period of 365 days. Here we compute a moving average so that the mean water level for a given day is computed by averaging 182 daily values before and 182 daily values after the day of interest as follows:

$$\overline{D}_n = \frac{1}{365}\sum_{i=n-182}^{n+182} D_i \tag{1}$$

For any given day n, one can compute the perturbation of the water level D_n' by subtracting the mean water level $\overline{D}_n$ from the observed water level D_n as:

$$D_n' = D_n - \overline{D}_n \tag{2}$$

Note that a positive water-level perturbation occurs when the water table rises above the annual moving average position and a negative water-level perturbation occurs when the water table drops below the moving annual average position (Fig. 1). Thus, we are comparing the position of the water table for any given day to the moving annual average position.

Each perturbation value is associated with a "day of year", which is simply the consecutive number of days after the start of each calendar year. Thus, if we have a number of years of data then we can average all water-level perturbations associated with a given day of year for all years of which data is available.

3. Recorder wells

There are a total of 17 active recorder wells on the high plains of the Llano Estacado and at least another 11 that have collected data in the past but are no longer in operation. It is possible to compute seasonal perturbation curves for each of these recorder wells; however, it is beyond the scope of this study to discuss results for all 28 well locations. Instead, three representative recorder wells