Article

Examining the Relationship between Drought Indices and Groundwater Levels

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Abstract: Thorough characterization of the response of finite water resources to climatic factors is essential for water monitoring and management. In this study, groundwater level data from U.S. Geological Survey Ground-Water Climate Response Network wells were used to analyze the relationship between selected drought indices and groundwater level fluctuation. The drought episodes included in this study were selected using climate division level drought indices. Indices included the Palmer Drought Severity Index, Palmer Hydrological Drought Index, and Standardized Precipitation Index (SPI-6, 9, 12, 24). Precipitation and the average temperature were also used. SPI-24 was found to correlate best with groundwater levels during drought. For 17 out of 32 wells, SPI-24 showed the best correlation amongst all of the indices. For 12 out of 32 wells, SPI-24 showed correlation coefficients of -0.6 or stronger; and for other wells, reasonably good correlation was demonstrated. The statistical significance of SPI-24 in predicting groundwater level was also tested. The correlation of average monthly groundwater levels with SPI-24 does not change much throughout the timeframe, for all of the studied wells. The duration of drought also had a significant correlation with the decline of groundwater levels. This study illustrates how drought indices can be used for a rapid assessment of drought impact on groundwater level.

Keywords: groundwater; drought; SPI; correlation; aquifers

1. Introduction

This paper reports the results [1] of a substantially expanded version of a preliminary study on the correlation between groundwater levels and drought indices, published in the 2015 Proceedings of World Environmental and Water Resources Congress. The main difference is that in this study, we are establishing a parametric linkage between groundwater level fluctuations and drought; a vital element for water monitoring and management. In most areas, groundwater is used either as a sole source, or as an alternative water source during drought events. Groundwater and drought have inherent complexities, yet are relatively concomitant. Although drought is contextual, without a universally accepted definition [2], its central theme is related to a period of water deficiency in relation to demand. Since it is inherently difficult to identify or predict a drought's onset and offset, indices are predominantly used [3–5]. These indices are utilized to identify and monitor drought [6]. The four types of drought which are generally recognized include: (i) meteorological; (ii) agricultural; (iii) hydrological; and (iv) socio-economic drought [2,7]. The first two types, that is, meteorological and agricultural droughts, are defined on the basis of precipitation and soil moisture deficits, respectively [2,7]. On the other hand, hydrological drought is applicable to shortfalls of surface/subsurface water supply, whereas socioeconomic drought is associated with the supply and demand of some economic good [2,7]. Mishra and Singh [8] suggested that groundwater deficit

should be classified as a type of drought, in addition to the aforementioned four types. Groundwater drought can only be defined in terms of groundwater level decline, due to difficulties of quantifying groundwater storage, recharge, aquifer type, and areal extents [9,10]. Loon [11] explained hydrological drought in detail. In the study, associated challenges were listed in hydrological drought studies, including: (a) the difficulty of quantifying drought impact; and (b) the lag of water system responses to drought.

Various authors emphasize the need to evaluate the relationship of stream flow and groundwater, with meteorological variables-based drought indices [12–21]. The relationship between stream flow and drought indices has been studied by several authors. For example, Haslinger et al. [18] established a methodology for directly relating various meteorological drought indices and stream flow data for gauging stations in northern Austria. These indices included: (i) Standardized Precipitation Index (SPI); (ii) Standardized Precipitation Evapotranspiration Index (SPEI); (iii) Palmer's Z-Index; and (iv) self-calibrating Palmer Drought Severity Index (scPDSI). Vasiliades and Loukas [19] used Palmer drought indices to ascertain hydrological drought, using simulated river discharges and soil moisture for riverine systems in Thessaly, Greece. Vicente-Serrano et al. [20] extensively studied the correlation between select drought indices and stream flow data from 151 basins worldwide. Lorenzo-Lacruz et al. [21] evaluated the ability of SPI and SPEI drought indices to correlate river discharge, investigate reservoir storage, and determine reservoir release. The knowledge base of studies linking drought and groundwater levels is limited, although Mall et al. [17] emphasized the need to study the impact of climate change and drought on groundwater resources in more depth. Most studies have used precipitation and temperature to study the relationship between drought and groundwater levels. For example, Panda et al. [15] reported the relationship between monsoon rainfall and groundwater fluctuation. Tirogo et al. [16] reported the groundwater response to rainfall for a study area in Burkina Faso, West Africa. The relationship between groundwater level fluctuation and rainfall was also studied for a selected well in Central Taiwan, by Jan et al. [14]. Chen et al. [13] found that groundwater levels greatly depended on precipitation and annual mean temperature, with a delayed response time. An empirical model developed by Chen et al. [12] linked annual precipitation and average temperature to groundwater levels, based on water budget and groundwater flow. Shahid and Hazarika [22] studied the relationship between groundwater level and rainfall for Northwestern Districts of Bangladesh, and related the groundwater drought to meteorological droughts using SPI. Fiorillo and Guadagno [23] also studied the relationship between groundwater drought and meteorological drought using SPI. However, the relationship between drought indices and groundwater level fluctuation has not been significantly explored in the past.

Our study differs from the aforementioned studies, since we have focused on groundwater response to drought by deriving a parametric relationship between drought indices and empirical groundwater levels. We conducted an event-by-event analysis to capture the specific behavior of groundwater level fluctuation during individual drought episodes. Some studies have utilized a different approach. Bloomfield and Marchant [24] developed a Standardized Groundwater level Index (SGI), incorporating a similar approach to SPI using groundwater level data from select wells in the United Kingdom. Mendicino et al. [25] proposed a Groundwater Resource Index (GRI) for drought monitoring and forecasting. This was based on a simple water balance model approach. Li and Rodell [26] empirically derived a groundwater drought index (GWI), based on Catchment Land Surface Model (CLSM) output. Li and Rodell [26] found a strong regional correlation between CLSM-based [27] GWI and in situ data-based GWI, and both GWIs displayed a higher correlation with SPI-12 and SPI-24. However, CLSM requires a substantial modeling effort. Sanchez et al. [28] proposed a standardized anomaly index, using different variables to represent different drought types. They used groundwater and stream flow to represent hydrological drought. Sawada et al. [29] developed an eco-hydrological model to identify different types of drought, and studied the mechanism of drought progress. Other studies have used remote sensing techniques to quantify declines in groundwater storage [30–33]. Most of these studies used precipitation and temperature as indicators of drought.

Groundwater systems are influenced by many factors, including the hydrological properties of the recharge area, the hydraulic properties of aquifer, and climatic variables. Therefore, deterministic approaches for quantifying groundwater level dynamics require aquifer properties, and recharge rates, amongst other factors. Due to the limitations of such data, deterministic approaches may be difficult to implement [12], which leaves statistical analysis as a viable alternative. Whittemore et al. [34] assessed the water-level changes using climatic indices for areas affected by pumping in the High Plains Aquifer system in central United States (Kansas), and predicted the water-level changes during extended drought. They used the mean annual water-level changes from five groundwater management districts, and climatic indices such as PDSI, Palmer Z index, and SPI. They also emphasized the need for simple correlation-based approaches for the rapid assessment of groundwater responses to external forces.

In this study, groundwater level data from the U.S. Geological Survey Ground-Water Climate Response Network (USGS CRN) wells were used. Wells in this network have the least anthropogenic-induced disturbances [35]. A total of eight indices were tested and a correlation matrix was developed between groundwater levels and drought indices to evaluate the capability of indices to elucidate dynamics of groundwater level fluctuations. Linear regression models were also developed for each well, to examine the relationship between drought and groundwater level. The statistical significance of a drought index for predicting groundwater level was also tested. The seasonal variability of the groundwater level, and its relationship with drought, was also studied for selected wells. The duration of drought events and lag times of groundwater responses, with respect to the onset and termination of drought events, were also studied.

2. Study Area and Methods

2.1. Study Area and Groundwater Levels Data

The study area and the selected well locations are shown in Figure 1. Criteria for the selection of CRN wells included: (a) located in unconfined aquifers or near-surface confined aquifers; (b) had minimal artificial influences (e.g., pumping, irrigation, canals, and artificial recharge); and (c) had never gone dry [35]. This study directly used the data from CRN wells, and we did not verify whether all of the criteria were met for each well. A total of 32 USGS CRN wells (Table A1) from the Great Plains States of the United States were analyzed (Figure 1). Wyoming (WY) did not have a CRN well when this study was conducted. The beginning of the time span of groundwater level data was chosen based on the beginning of consistently available groundwater level records (Table A2). December 2013 was chosen as the end of the time span. It should be noted that the USGS revises the CRN wells from time to time and alters the listing of wells. The USGS may add additional wells to the CRN network or remove some well data, if it finds that the wells no longer meet the criteria to be included in the CRN well network. For example, USGS removed the wells KS1, KS2, NE3, SD1, SD2, and TX2; and added a well in KS and another in WY. This study used the archived data from USGS CRN wells as listed, selecting those which met the criteria to be included in the CRN database.
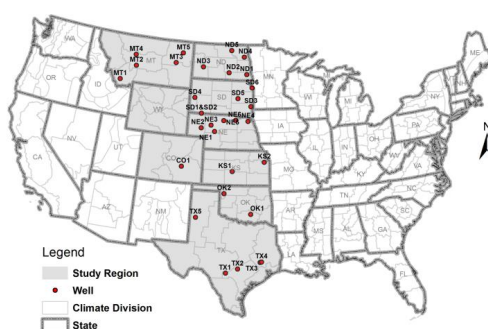

Figure 1. Study area showing selected wells' locations.

2.2. Drought Indices

The Palmer Drought Severity Index (PDSI) [36]), Palmer Hydrological Drought Index (PHDI) [37], Standardized Precipitation Index (SPI) [5,38], and meteorological parameters such as Precipitation (symbolized as PCP) and Average Temperature (TMP), were used in this study. The monthly values of the PDSI, PHDI, SPI, TMP, and PCP were derived from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) (Currently part of NOAA's National Centers for Environmental Information (NCEI)). The NCDC maintains historic data from 1895 to the present, in climatic division scale. NOAA's Gridded Climate Divisional Dataset (nCLIMDIV formerly known as Traditional Climate Division Dataset (TCDD) data) from NOAA NCDC were also used in this study. nCLIMDIV replaced the previous Traditional Climate Division Dataset (TCDD) in March 2014. The detailed description and major impacts of this transition can be found in Fenimore et al. [39]. Vose et al. [40] discussed the improvement in the nCLIMDIV data and suggested that this can be used in applied research and climatic monitoring.

The linear relationship between the monthly median depth to the water level from the land surface, *b*, and the corresponding monthly values of the PCP, TMP, PDSI, PHDI, SPI-6, SPI-9, SPI-12, and SPI-24 indices, was analyzed using the Pearson correlation coefficient. The SPI can be calculated for multiple timescales, indicating the impact on different water sectors. In this study, a SPI with a timescale of at least six months was used since it was suitable for analyzing hydrological drought impact, such as groundwater decline [41]. The drought indices used for each well were for the respective climatic division in which the well was located. In the US, each state encompasses groups of climatic divisions. The NOAA's NCDC compiles the climatic variable data at a climatic division scale (also see [42,43]).

Linear regression models were also developed for each well, to examine the relationship between SPI-24 and *b*. The rationale for focusing on SPI-24 is its inherent concomitancy with groundwater levels. The linear relationship between SPI-24 and *b* is expressed by the equation, $b = \beta_0 + \beta_1 (\text{SPI-24})$, where β_0 and β_1 are the coefficients. The coefficients were tested for statistical significance at the 5% level.

The monthly variations of groundwater levels, and correlations between SPI-24 with *b*, were studied for select wells. A subset of wells which had at least 25-year records of monthly groundwater level data, was demarcated from the rest of the dataset. This was done to identify the seasonal variability of the groundwater level and its relation to drought.

For each well, the duration in number of months under moderate or more severe drought conditions were derived, based on SPI-24. Drought is reported as moderate or more severe when SPI-24 $\leq$ −0.8, using NOAA's NCEI. Therefore, the drought events for each well were delineated based on SPI-24 $\leq$ −0.8, for at least 30 consecutive months. Corresponding groundwater *b* values were also noted. From this data, groundwater level decline, and the lag and recovery time of the groundwater level in relation to the selected drought events, were determined.

3. Results and Discussion

The Pearson correlation coefficients between *b* and climatic indices such as PCP, TMP, PDSI, PHDI, and SPI, for 6, 9, 12, and 24 month scales, are shown in Figure 2. The results show that precipitation and temperature have a relatively low correlation with the groundwater level. A total of 29 out of 32 wells show *r* in the range of −0.3 to 0.21. The highest correlation of *b* and precipitation (−0.51) is observed for well OK2. The *r* values of *b* and the temperature vary between −0.23 and 0.19. Precipitation, by and large, correlates negatively, as expected. Temperature, on the other hand, shows a positive and negative correlation with *b*.

Since *b* correlates negatively with drought indices; the more negative the index value (the more severe the drought), the greater the depth to the groundwater. The PHDI and SPI-24 displayed better correlations with groundwater levels, albeit inconsistently (Figure 2). A total of 12 out of 32 wells show an *r* value of −0.6 or better with SPI-24; 9 wells show an *r* of −0.6 or better with PHDI. A detailed description of *r* with indices follows: NE4 and NE5 displayed an *r* value of −0.9 and −0.8, for SPI-24. For (i) wells KS2 and MT5 with respect to SPI-24; (ii) OK1 with respect to PHDI; (iii) OK2 with respect

to PDSI; and (iv) TX2 with respect to SPI-9, the *r* value was $-0.8 \leq r \leq -0.7$. For wells KS1, MT2, ND5, NE2, SD3, and SD4 with SPI-24, the *r* value was $-0.7 \leq r \leq -0.6$, similar to wells ND1 and ND3 with respect to PHDI. The correlation values for wells MT1 and SD6 considering SPI-24; and for CO1 with respect to SPI-9, were $-0.6 \leq r \leq -0.5$. Four wells (ND4, SD5 and TX4 with SPI-24; and MT3 with SPI-12) had correlation values that ranged between -0.5 and -0.4; one well (ND2 with SPI-24) with a correlation value of -0.32; four wells (TX3 with SPI-24; NE3 and SD2 with PHDI; and TX1 with SPI-12) had correlation values between -0.3 and -0.2; and one well (NE6 with SPI-24) had a correlation value of -0.05. Wells MT4, NE1, SD1, and TX5 displayed positive correlation values with respect to drought indices. Some factors that can possibly be attributed to the inconsistent correlation may be due to different hydrostratigraphic and hydrological conditions at each well. However, we can still unequivocally state that the results show that drought indices are helpful in monitoring groundwater levels.
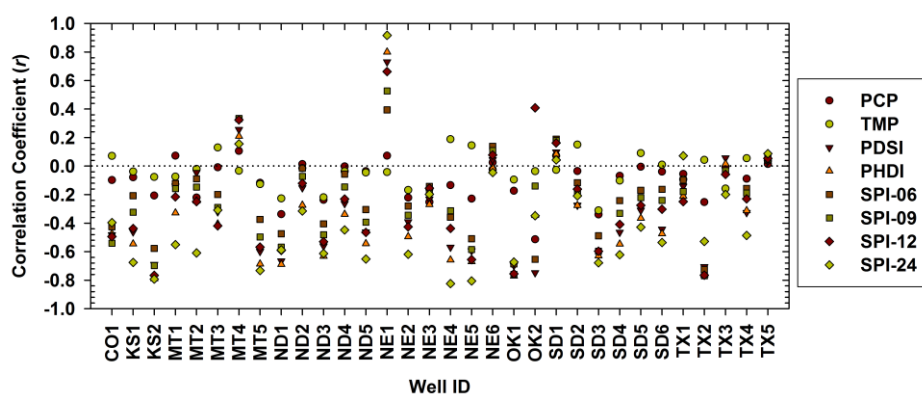

Figure 2. The Pearson correlation coefficient, *r*, between groundwater level, *b*, and drought index.

Based on the results of the overall correlation between *b* values and drought indices, the SPI-24 index is a viable candidate for understanding groundwater level fluctuations during a discernible drought. Even though an index like PDSI is extensively used for drought quantification, it does not effectively capture hydrological impacts such as groundwater deficit. The PDSI is an effective measurement index of soil moisture conditions. The PHDI, a modified version of PDSI, can capture groundwater deficit. However, the SPI is a simple index, solely based on precipitation records. The SPI quantifies the precipitation deficit for multiple time scales. The SPI with a longer time scale or a moving averaging window such as SPI-24, can capture distinctive wet or dry trends, and connect them to streamflow, reservoirs, and groundwater responses. A study of groundwater level responses to the SPI will be advantageous in groundwater management and monitoring during discernible drought episodes, owing to the fact that precipitation records are widely available. Thus, SPI-24 may be regarded as a proxy measure of groundwater levels.

Table 1 shows the estimated coefficients for the regression models of SPI-24 and *b*, estimated standard error (SE) of coefficients, *t*-test statistic values, and *p*-values for each well. Negative values of β_1 suggest that *b* reduces with increasing SPI-24, as expected. The wells MT4, NE1, SD1, TX1, and TX5 show the positive β_1. Even though TX1 shows a positive β_1, it shows a negative correlation with respect to other indices with SPI-24 (Figure 2). The small *p*-value (<0.05) suggests that the relationship between *b* and SPI-24 is significant, and β_1 is not null. The observed significant values (*p*-values) in *t*-tests for coefficient β_1, show that SPI-24 has a significant influence on *b* (at $\alpha = 0.05$) for all of the wells, except NE6, OK2, SD1, and TX1.

Table 1. Results of regression analysis.

Well ID		Coef.	SE	T	P	Well ID		Coef.	SE	T	P
CO1	β_0	6.25	0.01	602.78	0.000	NE4	β_0	0.78	0.04	17.38	0.000
	β_1	−0.04	0.01	−4.89	0.000		β_1	−0.25	0.03	−7.28	0.000
KS1	β_0	3.79	0.07	57.26	0.000	NE5	β_0	2.44	0.03	75.56	0.000
	β_1	−0.70	0.06	−11.57	0.000		β_1	−0.17	0.02	−9.52	0.000
KS2	β_0	6.35	0.02	360.74	0.000	NE6	β_0	14.18	0.05	258.48	0.000
	β_1	−0.60	0.02	−35.28	0.000		β_1	−0.05	0.05	−1.08	0.280
MT1	β_0	48.72	0.14	347.19	0.000	OK1	β_0	33.77	0.08	438.32	0.000
	β_1	−1.28	0.14	−8.88	0.000		β_1	−1.76	0.08	−22.91	0.000
MT2	β_0	26.83	0.05	577.91	0.000	OK2	β_0	38.07	0.09	404.35	0.000
	β_1	−0.26	0.04	−5.85	0.000		β_1	−0.13	0.09	−1.49	0.156
MT3	β_0	9.40	0.01	761.55	0.000	SD1	β_0	12.72	0.03	403.61	0.000
	β_1	−0.05	0.01	−4.37	0.000		β_1	0.02	0.03	0.73	0.464
MT4	β_0	42.09	0.01	3363.45	0.000	SD2	β_0	12.70	0.11	120.18	0.000
	β_1	0.03	0.01	2.09	0.038		β_1	−0.35	0.09	−3.71	0.000
MT5	β_0	13.30	0.01	1123.18	0.000	SD3	β_0	2.07	0.06	36.90	0.000
	β_1	−0.16	0.01	−14.37	0.000		β_1	−0.45	0.05	−9.94	0.000
ND1	β_0	1.72	0.02	83.83	0.000	SD4	β_0	2.00	0.42	4.73	0.000
	β_1	−0.35	0.02	−17.33	0.000		β_1	−5.21	0.40	−13.00	0.000
ND2	β_0	6.60	0.04	161.51	0.000	SD5	β_0	9.09	0.18	49.28	0.000
	β_1	−0.24	0.04	−6.62	0.000		β_1	−1.32	0.19	−7.07	0.000
ND3	β_0	5.64	0.02	348.93	0.000	SD6	β_0	9.68	0.09	110.93	0.000
	β_1	−0.27	0.02	−16.58	0.000		β_1	−0.89	0.10	−9.23	0.000
ND4	β_0	7.12	0.02	378.18	0.000	TX1	β_0	54.16	0.14	377.00	0.000
	β_1	−0.22	0.02	−11.58	0.000		β_1	0.08	0.13	0.58	0.565
ND5	β_0	3.10	0.02	160.01	0.000	TX2	β_0	7.66	0.04	196.64	0.000
	β_1	−0.29	0.02	−16.72	0.000		β_1	−0.44	0.04	−11.38	0.000
NE1	β_0	31.87	0.01	4149.44	0.000	TX3	β_0	15.21	0.03	436.75	0.000
	β_1	0.11	0.00	21.23	0.000		β_1	−0.09	0.03	−2.76	0.006
NE2	β_0	1.09	0.01	78.48	0.000	TX4	β_0	22.99	0.03	886.17	0.000
	β_1	−0.17	0.01	−13.75	0.000		β_1	−0.15	0.02	−6.59	0.000
NE3	β_0	1.93	0.04	45.52	0.000	TX5	β_0	24.23	0.40	60.91	0.000
	β_1	−0.09	0.03	−2.69	0.008		β_1	0.94	0.40	2.35	0.019

The variation of *b* and SPI-24 for the wells MT4, NE1, SD1, TX5, and KS2, is shown in Figure 3. The wells MT4, NE1, SD1, and TX5 displayed positive correlation with drought indices, as opposed to the expected negative *r*. The well KS2 displayed a strong linear negative correlation. From Figure 3, we can see that the *b* values are not reflecting drought conditions for the wells MT4, NE1, SD1, and TX5. Well MT4 is in an Upper Cretaceous aquifer comprised of mudstone, sandstone, and a basal conglomerate. The depth to the water is approximately 42 m, which implies that responses to precipitation or drought may take considerable time. In addition, the possibility that mudstone units may overlie the aquifer material in which the well is completed, could mean that surface responses to wet and dry periods would be further delayed. Well NE1 is in the High Plains aquifer and the depth to the water level is substantial enough (~31.5 m) that responses to precipitation may also take considerable time. Thus, the depth of the unsaturated zone could cause a delay in the response to wet and dry conditions. Perhaps the drop in the record's groundwater level is the response to the previous dry period, and the rise in the groundwater level is due to the wet period, over which the water-level record is superimposed. Well SD1 is 55 m deep and is in the Arikaree Formation. The depth to the water for SD1 is relatively shallow (~13 m). The well recharge might have been affected by the variation in pumping, in response to wet and dry conditions. Well SD1 was removed from the

CRN network by the USGS. Well TX5 most likely represents the long-term, continued decline of water levels in the High Plains Aquifer system of Texas, in response to irrigation pumping. The depth to the groundwater has become substantial and the area can be classified as semi-arid to arid, thus, the water level is little affected by precipitation. The well location is probably not close to pumping wells, otherwise a seasonal pumping signal would be expected. The inclusion of wells MT4, NE1, and TX5 in the CRN network, may need further reconsideration, and is beyond the scope of this study. However, wells located in shallow aquifers with no pumping or recharge effects can be used in assessing groundwater responses during drought.
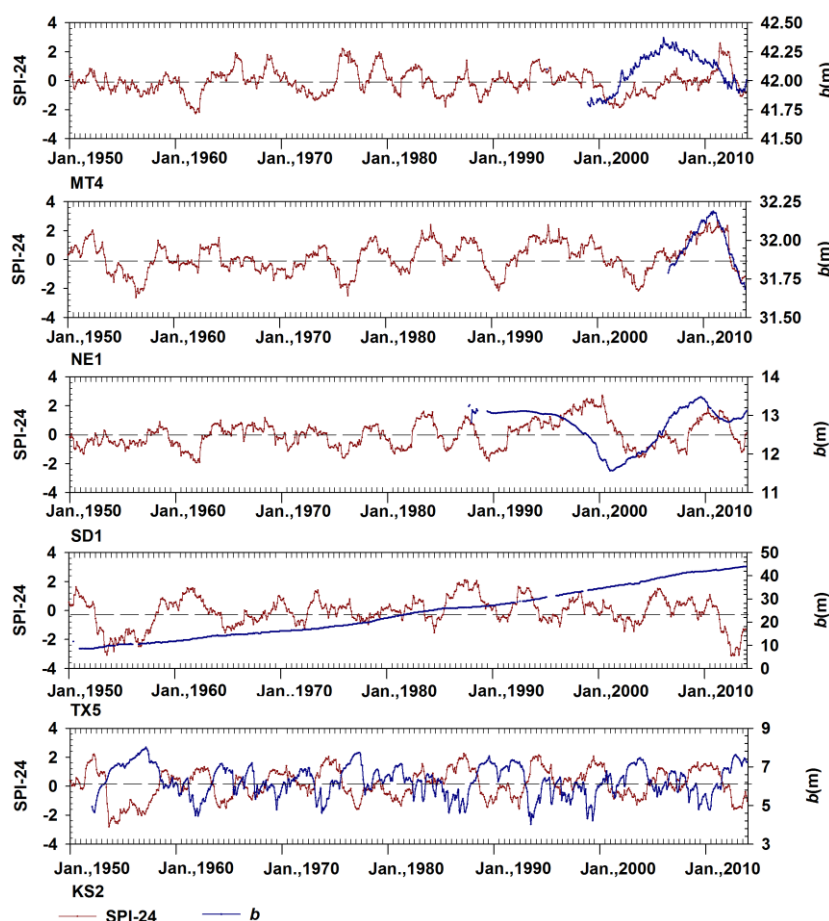

Figure 3. The variation of the 24-month Standardized Precipitation Index (SPI-24) and depth to water level, *b*, for wells MT4, NE1, SD1, and TX5, that displayed positive correlation.

The variation in the groundwater level and its correlation with SPI-24, were further analyzed on a monthly time basis for a select set of wells. The selected wells were KS2, ND1, ND2, ND3, ND4, ND5, NE6, OK1, and TX2. These wells had at least 25 years of reported monthly records. TX5 had more than 25 years of monthly records for each month, but was not used for this part of study because its water level was declining, irrespective of any established drought episodes (Figure 3). The tabulated results in Table 2 include correlation coefficient values (r') between SPI-24 and *b* for each month, and average values of depth to the water level, from the land surface, μ.

Table 2. Correlation coefficients between SPI-24 and *b* (*r*′), sample size (*n*), and average of monthly median values (*μ*).

ID (Time Frame)	Pr	January	February	March	April	May	June	July	August	September	October	November	December
KS2 (1953–2013)	*r*′	−0.84	−0.82	−0.82	−0.78	−0.81	−0.79	−0.77	−0.76	−0.75	−0.80	−0.81	−0.82
	n	61	60	61	61	61	61	61	61	61	61	61	60
	μ	6.38	6.39	6.34	6.24	6.14	6.03	6.12	6.31	6.38	6.32	6.32	6.35
ND1 (1964–2013)	*r*′	−0.75	−0.72	−0.73	−0.60	−0.57	−0.57	−0.60	−0.65	−0.67	−0.68	−0.69	−0.69
	n	49	44	48	49	46	47	47	47	47	48	48	49
	μ	1.92	1.97	1.83	1.21	1.18	1.31	1.48	1.79	1.87	1.77	1.67	1.77
ND2 (1979–2013)	*r*′	−0.42	−0.38	−0.31	−0.36	−0.30	−0.33	−0.32	−0.31	−0.29	−0.29	−0.24	−0.28
	n	29	28	33	33	35	35	35	35	34	35	35	32
	μ	6.52	6.52	6.48	6.41	6.36	6.36	6.47	6.65	6.69	6.58	6.50	6.51
ND3 (1969–2013)	*r*′	−0.68	−0.68	−0.67	−0.60	−0.73	−0.64	−0.55	−0.58	−0.65	−0.66	−0.67	−0.72
	n	36	37	39	36	32	42	39	41	36	44	40	36
	μ	5.77	5.76	5.64	5.45	5.45	5.40	5.47	5.58	5.68	5.66	5.67	5.73
ND4 (1966–2013)	*r*′	−0.43	−0.34	−0.34	−0.38	−0.36	−0.48	−0.43	−0.35	−0.36	−0.38	−0.37	−0.41
	n	45	45	47	46	46	46	45	46	47	46	47	47
	μ	7.07	7.08	7.11	7.06	7.03	7.00	7.03	7.11	7.14	7.09	7.08	7.07
ND5 (1981–2013)	*r*′	−0.68	−0.68	−0.67	−0.64	−0.68	−0.73	−0.58	−0.64	−0.63	−0.61	−0.62	−0.65
	n	31	29	29	31	33	33	30	31	30	33	32	31
	μ	2.96	3.01	3.04	3.03	3.03	2.95	2.90	2.85	2.93	2.93	2.93	2.93
NE6 (1967–2013)	*r*′	−0.04	−0.06	−0.06	−0.07	−0.08	−0.02	−0.04	−0.02	−0.02	−0.01	−0.04	−0.05
	n	46	46	47	47	47	47	46	46	47	47	47	47
	μ	14.18	14.17	14.11	14.06	14.01	13.98	14.02	14.24	14.35	14.37	14.35	14.33
OK1 (1960–2013)	*r*′	−0.75	−0.71	−0.73	−0.62	−0.73	−0.76	−0.71	−0.69	−0.75	−0.75	−0.71	−0.70
	n	52	52	52	54	52	53	54	52	53	54	53	54
	μ	33.71	33.75	33.42	32.66	32.27	32.14	32.79	33.80	34.44	34.49	34.20	34.02
TX2 (1981–2013)	*r*′	−0.52	−0.54	−0.50	−0.48	−0.59	−0.62	−0.53	−0.52	−0.55	−0.62	−0.59	−0.55
	n	28	25	30	28	27	27	29	27	28	28	27	26
	μ	7.44	7.44	7.56	7.56	7.59	7.37	7.40	7.59	7.69	7.74	7.59	7.48

Pr—Parameters; *r*′—correlation coefficient; *n*—number of monthly records; *μ*—average values of monthly median records in meters.

Figure 4 shows variation in r' and μ. The μ values for well KS2 vary between 6.03 m in June and 6.39 m in February. The r' values for KS2 vary between -0.84 in January and -0.75 in September. The μ and r' values for the KS2 well are relatively stable, and the groundwater level had a strong linear correlation with SPI-24. The highest differential value for r' is observed for ND1, where r' values range between -0.75 for the month of January, and -0.57 for the months of May and June. On the other hand, the μ value varies between 1.97 m in February and 1.18 m in May. The highest differential μ value was observed for the OK1 well, where the highest μ value was 34.49 m in October, and the lowest μ value was 32.14 m in June. μ values for ND4 vary between 7.14 m in September and 7 m in June, which was the lowest differential μ value. The r' values for NE6 are very low for all of the months, over the entire period. The annual water-level patterns for the wells show water-level rises during the spring to summer months, implying recharge periods, followed by water-level declines, implying the combined effects of discharge to streams, and possible pumping of the wells during the summer to early fall, followed by the recovery of water levels, possibly due to the cessation of stream discharge or pumping. We did not explore any general or specific patterns for the seasonal variability of r'. The r' values are relatively the same throughout the year. This implies that an extended drought influences the groundwater, regardless of the season of the year. Knowing the variation in the groundwater level, and its correlation with drought on a monthly basis, will be helpful in the identification of seasonal groundwater availability and its susceptibility to drought, and can contribute towards better planning and utility of groundwater resources.
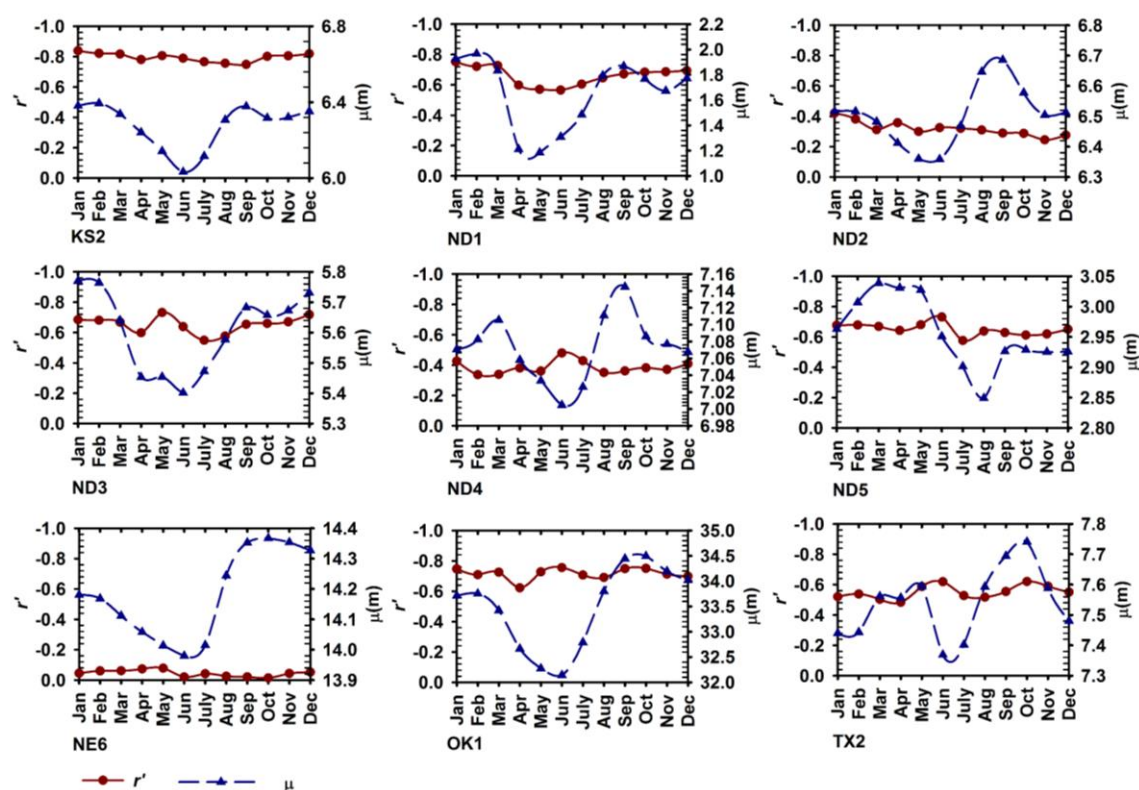

Figure 4. Monthly variation of r' and μ.

To study the effects of drought duration on groundwater decline, seven different events were identified that could satisfy the criteria of SPI-24 ≤ -0.8 in the area surrounding the well for at least 30 consecutive months. This was also complementary with complete well data spanning a similar time frame of 30 months. Table 3 shows the timeline of drought events (year and month of starting and ending), duration of drought events (number of months under moderate or more severe drought), and available monthly median records of groundwater level records within established drought events.

Table 3. Pertinent data showing selected drought events and number of groundwater level records.

ID	Drought Events			
	Start	**End**	**Duration (Months)**	**# Records**
KS2	July 1953	October 1957	52	52
MT1	June 2000	April 2003	35	35
MT4	June 2000	February 2003	33	32
ND3	May 1989	July 1992	39	39
ND4	July 1988	June 1991	36	36
ND5	July 1988	June 1991	36	35
NE2	August 1935	August 1938	37	30

The variation in the monthly SPI-24 values with temporal groundwater levels is shown in Figure 5 (a-1 to g-1). The *x*-axis shows the year and month. The time frame commences two years before the beginning of the drought, and ends two years after the drought event. As such, we can extract information on lag and recovery times of groundwater levels following a drought. From Figure 5 (a-2 to g-2), we can see the relationship between *b* and the duration, *d*, of a moderate or more severe drought, that is, a SPI-24 ≤ -0.8 condition. Wells MT1, MT4, ND3, ND4, and ND5 display a prominent linear relationship with respect to the duration of drought events ($r > 0.9$), when compared to wells KS2 and NE2 (Figure 5: a-2 and g-2). The location and hydrogeological properties of wells KS2 and NE2, such as the relatively shallow water table and proximity to a river, respectively, may be the reason for the relatively low correlation. Table 4 shows the results of: (i) total groundwater decline values during each drought event; (ii) correlation coefficient between depth to the water level and duration, *r*; (iii) fitted linear regression model equations for depth to the water level with duration; and (iv) coefficient of determination, R^2. The total decline in groundwater was determined from the difference in groundwater levels at the beginning and end of each drought event. The highest R^2 values were obtained for wells ND4 and ND5, which indicated that 97% of the variation in the groundwater level may be attributed to the duration of moderate or more severe drought, that is, SPI-24 ≤ -0.8 conditions. Well NE2 displayed the lowest R^2 value, of 39%. The water levels for wells KS2 and NE2 started to recover a few months ahead of the end of the associated drought event, thus displaying a relatively low linear correlation value (Figure 5).

The depth to the water level increased or continued to remain high, even after the end of a drought event for wells MT1 and MT4, which could be due to aquifer characteristics such as depth to the water. Wells MT1 and MT4 have relatively large depths to the water, and slow responses to dry and wet conditions. The consequent drought pattern following the defined drought event, may also be the reason for this type of anomaly. Wells MT4 and ND3 show a lag in the response to a drought event. In general, we can surmise that the groundwater decline was linear during established drought events defined as moderate to more severe, that is, those in which the SPI-24 ≤ -0.8. However, there was variation in groundwater responses before the onset and offset of drought events.

Drought impacts all water dependent sectors, and causes vast economic losses and environmental issues. Hays et al. [44] emphasizes that an impact assessment is vitally important for decision making, responding, and understanding vulnerabilities of drought. Above ground hydrological responses to drought using stream flow data is a vastly studied area compared to studies of influences of drought on groundwater resources. This study investigated the possibility of utilizing drought indices for exploring groundwater level responses to drought. It should also be recognized that inherent challenges also face the establishment of an uncontested parametric relationship between drought indices and groundwater dynamics due to the complex nature of aquifers, such as varying depth, properties of the aquifer and recharge area, and possible anthropogenic influences.
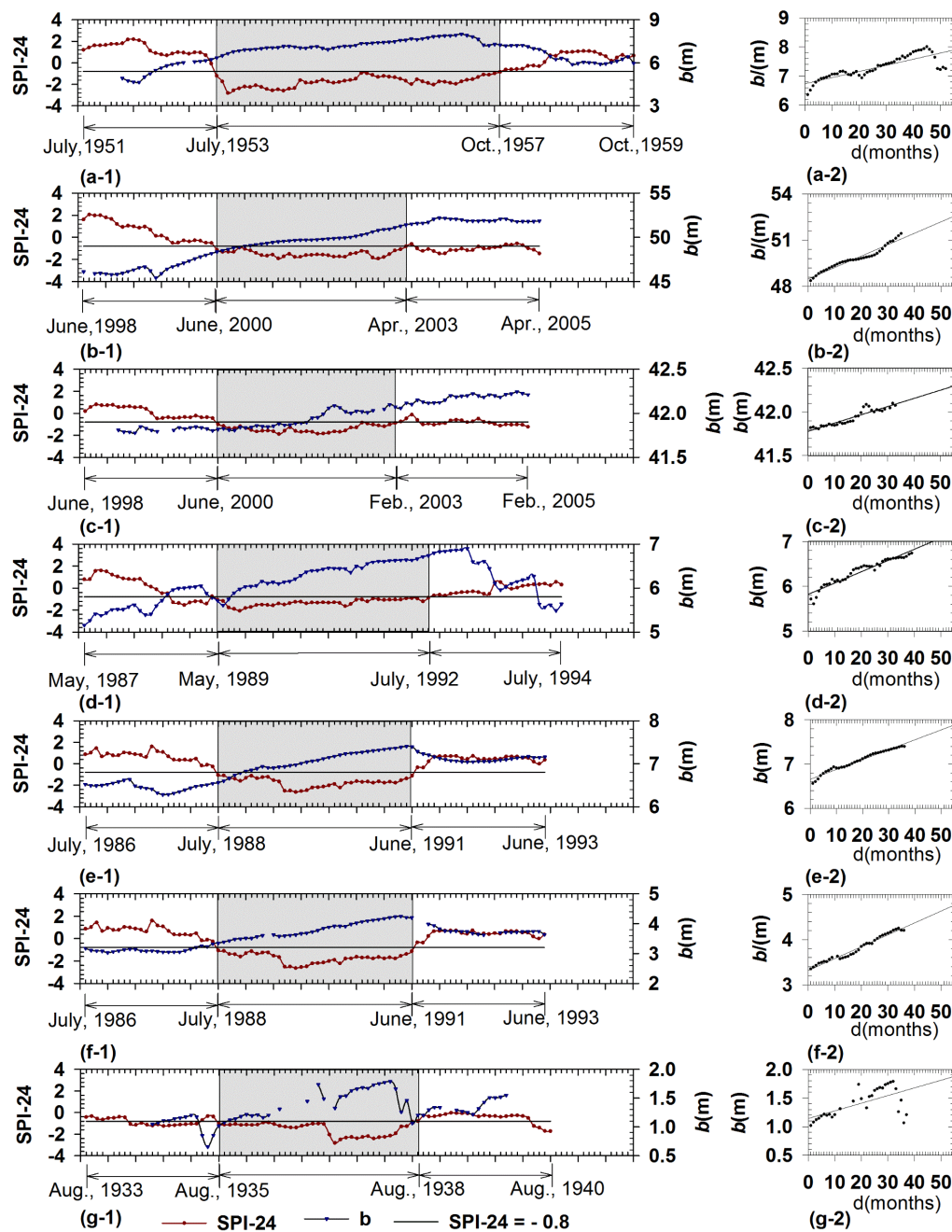
Figure 5. The variation of *b* with SPI-24 and duration (*d*) of selected drought events for (**a**) KS2; (**b**) MT1; (**c**) MT4; (**d**) ND3; (**e**) ND4; (**f**) ND5; and (**g**) NE2.

Table 4. The relationship between *b* and duration (*d*) of drought events.

ID	Time Frame		Total Drop (m)	*r*	Regression Model	R^2 (%)
	Start	End				
KS2	July 1953	October 1957	0.90	0.831	$b = 0.021d + 6.734$	69.1
MT1	June 2000	April 2003	3.05	0.976	$b = 0.074d + 48.478$	95.3
MT4	June 2000	February 2003	0.25	0.933	$b = 0.009d + 41.779$	87.1
ND3	May 1989	July 1992	1.02	0.962	$b = 0.025d + 5.825$	92.5
ND4	July 1988	June 1991	0.84	0.986	$b = 0.022d + 6.653$	97.3
ND5	July 1988	June 1991	0.85	0.987	$b = 0.026d + 3.318$	97.4
NE2	August 1935	August 1938	0.19	0.625	$b = 0.013d + 1.143$	39.0

4. Summary and Conclusions

This study explored the relationship between groundwater levels and drought indices for wells located in the Great Plains States of the United States. The groundwater level data from USGS CRN wells with minimum anthropogenic disturbances were used. A total of 32 wells were selected for the study. The correlation matrix of the drought indices and depth to groundwater levels (monthly median values) was calculated, and used to identify which reliable drought indices were most valuable for monitoring groundwater responses to drought. It should be noted that the drought indices used in this study were derived from NOAA's NCDC for each climatic division where a well was located. The groundwater observation wells may not represent the groundwater in the larger climatic divisions. It would be more appropriate to consider indices with areal coverage of the recharge area of each well, although this would be impractical for the rapid, simple approach discussed here. Regardless, from this study we found that drought indices were fairly reflective of groundwater responses to drought. The PHDI and SPI-24 indices superseded other indices used in this study and displayed a higher correlation with the groundwater level. Li and Rodell [26] also reported that SPI-24 is a promising drought index in studying groundwater responses to drought. The regression models were developed to examine the relationship between SPI-24 and *b*. The observed significant values (*p*-values) from *t*-tests show that SPI-24 has a significant influence on *b* (at $\alpha = 0.05$), for most of the wells.

The seasonal variability of groundwater levels, and the correlation of groundwater levels with SPI-24, were also studied for selected wells that had adequate data. The correlation with average values of monthly median depths to the water level remained relatively the same throughout the year. The fluctuations in groundwater levels for specific drought events were also examined. Drought events, for this purpose, were defined by a SPI-24 threshold of less than or equal to -0.8, a category used for moderate or more severe drought. There were seven drought episodes identified, using at least 30 months of groundwater level records. During each defined drought event, the duration of the event was found to have a significant influence on the response of groundwater levels to drought, displaying a prominent linear relationship to groundwater decline. A set of regression equations was developed to establish the relationship between drought duration and the depth to the water level from the land surface, for the selected seven drought events. Based on the R^2 values, for four wells (MT1, ND3, ND4, and ND5), more than 92% of the variation in groundwater level can be explained by the drought duration. Decline and recovery times were also discernible for groundwater levels for the defined drought episodes, with respect to each well location. For example, wells MT4 and ND3 had a lag time from the start of a drought event, to when the groundwater level decline was perceptible, whereas wells KS2 and NE4 began to recover prior to the end of the drought event, as represented by SPI-24. A better understanding of the lag and recovery could be gained by conducting an analysis using different indices, such as SPI-6, -9, -12, -24, and PDSI, and a Z-index, and incorporating different lengths of lags.

Observation of groundwater level fluctuations is essential for groundwater monitoring and management. There have been few studies conducted on utilizing other monitoring well networks to study the ground water fluctuation, such as the USGS CRN well network. Kansas has established an Index Well Program that is maintained for examining the response of groundwater to a variety of factors, including climatic and pumping variations. There is a lack of in situ observations in many states due to practical limitations of the establishment and maintenance of observation well networks. Alternatively, establishing a relationship between groundwater and meteorological drought indicators, as accomplished in this study, will be useful in groundwater monitoring and management. Such a study could enable managers to have an estimated groundwater level during drought, based on well-established and readily available drought indices from the widely used source, NOAA NCDC. In addition, the current understanding of the interaction between drought and groundwater is limited. A study like this can be helpful for understanding the response of groundwater levels to various characteristics of drought, such as intensity and duration. However, the relationship between drought and groundwater levels may be region- specific and thus needs to be studied for each region of interest.

A study using group of wells in an area of an aquifer with relatively similar hydrogeologic properties can help scientists to understand the influences of drought on groundwater.

Author Contributions: Navaratnam Leelaruban, G. Padmanabhan, and Peter Oduor conceived the main idea. Navaratnam Leelaruban performed data collection, construction of data base, and analysis of the data. All three authors jointly wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Geographical location of USGS CRN wells used in this study.

ID	USGS SITEID	DECLAT	DECLON	STATE	CLIM. DIVISION	COUNTY
CO1	382323104200701	38.390	−104.336	CO	ARKANSAS DRAINAGE BASIN	Pueblo
KS1	381119098435301	38.189	−98.732	KS	SOUTH CENTRAL	Stafford
KS2	390006095132301	39.002	−95.223	KS	EAST CENTRAL	Douglas
MT1	450524112380701	45.090	−112.636	MT	SOUTHWESTERN	Beaverhead
MT2	462641110561701	46.445	−110.939	MT	CENTRAL	Meagher
MT3	470709106061401	47.119	−106.104	MT	NORTHEASTERN	Garfield
MT4	472203111112602	47.368	−111.191	MT	CENTRAL	Cascade
MT5	480034105195401	48.009	−105.332	MT	NORTHEASTERN	McCone
ND1	462633097163402	46.442	−97.276	ND	SOUTHEAST	Richland
ND2	463417099271002	46.571	−99.453	ND	SOUTHEAST	Logan
ND3	465755102410701	46.965	−102.686	ND	SOUTHWEST	Stark
ND4	475646097372201	47.946	−97.622	ND	NORTHEAST	GrandForks
ND5	482908099134601	48.486	−99.230	ND	NORTHEAST	Towner
NE1	413130100531202	41.525	−100.888	NE	NORTH CENTRAL	McPherson
NE2	414607102263301	41.769	−102.443	NE	PANHANDLE	Garden
NE3	420204101200502	42.034	−101.335	NE	NORTH CENTRAL	Hooker
NE4	422802097031601	42.467	−97.055	NE	NORTHEAST	Cedar
NE5	422849099521503	42.480	−99.871	NE	NORTH CENTRAL	Brown
NE6	423148098300601	42.530	−98.502	NE	NORTH CENTRAL	Holt
OK1	343457096404501	34.583	−96.679	OK	SOUTH CENTRAL	Pontotoc
OK2	361739099323301	36.294	−99.543	OK	NORTH CENTRAL	Woodward
SD1	430027102311801	43.007	−102.522	SD	SOUTHWEST	Shannon
SD2	430027102311806	43.007	−102.522	SD	SOUTHWEST	Shannon
SD3	434330096434801	43.725	−96.730	SD	SOUTHEAST	Minnehaha
SD4	441759103261202	44.300	−103.437	SD	BLACK HILLS	Meade
SD5	442254098174501	44.382	−98.296	SD	EAST CENTRAL	Beadle
SD6	451848096363501	45.313	−96.610	SD	NORTHEAST	Grant
TX1	293202099063501	29.534	−99.110	TX	SOUTH CENTRAL	Medina
TX2	295443097554201	29.912	−97.929	TX	SOUTH CENTRAL	Hays
TX3	302948095422501	30.499	−95.711	TX	EAST TEXAS	Montgomery
TX4	303143095334801	30.528	−95.564	TX	EAST TEXAS	Walker
TX5	341010102240801	34.170	−102.403	TX	HIGH PLAINS	Lamb

SITEID—Site Identity, DECLAT—Latitude in decimal degrees, DECLON—Longitude in decimal degrees, CLIM. Division—Climatic Division.

Table A2. Descriptive statistics of groundwater level data used in this study.

State	Well ID	Time Span		Records (Months)	Median Depth to Water Level—Below Land Surface/(m)		
		Begin (Year/Month)	End (Year/Month)		Avg.	Max	Min
CO	CO1	2003/03	2013/12	130	6.27	6.53	6.04
KS	KS1	2000/04	2013/12	161	3.45	5.17	1.14
	KS2	1952/02	2013/12	741	6.26	8.01	4.02

Table A2. *Cont.*

State	Well ID	Time Span		Records (Months)	Median Depth to Water Level—Below Land Surface/(m)		
		Begin (Year/Month)	End (Year/Month)		Avg.	Max	Min
MT	MT1	1998/08	2013/12	183	49.28	52.19	44.33
	MT2	2009/01	2013/12	60	26.72	27.44	25.95
	MT3	1998/04	2013/12	183	9.38	9.78	8.98
	MT4	1998/12	2013/12	178	42.09	42.37	41.78
	MT5	1998/10	2013/12	180	13.22	13.39	12.42
ND	ND1	1963/09	2013/12	573	1.65	2.76	0.42
	ND2	1978/11	2013/12	400	6.50	8.41	4.47
	ND3	1968/12	2013/12	459	5.61	6.90	4.28
	ND4	1968/06	2013/12	538	7.05	8.07	5.93
	ND5	1980/06	2013/12	380	2.96	4.25	2.25
NE	NE1	2006/09	2013/12	88	31.97	32.19	31.68
	NE2	1934/08	2013/12	307	1.11	1.88	0.28
	NE3	1998/12	2013/12	180	1.89	3.51	0.98
	NE4	2011/10	2013/12	27	0.96	1.50	0.47
	NE5	2009/10	2013/12	51	2.26	2.84	1.78
	NE6	1966/10	2013/12	563	14.16	16.37	10.81
OK	OK1	1959/11	201312	637	33.48	38.96	22.98
	OK2	2012/07	201312	18	38.19	38.53	37.83
SD	SD1	1989/06	2013/12	294	12.73	13.48	11.57
	SD2	1987/10	2013/12	305	12.59	19.63	10.52
	SD3	2004/02	2013/12	118	1.71	3.04	0.52
	SD4	1990/11	2013/12	271	0.31	16.66	−13.22
	SD5	1979/06	2013/12	225	8.58	13.75	3.03
	SD6	1979/10	2013/12	213	9.58	11.70	5.86
TX	TX1	2002/03	2013/12	67	54.19	58.21	51.42
	TX2	1980/07	2013/10	336	7.55	8.64	4.56
	TX3	1952/11	2013/12	187	15.20	17.78	13.91
	TX4	1989/12	2013/12	142	22.96	23.68	21.71
	TX5	1951/01	2013/12	725	24.15	43.92	8.53

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