

Prepared in cooperation with the National Oceanic and Atmospheric Administration's National Integrated Drought Information System

# Spectral Analysis to Quantify the Response of Groundwater Levels to Precipitation—Northwestern United States

Open-File Report 2020–1007

U.S. Department of the Interior  
U.S. Geological Survey



**Cover:** U.S. Geological Survey groundwater site 473442118162201 (also known as the "Davenport well"), Lincoln County, Washington. [Shown in the picture are the well head and the equipment used for transmitting real-time data. Photograph by Kimberly Cesal, U.S. Geological Survey.]

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Andrew J. Long and Christopher P. Konrad

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DAVID BERNHARDT, Secretary

**U.S. Geological Survey**  
James F. Reilly II, Director

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## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi <sup>2</sup> )	259.0	hectare (ha)
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)

## Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) or the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.



# Spectral Analysis to Quantify the Response of Groundwater Levels to Precipitation—Northwestern United States

Andrew J. Long and Christopher P. Konrad

## Abstract

Persistent atmospheric patterns that lead to wet and dry seasons and droughts over periods of months to decades and longer-term climate change over periods of decades to millennia affect groundwater resources. Changes in groundwater storage and the resulting groundwater discharge from most aquifers are relatively slow and steady compared to the variability of daily precipitation. The response of groundwater levels to precipitation can be complex because of a combination of processes that include evapotranspiration, surface runoff, and infiltration of net recharge from precipitation through the vadose zone. Typically, this response is delayed and results in a change in groundwater storage reflected in a time series of groundwater levels. Understanding the relations between variations in precipitation and changes in groundwater storage is essential to water resources planning. The objectives of this study were to (1) characterize the relation between precipitation and responses in groundwater levels at seasonal to decadal scales and (2) develop methods that are transferable on a continental scale to any groundwater-level record. Spectral analysis was applied to daily precipitation and groundwater levels for eleven monitoring wells in the northwestern United States with records ranging in length from 5.9 to 23.9 years. The analysis provided a quantitative characterization for each monitoring well that met both objectives and indicated that maximum and minimum precipitation rates generally occurred in December and August, respectively. Maximum groundwater levels and storage occurred from February to August, and minimum values occurred from January to December. The lag in the annual peak response of groundwater to peak precipitation ranged from 2.2 to 8.8 months, with a median value of 5.3 months. Groundwater responses to wet and dry seasons were evident in the relatively high amplitude frequencies of 10 and 20 cycles per decade (cpdec). A high amplitude frequency at 1 cpdec represents a drought cycle that resulted in larger groundwater level changes than typical seasonal water level fluctuations.

## Introduction

Long-term records of groundwater levels are critical for assessing the effects of drought on water resources. The response of groundwater levels to precipitation occurs more slowly than the response of surface water (levels and flows) and is less sensitive to short-term variation in weather. Persistent atmospheric patterns, including wet and dry seasons and droughts, occurring over periods of months to decades, and longer-term climate change, occurring over periods of

decades to millennia, affect groundwater resources. For example, an aquifer might provide a reliable water supply during a drought when surface water availability is reduced. Thus, the aquifer may serve as a buffer to reduce the temporal variability of the overall water supply. At the end of an extended drought, however, surface water may recover quickly in response to increased precipitation, while the recovery of groundwater will likely lag. Understanding the relations between precipitation and groundwater storage is essential to water resources planning. Time series of groundwater-level measurements are the primary datasets, or records, used to monitor changes in groundwater storage. The objectives of this study were to (1) characterize the relation between precipitation and responses in groundwater levels at seasonal to decadal scales and (2) to develop methods that are transferable on a continental scale to any groundwater-level record of sufficient length. Groundwater-level response to precipitation was analyzed for eleven monitoring wells in the northwestern United States (fig. 1; table 1), which are part of the [Climate Response Network](#) (CRN) of the U.S. Geological Survey (2019a). The CRN consists of wells that are useful for monitoring groundwater responses to climate variability, because by design, they are minimally affected by human activities, such as nearby groundwater withdrawals and irrigation recharge.

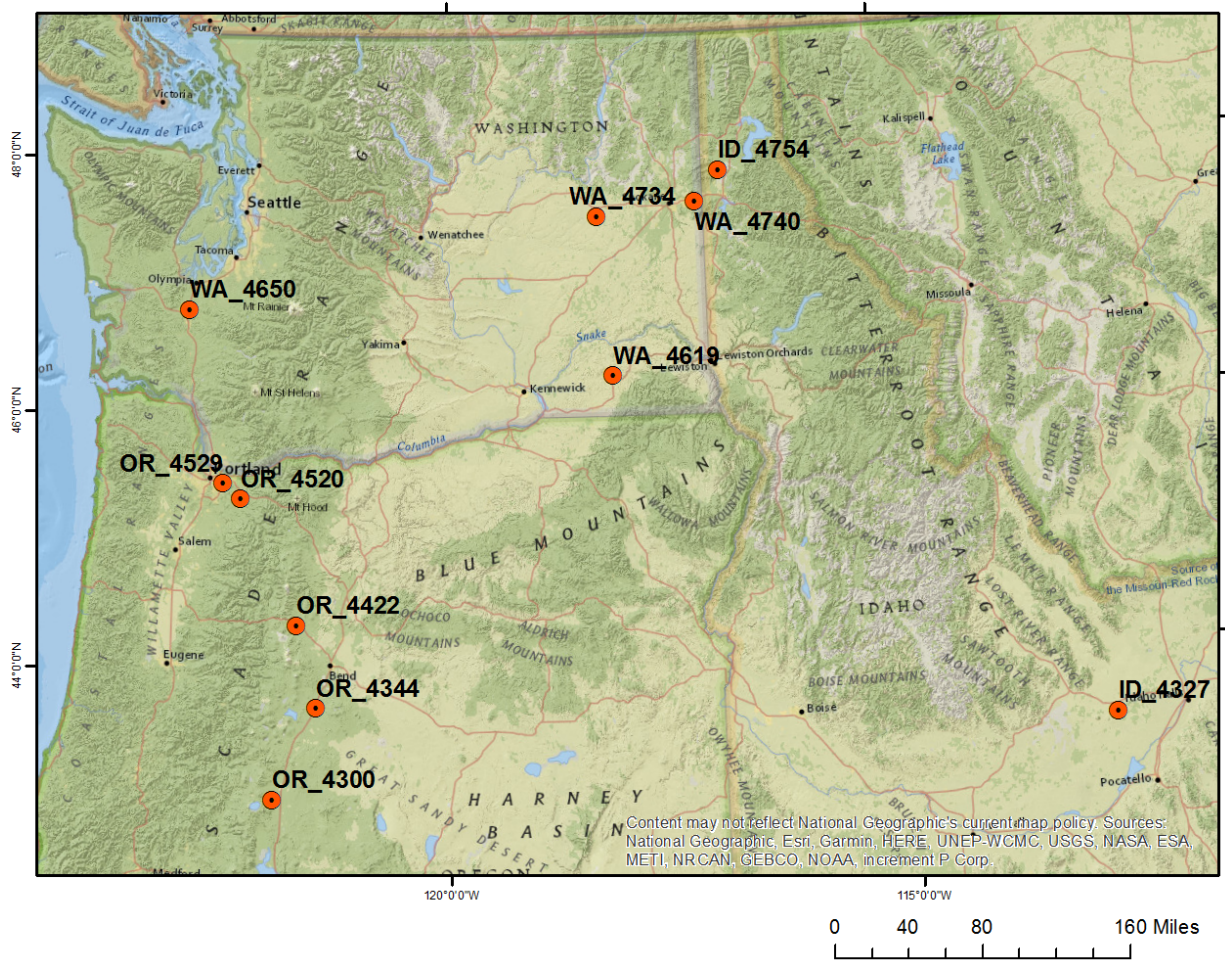


Figure 1. Map showing study area with monitoring wells included in groundwater-level analysis (red dots).



**Table 1.** Sites described and analyzed.

[A site is a location that includes one groundwater monitoring well. Data obtained from U.S. Geological Survey (2019b). **Site name:** WA (Washington), ID (Idaho), and OR (Oregon) indicate the state the site is located in. **Abbreviations:** ft, feet; NAVD88, North American Vertical Datum of 1988; NGVD29, National Geodetic Vertical Datum of 1929; USGS, U.S. Geological Survey]

Site name	USGS Groundwater station No.	Other identifier	Principal aquifer	Local aquifer	Land surface altitude, in ft	Well depth, in ft	Groundwater period of record		Years of record
							Begin date (year-month-day)	End date (year-month-day)	
WA_4734	473442118162201	Davenport	Columbia Plateau basaltic-rock aquifers	Wanapum Basalt Formation	2,371 <sup>1</sup>	117	2003-09-03	2017-11-02	14.2
WA_4619	461935118081501	Whetstone	Columbia Plateau basaltic-rock aquifers	Grande Ronde Basalt Formation	1,403 <sup>1</sup>	173	2011-11-22	2017-11-02	5.9
WA_4740	474011117072901	Spokane Valley	Columbia Plateau basin-fill aquifers	Scabland Flood Deposits	2,059 <sup>1</sup>	129	2011-12-21	2017-11-02	5.9
WA_4650	465033122570202	Scatter Creek	Puget Sound aquifer system	Unclassified Overburden	221 <sup>1</sup>	82	2003-09-30	2017-11-02	14.1
ID_4754	475439116503401	53N 04W 28CAB1	Pacific Northwest basin-fill aquifers	Outwash	2,432 <sup>1</sup>	449	2004-07-14	2017-11-02	13.3
ID_4327	432700112470801	02N 31E 35DCC1 USGS 1	Snake River Plain basaltic-rock aquifers	Snake River Group	5,022 <sup>2</sup>	630	1999-06-20	2017-11-02	18.4
OR_4300	430029121552101	30.00S/07.00E-06AAA01	Pacific Northwest volcanic-rock aquifers	Mazama Pumice	4,795 <sup>2</sup>	205	2000-09-12	2016-10-13	16.1
OR_4529	452912122312801	01.00S/02.00E-14ABC01	Willamette Lowland basin-fill aquifers	Troutdale Formation	229 <sup>2</sup>	59	1998-10-02	2017-11-01	19.1
OR_4520	452033122195901	02S/04E-29DAD	Other aquifers	Sandy River Mudstone	712 <sup>2</sup>	177	2001-09-07	2017-11-01	16.2
OR_4422	442242121405501	14S/09E-08ABA	Pacific Northwest volcanic-rock aquifers	Volcanic Rocks	3,380 <sup>2</sup>	403	1993-11-24	2017-11-01	23.9
OR_4344 <sup>3</sup>	434400121275801	21S/11E-19CCC	Pacific Northwest basin-fill aquifers	Valley Fill	4,220 <sup>2</sup>	100	1999-05-15	2016-10-26	17.5

<sup>1</sup>NAVD 88

<sup>2</sup>NGVD 29

<sup>3</sup>Discontinued in 2016 because of discontinued funding

Long periods of record for groundwater levels, in response to precipitation, allow analysis of climatic variation over seasonal to interdecadal scales. Seasonal cycles in this report refer to those that occur within a period of 1 year (yr). Of the 17 monitoring wells in Washington, Oregon, and Idaho that are part of the CRN, 6 were not suitable for this analysis because the periods of record were less than 5 yr. The remaining 11 CRN wells were included in

this study. Periods of daily record available for these 11 wells ranged from 5.9 to 23.9 yr, and all but 2 wells had more than 13 yr of record (table 1).

In this report, a “site” is defined as a location with a groundwater monitoring well. To describe the approach used in the study, one site is selected to demonstrate the methods, assumptions, and interpretations that were applied to all sites, for which results are then summarized. Site WA-4734, located in Lincoln County in eastern Washington, is used for demonstration (fig. 1; table 1). The well is 117 feet (ft) deep and open to the Wanapum Basalt Formation, which is a local aquifer contained within a principal aquifer named the Columbia Plateau basaltic-rock aquifers (fig. 1), one of many designated principal aquifers in the United States (U.S. Geological Survey, 2018). The Wanapum Basalt Formation has an areal extent of about 25,000 square miles (mi<sup>2</sup>) within the Columbia River basin and ranges in thickness from less than 10 to 1,200 ft (Kahle and others, 2009). At site WA-4734, the Wanapum Basalt Formation is exposed at land surface (2,371 ft above NAVD 88) and is about 400 ft thick. The formation comprises multiple basalt layers, also known as “basalt flows,” with permeable zones at the contacts between basalt layers. At this site, eight primary permeable zones are present within the Wanapum Basalt Formation and range in thickness from about 10 to 50 ft (Myers, 1972). The well is open to the uppermost permeable zone, which consists of broken and honeycombed basalt overlain by a basalt layer about 100 ft thick. The basalt layers generally have low permeability, but groundwater may flow vertically through fractures in these units and provide possible hydraulic connection between the land surface and the permeable zones (Vaccaro and others, 2015).

## Methods

Spectral analysis was used to characterize the dominant frequencies in the precipitation and groundwater-level records. The discrete Fourier transform (DFT) was executed in [MATLAB](#)<sup>®</sup> (MathWorks, 2019) to compute the frequency spectra of precipitation and groundwater-level (hydrologic) records by using methods described by Frigo and Johnson (1998) and FFTW (2018). The DFT was used to quantify the magnitude of variation in the hydrologic records for frequencies ranging from 0.25 to 45 cycles per decade (cpdec) and thereby characterize seasonal cycles, as well as possible longer-term climatic cycles. The DFT breaks down a time-series record into a set of sinusoidal functions, each with a specific amplitude and frequency (periodicity) that, when summed, reproduce the time-series record. Each frequency in the spectrum defines a single sinusoid, and any component with a particularly high amplitude indicates strong variation in the record at that frequency. A general description of spectral analysis, including the DFT, is provided in Jenkins and Watts (1968), Smith (2003), and other references on time-series analysis.

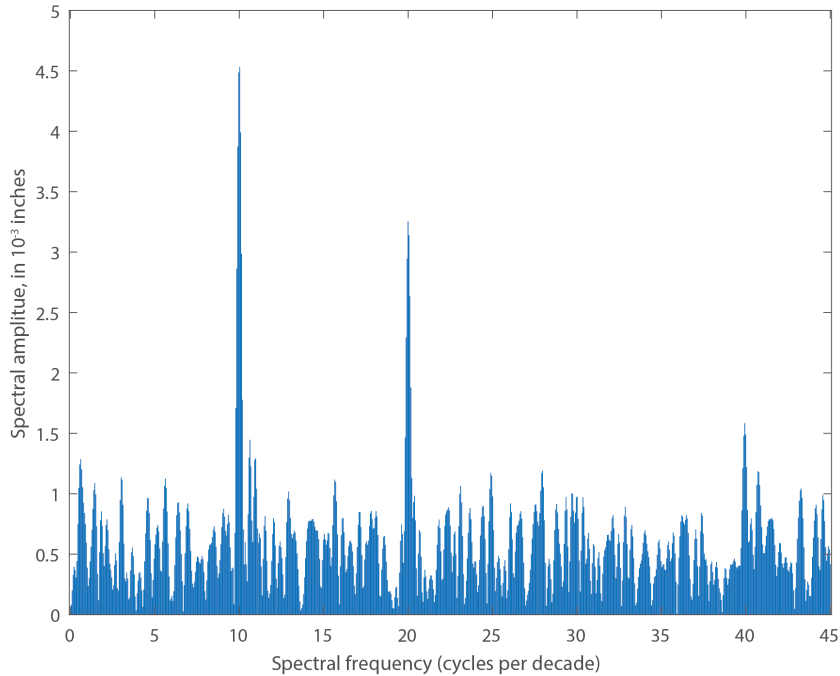
The cumulative departure from the mean (CDM) for daily precipitation was used to identify the timing (years and months) of wet and dry periods for the precipitation record. The CDM is calculated for each day as the difference between the cumulative sum of the difference between daily precipitation and mean daily precipitation. The DFT was applied to the CDM for precipitation, which provided information complimentary to the application of the DFT to the measured precipitation record.

## Precipitation Analysis for the Example Site

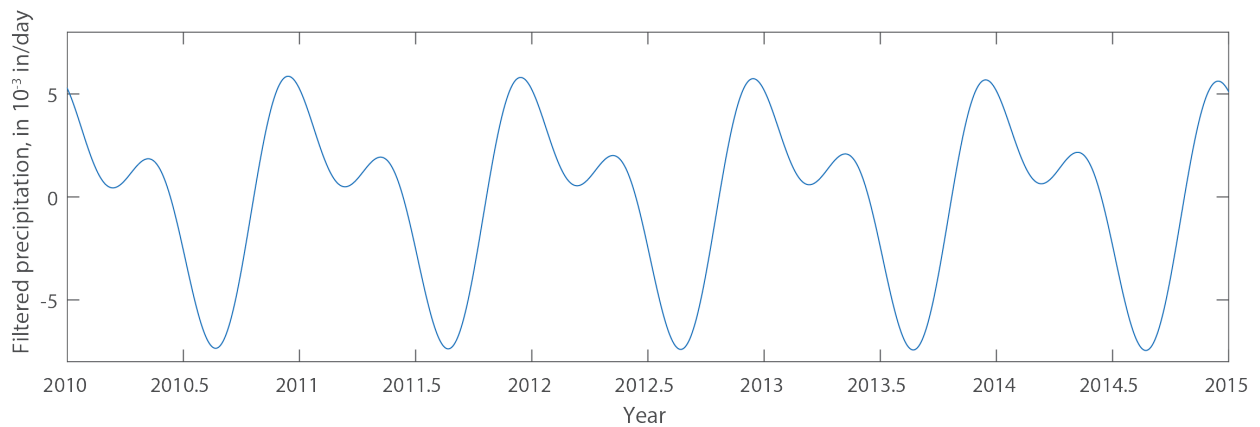
### Spectral Analysis

A record of estimated daily precipitation was obtained from DAYMET (Thornton and others, 2018) for the 1-kilometer (km)  $\times$  1-km grid cell containing each site for 1980–2016 (37-yr period). Advantages of using DAYMET are that precipitation estimates are available across the United States, with no missing daily values. For this analysis, we assumed that precipitation at a site provides an index, or proxy, for the timing and variation of groundwater recharge. However, precipitation stored as snowpack was considered in interpretation of results. The mean precipitation (1980–2016) from DAYMET for site WA-4734 was 16.3 inches per year (in/yr). As a comparison, the mean precipitation (1980–2016) measured daily by the National Oceanic and Atmospheric Administration (NOAA) at a location 7.6 miles to the northeast had a mean value of 14.0 in/yr (station number USC00452007, available at <https://www.ncdc.noaa.gov/>). About 1 percent of the daily values were missing from the measured record. Although site WA-4734 had a long-term precipitation station within 10 miles, this is not the case for most sites, and therefore, DAYMET precipitation was used for all sites.

The frequency spectrum for DAYMET precipitation at this site has a dominant (high amplitude) frequency component at 10 cpdec and a subdominant frequency at 20 cpdec (**fig. 2**), which equate to sinusoid wavelengths ( $\lambda$ ) of 1.0 and 0.5 yr, respectively. Because 1 year spans one complete cycle of the seasons, dominant wavelengths that are factors of 1.0 yr, such as 0.5 or 0.25, indicate strong seasonality. For example, a sinusoid with  $\lambda = 1$  yr contains one upward peak and one downward peak in a 1-yr period, which might represent a wet and a dry season, respectively. A sinusoid with  $\lambda = 0.5$  yr has two upward and two downward peaks that might represent other characteristics of seasonality. Therefore, to characterize seasonality, the inverse DFT was used to reconstruct the precipitation record as a function of time (time domain) from only the two dominant frequencies of 10 and 20 cpdec (frequency domain). This reconstruction is referred to as the filtered precipitation record because all but the two dominant frequencies were removed (**fig. 3**).



**Figure 2.** Graph showing frequency spectrum of precipitation for site WA-4734, Davenport, Washington. [Site information detailed in table 1.]



**Figure 3.** Graph showing filtered precipitation record for site WA-4734 (Davenport, Washington), with all frequencies removed except those at 10 and 20 cycles per decade. [Site information detailed in table 1. The record was shifted to a mean of zero.]

Because the sinusoids composing the filtered precipitation record have wavelengths that are factors of 1 yr ( $\lambda = 0.5$  and  $1.0$ ), the high and low spectral amplitude values occur at the same time during each year. These values represent the most likely time of occurrence of extremes that reoccur on an annual basis and provide a way to characterize seasonality. The filtered precipitation record for WA-4734 indicates that the maximum and minimum values ( $5.9 \times 10^{-3}$

and  $-7.3 \times 10^{-3}$ ) occur on December 10 and August 17, respectively, indicating a time difference from maximum to minimum (annual period of decrease) of about 8.2 months (table 2). The period from maximum dry to maximum wet (annual period of increase) occurs over 3.8 months (table 2).

**Table 2.** Results of data analysis for each site.

[**Period of annual increase:** Time between the annual minimum to the annual maximum. **Period of annual decrease:** Time between the annual maximum to the annual minimum. **Lag in water level response:** Time period from annual maximum precipitation to annual maximum groundwater level. **Abbreviations:** cpdec, cycles per decade; —, could not be determined from the analysis or not applicable]

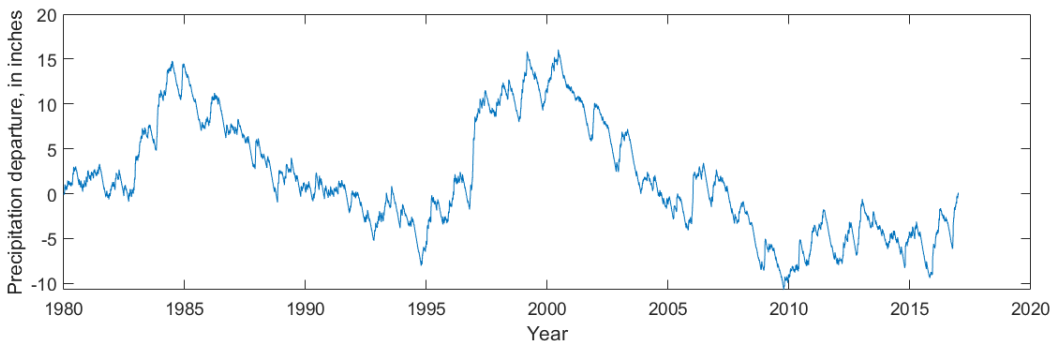
Site name	Precipitation analysis							Groundwater level analysis						
	Annual maximum (day-month)	Annual minimum (day-month)	Period of annual increase, in months	Period of annual decrease, in months	Dominant seasonal frequencies, in cpdec	Relative dominance of seasonal frequencies	Average annual precipitation, in inches	Annual maximum (day-month)	Annual minimum (day-month)	Period of annual increase, in months	Period of annual decrease, in months	Dominant seasonal frequencies, in cpdec	Relative dominance of seasonal frequencies	Lag in water level response, in months
WA_4734	10-Dec	17-Aug	3.8	8.2	10, 20	Strong	16.3	22-Apr	5-Dec	4.5	7.5	10, 20	Strong	4.4
WA_4740	12-Dec	18-Aug	3.8	8.2	10, 20	Strong	21.9	23-May	6-Feb	3.5	8.5	10, 20	Strong	5.3
WA_4619	10-Dec	10-Aug	4.0	8.0	10, 20	Strong	18.7	3-May	20-Dec	4.4	7.6	10, 20	Moderate	4.7
WA_4650	13-Dec	30-Jul	4.5	7.5	10, 20	Strong	54.6	19-Feb	9-Oct	4.4	7.6	10, 20	Strong	2.2
ID_4754	12-Dec	16-Aug	3.9	8.1	10, 20	Strong	31.1	3-Aug	31-Jan	6.1	5.9	10	Moderate	7.7
ID_4327	9-May	21-Aug	8.6	3.4	10, 20	Weak	10.4	1-Feb	4-Aug	6.0	6.0	10	Moderate	8.8
OR_4529	13-Dec	5-Aug	4.3	7.7	10, 20	Strong	51.9	3-Apr	1-Oct	6.0	6.0	10	Strong	3.6
OR_4520	12-Dec	5-Aug	4.2	7.8	10, 20	Strong	65.5	18-May	16-Nov	6.0	6.0	10, 20	Strong	5.2
OR_4422	20-Dec	9-Aug	4.4	7.6	10, 20	Strong	46.3	19-Jul	15-Jan	6.1	5.9	10	Moderate	6.9
OR_4344	21-Dec	21-Aug	4.0	8.0	10, 20	Strong	18.1	13-Aug	10-Feb	6.1	5.9	10	Strong	7.7
OR_4300	27-Dec	11-Aug	4.5	7.5	10, 20	Strong	36.5	—	—	—	—	None	—	—
<i>Median</i>	12-Dec	11-Aug	4.2	7.8	—	—	31.1	10-May	2-Sep	6.0	6.0	—	—	5.3

The 20 cpdec frequency ( $\lambda = 0.5$  yr) results in a small precipitation increase in the filtered record at about 0.3 yr into the middle of the overall period of decreasing precipitation (fig. 3). This increase in the filtered precipitation record may not represent an actual increase in precipitation during spring but probably is because of omitted frequencies. The physically meaningful effect of the 20 cpdec frequency is that, when combined with the 10 cpdec frequency ( $\lambda = 1$  yr), it has the effect of lengthening the period of annual decreasing precipitation. Without the 20 cpdec frequency, the periods of annual increase and decrease each would be 6 months. If other dominant frequencies in multiples of 10 were present, those might indicate additional aspects of seasonality. Dominant frequencies not in multiples of 10 might indicate additional climatic cyclicity.



## Cumulative Departure from the Mean

Dominant frequencies less than 10 cpdec ( $\lambda > 1$  yr) are not apparent in the frequency spectrum for precipitation (fig. 2), so longer term climate variation, such as recurrent drought, are not evident from the spectrum. However, the CDM for the precipitation record indicates two interannual wet periods and two interannual dry periods for site WA-4734 (fig. 4). Upward and downward slopes in the CDM represent wet and dry periods, respectively, and major upward and downward trends occur on roughly decadal scales. Also evident in figure 4 are annual fluctuations that represent seasonality, and higher frequency fluctuations at the sub-month scale. Therefore, the CDM provides useful precipitation information at a wide range of time scales.

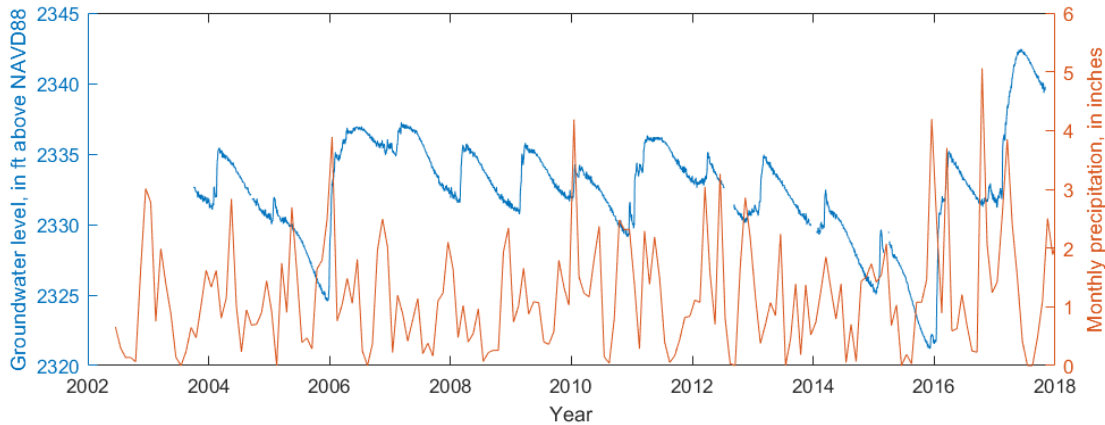


**Figure 4.** Graph showing cumulative departure from the mean, computed on a daily basis, for precipitation at site WA-4734, Davenport, Washington. [Site information detailed in table 1.]

The DFT fits sinusoids to a hydrologic record, and these sinusoids are stationary because these functions do not have an overall upward or downward trend. Therefore, the DFT is most appropriate and meaningful if the record also is a stationary time series, and a useful application of the CDM is for assessing the stationarity of a time series. If the mean of the CDM is nearly zero, the underlying time series is nearly stationary because departures from the mean are balanced between positive and negative. For site WA-4734, we consider the precipitation record to be nearly stationary because the CDM mean is about 1.7 inches, which is small in comparison to its total range of values (26.6).

## Groundwater Analysis for the Example Site

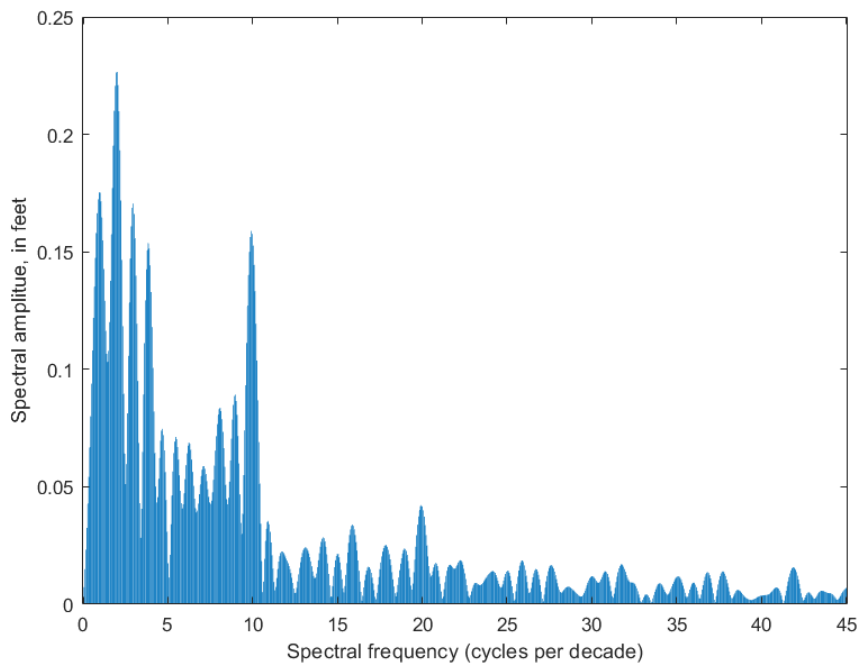
The period of record analyzed for site WA-4734 is October 2003–October 2017 (14-yr period), with a groundwater level ranging from 2,321 to 2,342 ft above NAVD 88 and median value of 2,333 ft (fig. 5). During this period, seasonal water level fluctuations ranged from 2 to 14 ft, and decadal fluctuations were as high as 15–20 ft. Groundwater-level records for all sites were obtained from the National Water Information System (NWIS; U.S. Geological Survey, 2019b). All groundwater stations and available data are searchable and retrievable, respectively, in NWIS by the station number shown in table 1.



**Figure 5.** Graph showing groundwater level for site WA-4734 and monthly precipitation at National Oceanic and Atmospheric Administration station USC00452007. [Site information for site WA-4734 detailed in table 1.]

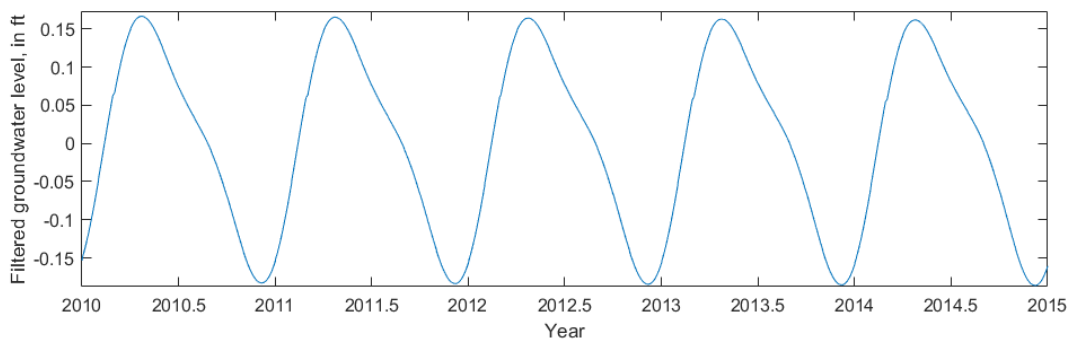
### Spectral Analysis

The frequency spectrum for groundwater level for site WA-4734 has dominant (high amplitude) frequencies in the bandwidth of 1–4 cpdec, which correspond to wavelengths of 10.0, 5.0, 3.4 and 2.6 yr (**fig. 6**). These represent interannual fluctuations in the record. For example, the 11-yr period 2005–15 began and ended with anomalous declines in groundwater levels, when seasonal recharge was insufficient for recovery to typical annual maximum levels (~2335 ft) (**fig. 5**). Both of these declines were followed by a rapid recovery (2006 and 2016–17). Most of this area was in drought during 2005 and 2014–15 (U.S. Drought Monitor, 2019) indicating that the declining groundwater levels were likely a result of low recharge. These two droughts were separated by about 1 decade, and the high amplitude at 1 cpdec largely represents the timing of the two droughts, which resulted in larger groundwater level changes than typical seasonal water level fluctuations (**fig. 5**). The meaning of the frequency bandwidth of 2–4 cpdec is less obvious but represents a combination of climatic and hydrologic factors that may be partly related to drought. For example, these frequencies may reflect differences in the severity of the two droughts, as well as the rapid post-drought groundwater recoveries in contrast to the slower groundwater recession rates during droughts. Also, the groundwater level peaks gradually declined for the periods 2007–10 and 2011–14 (**fig. 5**), a pattern that likely is represented by some combination of the 2–4 cpdec bandwidth.



**Figure 6.** Graph showing frequency spectrum of groundwater level for site WA-4734, Davenport, Washington. [Site information detailed in table 1.]

Within the bandwidth of potential seasonality (10–40 cpdec), there is a dominant and subdominant frequency peak at 10 and 20 cpdec, respectively (fig. 6), which is similar to the precipitation spectrum. These are the two highest peaks within this bandwidth; frequencies less than 10 cpdec represent longer hydrologic cycles that include drought. Therefore, to characterize the groundwater seasonality, the inverse DFT was used to reconstruct the groundwater-level record from only these two seasonal frequencies, similarly to the approach applied to precipitation. This reconstruction is referred to as the filtered groundwater-level record and indicates that the highest groundwater levels generally occurred in mid-April, and lowest levels about 7.5 months later in early December (fig. 7; table 2). Therefore, periods of annual increasing and decreasing groundwater levels occurred over 4.5 and 7.5 months, respectively.



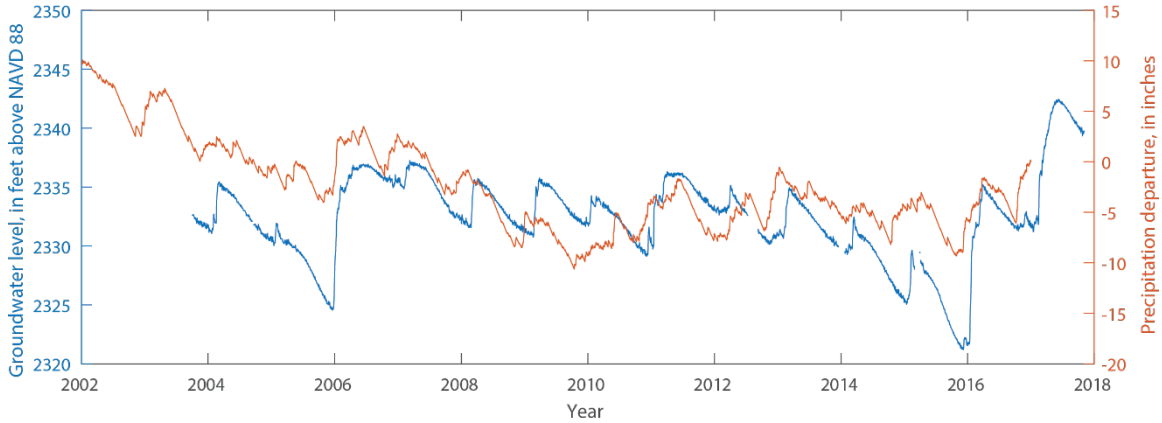
**Figure 7.** Filtered groundwater-level record for site WA-4734 (Davenport, Washington), with all frequencies removed except those at 10 and 20 cycles per decade. [Site information detailed in table 1. The record was shifted to a mean of zero.]

It is noteworthy that the seasonal fluctuation in the filtered record (fig. 7) is much smaller than the seasonal fluctuation in the measured groundwater record (fig. 5). The reason is that the filtered groundwater-level record includes only the water-level change corresponding to exactly 10 and 20 cpdec. However, the 10 cpdec frequency peak is centered on a bandwidth of relatively high amplitudes (9.7–10.3 cpdec) that contributes to seasonal fluctuations in the groundwater-level record, and the 20 cpdec frequency is centered on another bandwidth of similar effect (19.7–20.3 cpdec; fig. 6). To determine the occurrence of annual high and low groundwater levels, only the highest amplitude frequency component within each of these bandwidths was necessary. Therefore, by ignoring the full bandwidths that capture seasonal water-level fluctuations, the amplitudes of the seasonal fluctuations in the filtered record were reduced, but the temporal characterization of the seasonal fluctuation was achieved. If the full bandwidths of the two frequency peaks were used to construct the filtered record, this would provide an estimate of the magnitude of temporal variation resulting from those seasonal bandwidths. However, the specific upper and lower bounds of the bandwidths would have to be selected carefully to obtain a useful estimate.

### Cumulative Departure from the Mean

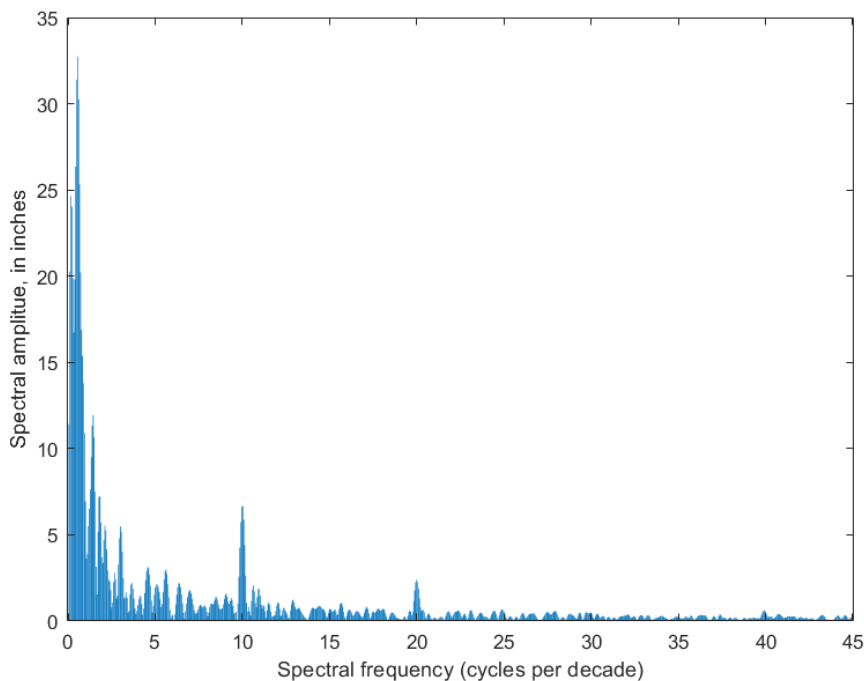
The CDM for precipitation has some synchrony to the measured groundwater-level record (fig. 8). The CDM for precipitation is similar to the measured groundwater-level record, particularly regarding seasonal fluctuations. Vaccaro and others (2015) compared the CDM for annual precipitation at NOAA station USC00452007 to the groundwater-level record for WA-4734 and also noticed similarities. The similarity suggests that, in a general sense, groundwater levels represent the cumulative effects of precipitation. Limitations in interpretation of the CDM for hydrologic analysis were discussed by Weber and Stewart (2004); application of the CDM in this report avoids these limitations by focusing on the CDM's spectral characteristics for understanding groundwater response periodicity, rather than as a proxy for actual groundwater storage or levels.

The smoothing effect of the CDM for precipitation provides useful information over a wide range of time scales that otherwise would be difficult to obtain by examining the measured daily precipitation record directly. However, computing the CDM for groundwater levels was not useful. Because groundwater processes controlling the response of water levels to recharge from precipitation inherently act as a filter to attenuate and smooth the response, a computed CDM for groundwater level represents an additional smoothing of the water-level response that obscures critical information related to these controlling processes. Therefore, for the purposes of this study, the CDM for groundwater level was not used in the subsequent analyses.



**Figure 8.** Graph showing measured groundwater level (red) and cumulative departure from the mean (CDM) for precipitation (blue) for site WA-4734, Davenport, Washington. [Site information detailed in table 1.]

The similarity of the measured groundwater-level record to the CDM for precipitation (fig. 8) suggests that their respective frequency spectra also might be similar. Therefore, the DFT was applied to the CDM for precipitation (fig. 9). This frequency spectrum has characteristics similar to the spectrum of the groundwater-level record, which is evident by comparison of fig. 9 to fig. 6. Both spectra have dominant frequencies of 10 and 20 cpdec, as well as dominant low frequencies less than 5 cpdec. The similarity of these two spectra might increase if the groundwater-level record (14-yr period) was similar in length to that of the precipitation record (37 yr).



**Figure 9.** Graph showing frequency spectrum of the cumulative departure from mean precipitation at site WA-4734, Davenport, Washington. [Site information detailed in table 1.]

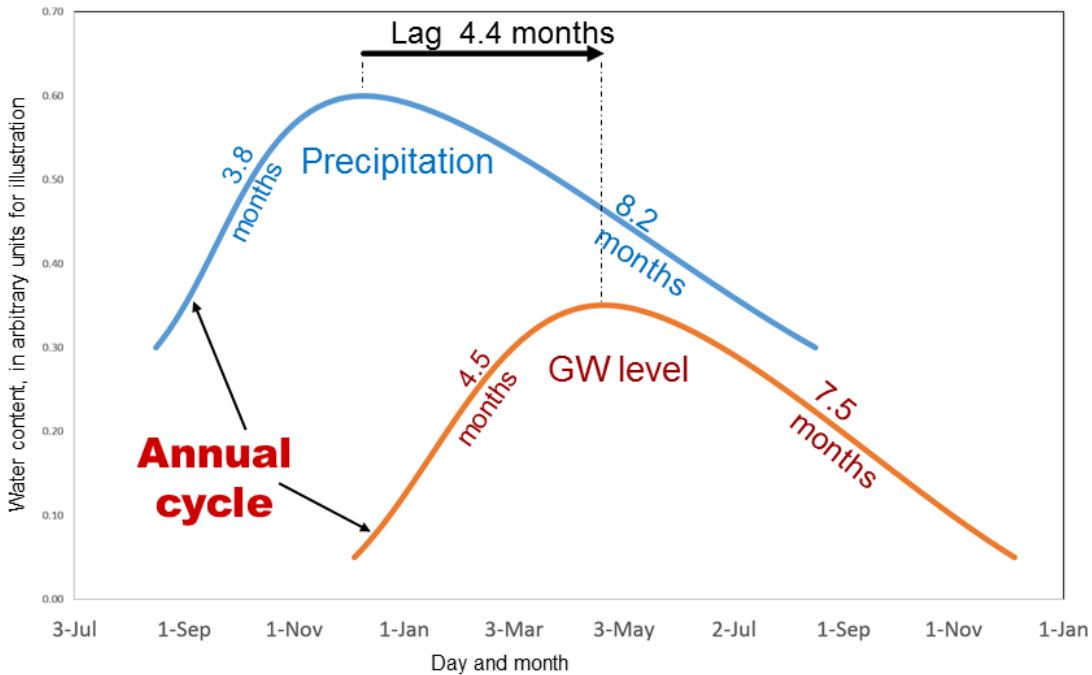


The frequency spectrum of the CDM for precipitation has dominant frequencies at 10 and 20 cpdec (fig. 9), similarly to that of the original precipitation record (fig. 2). However, a characteristic in the frequency spectrum for the CDM for precipitation that is absent from the frequency spectrum of the original precipitation record is the dominance of low frequencies, with a peak at 0.56 cpdec, which corresponds to a wavelength of 18 yr (fig. 9) and indicates interannual or interdecadal cycles that were not detectable from spectral analysis of the original precipitation record (fig. 2). Therefore, the analysis shown in figure 9 preserved useful information from the original precipitation record (seasonal cycling), but also provided information regarding interannual and interdecadal cycling.

The interannual cycling of groundwater levels was previously determined to have wavelengths ranging from 2.6 to 10 yr (fig. 6). This range corresponds to that of the CDM for precipitation (3–100 yr), except that  $\lambda > 10$  yr are not dominant in the groundwater spectrum, because the period of record was only 14 yr. This suggests, however, that groundwater levels respond to interannual precipitation cycling, but quantification of this response through spectral analysis, such as estimating response lag times, is not possible without a longer groundwater record.

## Lag in Groundwater Response

Several factors affect the response of groundwater levels to precipitation, including those related to evapotranspiration, runoff, vadose zone infiltration, and aquifer hydraulics. Winter snow accumulation, sublimation, and spring snowmelt are additional factors in many climates, including the climate at site WA-4734. Comparison of the seasonality characteristics of precipitation to those of groundwater for this site indicates that the lag time from the annual precipitation peak (early December) to the annual groundwater peak (mid-April) is 4.4 months, which likely would be shortened if not for other factors, most notably snow accumulation. The lag in the annual peak response of groundwater following the annual peak precipitation was computed as the time difference between these two peaks in the filtered records, as quantified by the DFT analysis. **Figure 10** illustrates the hydrologic characteristics of site WA-4734 as determined by the analysis: the times of occurrence of the highest and lowest hydrologic values, the lag time from peak precipitation to peak groundwater level, and the periods of annual increasing and decreasing hydrologic values.



**Figure 10.** Graph showing illustrative graph showing typical annual cycles of precipitation and groundwater (GW) level for site WA-4734. [The time lag from the peak in precipitation to the peak in groundwater level is 4.4 months.]

## Synthesis of Results for all Sites

All sites were analyzed by the same methods as those described for the example site (WA-4734), and results are summarized in table 2. Dominant seasonal frequencies were those at 10 and 20 cpdec, which were evident in the precipitation spectra for all sites. For groundwater, five sites had dominant frequencies at 10 and 20 cpdec, and five sites had dominant frequencies at 10 cpdec but not at 20 cpdec (table 2). One site (OR-4300) had dominant frequencies only at the lowest end of the spectrum, with no indication of dominant seasonal frequencies. The relative dominance of seasonal frequencies, as a comparison between all sites, was qualitatively assigned as “strong,” “moderate,” or “weak.” Ten sites were characterized as having strong seasonal precipitation. The one site with weak seasonal frequencies for precipitation (ID-4327) had the lowest average precipitation of all sites (10.4 in/yr). For groundwater levels, six sites were characterized as having strong seasonality, and four were characterized as having moderate seasonality (table 2).

The time of occurrence of annual maximum and minimum values for precipitation and groundwater levels were determined for all sites (table 2). For precipitation, the annual maximum values were primarily in December for 10 sites and May for 1 site (ID-4327), whereas the annual minimum values were in late July or August for all sites. The annual period of decrease, or time from maximum to minimum precipitation, ranged from 7.5 to 8.2 months for ten sites, with one site far outside of this range (3.4 months for site ID-4327). For groundwater, the occurrence of annual maximum and minimum values had much larger ranges than those for precipitation: maximum values ranged from February to August, and minimum values ranged from January to December. The annual period of decrease for groundwater also had a wider

range than that of precipitation, ranging from 5.9 to 8.5 months, with a median value of 6.0 months.

The lag in the annual peak response of groundwater following the annual peak precipitation is influenced by several factors, as previously discussed, and may vary widely across the study area, ranging from 2.2 to 8.8 months, with a median value of 5.3 months (table 2). In some cases, this lag results in groundwater levels that are highest during dry seasons, as evidenced by three sites that had annual groundwater maximums at about the same time that precipitation was at a minimum (ID-4754, OR-4422, and OR-4344). This information is useful for management of groundwater and surface water resources on a seasonal basis.

The first objective of this study was to characterize the relation between precipitation and responses in groundwater levels at seasonal to decadal scales. The first objective was met, in that seasonal cycles were characterized well, and it was concluded that groundwater levels respond to interannual precipitation cycling. However, quantification of the interannual response through spectral analysis was not possible without longer groundwater records. Therefore, while spectral analysis indicated that the peak groundwater response is delayed by several months after peak precipitation, it did not provide an estimate of the full length of time that the effects of precipitation on groundwater may last. For example, Long and Mahler (2013) estimated that this *system memory* generally was on the order of years to decades and was a substantial factor in the long-term groundwater response. Additional methods are available and could provide more detailed assessments of how groundwater storage responds to precipitation over a wide range of time scales. The following section briefly describes these methods.

The second objective was to develop methods that are transferable on a continental scale to any groundwater-level record. Because this method was applied to 11 wells that are widely distributed across the northwestern United States and are located in a variety of aquifer settings, the method is likely to be effective for any groundwater system that responds primarily to precipitation.

## Possible Alternative Methods

Spectral analysis was useful in estimating the time lag of seasonal groundwater response to seasonal precipitation cycles and for general comparison of interannual and interdecadal cycles in precipitation and groundwater level. However, a useful next step in time-series analysis that would quantifiably characterize the response of groundwater levels to precipitation over all relevant time scales (seasonal, interannual, and interdecadal) is time-series modeling. For example, Jakeman and Hornberger (1993), Von Asmuth and others (2002), and Long and Mahler (2013) described time-series models to simulate groundwater and surface-water responses to precipitation by estimation of an impulse-response function (IRF). The IRF succinctly represents the full spectrum of long- and short-term responses. By examining the IRF, these authors estimated that the response of groundwater levels to a single precipitation event can last for decades, in some cases. The IRF also defines the peak response and recession curve of groundwater levels. Another advantage of modeling is that a quantitative measure of the goodness of fit between measured and simulated water levels can be computed, providing an indication of the accuracy of the estimated response times and groundwater storage changes over those response times. The Rainfall-Response Aquifer and Watershed Flow Model (RRAWFLOW) could be used for this purpose and is available without cost (Long, 2015, 2019).

## Summary and Conclusions

Understanding the relations between variations in precipitation and changes in groundwater storage as indicated by changes in groundwater levels is essential to water resources planning. The objectives of this study were to (1) characterize the relation between precipitation and responses in groundwater levels at seasonal to decadal scales and (2) to develop methods that are transferable on a continental scale to any groundwater-level record. Eleven groundwater-level monitoring wells were selected for this study, with periods of record ranging from 5.9 to 23.9 years (yr). For each well location, estimated precipitation records of 37 yr in length were analyzed.

For analyzing precipitation records, spectral analysis was useful for characterizing seasonality, and examining the cumulative departure from the mean (CDM) was useful for assessing precipitation cycles over short- and long-term time scales. The smoothing effect of the CDM provides useful information that otherwise would be difficult to obtain by examining the measured daily precipitation record directly. Spectral analysis of the precipitation CDM was useful for quantifiably characterizing seasonal, interannual, and interdecadal cycling. Therefore, spectral analysis of the precipitation record and of the CDM for precipitation is recommended, but the latter might provide all necessary information. Maximum and minimum precipitation rates generally occurred in December and August, respectively, in the study area. The period from annual minimum-to-maximum precipitation generally was shorter (<6 months) than period of annual maximum-to-minimum precipitation (>6 months).

For analyzing groundwater-level records, spectral analysis was useful for relating the seasonality of precipitation to groundwater responses and provided a general characterization of interannual groundwater-level cycles. Because groundwater moves slowly, allowing aquifers to store water for long periods, the groundwater-level record may represent the cumulative effects of precipitation over long time scales. Therefore, the groundwater-level record may resemble the CDM for precipitation for the same location. For the sites analyzed, maximum groundwater levels occurred from February to August, and minimum values occurred from January to December. The magnitudes of groundwater level responses to episodic droughts in comparison to those of seasonal cycles can be assessed from the higher amplitudes of the frequency spectrum at frequencies less than about 4 cycles per decade (cpdec) relative to smaller amplitudes for frequencies at 10 and 20 cpdec.

Comparing the frequency spectrum of groundwater levels to that of the precipitation record provides an estimate of the typical lag time required for groundwater levels to reach a peak response that follows the annual precipitation peak. This method also provides the typical times of year that precipitation and groundwater levels reach their highest and lowest values. Lag times for this study ranged from 2.2 to 8.8 months, with a median value of 5.3 months. Advantages of this method are that (1) it provides important metrics to characterize an aquifer's response to precipitation, (2) it requires only daily precipitation and daily groundwater levels, and (3) it is not labor intensive and does not require model calibration.

Time-series modeling is a related method that also uses daily precipitation and groundwater levels but would more fully characterize the response of groundwater levels to precipitation. Groundwater at a single location can respond to precipitation on a wide range of time scales, and these responses may be superimposed in the measured water-level record. Time-series modeling can be used to characterize these different responses; for example, over monthly, seasonal, interannual, and interdecadal time scales.

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