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A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States

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Abstract

A new method for frequency analysis of hydrologic time series was developed to facilitate the estimation and reconstruction of individual or groups of frequencies from hydrologic time-series and facilitate the comparison of these isolated time-series components across data types, between different hydrologic settings within a watershed, between watersheds, and across frequencies. While climate-related variations in inflow to and outflow from aquifers have often been neglected, the development and management of ground-water and surface-water resources has required the inclusion of the assessment of the effects of climatic variability on the supply and demand and sustainability of use. The regional assessment of climatic variability of surface-water and ground-water flow throughout the southwestern United States required this new systematic method of hydrologic time-series analysis.

To demonstrate the application of this new method, six hydrologic time-series from the Mojave River Basin, California were analyzed. The results indicate that climatic variability exists in all the data types and are partially coincident with known climate cycles such as the Pacific Decadal Oscillation and the El Niño–Southern Oscillation. The time-series also indicate lagged correlations between tree-ring indices, streamflow, stream base flow, and ground-water levels. These correlations and reconstructed time-series can be used to better understand the relation of hydrologic response to climatic forcings and to facilitate the simulation of streamflow and ground-water recharge for a more realistic approach to water-resource management.

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Keywords: Ground-water; Surface-water; Climate; Climate cycles; Recharge; Discharge

1. Introduction

The potential consequences of climate variability and climate change has been identified as a major issue for the sustainability of the water resources of the United States (Gleick and Adams, 2000). From

tree-ring reconstructions, the climate of the southwestern United States is known to contain several quasi-periodic modes of variability with time scales varying from several years to centuries. These reconstructions also indicate that the last 200 years have been the wettest period in the past 2200 years and the last 20 years have been the wettest of this period (Merideth, 2000). Sustained droughts have also occurred during previous centuries that were

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drier and longer in duration than the mid-20th century drought (Merideth, 2000). Tree-ring reconstructions also indicate that climatic variability may have shifted in frequency and amplitude of wet and dry periods since the late 1600s—from relatively long (40 to more than 60 years) wet and dry periods to shorter (5–20 years) periods in the southwestern United States (Hanson et al., 2002). Superimposed upon these long-term cycles and shifts, during the historical period of record, interannual to interdecadal cycles have dominated observed fluctuations of ground-water recharge and streamflow. All of these fluctuations may be joined by relatively sudden trends and changes associated with increasing greenhouse-gas concentrations in the atmosphere and resulting global climate changes (Cubasch and Meehl, 2001).

1.1. Considerations for water-resources management

The development and management of ground- and surface-water resources requires the inclusion of the assessments of the effects of climatic variability on water supply and demand. Many developed areas in the southwestern United States are close to the limits of the sustainability for human use of water resources, which makes even marginal changes in supply and demand of even greater importance. Since ground-water flow models are now used to address many of these water-resource issues, there is an increasing need to develop more realistic simulations that provide managers with more accurate projections of the consequences of resource decisions and actions. Such simulations not only need to model the mean trend of the inflow as recharge (supply) and outflow as pumpage (demand) components, but also increasingly need to project interannual and decadal variability and responses. While the mean trend of flows gives a general depiction of the state and movement of water, the variability of flows determines the extreme conditions that may limit availability of supply and feasibility of meeting demand that are increasingly required to accommodate year-to-year resource fluctuations. Most policies or projects are implemented to reconcile the differences between the amount and timing of supply and demand as part of water-resource management. For example, dry periods limit supply of natural recharge and streamflow, and must be

compensated during wet periods by the capture of additional streamflow or by additional artificial or natural recharge.

Water-resource planning horizons currently range from months to seasons for annual operational decisions, to years and decades for the implementation of capital improvement projects and long-term water sustainability policies. In addition, many of these projects and policies are dependent on the near-future conditions and the transition from the past to the immediate future. Many current models simulate regional flow systems for periods of several decades or more and descritize the changing inflows and outflows into periods of months to seasons. The combination of the extended periods of simulation with finer temporal discretization allows simulation of separate supply and demand events. This allows water managers to use the simulations of ground-water/surface-water flow to address a wide range of operational and planning issues that can now include climatic variability.

1.2. Regional assessment of climatic variability

In the past, hydrologists studying ground-water flow have neglected climate-related variations in inflow to, and outflow from, aquifers. Instead, long-term average estimates of recharge rates have been used in resource analyses. This has especially been an issue for resource analysis that is based upon the application of average recharge conditions to temporal simulations of ground-water flow. In many aquifers, especially where data sets are short or where there is extensive aquifer development, this approach has provided useful depictions and predictions of large-scale changes in ground-water storage. In the future, however, given ever narrower margins for error in many water-resource decisions, this approach will not be suitable. In order to determine how variations of inflow affect ground-water availability as aquifer systems are developed to and beyond their natural limits of inflow, evaluate the likelihood that future climate change will affect ground-water availability, and assess how to maintain outflow to perennial streams and riparian areas, a more comprehensive approach to assessing ground-water variability is needed. Furthermore, neglect of the natural fluctuations of ground-water systems can allow

potentially erroneous assumptions about recharge and discharge mechanisms to go untested in some studies.

This study quantifies the climatic variations that affect ground-water levels and discharge. Precipitation and streamflow are used as partial proxies for ground-water recharge, and the base flow contributions to streamflow are used as an indicator of ground-water discharge. Tree-ring indices also are used as surrogates for precipitation to suggest likely longer term fluctuations of streamflow (Meko et al., 1991) and climatic events such as droughts (Meko et al., 1980; Benson et al., 2002).

The work presented here was part of a larger study of ground-water in the southwestern United States (Leake et al., 2000). This article describes spectral methods developed for systematic frequency analysis of hydrologic time-series to allow comparisons across data types and frequencies and between different locations. The methods developed for this study are described and demonstrated with a simple synthetic time-series. A suite of hydrologic time-series from the Mojave River Basin, California, is then analyzed to demonstrate the utility of the approach (Fig. 1).

2. Previous studies of climate variability

2.1. Climatic variability

The 20th Century in the southwestern United States was initially wetter than average, followed by a mid-century dry period that was, in turn, followed by a wetter period at the end of the century (Merideth, 2000). Embedded in these multidecadal fluctuations were as many as six wet and six dry periods (Hanson et al., 2002). Interannual to interdecadal climate variability includes variations ranging from 2 to 6 years resulting from the reversal of the tropical Pacific trade winds and warming of tropical oceans known as El Nino/Southern Oscillation (ENSO), along with less well-known variations on the order of 6–10 years that may be related to cycles in Monsoonal moisture flow that are present in many hydrologic time-series analyzed by this study. Interdecadal variations on the order of 10–25 years may be related to the Pacific Decadal Oscillation (PDO) (Mantua and Steven, 2002). The combination of all these forcings results in climatic variability that affects the distribution of

precipitation and, in turn, affects the amount and distribution of streamflow and recharge to groundwater flow systems in the southwest.

Climatic periodicity in the Americas has been identified from the interhemispheric effects of interannual and decadal ENSO-like climate variations (Dettinger et al., 2001). The specific cause of variations of precipitation in the southwestern United States with periodicities of 6–10 years remains unknown but may have a source in the Pacific Ocean. Spectral analyses of June–September water-vapor fluxes associated with the monsoon in the southwest indicate a concentration of variability in the monsoon on the 6–10 year time scales that may explain some of the variance in this range in hydrologic series. Therefore, monsoonal moisture flow from the tropical latitudes up through the Gulf of California also may contribute precipitation with periodicities of 6–10 years.

The definition and effects of the PDO were identified by Mantua and Steven (2002) with extended dry periods in the southwestern United States that were associated with negative PDO indices occurred from 1890 to 1924 (34 years) and from 1947 to 1976 (20 years). Wetter periods in the southwestern United States that were associated with positive PDO indices occurred from 1925 to 1946 (22 years) and from 1977 to 1999 (23 years). Since 1999, a renewed negative PDO index (Schmidt and Webb, 2001) has resulted in at least 3 years of drier than normal climate in the southwestern United States. Periods of climate variability greater than 25 years are also present in climate indicators, such as 70-year periods of sea-surface temperature variations in the North Pacific (Chao et al., 2000), but the source and stationarity of these forcings remain unknown. These longer periods will be referred to as greater than PDO (> PDO).

Parallels to these climatic influences on hydrologic systems, especially on interannual time scales, are present elsewhere in the Americas. Notably, strong parallels linking the southwest to similar latitudes in the southern hemisphere were reported by Dettinger et al. (2001). A few studies have focused on the effects of drought and El Nino on rivers and ground-water levels in the dry areas of South America. Studies of the Pampa Humeda in Argentina have identified correlations of low-frequency (greater than 1.5 years)

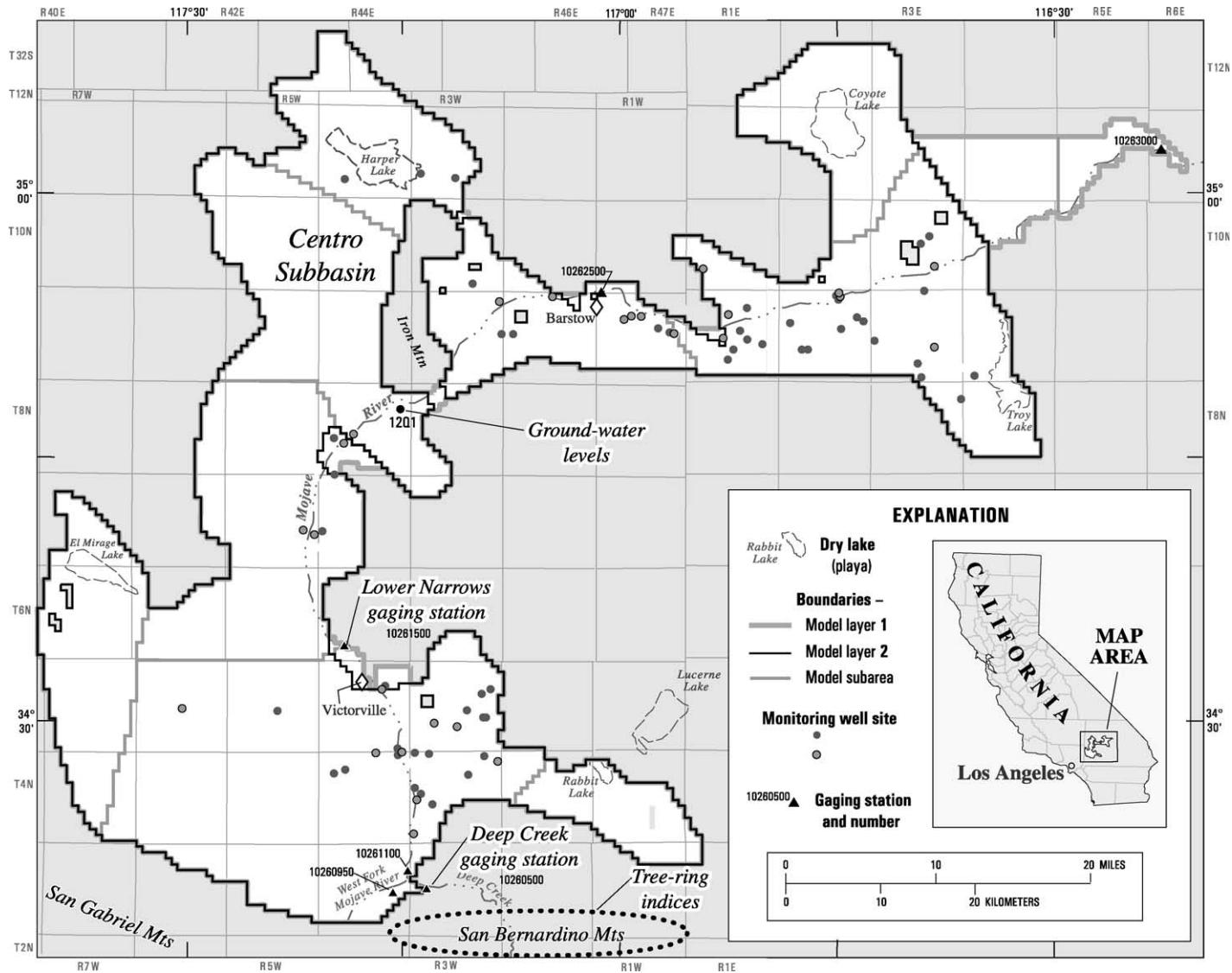


Fig. 1. Map showing location of sites for tree-ring, streamflow, and ground-water levels used for hydrologic time-series analysis for the Mojave River Basin, California.

variations between precipitation and water levels in an unconfined aquifer (Venencio, 2002), and relations between ENSO and water levels in an unconfined aquifer with 50% of the variance in water levels explained by periods of 2–7 years (Venencio and Garcia, 1998, 1999, 2000). Similarly, studies of streamflow variation in the Parana River yielded estimated periods of variable streamflow of 2–5, 8 and 17 years (Robertson et al., 2001). On the basis of principal component analysis of monthly mean streamflows, the variation of seasonal streamflow in the southwestern United States was identified to vary inversely from the Pacific Northwest (Lins, 1997) and has been correlated with ENSO and PDO (Dettinger et al., 2001). And most recently the implications of vulnerability of the availability of water resources from interdecadal streamflow variations have been identified by Jain et al. (2002) for the interior United States.

2.2. Climatic influences on hydrologic systems

Periodic forcings on aquifers has been previously addressed at periods shorter than the annual cycle, including notably, the analytic solutions presented by Townley (1995) for periodicities ranging from tidal to seasonal forcings. The effects of seasonal pumpage on the ‘capture’ of streamflow infiltration and evapotranspiration in the San Pedro River basin was analyzed to determine the long-term effects of seasonal variations for flow conditions and differences from time-averaged (steady-state) estimates of capture (Maddock and Vionnet, 1998).

Within the last decade some regional simulations of ground-water flow have moved towards smaller temporal discretization such as monthly, seasonal, and biannual time intervals, in simulations that extend from decades to more than a century. This mode of simulation has implicitly embedded climate variation in some models of ground-water flow through the finer temporal discretization of streamflow and pumpage. While some regional simulations have climate-based partitioning of recharge (Hanson et al., 2002), many simulations of ground-water flow still use long-term average precipitation to estimate ground-water recharge that is applied uniformly to these smaller time intervals (Stamos et al., 2001). Climatic synthesis of precipitation-based recharge

and streamflow also have been used to simulate long-term projections of ground-water and surface-water flow for the evaluation of future projects and policies using reconstructed cyclic precipitation derived from the spectral methods applied in this study (Hanson et al., 2002). Previous studies (Venencio, 2002; Venencio and Garcia, 1998, 1999, 2000) of climate variability have analyzed relations between climatic and hydrologic time-series to estimate trends, correlations, and frequencies. The trends have been estimated by regression, Kendall-Tau and other nonparametric statistical methods. However, trends and related statistics can be affected by the presence of incomplete ‘cycles’ present in the period of record of any hydrologic time-series. Previous studies have used lag correlations between data types such as precipitation and water levels and principal component analysis of streamflow and precipitation data. Climate periods have been estimated empirically from cumulative departure curves and moving averages, or were estimated directly from the time-series using Fast-Fourier Transform methods (Fraedrich and Boettger, 1978; Mann and Park, 1994; Diaz and Pulwarty, 1994; Venencio and Garcia, 1998).

3. Methods

While a few previous studies discussed above have used frequency analysis to assess the periodic variation of precipitation, streamflow, or ground-water levels for specific watersheds (Perry, 1994, 1995; Perry and Hsu, 2000), there has been no systematic analysis of the combination of these attributes throughout a large part of a land mass such as the southwestern part of the United States. A regional assessment (Leake, 2001) required the development of a systematic method of analysis that allows for the detrending, analysis, and comparison across data types and frequencies, across hydrologic settings, and across different basins. The systematic method must provide a means for detrending that removes anthropogenic effects and parts of larger ‘cycles’ that are longer than half the period of record. The systematic approach must normalize each data type to allow for comparisons (e.g. correlations) across data types. Finally, the systematic approach must provide serial correlation for discontinuous

temporal processes, such as precipitation and ephemeral streamflow that are more comparable to cumulative change in storage in ground-water systems that are represented by time-series of ground-water levels. This is especially problematic in the southwestern United States where streamflow is typically ephemeral. Such a systematic scheme not only facilitates the estimation and reconstruction of specific climate periods but also provides a means of comparison between different hydrologic settings, such as confined and unconfined ground-water flow systems or perennial and ephemeral rivers. The method presented here meets these requirements.

3.1. Data processing

Long-term continuous data have been collected throughout parts of the southwestern United States and provide the nominal basis for analyses of the effects of climatic variability on ground-water systems. Ground-water levels from wells, streamflow data from river gaging stations, tree-ring widths from tree cores, and precipitation data from rain gages were assembled from the Mojave River Basin (Fig. 1) to demonstrate the methods developed for systematic analysis of climatic variability. Data were selected on the basis of location within the overall study area, length and completeness of record, and association with an ensemble of data types within specific basins. When available, water levels were selected from wells with long-term records from hydrologic settings that include mountain-front regions, river floodplains, near pumping centers, and near basin outflow regions. While a national need for the long-term ground-water monitoring network has been recently identified (Taylor and Alley, 2001), there are relatively few long-term records that fulfill the requirements needed for this type of study.

Climatic variations of recharge were assessed from the relations between cumulative change in ground-water storage indicated by water-level hydrographs and corresponding precipitation, streamflow and tree-ring series. In order to assess climatic variability that may be related to interannual ENSO and interdecadal PDO periods, data with records that exceed 30 years were assembled. The hydrologic time-series were required to have at least annual values with few or no multi-year gaps in the record. The changes in

ground-water levels represent the cumulative departure of changes in ground-water storage. To conceptually align the other data types and facilitate comparison with changes in ground-water levels, all other data types are converted to cumulative-departure time-series (Meko et al., 1980).

In this article, tree-ring indices are used as a surrogate for long-term precipitation records. Tree-ring indices are indications of tree growth that are largely affected by the annual amount of precipitation and are based upon counting backwards from the year the tree core is sampled through a series of growth rings. The tree produces a new ring every year and this results in a continuous annual time-series. While the thickness of each ring is generally a function of the amount of water the tree receives, some trees are more dependent on temperature than precipitation and are only sensitive to precipitation in brief seasons. For each record studied here, an index of 1000 was assigned as a measure of average thickness (Stokes et al., 1973). Narrow dry-year rings are assigned indices less than 1000 and wide wet-year rings are assigned indices greater than 1000. The greater the departure from 1000, the greater the departure from the mean thickness. Therefore, performing a cumulative departure from 1000 results in a time-series curve ready for time-series analysis.

Monthly time-series of southwestern precipitation and streamflow typically contain many zero values. For frequency analysis of the precipitation and streamflow data and to make these data compatible with the ground-water levels the zero values were utilized by transforming these data types into a monthly cumulative departure from the period-of-record using the monthly means.

In order to eliminate the anthropogenic effects of long-term ground-water development on the ground-water levels analyzed, while at the same time maintaining consistency among the series analyzed, the various time-series were detrended. Each time-series was converted into monthly cumulative departure series. The residuals for each series were obtained by subtracting a regression fitted low-order polynomial from the cumulative departure curve over the period of record. The overall shape of any hydrologic record is referred to here as the trend, and tends to be dominated by the lowest frequency containing the greatest variance. These nonlinear trends in the data

may represent a combination of parts of larger climatic cycles or periods of anthropogenic effects. Detrending of the data, therefore, eliminates parts of the lowest-frequency cycles that would dominate the variance of the time-series analysis.

Ground-water levels are typically represented by measurements at somewhat irregular intervals that can range from daily to annual values. Short and incomplete records of ground-water levels were, in some cases, combined with those adjacent wells to form temporal composite records. For ground-water levels the detrending also eliminates any possible anthropogenic effects such as changes in pumping from long-term changes in ground-water development. Residuals for ground-water levels were obtained by subtracting the detrending polynomial from the ground-water levels and then interpolating with a global spline to obtain regular monthly values. The splined residuals were normalized by the mean and variance to facilitate statistical comparisons between data types.

3.2. Data analysis

Time-series frequency analyses were performed by singular-spectrum analysis (SSA) as described by Vautard et al. (1992) and implemented by Dettinger et al. (1995). The SSA is a form of principal-component analysis in lag-time domain that is used to detect periodic signals in short, often noisy time-series. SSA automatically (data adaptively) develops filters that extract the most information from

the series using the simplest forms. In this application, by considering the time-series variability with lags from 1 to 25 years, most of the variability in most of the time-series considered could be described in terms of about 10 simple forms. SSA also allows these simple components to be extracted from the original series in the form of reconstructed components (RC's). Typically the 'simple' components extracted from natural time-series by SSA take the form of quasi-periodic, almost-sinusoidal oscillations. Each of the oscillatory modes with longer than annual periodicities were extracted separately from the original series by application of the data-adaptive filters that SSA provides. This is performed with a spectral form of principal components analysis that results in the deconstruction of each frequency with a linear sum of frequency components (RC's). In addition the frequencies that contribute the most to the total variance in the time-series data can be combined to reconstruct a representation of the original time-series or to extrapolate the time-series over future time periods.

4. Synthetic example

To demonstrate the method of analysis, we first apply the technique to a synthetic time-series record that is a sum of a trend, sinusoids with three different periods (10 year, 6 year, and 1 year cycles) with different magnitudes of variation, and random noise (Fig. 2). The three cyclic signals are

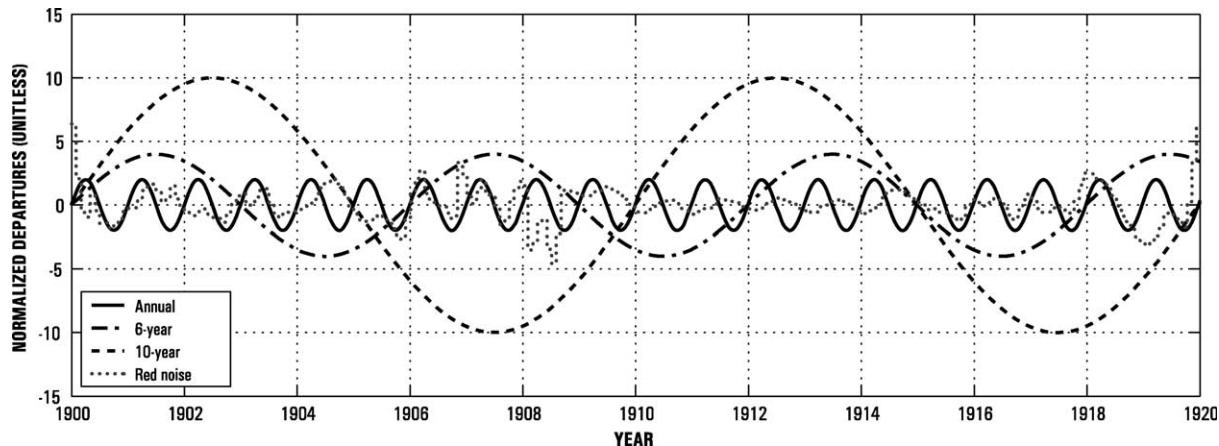


Fig. 2. Graph showing a synthetic time-series record composed of a 10-year, 6-year, annual, and random noise components.

independent of each other and, therefore, do not have any frequency or amplitude covariance. After the trend is removed with the global fit of a low-order polynomial, the residuals are normalized by the mean and variance. The resulting time-series is then analyzed by the SSA method. Using SSA allows one to deconstruct our synthetic time-series into its three distinct oscillatory components, while identifying the magnitude of the contributing signals from each. Similar to real climate variation, this synthetic model contains low frequency variability that contributes the greatest variance (Figs. 2 and 3). In this example, the 10, 6 and 1 year components contribute 81, 13.1, and 3.2% of the variance of the composite signal, respectively (Fig. 3). An additional 2.7% of the variation in the synthetic example series represents red noise. The composite of the four components (Fig. 3) represents a time-series similar in appearance to many of the hydrologic time-series investigated by this study.

The interaction between these three periods will produce a cumulative effect in various hydrologic time-series. For example, an annual precipitation signal will be less evident if it lies coincident with the decreasing (negative) variation of the 10-year period; for example, around 1907 in Fig. 2. Conversely, annual precipitation contributions may be magnified several fold if both the 10-year period and the 6-year period are in a increasing (positive) phases of variation, for example 1913 (Fig. 2). Relatively

severe dry conditions may exist when all three periods are in decreasing (negative) phases, such as 1917 of the synthetic example (Fig. 2).

The systematic application of this method will facilitate the decomposition and isolation of individual frequencies that can then be compared with each other and across data types (Fig. 2). This, in turn, allows for the systematic estimation of not only trend, but also phase lag and amplitude. Comparison across data types will facilitate inference of hydrologic processes and relation of these processes to the major indices of periodic climatic variability.

5. Mojave example

Six hydrologic time-series from the Mojave River Basin of southern California (Fig. 1) are presented as an example of the analysis method presented here. These series include the tree-ring index of a group of Douglas Fir trees from the San Bernadino Mountains from series CA536 (NOAA, 2001), streamflow from the major tributary of the Mojave River at Deep Creek, streamflow on the Mojave River downstream at the Lower Narrows, estimated base flow from streamflow at the Lower Narrows of the Mojave River (Lines, 1996), and water levels from a well in the Mojave River floodplain that was used to calibrate a regional ground-water model (Stamos et al.,

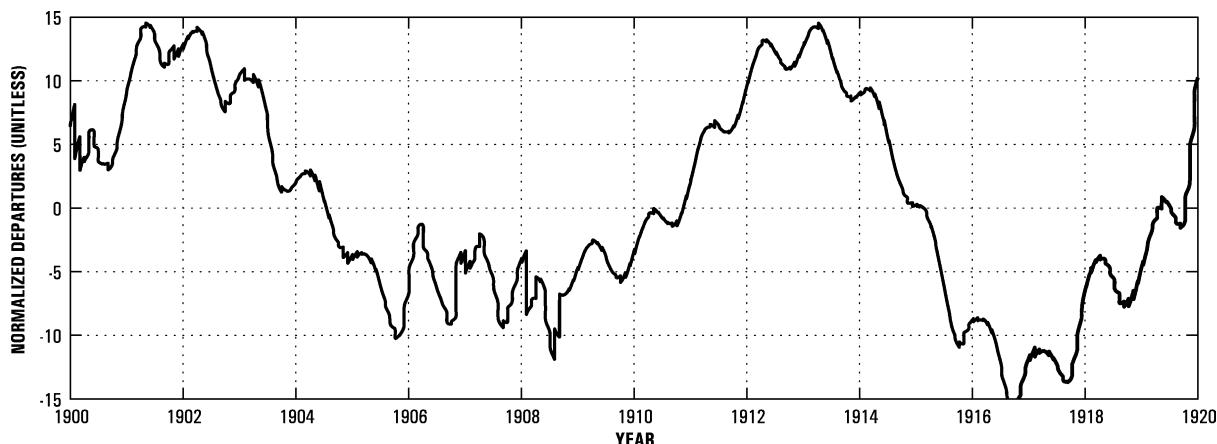


Fig. 3. Graph showing sum of synthetic PDO, ENSO, annual signals, and red noise.

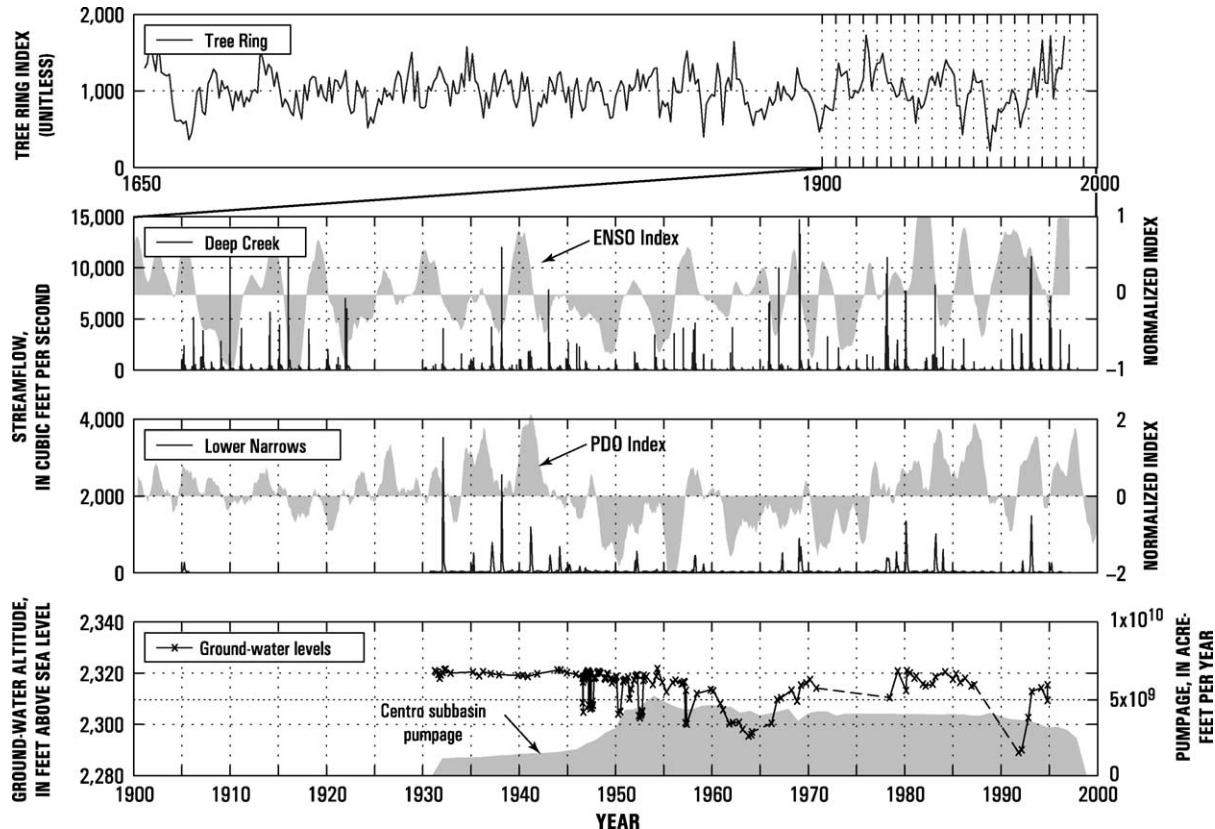


Fig. 4. Graph showing hydrologic time series for tree-ring indices, streamflow, and ground-water levels for the Mojave River Basin, California.

2001) (Fig. 4). In addition, the time-series of pumpage from the Centro subbasin (Fig. 1) of the Mojave River Basin ground-water system (Stamos et al., 2001) was used to assess the influence of ground-water pumpage on the ground-water level variations extracted, as well as possible relations between climate variation and ground-water pumpage.

The 335-year period of record for tree-ring indices (CA536), the 92-year period of record for streamflow at Deep Creek, the 67-year period of record for streamflow at the Lower Narrows, and the 63-year period of record for stream base flow at the Lower Narrows were converted into annual and monthly cumulative departures respectively. All departure curves were then detrended with low-order polynomials. After detrending, the residuals were normalized by mean and variance and the resulting time-series were subjected to frequency analyses using the SSA toolkit (Dettinger et al., 1995), along

with the normalized 63-year period to record ground-water levels from the well located in the floodplain of the Mojave River (Fig. 5). Only the period from 1900 to 1988 are shown for the reconstructed components of the tree-ring indices (Figs. 6(a) and 7(a)). The original record for the estimated base flow required the removal of variable discharge into the Mojave River from two upstream fish hatcheries (Stamos et al., 2001, Table 4). The estimated base flow record represents a substantial decrease in base flow owing to increased ground-water pumpage since the onset of ground-water development (Lines, 1996). Even with these dominant anthropogenic effects the method successfully estimated climatic cycles from the detrended data. Similarly, although there were several multi-year gaps in the ground-water levels (2–8 years), the method also successfully estimated the climate cycles. The water-level data demonstrate that time-series that typically have

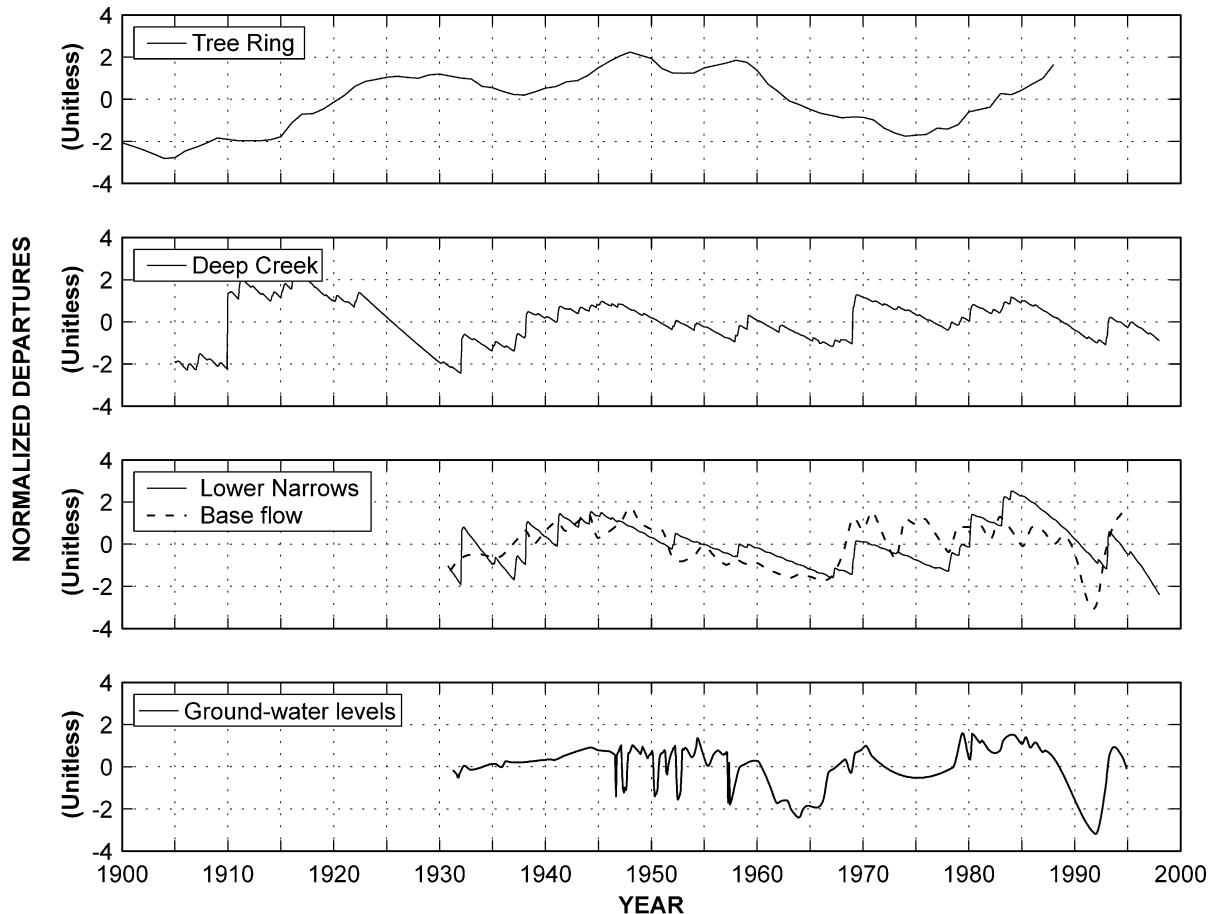


Fig. 5. Graph showing normalized residuals for tree-ring indices, streamflow, and ground-water levels.

small gaps or gaps not occurring during a transition from wet to dry conditions can be overcome in some instances.

All of the hydrologic time-series for the Mojave Desert included variations in the key climatic periods of variations for the southwest (Table 1). The resulting reconstructed components (RC's) from the hydrologic time-series that have been detrended to remove large-scale cycles and anthropogenic effects show a strong relation to their respective climate indices. Over 84% of the variation in these time-series were explained with three to four cycles (RC's) (Table 1). The variance captured by RC's for the PDO periods (10–25 years) represent 12% in tree-ring indices (using seven cycles), about 83% in the two streamflow

records, 51% in the stream base flow, and 75% in the ground-water levels (Table 1, Fig. 6(a)–(d)). The 23-year period captured the largest percent of variance for Deep Creek (Fig. 6b), the Mojave River at the Lower Narrows (Fig. 6c), and stream base flow of the Mojave River at the Lower Narrows (Fig. 6d). Similarly the 17-year cycle captured the largest percent of variance in the ground-water levels (Fig. 6d). The stream base flow and ground-water levels also yield components from the ENSO range (2–6 years), capturing 22 and 17% of the variance of the normalized residuals, respectively (Table 1, Fig. 7(c) and (d)). The difference in periodicities between surface-water and ground-water time-series may be due to a combination of physical processes

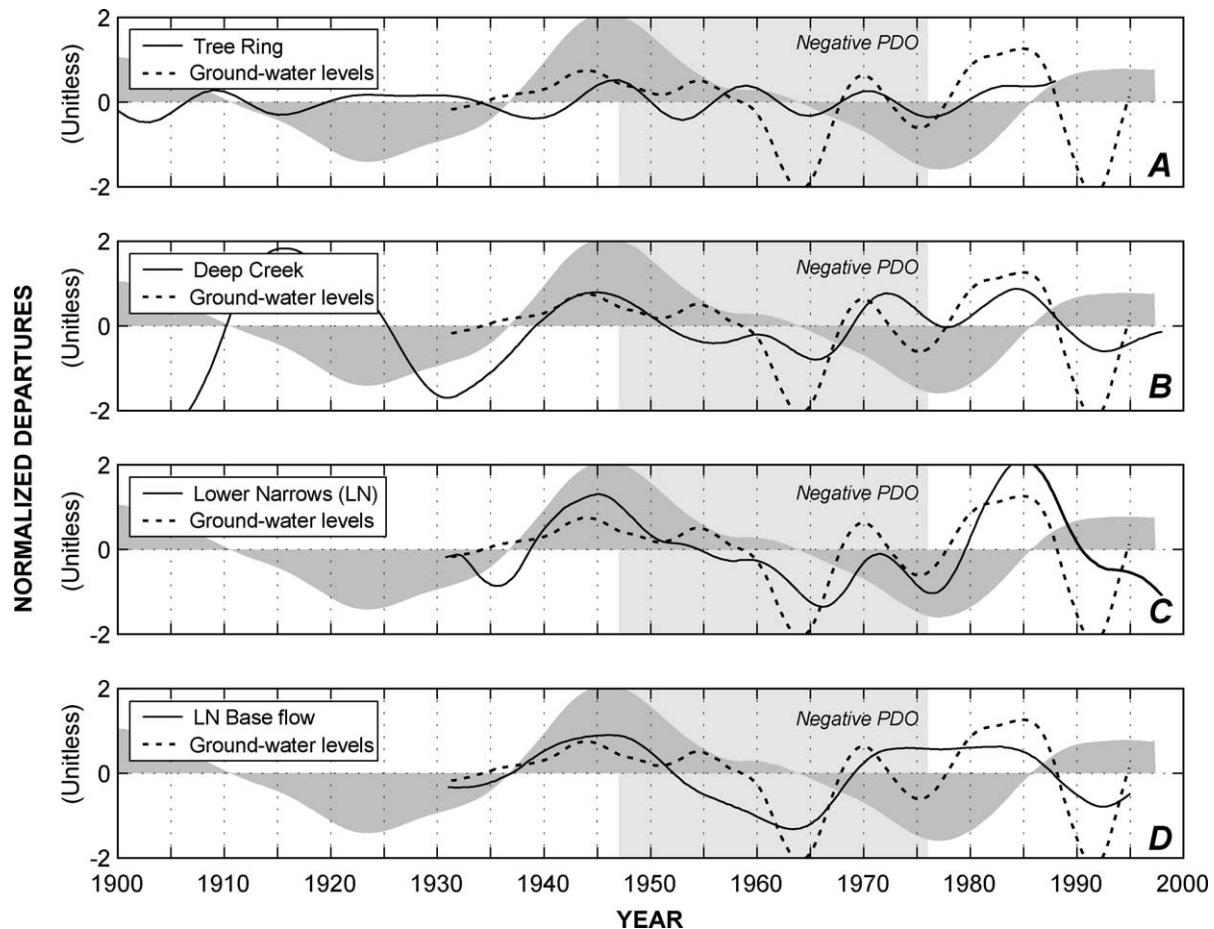


Fig. 6. Graph showing reconstructed components for all data types for PDO-range cycles (10–25 years) for hydrologic time series for the Mojave River Basin, California.

related to hydrostratigraphy and the geometry of the flow system. Since the well used is located in the floodplain in proximity to the Mojave River, it is assumed that effects from delayed flow through the saturated or unsaturated parts of the aquifer system may be small relative to the length of the periods. The well is also about 17 miles downstream from the Lower Narrows and this may contribute to lag in the estimated correlations. However, delayed flow may become even more significant in other hydrologic settings such as unconfined ground-water flow related to infiltration of bedrock or mountain-front recharge.

The best correlation and related phase lag was estimated by matching pairs of time-series. This

technique was used to estimate lagged correlations between pairs of selected reconstructed components. The estimated correlation coefficients and lag time for the best correlations are expressed in years (Table 2). The 68-year pumpage record appears to have a lagged correlation with ground-water levels in the PDO range of 30 years and with the other hydrologic time-series for periods of ~55–58 years. Thus, most of the hydrologic time-series are not correlated with annual pumpage for interannual and interdecadal cycles as indicated by the lags on the order of the length of the period of record for the pumpage (Table 2). While there is a strong relation between the effects of pumpage and decreased streamflow and base flow at

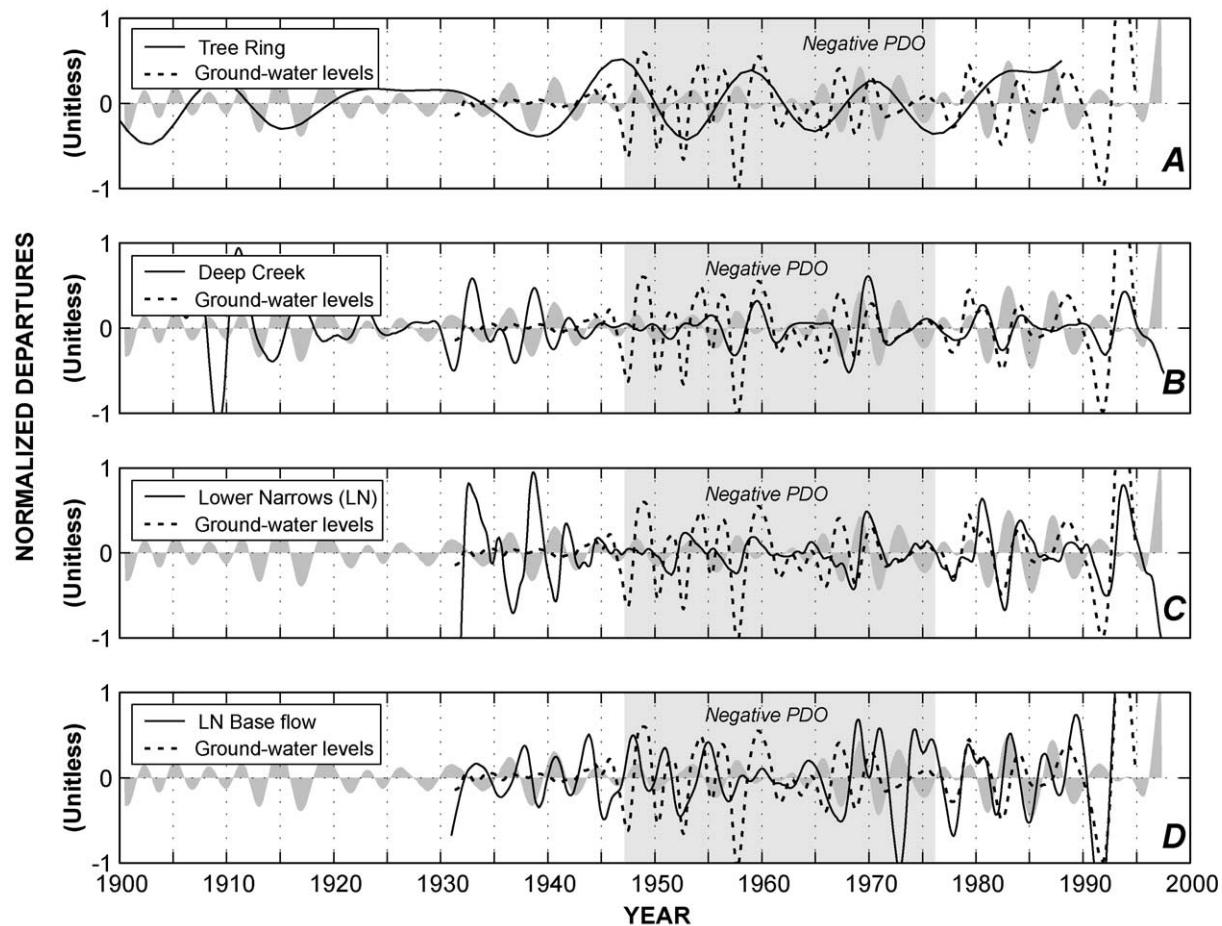


Fig. 7. Graph showing reconstructed components for all data types for ENSO-range cycles (2–6 years) for hydrologic time series for the Mojave River Basin, California.

the Lower Narrows (Stamos et al., 2001; Lines, 1996), there is little to no apparent correlation between climatic cycles and ground-water pumpage tends to suggest that the ‘cycles’ determined from the detrended hydrologic time-series were based upon and driven by climatic factors. Therefore, climatic variability is present along with the anthropogenic effects of ground-water and surface-water development and climatic variability is a strong forcing in the example presented by the Mojave River Basin hydrologic time-series.

The estimated lag correlations of 0.4–0.97 between tree-ring indices and the streamflow series for the PDO range result in decadal lags that range

from 9 years for Deep Creek to 41 years for Lower Narrows (Table 2). These estimates suggest that the lags become longer and the correlation with PDO-range cycles become larger downstream. Streamflow also showed correlations of 0.36–0.58 with the PDO index with lags of 1.5–2.7 years. The stream base flow and ground-water levels lagged further behind the PDO index by 2.2 and 5 years, respectively (Fig. 6d, Table 2). The changes in streamflow in the PDO-range at the Lower Narrows lag behind Deep Creek by about three quarters of a year, which may represent a delay in sustained downstream flows owing to streamflow infiltration to the floodplain aquifer. Changes in stream base flow

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Table 1

Summary of frequencies and percent variance for Mojave River Basin hydrologic time-series ==, indicates no estimate was made for this component, > PDO cycles (>25 years) lighter shaded cells, PDO cycles (10–25 years) are darker shaded cells, Monsoonal flow cycles (6–10 years) are thicker bounded cells, and ENSO cycles (2–6 years) are thinner bounded cells

Data Type	Tree Ring Indices (CA536)	Streamflow (Deep Creek)	Streamflow (Lower Narrows)	Stream Base Flow (Lower Narrows)	Ground-Water Levels (12Q01)	Pumpage (Centro Subbasin)
Period of Record	1654-1988	1905-1997	1930-1997	1931-1994	1931-1994	1931-1999
Reconstructed Component Number	Period, in years (Percent Variance/Cumulative Percent Variance)					
1	80.0 (38.5/38.5)	23.2 (53.0/53.0)	23.8 (63.3/63.3)	23.8 (51.4/51.4)	16.7 (46.6/46.6)	30.3 (40.2/40.2)
2	52.6 (33.3/71.8)	15.5 (29.4/82.4)	12.8 (20.1/83.4)	8.3 (25.8/77.2)	10.4 (28.1/74.7)	2.0 (18.2/58.4)
3	26.3 (14.0/85.8)	7.7 (5.6/88.0)	6.0 (5.7/89.1)	5.6 (12.4/89.6)	5.6 (8.4/83.1)	2.7 (13.7/72.1)
4	21.3 (7.2/93.0)	6.0 (3.8/91.8)	4.4 (2.8/91.9)	4.0 (5.1/94.7)	4.2 (3.9/87.0)	3.1 (11.7/83.8)
5	15.7 (2.9/95.9)	4.4 (2.0/93.8)	3.1 (1.9/93.8/)	3.1 (2.6/97.3)	3.0 (2.6/89.6)	5.2 (9.4/93.2)
6	13.2 (1.4/97.3)	3.6 (1.1/94.9)	2.6 (1.3/95.1)	2.6 (1.3/98.6)	2.5 (2.0/91.6)	6.0 (6.8/100.)
7	11.0 (0.9/98.2)	3.0 (0.9/95.8)	2.2 (0.6/95.7)	2.1 (0.5/99.1)	1.2 (1.1/92.7)	=====
8	9.6 (0.5/98.7)	2.7 (0.5/96.3)	1.8 (0.5/96.2)	1.8 (0.3/99.4)	1.3 (0.9/93.6)	=====
9	8.4 (0.2/98.9)	2.3 (0.3/96.6)	1.7 (0.4/96.6)	1.6 (0.3/99.7)	1.9 (0.9/94.5)	=====
10	7.6 (0.2/99.1)	2.1 (0.3/96.9)	1.0 (0.4/97.0)	1.4 (0.1/99.8)	1.0 (0.8/95.3)	====

and ground-water levels tend to precede streamflow at Deep Creek and at Lower Narrows by about 1 or 2 years, which may suggest that streamflow infiltration may dominate prior to sustained streamflow during wet periods (Fig. 6(b)–(d), Table 2). The changes in stream base flow lag behind the changes in ground-water levels for PDO cycles by about a season which may represent the filling of the aquifer prior to the onset of a base flow contribution to streamflow. The stream base flow shows little correlation with the PDO index, yet the ground-water levels show some correlation with the PDO index that lag the index by about 2–5 years, respectively. Overall these

correlations and lags demonstrate that the effects of the longer PDO cycle on streamflow, stream base flow, and ground-water levels are correlated but display different lag relations that may reflect the ground-water/surface-water relations and other possible effects such as delayed flow or increased drainage area. Thus, the streamflow, stream base flow, and ground-water levels are varying to some degree with the PDO-range cycles in the Mojave River Basin but show different relations and lags with the PDO index.

The lag correlations of streamflow with the components in the ENSO range are lag correlated

Table 2
Summary of correlations and phase lags at selected climate cycles for Mojave River Basin hydrologic time-series

Correlation–phase lag categories for reference hydrologic-time-series	PDO cycles (10–25 years)		Monsoonal cycles (6–10 years)		ENSO cycles (2–6 years)	
	Lag correlation	Phase lag	Lag correlation	Phase lag	Lag correlation	Phase lag
	(1) PDO index	(1) PDO index	(1) Streamflow-DC	(1) Streamflow-DC	(1) ENSO index	(1) ENSO index
	(2) Streamflow-DC	(2) Streamflow-DC	(2) Base Flow	(2) Base flow	(2) Streamflow-DC	(2) Streamflow-DC
	(3) Streamflow-LN	(3) Streamflow-LN	(3) Pumpage	(3) Pumpage	(3) Streamflow-LN	(3) Streamflow-LN
	(4) Base flow	(4) Base flow			(4) Base flow	(4) Base flow
	(5) Water-level	(5) Water-level			(5) Water-level	(5) Water-level
	(6) Pumpage	(6) Pumpage			(6) Pumpage	(6) Pumpage
Tree ring indices (CA536)	(1) 0.75	(1) -42	(2) 0.35	(2) 53	-	-
	(2) 0.40	(2) 9	(3) 0.93	(3) -50		
	(3) 0.97	(3) 41				
	(4) 0.86	(4) 35				
	(5) 0.93	(5) -52				
	(6) 0.99	(6) 48				
Streamflow-DC (Deep Creek)	(1) 0.36	(1) 1.50	(2) 0.39	(2) 0	(1) 0.45	(1) 3.2
	(3) 0.68	(3) 0.75	(3) 0.65	(3) -0.75	(3) 0.87	(3) 0.1
	(4) 0.78	(4) -1.25			(4) 0.45	(4) -0.6
	(5) 0.66	(5) -1.75			(5) 0.40	(5) 0.0
	(6) 0.70	(6) 35			(6) 0.41	(6) 47
Streamflow-LN (Mojave River at Lower Narrows)	(1) 0.58	(1) 2.7	= = =	= = =	(1) 0.45	(1) 2.75
	(4) 0.68	(4) -2.6			(4) 0.49	(4) 4.8
	(5) 0.76	(5) -1.75			(5) 0.41	(5) -0.2
	(6) 0.93	(6) -36			(6) 0.49	(6) 37
Stream base flow (Lower Narrows)	(1) 0.08	(1) 2.2	= = =	= = =	(1) 0.34	(1) 3.75
	(5) 0.70	(5) 0.25			(5) 0.56	(5) 0.16
	(6) 0.81	(6) -31			(6) 0.77	(6) -55
Ground-water levels (12Q01)	(1) 0.27	(1) 5.0	= = =	= = =	(1) 0.32	(1) -1.58
	(6) 0.95	(6) 30			(6) 0.99	(6) 58
Pumpage (Centro Subbasin)	(1) 0.81	(1) 42	= = =	= = =	(1) 0.78	(1) 60

= = =, indicates that no estimates made, negative lags indicate the time-series leads the reference hydrologic-time-series. DC = Deep Creek, LN = Lower Narrows.

with an ENSO index with lag correlation coefficients of 0.45 at Deep Creek and 0.45 at the Lower Narrows (**Table 2**). Streamflow lags behind the ENSO by about 3 years (**Fig. 7(b)** and **(c)**) and stream base flow at the Lower Narrows lags further behind the ENSO-range cycles by 3.75 years (**Table 2**, **Fig. 7d**). The ground-water levels precede the ENSO index by about 1.6 years (**Table 2**, **Fig. 7d**) yet show little to no lag with streamflow and stream base flow (**Table 2**, **Fig. 7(b)–(d)**) and is opposite (negative lag means leading the reference time-series) and smaller than the 5-year lag behind the PDO cycle (**Table 2**). The amplitude of ENSO range oscillations for streamflow show damped amplitudes during periods of negative (warmer and drier) PDO period such as the period 1946–1976 (shaded region in **Figs. 6** and **7**). The stream base flow and ground-water levels do not show this dampening of amplitude during this entire negative PDO period (**Fig. 7d**). While the ENSO-range cycles of the downstream base flow precedes the streamflow at Deep Creek, it lags behind the streamflow at the Lower Narrows by about 4.8 years (**Table 2**, **Fig. 7(c)** and **(d)**). This suggests a complex relation between changes in ground-water storage and surface-water flow in the floodplain of the Mojave River for ENSO-range cycles. The ENSO cycles are similar to the PDO cycles for groundwater levels that indicate a general rise that precedes the rise in stream base flow at the Lower Narrows by a couple of months (**Table 2**, **Fig. 7d**). The changes in ground-water levels downstream from the Lower Narrows precede the streamflow by a couple of months yet the changes in base flow lags by a couple of months. Thus, there is also a correlation between changes in streamflow and ground-water storage in the ENSO-range cycles (**Fig. 7d**).

6. Discussion and conclusions

A systematic method was developed for the frequency analysis of hydrologic time-series, which isolates components of temporal variability in hydrologic time-series related to ground-water recharge and streamflow. The method also provides a basis for comparing the lag correlation, phase and amplitude (percent variance) among data types or across frequencies. The reconstruction of specific components as part of this method provides

a means of determining the major forcings within hydrologic systems. This new method for analyzing climatic variability in hydrologic time-series also allows for the systematic reconstruction of variations in data-adaptively reconstructed frequency ranges.

This method was used to isolate hydrologic variations in PDO, 6–10 year, and ENSO ranges in four kinds of hydrologic time-series (**Fig. 8**) from the Mojave River Basin, California. The climatic variability in the hydrologic series for the Mojave River Basin are aligned with PDO and ENSO indices (**Figs. 6–8**). Lag correlations of the hydrologic series with the ENSO index are similar to those with the PDO index but demonstrate different phase lags and amplitudes for the different length cycles (**Figs. 6 and 7; Table 2**). The correlations with climate indices are also consistent with relations between climate variation and geomorphic processes estimated for the Mojave Desert where wetter climate periods resulted in high-intensity precipitation that, in turn, increases hillslope runoff and drives geomorphic changes (Hereford and Webb, 2001, 2002). The Mojave River example demonstrates potential ground-water/surface-water relations driven by climatic variability. The statistical analyses of the ensemble of hydrologic time-series was used to infer a sequence of hydrologic relations. These relations suggest that streamflow infiltration is followed by accretion in ground-water storage that can culminate in increased ground-water contributions to stream base flow in the Mojave River streamflow downstream at the Lower Narrows (**Figs. 6 and 7**). Additional ground-water storage accretion may then occur further down the ground-water flow path below the rejected streamflow (base flow) at the Lower Narrows.

Several components for the Mojave River example are aligned with the PDO and ENSO indices (**Figs. 4 and 6–8**). A large portion of the detrended variance is captured by and correlated for reasonable lags with the groups of cycles that represent the climatic variability (**Table 1**). On the basis of the estimates provided by this method for the Mojave River Basin example, ground-water/surface-water relations can be quantitatively related to major modes of climate variation even with strong anthropogenic effects present in the original hydrologic time-series.

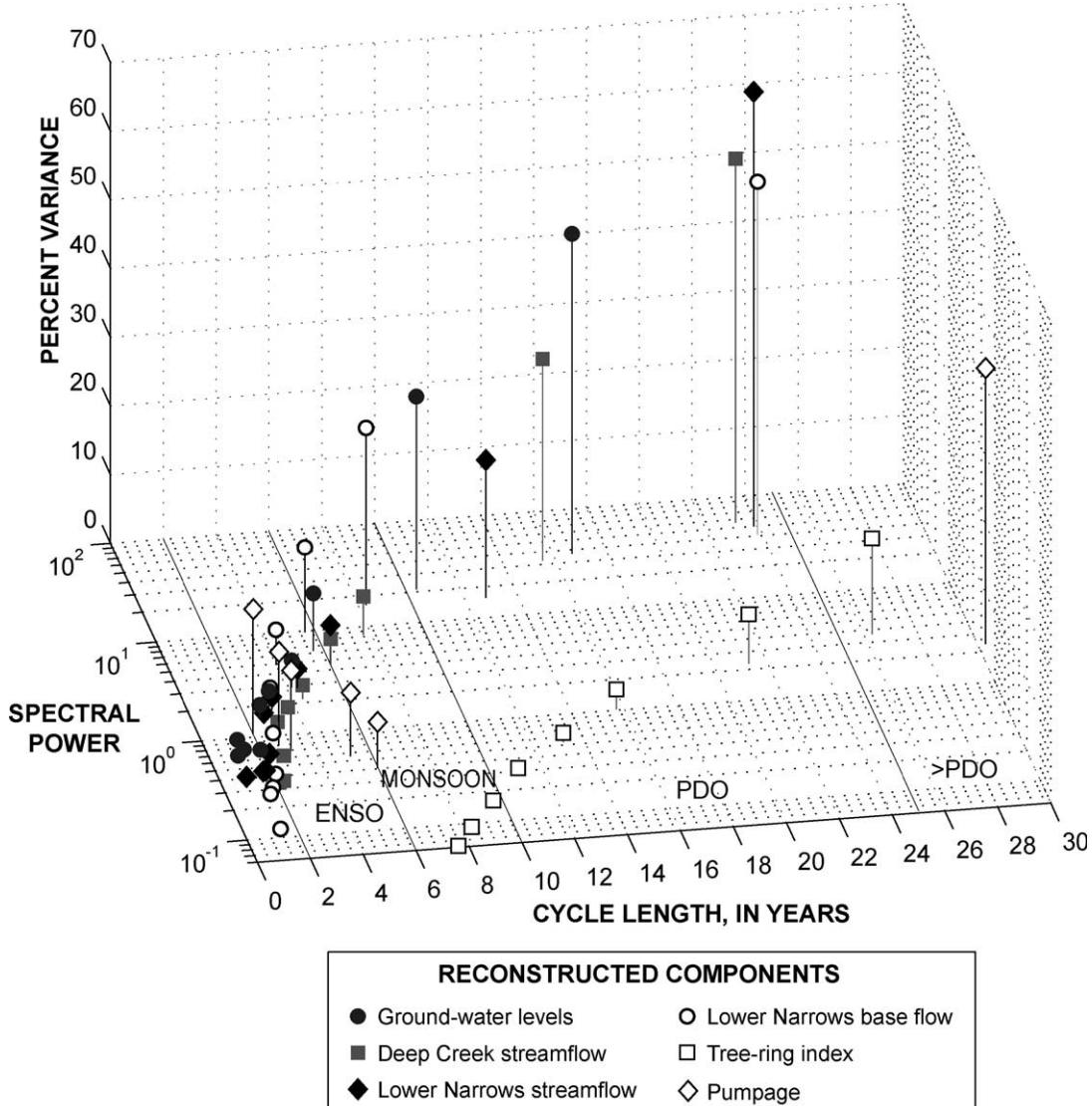


Fig. 8. Graph showing reconstructed components for all data types for the Mojave River Basin and related climate indices.

These correlations and reconstructed time-series can be used to better understand the relation of hydrologic response to climatic forcings and to facilitate the simulation of streamflow and ground-water recharge for a more realistic approach to water-resource management. These methods can be applied in basins with ground-water and surface-water development throughout the southwestern United States where the anthropogenic effects need to be separated

from natural climatic variability to assess the timing and magnitude of supply and demand for water resources. The identification of cycles, correlations, and lags could be used to help with the simulation of artificial recharge projects or streamflow diversions, the planning for importation of water, or developing policies and regulations that align supply and demand cycles of ground-water and surface-water development with climatic cycles.

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