Spatial-temporal variation patterns of groundwater tables in the middle section of the Hexi Corridor

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Abstract. It is of great significance to research spatial-temporal variations of groundwater tables from the perspective of the whole groundwater variable field in a basin. In this study, the original observation matrix was constructed using 38 monitoring wells data from 1984 to 2019 in the Heihe River Basin in the middle section of the Hexi Corridor and processed to be centered and standardized, respectively. The empirical orthogonal function (EOF) method was used to decompose the transformed matrices to obtain spatial and temporal variation patterns of groundwater tables which were represented by the spatial weights of typical uncorrelated modes with the corresponding temporal functions (TF). The resulting main variation pattern showed general drops in regional groundwater tables for both centered and standardized cases, especially in the southeast regions when using centered EOF modes. The second to fifth modes presented reverse distribution characteristics from the northwest to southeast directions. The downward trend in the first TF series indicated that the groundwater depth of the whole basin varied to be deeper. The local rise occurring at some sites demonstrated the positive effects of continuous ecological water delivery since 2000, but was still not recovered to the previous level due to long-term serious groundwater overdraining.

1. Introduction

Under the background of a severe global water crisis, water resource has become a major issue concerning the human living environment, society sustainable development, and national poverty and wealth. In Northwest China, especially the inland river basin of the Hexi Corridor, the degree of ecological water shortage has been reported to reach more than 80% due to the high water consumption by industry, agriculture, etc [1]. The poor water resources endowment (e.g., the small total amount of available water resources, the uneven spatial and temporal distribution of water resources) and anthropogenic impact on the excessive expansion of irrigated areas both undoubtedly have exacerbated the contradiction between water resources development and the downstream ecological deterioration [2]. Water shortage has become the key factor in continental river basins in the northwest ecological economic development and ecological protection, and meanwhile, led to a high dependence of this regional development on groundwater exploitation. However, the problems of excessive exploitation and abuse of groundwater resources have gradually become prominent and brought many adverse effects, such as the drought of land, ground subsidence, degradation of natural vegetation and oasis, deterioration of ecological environments, and reduced agricultural production [3-4].
Several studies have shown sharp declines of groundwater tables in inland river basins in the Hexi Corridor of Northwest China, and even different levels of local groundwater depression cones [5]. This phenomenon of groundwater over-extraction has therefore seriously hampered the development of the Hexi Corridor region. The Heihe River Basin is a typical example where the terminal Juyan Lake has dried up intermittently since the 1960s, and dried up completely in the 1990s, accompanied by surrounding desertification [6]. To restore the ecological environment and recover river health and life, water-resources scheduling for ecological water conveyance in the Heihe River Basin has been implemented under unified government management annually since 2000, and so far it has lasted 20 years. According to relevant studies, this unified water resources management enables raising the groundwater table and moderating the downstream water stress [7-8]. In this context, research on the assessment of the spatial-temporal variations in groundwater tables and the comparison of effects of ecological water conveyance before and after 2000 is of great practical significance to improve effective utilization and rational development of groundwater resources.

The empirical orthogonal function (EOF) method, as a kind of multivariate statistical analysis method, is earliest applied to extract the main signal characteristics of meteorological variable fields. It is powerful for dimensionality reduction in the field of pattern recognition and data mining, given the multidimensional variables [9]. In addition, the orthogonal eigenvectors (decomposed by the EOF method) corresponding to the first several eigenvalues with large variance contributions can identify main variation patterns in the complex variable field through the separate description of spatial and temporal information without a loss of physical significance [10-11]. Therefore, on account of these advantages, the EOF method has been gradually promoted and employed in the field of hydrological and water resources to carry out studies on the temporal and spatial distribution of hydro-meteorological events.

The objectives of this paper are as follows: (1) analyze spatial and temporal variation characteristics using the EOF method in the Heihe River Basin in the middle section of the Hexi Corridor; (2) compare the differences in spatial-temporal variation patterns before and after the implementation of unified water resources management since 2000.

2. Empirical orthogonal function (EOF) method

Supposing a matrix $Q_{m \times n}$ of original series $Q(t, u)$ (where $t=1, 2, \ldots, n$ and $u=1, 2, \ldots, m$ denote the number of yearly observations and gauging stations, respectively), $Q_{m \times n}$ is first processed to be a centered matrix $X_{m \times n}$ in which each vector $X(t, u)$ is obtained by decomposing $Q(t, u)$ into the long-term mean value of the discharge $\mu_Q(u)$ for a certain site $u$ and the corresponding centered observation $X(t, u)$ as follows:

$$X(t, u) = Q(t, u) - \mu_Q(u) \quad (1)$$

Similarly, the matrix $X_{m \times n}$ can also be standardized $Q_{m \times n}$ [10], thus $X(t, u)$ is calculated by

$$X(t, u) = [Q(t, u) - \mu_Q(u)] / \sigma_Q(u) \quad (2)$$

where $\sigma_Q(u)$ is the standard deviation of the long-term series $Q(t, u)$.

In the EOF method, this centered or standardized matrix $X_{m \times n}$ can be expanded into double orthogonal series of empirical orthogonal functions $V_{m \times n} = \{ V_1, V_2, \ldots, V_m \}$ and principal components $P_{m \times n} = \{ P_1, P_2, \ldots, P_n \}$, which include the information for spatial weights and temporal functions, respectively [10]. The spatial weights $V_{m \times n}$ are determined via the following formula:

$$C_{m \times n} \times V_{m \times n} = V_{m \times n} \times E_{m \times n} \quad (3)$$
where $C_{mm}$ means the variance-covariance matrix equal to $C_{mm} = \frac{X_{mm}X_{mm}^T}{n}$ for the case of Eq.(1) or the correlation matrix when using Eq.(2). $X_{mm}^T$ is the transposed matrix of $X_{mm}$.

Each vector $V_m$ of the spatial weights $V_{mm}$ exactly equals to the eigenvector of the matrix $C_{mm}$. $E_{mm}$ is a $m \times m$ diagonal matrix constituted by the eigenvalues $\lambda_i$, $i = 1, 2, ..., m$ (arranged from the largest to the smallest) having the following form as:

$$E_{mm} = \begin{bmatrix}
\lambda_1 & 0 & \cdots & 0 \\
0 & \lambda_2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \lambda_m
\end{bmatrix}$$

that each non-zero eigenvalue corresponds to an eigenvector (i.e., spatial weight from the EOF method). The bigger the $k^{th}$ eigenvalue $\lambda_k$, the more important the corresponding eigenvector, yielding a larger contribution rate ($R_k$) to the total variance (i.e., relative variance explained):

$$R_k = \frac{\lambda_k}{\sum_{i=1}^{m} \lambda_i}$$

The error band of $\lambda_i$ in Eq. (6) is tested to confirm the significance of the decomposition results of the EOF method that the adjacent eigenvalues should at least differ by $\epsilon_i$:

$$\lambda_i - \lambda_{i+1} \geq \epsilon_i$$

The temporal functions $P_{mm}$ are then derived by a weighted average of the centered or standardized observed series:

$$P_{mm} = V_{mm}^T \times X_{mm}$$

3. Study area and data
The Heihe River Basin is the second-largest inland arid basin located in Northwest China [4, 9]. The study area is upstream of the Zhengyixia hydrological station in the Heihe River Basin in the middle section of the Hexi Corridor and consists of the Gaotai County, Linze County, and Ganzhou District, with a total land area of 11316km$^2$ (Figure 1).

![Figure 1. The study area in the Heihe River Basin of the Hexi Corridor, China.](image)

This region belongs to the warm temperate continental drought climatic zone, with strong radiation, less precipitation, and dry air [1-2]. The annual precipitation is 300-700 mm while the potential
evaporation reaches 700-1800 mm. With the rapid growth of population and socioeconomic development, there has been a high level of water-resources utilization and serious water contradiction in the Heihe River Basin. Due to overexploitation of water resources, surface water draining into the lower reaches has gradually decreased over recent decades, and the heavy dependence on groundwater use resulted in a sharp decrease in the groundwater table, which greatly degraded local ecosystems and caused the lower reaches and terminal lake to completely dry up [8-9]. Given the fact that the government has implemented the unified management of ecological water conveyance in the Heihe River Basin for about 20 years, it is necessary to assess the spatial-temporal variations in the groundwater table before and after the year 2000 for comparison of the effect of ecological water conveyance. The observed groundwater table data from 1984 to 2019 collected from 38 monitoring wells were provided by the Hydrology and Water Resources Survey Bureau of Gansu Province.

4. Results

4.1. Decomposition of groundwater table based on EOF analysis

The average annual groundwater table data of the Heihe River Basin were centered and standardized using Eq.(1) and Eq.(2), respectively. Each of the two processed data constituted a $38 \times 36$ matrix according to the wells' quantities and length of the annual series. The resulting matrix was decomposed by the EOF method, which gave 38 eigenvalues and the corresponding 38 eigenvectors. The spatial distribution of the orthogonal eigenvectors was named as the modes represented by spatial weights and the modes were mutually independent in groundwater table variable fields in the Heihe River Basin. It was numbered to be mode 1 for the eigenvector corresponding to the first (largest) eigenvalue, mode 2 for the eigenvector corresponding to the second eigenvalue, and so on.

The relative variance explained and cumulative variance explained for different modes were calculated using Eq. (5). The eigenvalues were arranged with the values in descending order, as shown in Table 1. In general, to avoid information redundancy and pursue dimensionality reduction, only the first few modes that can approach an above-85% cumulative variance explained would be adopted in the EOF analysis, rather than the use of the whole 38 modes (certainly a 100% cumulative variance explained).

Table 1. The EOF decomposition results.

| Number of mode | Centered data | Standardized data |
|---------------|--------------|------------------|
|               | 1  | 2  | 3  | 4  | 5  | 1  | 2  | 3  | 4  | 5  |
| Eigenvalue    | 161.08 | 9.54 | 4.86 | 1.95 | 0.82 | 17.62 | 6.25 | 3.96 | 1.90 | 1.51 |
| Relative variance explained (%) | 88.96 | 5.27 | 2.68 | 1.07 | 0.45 | 47.69 | 16.92 | 10.72 | 5.14 | 4.08 |
| Cumulative variance explained (%) | 88.96 | 94.23 | 96.91 | 97.98 | 98.43 | 47.69 | 64.61 | 75.33 | 80.47 | 84.55 |

In Table 1, for the centered data, the cumulative variance contribution rate reached 88.96% merely using the first mode (mode 1), but it can be close to 85% for standardized data which needed more modes, i.e., the first five modes. This result illustrated that the most changeful features were captured faster by centered processing than by data standardization. For ease of comparison, the first five modes were adopted to describe the spatial-temporal variation patterns of groundwater table in the Heihe River Basin from 1984 to 2019.

4.2. Spatial distribution characteristics of groundwater table

The coincidence of sign (all positive or negative) for each weight value contained in a mode indicates that the eigenvector reflects the consistency of the changes in the groundwater table (rise everywhere or all fall). If the weights are spatially distributed between positive and negative, it shows an opposite trend
of increase or decrease in groundwater table in certain regions. The extreme value (absolute value) of each mode discerns the sensitive location of variations under this mode.

Figure 2 shows the results for different modes when using the centered and standardized data for the EOF analysis. In Figure 2a, the main spatial distribution characteristics of groundwater table variable fields in the Heihe River Basin were shown in mode 1. This result of centered EOF decomposition mode displays that almost all the weight values were negative, which represented a general decline in the groundwater table (i.e., the increase in groundwater depth) in the whole region. The small absolute values often located in the northwest region, whereas the high extreme value center (absolute value) appeared in the southeastern direction of the study area which was located in the sites of Ganzhou District and always presented descending tendencies in the groundwater table with frequent annual fluctuations and large variation ranges. In the case of standardization, the EOF results (Figure 2b) also showed general drops in regional groundwater tables but were different from those with the centered processing. Because of the removal of the large influence of local standard deviation via the standardization, high absolute values of weights did not demonstrate any spatial trends but were widely distributed in Gaotai County, Linze County, and Ganzhou District. It is thus seen that the variations in groundwater depth in different local regions can be described better through standardization, although the EOF modes with centered processing captured more variabilities on account of the local sites with larger data variance (see the relative variance explained in Table 1).

Figure 2. The spatial weights for mode 1 to mode 5 obtained from the EOF decomposition using the (a) centered and (b) standardized observations.

The weights in mode 2 to mode 5 were characterized by both positive and negative values, reflecting different degrees of spatial variations in the groundwater table. Taking Linze County as the transition zone, the spatial distribution of these modes was approximately negative in the northwest areas and positive in the southeast areas, which presented reverse distribution types for northwest-southeast directions. In other words, if the groundwater table falls in the southeast of the region, there could exist a rise in a certain northwest area and vice versa.

4.3. Temporal variation patterns of groundwater table

The temporal functions (TF) corresponding to eigenvectors in Figure 3 reflect the serial variation characteristics of the modes represented by the spatial weights in the study area. The coefficient symbol reflects the direction of the mode, i.e., the positive value indicates the same direction as the mode, while
the negative value is the opposite. The greater the absolute value of the TF is, the more typical such mode is at the annual timescale.

In Figure 3, the 1st TF series showed an obvious downward trend, indicating that the groundwater table of mode 1 changed from the shallower groundwater depth of the whole basin to the general descending variation pattern, and the 1st TF from the centered EOF result showed a greater decline than that obtained by standardized EOF analysis. Combined with the spatial distribution result of mode 1 (Figure 2), it was found that in the past 36 years, the most prominent fluctuation and decline in groundwater table occurred in Ganzhou District. The 2nd to the 5th TFs can well capture the changes in the groundwater table with both rising and dropping variation patterns in certain local sites in the study area. The phenomenon of groundwater table rising appeared in some years for the 2nd to the 5th TFs. For example, in the case of standardization, the 4th and the 5th TFs showed upward trends after 2000 and reached their maximum values in 2008 and 2010, respectively. All these results demonstrated that ecological water transport played a positive role in the recovery of the groundwater table.

Figure 3. The temporal functions (TF) obtained from the EOF decomposition using the (a) centered and (b) standardized observations (The black dotted lines show the starting year 2000 for the unified management of ecological water conveyance).

5. Discussion
Some studies have shown that the runoff in the inland river basins of the Hexi Corridor, affected by climate warming and melting icebergs, presented an overall increasing trend, and the recharge of groundwater increased [2]. Meanwhile, with the implementation of the Groundwater Over-exploitation Management Program, the amount of groundwater use has been drastically reduced [8]. Under the combined effect of natural and man-made factors, the downward trend of groundwater table in most groundwater over-exploitation areas has slowed down, the groundwater table in some areas has risen slightly, and the area of over-exploitation areas has significantly decreased [7]. However, due to the rapid economic and social development in the 20th century, there has been serious groundwater overdrawning that caused historical long-term unbalanced replenishment and deficits of groundwater, the groundwater table was still lower than that before the water transfer, such as for the Ganzhou District in the middle reaches of the Heihe River [2, 4]. Our study was consistent with these findings. It can be seen from the result in Figure 3 that the 1st TF values before 2000 were all positive, while the 1st TF values after 2000 were almost negative, indicating a tendency of groundwater depth from shallow to deep. Despite the continuous water conveyance since 2000 that has alleviated a certain amount of pressure on the ecological environment, the groundwater table has still dropped significantly in comparison with the periods of the 1980s and 1990s. Therefore, over-exploitation issues should not be underestimated and the relevant supervision should be strengthened. Otherwise, the negative effects of ecological and environmental degradation represented by water quality deterioration, soil salinization, vegetation degradation, and land desertification could spread rapidly in the Hexi Corridor [3].

6. Conclusions
The spatial-temporal variation patterns of the groundwater table were analyzed by applying the empirical orthogonal function (EOF) method to the Heihe River Basin in the Hexi Corridor, China. In the EOF decomposition, both centered and standardized annual groundwater table data matrices were
considered to derive the spatial weights of mutually independent EOF modes and the corresponding
temporal functions. Because of information redundancy and dimensionality reduction, the typical first
five modes with relatively high cumulative variance explained (above 95% for the centered case and
approximately 85% for the standardized case) were adopted to represent the main spatial-temporal
variation patterns of the groundwater variable field. The results showed that in the main variation pattern,
general drops in regional groundwater tables existed for both centered and standardized cases, especially
in the southeast regions when using centered EOF modes. The second to fifth modes presented reverse
distribution characteristics from the northwest to southeast directions. The downward trend in the first
temporal function series indicated that the groundwater depth of the whole basin varied to be deeper.
However, there also appeared local rise in some sites and thereby demonstrated the positive effects of
continuous ecological water delivery since 2000, but the facts that the recovered groundwater tables
were still lower than those before 2000 declared the severity of long-term groundwater overdrawling.

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