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Catchment water storage dynamics and its role in modulating streamflow generation in spectral perspective: a case study in the headwater of Baiyang Lake, China

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Abstract. Although it is important in hydrological cycles, catchment water storage dynamics is still not fully understood because it is affected by multiple drivers simultaneously and is difficult to be estimated using field hydrometric observations and hydrological models. Taking the headwater of Baiyang Lake, China as an example, this study employed a spectral approach to illustrate how catchment water storage was influenced by rainfall and vegetation, and how water storage modulated streamflow for the period of 1982 - 2015. The competence of the spectral approach in characterizing causality was verified and a more holistic understanding of hydrological cycles was gained. Results showed that under different climatic phases (wet/dry), catchment water storage dynamics were controlled by different factors and dominant streamflow generation mechanisms were not invariant. In the wet phase, catchment water storage dynamics was determined by rainfall. And groundwater flow was the most important part of streamflow, followed by subsurface flow and surface flow. Nevertheless, in the dry phase, catchment water storage dynamics was modulated by evapotranspiration. And the surface flow was the most important part of streamflow, followed by subsurface flow and groundwater flow. The land use change induced by human activities could alter the streamflow sensitivity to rainfall, but could not cause fundamental changes to hydrological cycles. We concluded that the spectral approach can be an effective supplement to the experimental methods and their integration can provide systematic insights into hydrological cycles in the study area and other watershed systems.

Short summary. The hydrological processes of a watershed system are affected by both natural conditions, such as rainfall and drought, and human activities, such as deforestation and afforestation. Therefore different hydrological responses to climatic and anthropogenic changes are expected. Using a spectral approach, this study confirmed that the driving factors of water storage and streamflow generation mechanism vary over time. This is important for water resources management under changing world.

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1 Introduction

Water storage in a catchment plays a critical role in runoff generation. Tracer-based observations showed that ~60% of the global surface water consists of "old water", which means most rainfall propagates along deeper subsurface pathways and then discharges into streamflow (Good et al., 2015). Understanding water storage dynamics is important for gaining deep insights into the water cycle. However, water storage dynamics is complex and scale-dependent, and it is influenced by storm properties, topography, soil properties, vegetation coverages, and human activities. How these different drivers exert various degrees of control on the water storage and how streamflow responds to the change in water storage remain poorly understood (Singh et al., 2021).

Nested field hydrometric observations coupled with emerging environmental tracers and geophysical techniques can reveal water storage dynamics and streamflow responses in a catchment. For instance, in a humid and subtropic catchment in Georgia, USA, after monitoring soil-bedrock interaction on a 2 by 2 m grid on a hillslope, Tromp-van Meerveld and McDonnell (2006) proposed the "fill-and-spill" hypothesis of the subsurface stormflow generation. Through monitoring soil moisture, groundwater levels, and water isotopes along three hydropedological units in a Scotland peatland catchment with cold and wet hydroclimatic conditions, Tetzlaff et al. (2014) found that the low-lying areas of riparian zones generated up to 65% of annual discharge and damped the isotopic composition of stream water through the water stored here for > 2 years. Also by monitoring soil moisture at 45 locations on three hillslopes in a humid temperate catchment in Northwest Carolina, USA, the lag correlations between soil moisture and runoff were quantified and results showed that correlations were similar among hillslopes with average lags varying from 0.5 h to -0.5 h (Singh et al., 2021). Using a ground penetrating radar grid integrated with high-frequency subsurface moisture monitoring, Guo et al. (2019) found that subsurface flow networks were important for runoff generation in Susquehanna Shale Hills Critical Zone Observatory in Pennsylvania, USA, with stormwater transporting downslope from planar and convex hillslopes to concave hillslopes. While detailed water storage dynamics and streamflow responses in specific catchments can be illustrated by experimental methods, the highly variable results make it difficult to provide holistic knowledge due to the limited spatial coverage and temporal duration induced by high maintenance costs (Zhang and Wei, 2021).

Numerical models often employ the "leaky bucket" as a conceptual representation of catchment water storage. However, the simplified description has been proved unrealistic. First, in bucket models, when conceptual buckets approach emptiness, the simulated evapotranspiration approaches zero (Fowler et al., 2021). In reality, many plants continue transpiration during extended dry periods because plants modulate their water use strategies in pre-drought, severe drought and rewetting periods (Tague and Moritz, 2019; Dralle et al., 2020; Werner et al., 2021). In addition, numerical models cannot accumulate the long, slow drying up, because "buckets" are already "empty" on a seasonal basis (Fowler et al., 2020). Second, usually a single (average) storage is filled and spilled in bucket models. In reality, there are multiple storages in a catchment and the spilled water from one storage is used to fill another storage, resulting in a cascading type of flow path (McDonnell et al., 2021).

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With the aforementioned limitations, numerical models may lead to an inaccurate understanding of water storage dynamics and streamflow responses (Romano et al., 2011).

It has long been recognized that streamflow is related to rainfall with significant multi-annual periodicities (Labat, 2010; Fischer et al., 2013; Kuss and Gurdak, 2014; Nalley et al., 2016). The magnitude and legacy effects of periodicities in streamflow demonstrate how periodic rainfall signals are damped and lagged by mixing processes of different hydrological pathways (Rust et al., 2019). Generally, surface hydrological pathways have the shortest response time in the order of hours to days and minimal damping, while groundwater hydrological pathways have the longest response time in the order of years to decades and maximum damping (Rust et al., 2021). Subsurface hydrological pathways are in the middle. Often, spectral analysis is used to identify the connections between large-scale ocean-atmosphere systems and hydrological variability (McGregor, 2017). However, the lack of water storage data greatly weakens its capability to understand water propagation processes in the soil-vegetation-atmosphere system under the influence of climate change and human activity. Moreover, there are multiple periodicities in hydroclimatic time series at different time scales, which are caused by different internal processes, external forcings, and their interactions (von der Heydt et al., 2021). Therefore, it is critical to determine the important periodicities that affect the trends in time series according to the purposes of studies (Wu et al., 2007).

This paper aims at filling such a knowledge gap as identified by employing the wavelet analysis for a case study in the headwater of Baiyang Lake, China. The specific objectives include:

i) detect the key periodicity affecting trend and identify periodic characteristics in rainfall, streamflow, catchment water storage and actual evapotranspiration;

ii) investigate the influence of land-use change on catchment water storage dynamics and streamflow responses; and

iii) use the hysteresis effects to determine the streamflow generation mechanisms with different dominant hydrological pathways in the study area.

2 Methods, Study Area, and Data

2.1 Methods

In this paper, Continuous Wavelet Transform (CWT) and Cross-Correlation Analysis (CCA) were employed to detect periodicities and legacy effects in the time series of the hydrological data as described below.

The wavelet transform acts as a time and frequency localization operator and has emerged as one of the most promising function transformation methods (Pathak, 2009). The advantage of wavelet transform is that it can reflect the evolution over time of non-stationary time series. Here the CWT analysis was used to generate varying coefficients that signify the similarity between the signal and mother wavelets at any specific scale base. The CWT of a function *f* with respect to the mother wavelet Ψ is defined by:

$$W_f(a,b) = \frac{1}{\sqrt{|a|}} \int f(t)\Psi\left(\frac{t-b}{a}\right)dt$$,

where $W_f(a,b)$ is the wavelet coefficient, a is the wavelet scale associated with dilation and contraction of a wavelet, and b is a time index describing the location of the wavelet in time.

The CCA is regarded as a standardized method for estimating the time delay between the leading and lagging signals based on convolution operation (Choudhury, 2017). The correlation coefficient shows how well the two signals are correlated, and it varies from -1 to 1.

All the time series data were first standardized by subtracting the mean and dividing the standard deviation before analysis.

It is noteworthy that this study more concerned about the characteristics of hydrological signals and their correlations in a key periodicity, instead of detecting the presence of all periodicities in different variables. This could demonstrate the causal links among hydrological variables because streamflow is the combination of surface flow, subsurface flow, and groundwater flow, which have different responses to rainfall signal. The discrepancies can be feasibly reflected in the form of waves with different amplitudes, frequencies, and phases. The usage can be applied in any watershed system across the world.

2.2 Site description of a case study

Baiyang Lake is the largest freshwater lake in North China Plain (Figure 1) and plays an important role in providing ecosystem services in this highly populated region (Zhuang et al., 2011). Due to prolonged droughts and intensive human disturbances since the 1980s, however, the amount of water that flows into the lake from upstream rivers has decreased significantly. This has resulted in a continuous shrinkage of the water body and ecological degradation in the lake region (Han et al., 2020). Although efforts are being made to pinpoint the driving factors of the hydrological changes, the role of catchment water storage in this change is so far not well studied (Zhuang et al., 2011; Hu et al., 2012).

The headwater of Baiyang Lake lies in Taihang Mountain in northern China. The climate is semi-arid with continental monsoons, i.e., hot humid summers, and cold dry winters. The average annual temperature, precipitation, and potential evapotranspiration in the headwater region are 7-12 °C, 556 mm, and 1369 mm respectively (Zeng et al., 2021). The main geologic characteristics of Taihang Mountain are "soil and rock dual-texture", with thin topsoil and thick weathered granite gneiss subsoil (Cao et al., 2022). The topsoil is about 0.2-0.5 m thick and rich in plant roots and gravel. The subsoil is about 0.5-10 m thick with highly developed fractures.

Insert Figure 1 here

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2.3 Data compilation and processing

Monthly streamflow, rainfall, and actual evapotranspiration data spanning the years 1982-2015 were compiled for the four catchments as shown in Figure 1.

Streamflow data (Q) from four hydrological stations — Fuping (FP), Daomaguan (DMG), Zijingguan (ZJG), and Zhangfang (ZF) — were acquired from the Department of Water Resources of Hebei Province. FP station is located in the Sha River catchment with a controlling area of 2,160 km2. DMG station is located in the Tang River catchment with a controlling area of 2,704 km2. ZJG and ZF are the upstream and downstream stations of the Juma River with controlling areas of 1,751 and 4,737 km2, respectively. The unit of streamflow data was 108 m3.

Rainfall data (P) from 5 national climate stations — Fuping, Lingqiu, Laiyuan, Zijingguan, and Xiayunling — were downloaded from the China Meteorological Data Sharing Service System (http://data.cma.cn/). Due to the sparsity of the stations, rainfall of Fuping station was used to represent the rainfall of FP catchment, and rainfall of Lingqiu station was used to represent the rainfall of DMG catchment. Averaged rainfall of Laiyuan and Zijinguan stations was used for rainfall of ZJG catchment, while averaged rainfall of Laiyuan, Zijingguan and Xiayunling stations was used for rainfall of ZF catchment. The rainfall data from 1960 to 2015 was used to help detect climatic periodicities. The unit of rainfall data was in mm then converted to the volume in 108 m3 by multiplying by the area of catchments.

Catchment actual evapotranspiration (ET) was the average of gridded remote-sensing based ET data, which consisted of two datasets. ET for 1984-2015 was provided by ETWatch website (Haihe Basin ET Dataset, www.etwatch.cn). ETWatch model estimated ET using the Penman-Monteith model integrated with SEBAL and SEBS models (Wu et al., 2008; Wu et al., 2021). Studies showed that ETWatch-estimated ET was quite reliable in Haihe Basin where the study area lies (Moiwo et al., 2011; Wu et al., 2012). The spatial resolutions of ETWatch-based ET were 8 km for the period 1984-1989 and 1 km for the period 1990-2015. ET for 1982-1983 was downloaded from NTSG website (Numerical Terra-dynamic Simulation Group, www.ntsg.umt.edu). NTSG-estimated ET is also a Penman-Monteith-model based dataset with a spatial resolution of 8 km (Zhang et al., 2009, 2010). The NTSG-based ET was comparable with ETWatch-based ET. The unit of ET data was in mm then converted to the volume in 108 m3 by multiplying by the area of catchments.

Catchment water storage (WS) was calculated based on the water balance method with rainfall subtracting streamflow and actual evapotranspiration (WS = P - Q - ET). Here WS represented the mixture of "old water" and "young water" in the whole catchment. For comparison, surface soil moisture (SM) data from ESA CCI (European Space Agency Climate Change Initiative) with spatial resolution of 0.25° was downloaded from its website (www.esa-soilmoisture-cci.org/). This dataset had a high outperformance among satellite-based products (Ma et al., 2019). The units of the WS and SM data were in 108 m3 and m3/m3 respectively.

Land use data for Haihe Basin for the 1980s, 1990s, 2000s, and 2010s were also obtained at ETWatch website (Haihe Basin Landuse, www.etwatch.cn). The spatial resolution of land use data is 30 m.

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3 Results

Here DMG catchment is taken as a representative headwater catchment of Baiyang Lake to show the dynamics of hydrological variables and their relationships. This is because (1) the hydroclimatic characteristics of DMG catchment are typical in the study area, with a significant decrease in annual streamflow and insignificant decrease in annual rainfall and ET in 1982–2015 (Figure 2a); (2) water storage in DMG catchment fluctuates around zero with varying amplitudes and frequencies over time. The negative storages occur in the periods 1982–1986, 1991–1993, and 1997–2001, while the positive ones occur in 1987–1990, 1994–1996, and 2002–2015 (Figure 2a).

3.1 Key periodicity

DMG catchment shows a high wavelet power spectrum (Kirby, 2005) in rainfall periodicities of approximately 7, 15, 25, 30, and 35 years (Figure 2b). Among the periodicities, the multi-decadal periodicities are more of a concern due to the long-term decrease in streamflow. A scale parameter of 8 is used in this study because the wavelet power spectrum of multi-decadal periodicities is the highest for that scale parameter.

Insert Figure 2 here

Figure 3a shows that annual rainfall in DMG catchment regularly fluctuates before the year 2000, while the regularity is broken after the year 2000 with weaker amplitudes and lower frequencies. According to the phenomenon and our record length, two climatic phases — wet phase and dry phase — are defined. The wet phase starts in 1984 with the lowest wavelet coefficient of rainfall, and ends in 2000 with the second lowest coefficient. The dry phase is from 2001 to 2015. Hereafter the greater than 30-years climatic periodicity with ~16 years of wet and dry phase is of a particularly concern.

For the headwater of Baiyang Lake, previous studies using the Mann-Kendell test showed that an abrupt change in streamflow occurred in 1998, which is very close to 2000 (Cui et al., 2019; Xu et al., 2019). This further confirms the reliability of choosing 2000 as the dividing time for the wet and dry phases.

3.2 Annual basis

3.2.1 Signals comparison

As mentioned above, in the over 30-years periodicity, the rainfall signal shows weaker amplitude and lower frequency from wet phase to dry phase. Nevertheless, the ET signal is not synchronous with rainfall signal. The ET signal keeps enhancing when the rainfall signal starts weakening, resulting in the greatest amplitude of ET signal lagging behind that of rainfall signal (Figure 3a). The correlation coefficients between ET and rainfall are negative in the whole study period (insignificant) and the wet phase (significant). While in the dry phase, there is no correlation between the two signals (Figure 3b). Due to the asynchronization of the two factors, catchment water storage and streamflow show different characteristics of periodicity. Catchment water storage signal has similar amplitude and frequency with rainfall signal in the wet phase. The similarity, however, disappears in the dry phase. Correspondingly, their correlation coefficients are significantly positive in the whole

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study period and wet phase, while insignificant positive in the dry phase. ET signal is not synchronous with water storage signal. Their correlation coefficients are significantly negative in all the three periods, with the largest negative coefficient occurring in the dry phase. It is also noteworthy that the satellite-based surface soil moisture signal has a significant negative correlation with ET signal (R=-0.56, p<0.01) while an insignificant positive correlation with water storage signal (R=0.27, p=0.12).

Streamflow signal is roughly synchronous with rainfall signal, with similar amplitude and frequency. Meanwhile the significant positive correlations between streamflow and rainfall signals are observed in the whole study period, the wet phase and the dry phase. On the contrary, streamflow signal is negatively correlated to ET signal, with significant negative correlation in the wet phase.

Insert Figure 3 here

3.2.2 Hysteresis effects

The hysteresis effects between rainfall and water storage signals, ET and water storage signals, water storage and streamflow signals are shown in Figure 4 to demonstrate how the catchment water storage is affected by rainfall and ET, and how catchment water storage modulates streamflow. In the whole study period, there are no hysteresis effects between rainfall and water storage signals, and ET signal lags behind water storage signal by 4 years. Streamflow signal lags behind water storage signal by 1 year in the whole study period, and similarly it lags behind rainfall signal by 1 year. All the coefficients are positive.

In the wet phase, there are no hysteresis effects between rainfall and water storage signals, and ET and water storage signals. Streamflow signal lags behind water storage signal by 1 year in the wet phase, indicating that streamflow signal lags behind rainfall signal by 1 year as well. Water storage signal is positively correlated to rainfall and streamflow signals, but negatively correlated to ET signal.

In the dry phases, there are no hysteresis effects between ET and water storage signals. Water storage signal lags behind rainfall and streamflow signals by 3 years, suggesting that there are no hysteresis effects between rainfall and streamflow signals in the dry phase. All the coefficients are negative. These hysteresis effects will be interpreted in detail in section 3.4.

Insert Figure 4 here

3.3 Seasonal basis

Figure 5a shows that the four hydrological variables have different seasonal changes in the wet and dry phases. For rainfall, there is an obvious peak in July in the wet phase while the peak has flattened in the dry phase. For ET, the trough in April in the wet phase does not recur in the dry phase, while the two peaks in July and September in the wet phase have changed to May and July in the dry phase. As a consequence, water storage in April has changed from positive in the wet phase to negative in the dry phase. The lowest water storage occurs earlier (in May) in the dry phase. This is one month earlier than that in the wet phase. Compared with the unimodal pattern and two-month positive value in the wet phase, water storage has remained positive throughout the period from June to November and shows a bimodal distribution in the dry phase. Correspondingly, the peak of streamflow that occurs in August in the wet phase comes earlier by one month to July than in the dry phase. Meanwhile, the recession processes of streamflow become much slower in the dry phase, resulting in a "fat tail" effect.

Figure 5b shows that all the hydrological variables are positively correlated to each other on a seasonal basis. ET, streamflow and water storage are significantly correlated to rainfall for the whole study period, the wet phase, and the dry phase, suggesting that seasonal change in rainfall determines the change of other variables. Overall, the correlations among the hydrological variables are weaker in the dry phase than the counterparts in the wet phase and the whole study period.

Insert Figure 5 here

3.4 Results interpretation- Streamflow generation mechanisms

Streamflow generation mechanisms of DMG catchment are explored based on the corresponding relationships between dominant hydrological pathways and hysteresis time (streamflow vs. rainfall). According to previous studies (Rust et al., 2021), the relationships are defined as: surface hydrological pathways correspond to time delays in the order of days, subsurface hydrological pathways correspond to time delays in the order of months, and groundwater hydrological pathways correspond to time delays in the order of years.

Annual basis: In the wet phase, rainfall and ET modulate water storage simultaneously, with positive influence from rainfall and negative influence from ET. The influence of rainfall on water storage outweighs that of ET due to the higher coefficients between rainfall and water storage. Meanwhile, streamflow lags behind water storage and rainfall by 1 year, suggesting that groundwater flow largely contributes to streamflow in the wet phase.

In the dry phase, the concurrent change and high coefficients between ET and water storage indicate that ET determines water storage dynamics. The negative correlations suggests that soil water is depleted when vegetation cover is high, and it is replenished when vegetation cover is low. Meanwhile, there is no hysteresis effect between rainfall and streamflow signals in the dry phase, suggesting that surface flow or subsurface flow is dominant in streamflow. Seasonal analysis will help further weighing up the two flows.

Seasonal basis: In the wet phase, rainfall, ET and water storage all hit their peak in July. Streamflow, however, peaks in August, lagging one month behind other variables. It suggests that subsurface flow also contributes to streamflow in the wet phase.

In the dry phase, rainfall and streamflow hit their peaks in July concurrently, suggesting that surface flow is the most important streamflow generation mechanism in the dry phase. Meanwhile, the longer span of positive water storage is possibly related to the slow recession of streamflow. Thus, subsurface flow also contributes to streamflow in the dry phase.

According to the analysis, two noteworthy conclusions are made. Firstly, the streamflow generation mechanism is varying over time in the study area.

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In the wet phase, groundwater flow is the most important, followed by subsurface flow and surface flow. It is because there is enough rainfall in the wet phase, to replenish water storage, which promotes vegetation growth. The growth of vegetation cannot exhaust water storage in the humid environment, instead, it enhances water infiltration due to more roots and soil animals' activities. When more water infiltrates into the soil, most of it moves vertically, recharging groundwater and flowing out years later. The rest water laterally propagates and contributes to streamflow several months later.

While in the dry phase, surface flow is the most important, followed by the subsurface flow and groundwater flow. It is because in the dry phase, the decline in water storage makes the soil more hydrophobic. In addition, drought-induced vegetation death reduces plant roots and soil animals' activities. These two factors drive most of the rainfall flows along surface hydrological pathways and force it to become streamflow very soon. The rest of the rain water infiltrates into the soil, with part of it depleted by vegetation and another part flowing laterally as subsurface flow. Groundwater is hardly replenished and thus contributes very little to streamflow.

Secondly, water storage, replenished by rainfall and depleted by vegetation, can largely modulate the sensitivity (amplitude) of streamflow to rainfall. Generally, more water storage results in lower sensitivity while less water storage leads to higher sensitivity. The influence of other factors on streamflow sensitivity, e.g., canopy interception, and water detainment of forest floor, would be much less. A sketch is given in Figure 6 to illustrate the interpretation.

Insert Figure 6 here

4 The influence of land-use change

Here the same wet and dry phases in DMG catchment are also used in the other three catchments of study area due to the highly similar periodicities of rainfall. Therefore, it is the variation in ET that leads to the difference in water storage dynamics and streamflow responses.

4.1 Differences in four catchments

Figure 7 shows annual variations in wavelet coefficients of rainfall, streamflow, ET, water storage and surface soil moisture in the four catchments. For FP catchment, ET for the period 1986–1987 is the lowest and therefore results in the highest water storage across all four catchments. Because of this, streamflow is less sensitive to rainfall in the catchment. In contrast, ET for 1995–1996 is the highest and therefore results in the lowest water storage across the four catchments. Also because of this, streamflow is highly sensitive to rainfall. It then suggests that streamflow does not respond to the increase in rainfall around 2003 because of the high water storage.

ZJG and ZF catchments have similar hydrological changes because ZJG is the upper reach of ZF catchment. Unlike FP and DMG catchments, ET does not show an obvious decrease in the 1980s, but it decreases in the 1990s in these two catchments. Nevertheless, water storage is not apparently influenced by ET because it is more related to rainfall in the wet phase. However, the sensitivity of streamflow to rainfall is strongly affected by both water storage and ET. The sensitivity of

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streamflow to rainfall in ~1986–1987 decreases due to the high water storage and ET, but increases in ~1995–1996 due to the low water storage and ET. After 2000, the changes in ET in ZJG and ZF catchments are similar to those in the other two catchments. It is also worth noting that in spite of the dry phase, water storage dynamics in ZJG and ZF catchments have been influenced by rainfall rather than ET in the 2010s.

Insert Figure 7 here

In combination with correlation analysis, it is found that compared to FP and DMG catchments, the influence of ET on water storage and streamflow is weaker in ZJG and ZF catchments (Figure 8). FP catchment is similar to DMG catchment, with all variables significantly correlated with each other in the wet phase. While streamflow significantly and positively correlates to rainfall and water storage significantly and negatively correlates to ET in the dry phase. For ZJG and ZF catchments, water storage and streamflow significantly correlate to rainfall, but insignificantly correlate to ET in the wet phase. In the dry phase, although the correlation between ET and water storage becomes significant, the correlation between rainfall and water storage is even stronger.

Insert Figure 8 here

Figure 9 shows that the four catchments have similar seasonal variations in both the wet and dry phases, and the similarities outweigh the differences. For instance, the sharp rainfall curves in the wet phase have flattened in the dry phase. ET peak occurs in June in the wet phase and it delays by one month in the dry phase. Streamflow peaks in August in the wet phase but it hits the peak in July in the dry phase. The rapid recession of streamflow in the wet phase becomes slower in the dry phase. Water storage remains positive for a longer duration in the dry phase.

Insert Figure 9 here

4.2 Vegetation succession

Figure 10 shows the vegetation succession in the four catchments for the study period. Here it is assumed that the former two periods — the 1980s and 1990s — correspond to the wet phase, and the latter two periods — the 2000s and 2010s — correspond to the dry phase.

For FP catchment, the arable land is marginal and changes little over time. Natural vegetation is dominant and changes vastly over time. The composition of natural vegetation is stable in the wet phase. The high-coverage vegetation dies, replaced with the low-coverage vegetation such as open woodland and grassland in the 2000s. Finally, shrub land occupies some space of the open woodland in the 2010s. The vegetation succession can explain the dramatic decrease in annual ET in ~2004–2005. Seasonal change in ET can also be explained by phenological change because low-coverage vegetation may have an earlier onset and maturity time than high-coverage vegetation.

For DMG catchment, the succession of natural vegetation is similar to that in FP catchment. However, arable land accounts for 20–25% of the total area, resulting in a smaller proportion of natural vegetation. This might be the reason for the smaller amplitude fluctuations in ET in ~1986–1987 compared with FP catchment.

For ZJG and ZF catchments, the vegetation change is not as dramatic as that in FP and DMG catchments in the study period. The decrease of low-coverage open woodland and the increase of high-coverage vegetation in the 1990s can explain the high ET at the end of the 1980s. Then the low-coverage vegetation increases while the high-coverage vegetation decreases again in the 2010s.

Insert Figure 10 here

4.3 Rethinking the role of human activities

Previous studies showed that in the study area, human activities (e.g., afforestation, deforestation, agriculture intensification) should in large part be responsible for the decrease of streamflow (Ma et al., 2010; Wang et al., 2012; Lei et al., 2014). Nevertheless, this study forces us to rethink the role of human activities. In ZJG and ZF catchments, vegetation coverage has increased in the end of 1980s, which could be attributed to the "Taihang Mountain Afforestation Project" launched in 1984 (CNKI, 1995). Although the increase of vegetation coverage does affect the magnitude of fluctuations in water storage and streamflow, it doesn't alter the fact that the water storage dynamics and streamflow are mainly controlled by rainfall in the wet phase. On the contrary, the vegetation coverage change is less affected by human activities in the dry phase. However, the stronger correlation between vegetation and water storage dynamics has been observed. In other words, in the wet phase, people has largely altered the land use but these changes could not lead to essential changes on surrounding environment. In the dry phase, however, people have tried to conserve the environment but the efforts seem to have limited impacts.

It reminds us that hydrological resilience (the ability to recover from anthropogenic disturbances) is variable along a long-term rainfall variability, with higher resilience in the wet phase and lower resilience in the dry phase. It is a hot topic in recent years (Helman et al., 2017; Ahlström et al., 2017; Yi and Jackson, 2021; Smith et al., 2022). But the mechanisms related to the resilience variability are still not fully understood. Here we consider that the mechanism is probably related to the influence of vegetation roots on water storage. In the wet phase, higher vegetation coverage means more and deeper roots which can retain more water in the soil and help increase hydrological resilience (Ciemer et al., 2019). On the contrary, in the dry phase, lower vegetation coverage means fewer and shallower roots. Less soil water is likely related to lower hydrological resilience. It is also interesting to note that there is a transition phase when the climate shifts from the wet phase to the dry phase. In the transition phase, rainfall is weakening but ET is enhanced. This is probably caused by the hysteresis effects of root morphological traits. The plant can "remember" its former climatic conditions for a while, thus affecting root traits of the next generation of plant individuals (Lozano et al., 2021). As a result, these plants decide that rainfall will increase soon and would have increased root density, diameter, and length in advance even in drought conditions (Staal et al., 2020). Therefore, although human activities can alter surface vegetation coverage, the underground roots could not be changed.

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5 Discussion

5.1 Coordination of disputes

There are still intense debates on the dominant streamflow component of Taihang Mountain. Some suggested that surface streamflow was dominant. Yu et al. (2009) conducted 13 simulated rainfall experiments on a 5 m × 10 m plot in Dongtaigou catchment in Taihang Mountain and concluded that surface flow accounted for over 60% of total streamflow. In studying the effect of grassland on streamflow at Daxing experimental base in the Beijing area, Zhao et al. (2014) prepared 3 soil bins (200 cm × 50 cm × 50 cm) filled with silty loam soil and planted ryegrass with different row spacings in the artificial rainfall experiments. Their results showed that the overland flow was the dominant runoff component for the high-intensity rainfall events, but the interflow predominantly occurred under continuous rainfall events. Yet other studies showed that vertical infiltration was strong in this region. Han et al. (2012) collected the surface and subsurface (10 and 20 cm) flow in four plots with varying slope lengths in Shimen catchment in Taihang Mountain for the period 2006–2008. Results showed that surface flow was generally higher than subsurface flow. However, both surface and subsurface flow rapidly decreased along with the increase of slope lengths, suggesting strong infiltration loss through vertical percolation. In combination with a constant water head, Cao et al. (2022) designed a permeameter device (2 m × 1 m × 3 m) filled with rocks and soil to analyze the infiltration process in Taihang Mountain Ecological Experimental Station. Results showed that lateral flow mainly occurred at the soil-rock interface with a permeability coefficient of 1.26 × 10-3 cm/s. Song et al. (2007) analyzed the changes in rainfall, streamflow, soil moisture, groundwater, and their isotopic compositions in Niujiazhuang and Shimen catchments of Taihang Mountain for the period 2003–2004. Results showed that the amount of lateral recharge from the mountainous area to the adjacent piedmont was 1.53 × 106 m3/year. These highly varying results from the different locations, scales, and methods failed to clarify the issue, instead, they added more confusion to streamflow generation mechanisms.

Using the spectral approach, many questions can be clearly answered. For instance, "what is the dominant streamflow generation mechanism in Taihang Mountain?", and "does the forest conserve or deplete water?" The results from this study showed that the answer is not constant but variable over time. The groundwater hydrological pathways are dominant in the wet phase and surface hydrological pathways are dominant in the dry phase. Similarly, the forest plays a role in conserving water in the wet phase while depleting water in the dry phase. Nevertheless, as a top-down approach, the detailed process of water movements cannot be demonstrated by spectral approach. Field hydrometric experiment is bottom-up approach which can effectively supplement the deficiency. Their combination can be more insightful in studying streamflow generation mechanisms in Taihang Mountain and other regions and be helpful for model development.

5.2 Future prediction

By using trend analysis techniques, e.g., Mann-Kendall, Least Square, a long-term decreasing trend in streamflow was detected in the study area (Zhuang et al., 2011; Hu et al., 2012). Here the "trend" is usually a straight line fitted with the data by a monotonic function, which implies that the tendency will extend into the future (Wu et al., 2007). Such a trend may suit well in a linear and stationary system, but is inappropriate in a nonlinear and nonstationary real world. As stated by Stock and Watson (1988): "one economist's 'trend' can be another's 'cycle'". Thus, the trend should exist within a given data span. The spectral approach can overcome the drawback and clearly separate "trend" from "cycle" by introducing local time scales. For the study area, the interdecadal climatic change was probably caused by the shifting of the PDO (Pacific Decadal Oscillation) phase from the positive mode to the negative one in the late 1990s (Zhu et al., 2015). Until 2021, the PDO phase was still negative (www.ncdc.noaa.gov/teleconnections/pdo/), suggesting the drought will be continuous over East China in the future. Usually a PDO phase may last for about 2-3 decades or more (Nalley et al., 2016). Therefore, it can be predicted that catchment water storage dynamics is still controlled by vegetation change and surface flow is still the dominant streamflow generation component in the study area.

6 Conclusions

The case study in the headwater of Baiyang Lake, China indicated that the spectral approach was a useful tool for analyzing the catchment water storage (P-ET-Q) dynamics and streamflow responses at seasonal and annual scales. A greater-than-30-years periodicity was particularly concerned corresponding to a long-term decreasing trend in streamflow.

Results showed that the periodicity had two climatic phases — the wet phase and the dry phase. The periodic characteristics of four hydrological variables, e.g., water storage, streamflow, rainfall, and ET, were different in the two phases. In the wet phase, seasonal variations in water storage and streamflow were sharp and the annual variations of them were driven by rainfall. In the dry phase, seasonal variations in water storage and streamflow flatten out and the annual change in water storage was controlled by ET.

The analysis of hysteresis effects clearly showed that groundwater hydrological pathways were dominant in the wet phase because streamflow lags 1 year behind rainfall. Then surface hydrological pathways were dominant in the dry phase due to the concurrent change between streamflow and rainfall.

The sensitivity (amplitude) of streamflow to rainfall in both the wet and dry phases was determined by catchment water storage, indicating impacts of land use changes.

Therefore, it can be concluded that the spectral approach can be taken as an effective supplement to the experimental methods and the integration of the two methods can increase the synergy for deeper insights into streamflow generation mechanisms in Taihang Mountain and other regions with similar climate conditions.

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Data Availability

The gridded data are available in the main text and the catchment-scale data can be obtained by contacting Xinyao Zhou (zhouxy@sjziam.ac.cn) and Yonghui Yang (yonghui.yang@sjziam.ac.cn).

Author contributions

Xinyao Zhou: Conceptualization, Methodology, Visualization, Writing- Original draft preparation. **Zhuping Sheng:** Supervision, Writing- Review & Editing. **Yanming Yang and Shumin Han:** Project administration. **Qingzhou Zhang and Huilong Li:** Resources. **Yonghui Yang:** Funding acquisition.

Competing interests

The authors declare that they have no conflict of interest.

References

Ahlström, A., Canadell, J.G., Schurgers, G., Wu, M., Berry, J.A., Guan, K., and Jackson, R.B., 2017. Hydrologic resilience and Amazon productivity. Nature Communications, 8, 387.

Cao, J., Yang, H., and Zhao, Y., 2022. Experimental analysis of infiltration process and hydraulic properties in soil and rock profile in the Taihang Mountain, North China. Water Supply, 22(2), 1691-1703.

Ciemer, C., Boers, N., Hirota, M., Kurths, J., Muller-Hansen, F., Oliveira, R.S., and Winkelmann, R., 2019. Higher resilience to climatic disturbances in tropical vegetation exposed to more variable rainfall. Nature Geoscience, 12, 174-179.

Choudhury, D., 2017. Teaching the concept of convolution and correlation using Fourier transform. Proceeding of SPIE 10452, 14th Conference on Education and Training in Optics and Photonics, ETOP 2017, Hangzhou, China.

CNKI, 1995. Afforestation Project on Mount Taihang. China's Foreign Trade, 09: 18. doi: CNKI:SUN:ZDWY.0.1995-09-008

Cui, H., Xiao, W., Zhou, Y., et al., 2019. Runoff responses to climate change and human activities in the upper Daqing River Basin. South-to-North Water Transfers and Water Science & Technology, 17(4), 54-62. (in Chinese)

Dralle, D.N., Hahm, W.J., Rempe, D.M., et al., 2020. Plant as sensors: vegetation response to rainfall predicts root-zone water storage capacity in Mediterranean-type climates. Environmental Research Letters, 15, 104074.

Hydrology and Earth System Sciences
Open Access
Discussions

Fischer, T., Gemmer, M., Su, B., and Scholten, T., 2013. Hydrological long-term dry and wet periods in the Xijiang River basin, South China. Hydrology and Earth System Sciences, 17, 135-148.

Fowler, K., Knoben, W., Peel, M., et al., 2020. Many commonly used rainfall-runoff models lack long, slow dynamics: Implications for runoff projections. Water Resources Research, 56, e2019WR025286.

Fowler, K.J.A., Coxon, G., Freer, J.E., et al., 2021. Towards more realistic runoff projections by removing limits on simulated soil moisture deficit. Journal of Hydrology, 600, 126505.

Good, S.P., Noone, D., and Bowen, G., 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science, 349(6244), 175-177.

Guo, L., Lin, H., Fan, B., Nyquist, J., Toran, L., Mount, G.J., 2019. Preferential flow through shallow fractured bedrock and a 3D fill-and-spill model of hillslope subsurface hydrology. Journal of Hydrology, 576, 430-442.

Han, Q., Tong, R., Sun, W., et al., 2020. Anthropogenic influences on the water quality of the Baiyangdian Lake in North China over the last decade. Science of the Total Environment, 701, 134929.

Han, S., Yang, Y., Fan, T., et al., 2012. Precipitation-runoff processes in Shimen hillslope micro-catchment of Taihang Mountain, north China. Hydrological Processes, 26, 1332-1341.

Helman, D., Lensky, I.M., Yakir, D., and Osem, Y., 2017. Forests growing under dry conditions have higher hydrological resilience to drough than do more humid forests. Global Change Biology, 23, 2801-2817.

Hu, S., Liu, C., Zheng, H., et al., 2012. Assessing the impacts of climate variability and human activities on streamflow in the water source area of Baiyangdian Lake. Journal of Geographical Sciences, 22(5), 895-905.

Kirby, J.F., 2005. Which wavelet best reproduces the Fourier power spectrum? Computers & Geosciences, 31, 846-864.

Kuss, A.M., and Gurdak, J.J., 2014. Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO. Journal of Hydrology, 519, 1939-1952.

Labat, D., 2010. Wavelet analyses of annual continental freshwater discharge and selected climate indices. Journal of Hydrology, 385, 269-278.

Lei, H., Yang, D., and Huang, M., 2014. Impacts of climate change and vegetation dynamics on runoff in the mountainous region of the Haihe River basin in the past five decades. Journal of Hydrology, 511, 786-799.

Lozano, Y.M., Aguilar-Trigueros, C.A., Roy, J., and Rillig, M.C., 2021. Drought induces shifts in soil fungal communities that can be linked to root traits across 24 plant species. New Phytologist, 232, 1917-1929.

Ma, H., Yang, D., Tan, S.K., Gao, B., and Hu, Q., 2010. Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. Journal of Hydrology, 389(3-4), 317-324.

Ma, H., Zeng, J., Chen, N., et al., 2019. Satellite surface soil moisture from SMAP, SMOS, AMSR2 and ESA CCI: A comprehensive assessment using global ground-based observations. Remote Sensing of Environment, 231, 111215.

McGregor, G., 2017. Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. Progress in Physical Geography, 41(4), 496-512.

https://doi.org/10.5194/hess-2022-357
Preprint. Discussion started: 10 November 2022

McDonnell, J.J., Spence, C., Karran, D.J., van Meerveld, H.J., and Harman, C.J., 2021. Fill-and Spill: A process description of runoff generation at the scale of the beholder. Water Resources Research, 57, e2020WR027514.

Moiwo, J.P., Yang, Y., Yan, N., and Wu, B., 2011. Comparison of evapotranspiration estimated by ETWatch with that derived from combined GRACE and measured precipitation data in Hai River Basin, North China. Hydrological Sciences Journal, 56(2), 249-267.

Nalley, D., Adamowski, J., Khalil, B., et al., 2016. Inter-annual to inter-decadal streamflow variability in Quebec and Ontario in relation to dominant large-scale climate indices. Journal of Hydrology, 536, 426-446.

Pathak, R.S., 2009. The wavelet transform. Atlantis Studies in Mathematics for Engineering and Science. Series Editor: Chui, C.K. Atlantis Press, Paris, France.

Romano, N., Palladino, M., and Chirico, G.B., 2011. Parameterization of a bucket model for soil-vegetation-atmosphere modeling under seasonal climatic regimes. Hydrology and Earth System Sciences, 15, 3877-3893.

Rust, W., Holman, I., Bloomfield, J., Cuthbert, M., and Corstanje, R., 2019. Understanding the potential of climate teleconnections to project future groundwater drought. Hydrology and Earth System Sciences, 23, 3233-3245.

Rust, W., Cuthbert, M., Bloomfield, J., et al., 2021. Exploring the role of hydrological pathways in modulating multi-annual climate teleconnection periodicities from UK rainfall to streamflow. Hydrology and Earth System Sciences, 25, 2223-2237.

Singh, N.K., Emanuel, R.E., McGlynn, B.L., and Miniat, C.F., 2021. Soil moisture responses to rainfall: Implications for runoff generation. Water Resources Research, 57, e2020WR028827.

Smith, T., Traxl, D., and Boers, N., 2022. Empirical evidence for recent global shifts in vegetation resilience. Nature Climate Change, 12, 477-484.

Song, X., Li, F., Liu, C., et al., 2007. Water cycle in Taihang Mt. and its recharge to groundwater in North China Plain. Journal of Natural Resources, 22(3), 398-408. (in Chinese)

Staal, A. Fetzer, I., Wang-Erlandsson, L., Bosmans, J.H.C., Dekker, S.C., van Nes, E.H., Rockstrom, J., and tuinenburg, O.A., 2020. Hysteresis of tropical forests in the 21st century. Nature Communications, 11, 4978.

Stock, J.H., and Watson, M.W., 1988. Variable trends in economic time series. Journal of Economic Perspectives, 2(3), 147-174.

Tetzlaff, D., Birkel, C., Dick, J., et al., 2014. Storage dynamics in hydropedological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions. Water Resources Research, 50, 969-985.

Tague, C.L., and Moritz, M.A., 2019. Plant accessible water storage capacity and tree-scale root interactions determine how forest density reductions alter forest water use and productivity. Frontiers in Forest and Global Change, 2, 36.

Tromp-van Meerveld, H.J., and McDonnell, J.J., 2006. Threshold relations in subsurface flow: 2. The fill and spill hypothesis. Water Resources Research, 42, W02411.

von der Heydt, A.S., Ashwin, P., Camp, C.D., Crucifix, M., Dijkstra, H.A., Ditlevsen, P., and Lenton, T.M., 2021. Quantification and interpretation of the climate variability record. Global and Planetary Change, 197, 103399.

Wang, W., Shao, Q., Yang, T.Peng, S., Xing, W., Sun, F., and Luo, Y., 2012. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydrological Processes, 27(8), 1158-1174.

Werner, C., Meredith, L.K., Ladd, S.N., et al., 2021. Ecosystem fluxes during drought and recovery in an experimental forest. Science, 374(6574), 1514-1518.

Wu, Z., Huang, N.E., Long, S.R., and Peng, C-K, 2007. On the trend, detrending, and variability of nonlinear and nonstationary time series. PNAS, 104(38), 14889-14894.

Wu, B., Xiong, J., and Yan, N., 2008. ETWatch for monitor regional evapotranspiration with remote sensing. Advances in Water Science, 19(5), 671-678.

Wu, B., Yan, N., Xiong, J., et al., 2012. Validation of ETWatch using field measurements at diverse landscapes: A case study in Hai Basin of China. Journal of Hydrology, 436-437, 67-80.

Wu, F., Wu, B., Zhu, W., et al., 2021. ETWatch cloud: APIs for regional actual evapotranspiration data generation. Environmental Modelling & Software, 145, 105174.

Xu, Q., Cheng, W., Sun, T., et al., 2019. The influence of climate factors on runoff of major rivers in upper reaches of Baiyangdian lake. Journal of Hebei Agricultural University, 42(2), 110-115. (in Chinese)

Yi, C. and Jackson, N., 2021. A review of measuring ecosystem resilience to disturbance. Environmental Research Letters, 16, 053008.

Yu, J., Yang, C., Liu, C., et al., 2009. Slope runoff study in situ using rainfall simulator in mountainous area of North China. Journal of Geographical Sciences, 19, 461-470.

Zeng, Y., Zhao Y., and Qi, Z., 2021. Evaluating the ecological state of Chinese Lake Baiyangdian (BYD) based on ecological network analysis. Ecological Indicators, 127, 107788.

Zhang, M., and Wei, X., 2021. Deforestation, forestation, and water supply. Science, 371(6533), 990-991.

Zhang, K., Kimball, J.S., Mu, Q., Jones, L.A., Goetz, S.J., Running, S.W., 2009. Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983 to 2005. Journal of Hydrology, 379, 92–110.

Zhang, K., Kimbal, J.S., Nemani, R.R., Running, S.W., 2010. A continuous satellite-derived global record of land surface evapotranspiration from 1983 to 2006. Water Resource Research, 46, W09522.

Zhao N., Yu, F., Li, C., et al., 2014. Investigation of rainfall-runoff processes and soil moisture dynamics in grassland plots under simulated rainfall conditions. Water, 6, 2671-2689.

Zhu, Y., Wang, H., Ma, J., et al., 2015. Contribution of the phase transition of Pacific Decadal Oscillation to the late 1990s' shift in East China summer rainfall. Journal of Geophysical Research: Atmospheres, 120, 8817-8827.

Zhuang, C., Ouyang, Z., Xu, W., et al., 2011. Impacts of human activities on the hydrology of Baiyangdian Lake, China. Environmental Earth Sciences, 62, 1343-1350.

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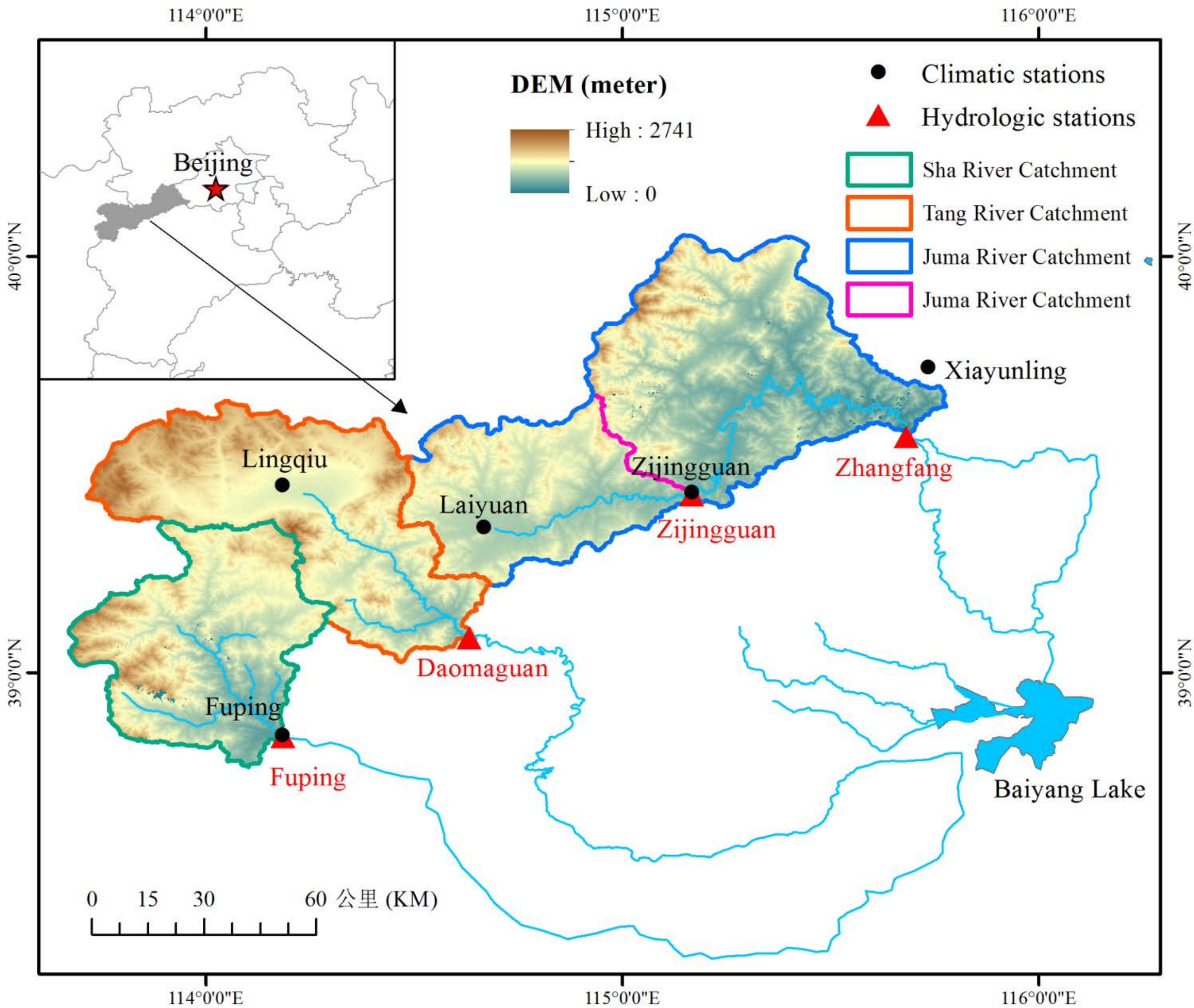

Figure 1: Study area, Baiyang Lake and its headwaters.

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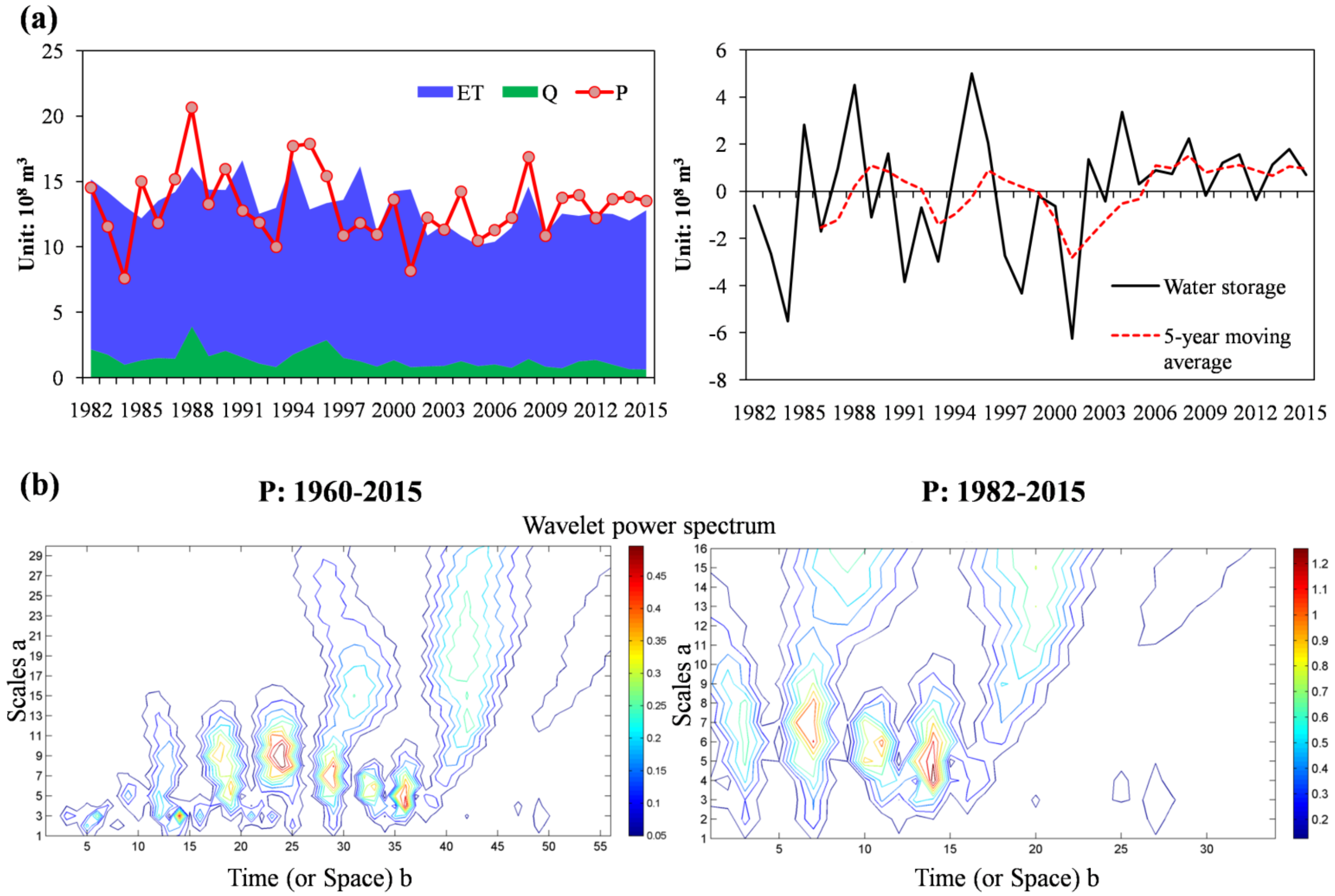

Figure 2: (a) Rainfall, streamflow, ET, water storage in DMG catchment for 1982–2015, and (b) wavelet power spectrum of rainfall time series in DMG catchment with record lengths of 56 and 34 years. Wavelet power spectrum is calculated as $\left|coef \cdot coef\right| / \sum \left|coef \cdot coef\right|$.

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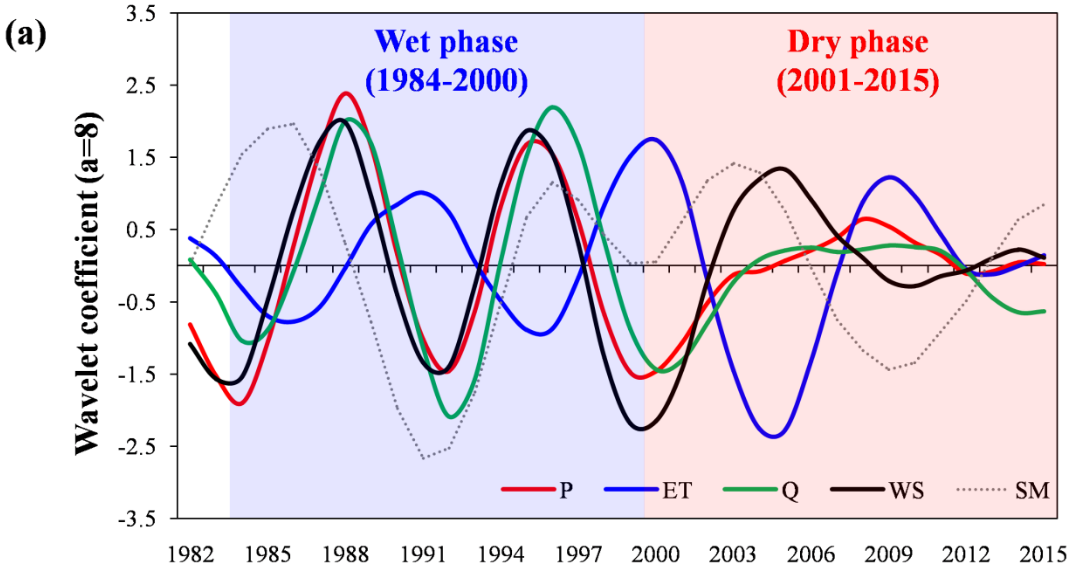


(b)

1982-2015

	P	ET	Q	WS
P	1	-0.29	0.86**	0.88**
ET	-0.29	1	-0.29	-0.69**
Q	0.86**	-0.29	1	0.72**
WS	0.88**	-0.69**	0.72**	1

Wet phase

	P	ET	Q	WS
P	1	-0.62**	0.90**	0.95**
ET	-0.62**	1	-0.5*	-0.82**
Q	0.90**	-0.5*	1	0.79**
WS	0.95**	-0.82**	0.79**	1

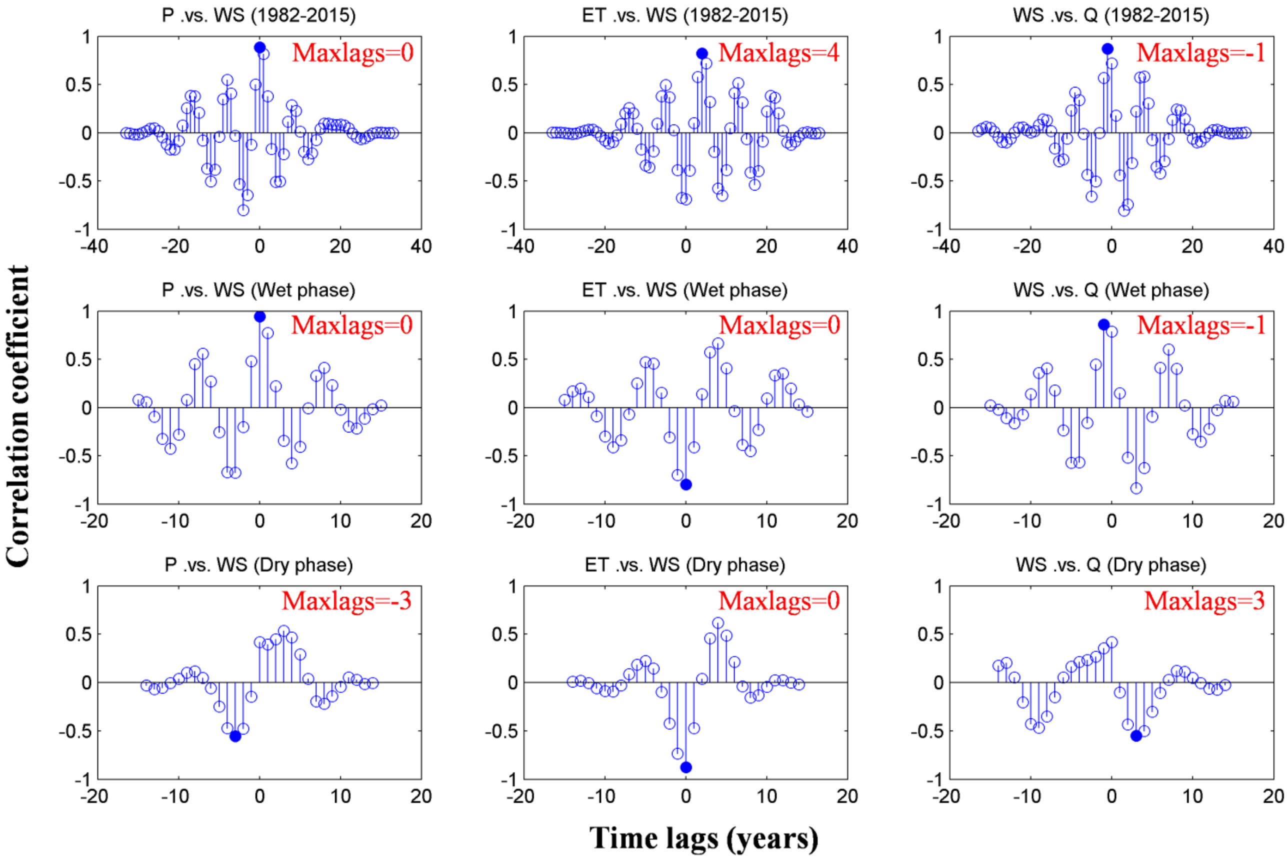
Dry phase

	P	ET	Q	WS
P	1	0.06	0.84**	0.42
ET	0.06	1	-0.21	-0.88**
Q	0.84**	-0.21	1	0.55*
WS	0.42	-0.88**	0.55*	1

**: p<0.01, *: 0.01<p<0.05

-0.9 1

535 **Figure 3: (a) Annual variations in wavelet coefficients of rainfall, ET, streamflow, water storage and surface soil moisture signals in DMG catchment, and (b) annual correlation matrices for four variables for the whole study period, the wet phase and the dry phase. The calculation is based on wavelet coefficients at scale of 8.**



540 **Figure 4: Hysteresis effects among rainfall, ET, streamflow and water storage (WS) signals (a=8) in DMG catchment for the whole study period, the wet phase and the dry phase. The positive maxlags between A and B indicate that A lags behind B by maxlags years, while the negative values indicate B lags behind A by maxlags years.**

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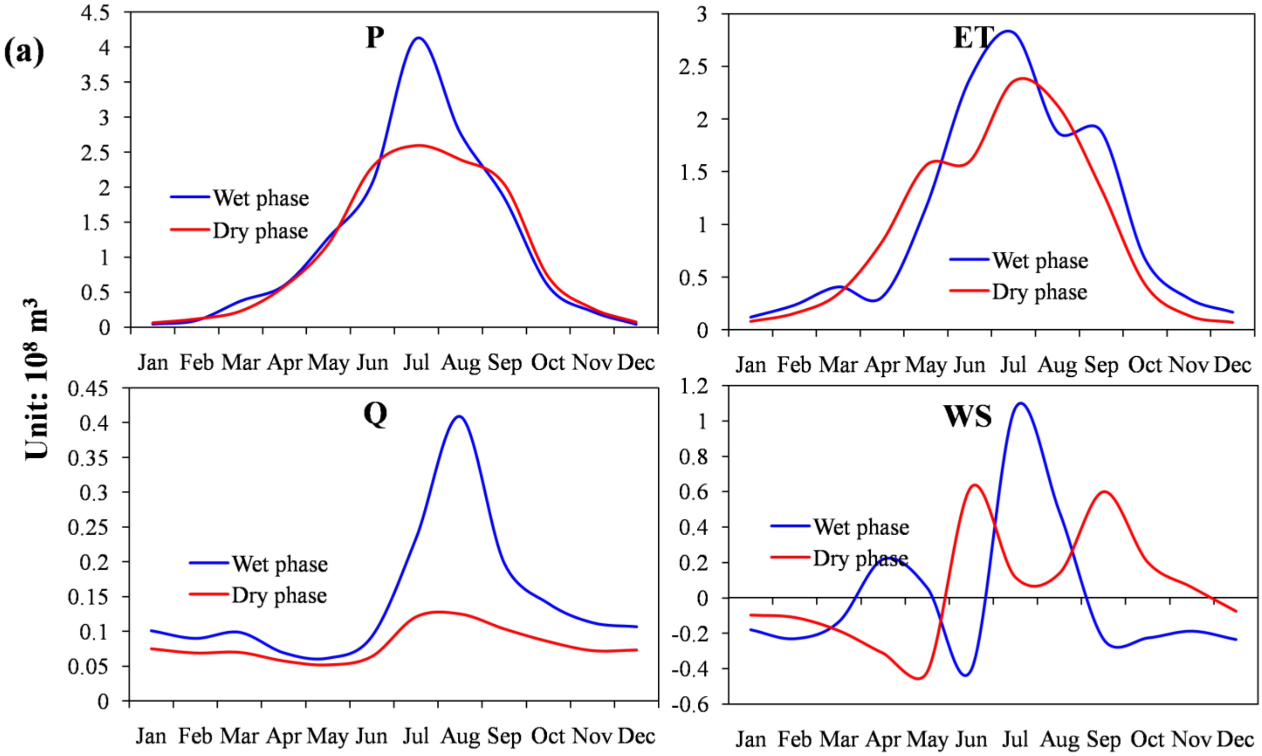

(b)

1982-2015

	P	ET	Q	WS
P	1	0.9**	0.65*	0.89**
ET	0.99**	1	0.57	0.82**
Q	0.65*	0.57	1	0.73**
WS	0.89**	0.82**	0.73**	1

Wet phase

	P	ET	Q	WS
P	1	0.95**	0.66*	0.70*
ET	0.95**	1	0.54	0.45
Q	0.66*	0.54	1	0.55
WS	0.70*	0.45	0.55	1

Dry phase

	P	ET	Q	WS
P	1	0.95**	0.64*	0.60*
ET	0.95**	1	0.56	0.32
Q	0.64*	0.56	1	0.46
WS	0.60*	0.32	0.46	1

**: p<0.01, *: 0.01<p<0.05 0.3 — 1

Figure 5: (a) Seasonal variations in rainfall, ET, streamflow, and water storage in the wet phase and dry phase in DMG catchment, and (b) seasonal correlation matrices for four signals for the whole study period, wet phase and dry phase.

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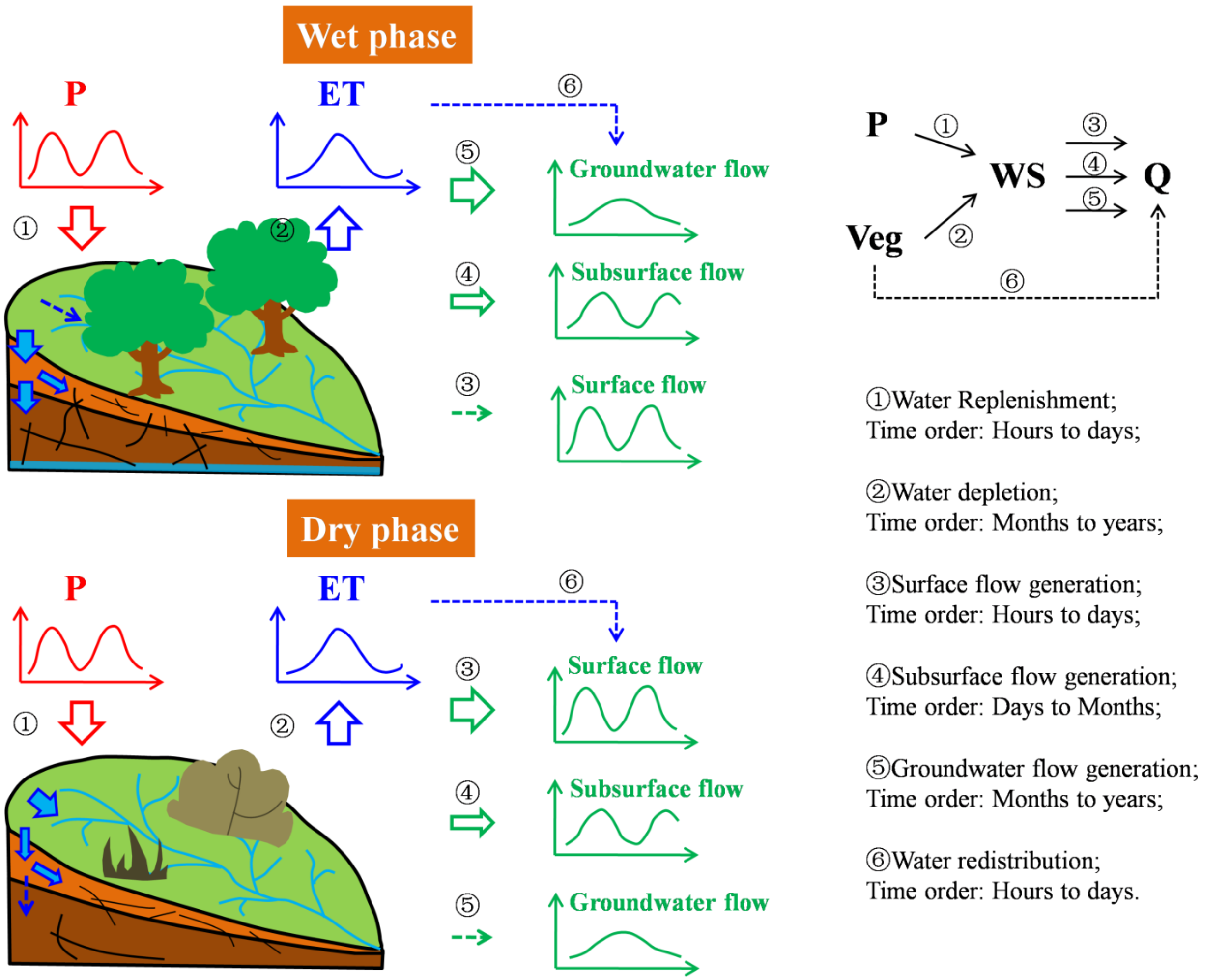

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Figure 6: Varying streamflow generation mechanisms with dominant hydrological pathways and the corresponding time lags in the headwater of Baiyang Lake.

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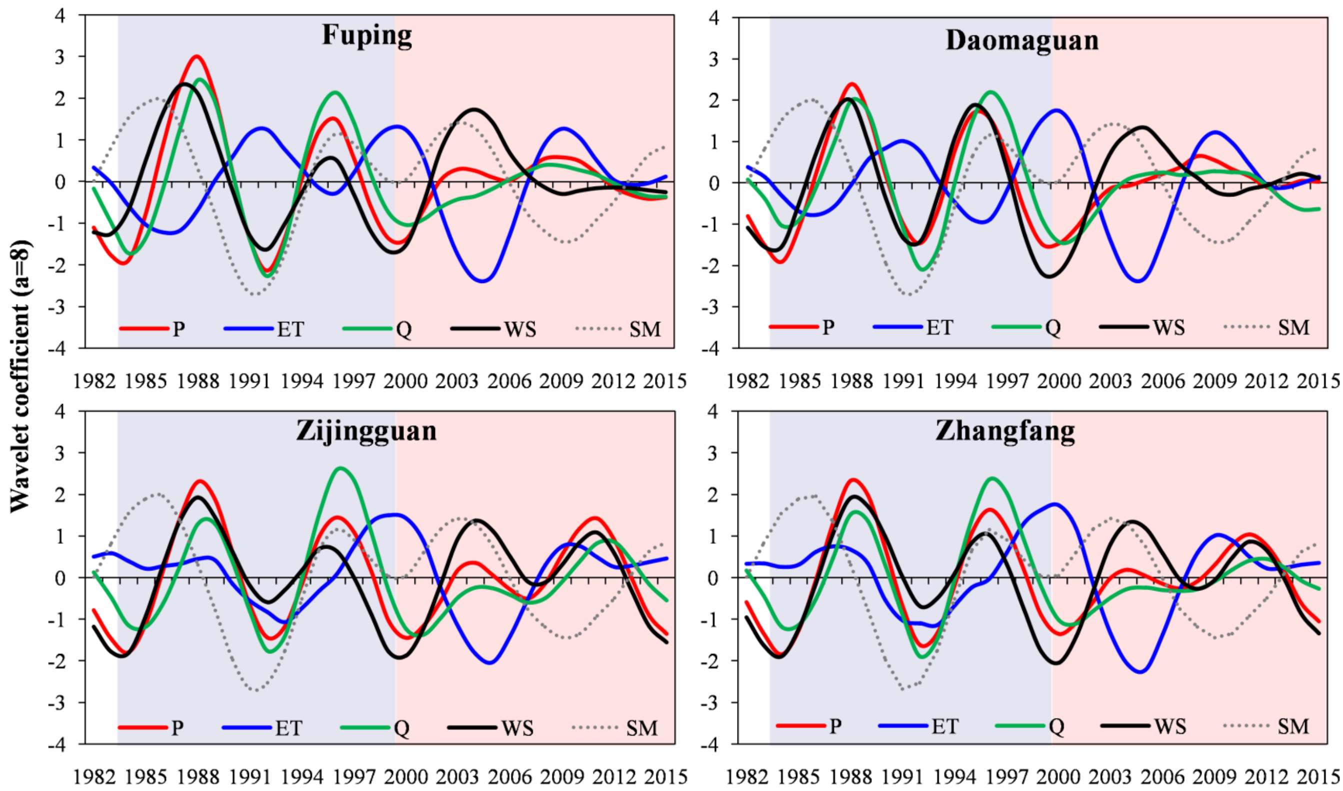

550 **Figure 7: Annual variations in wavelet coefficients of rainfall, ET, streamflow, water storage and surface soil moisture in all four catchments.**

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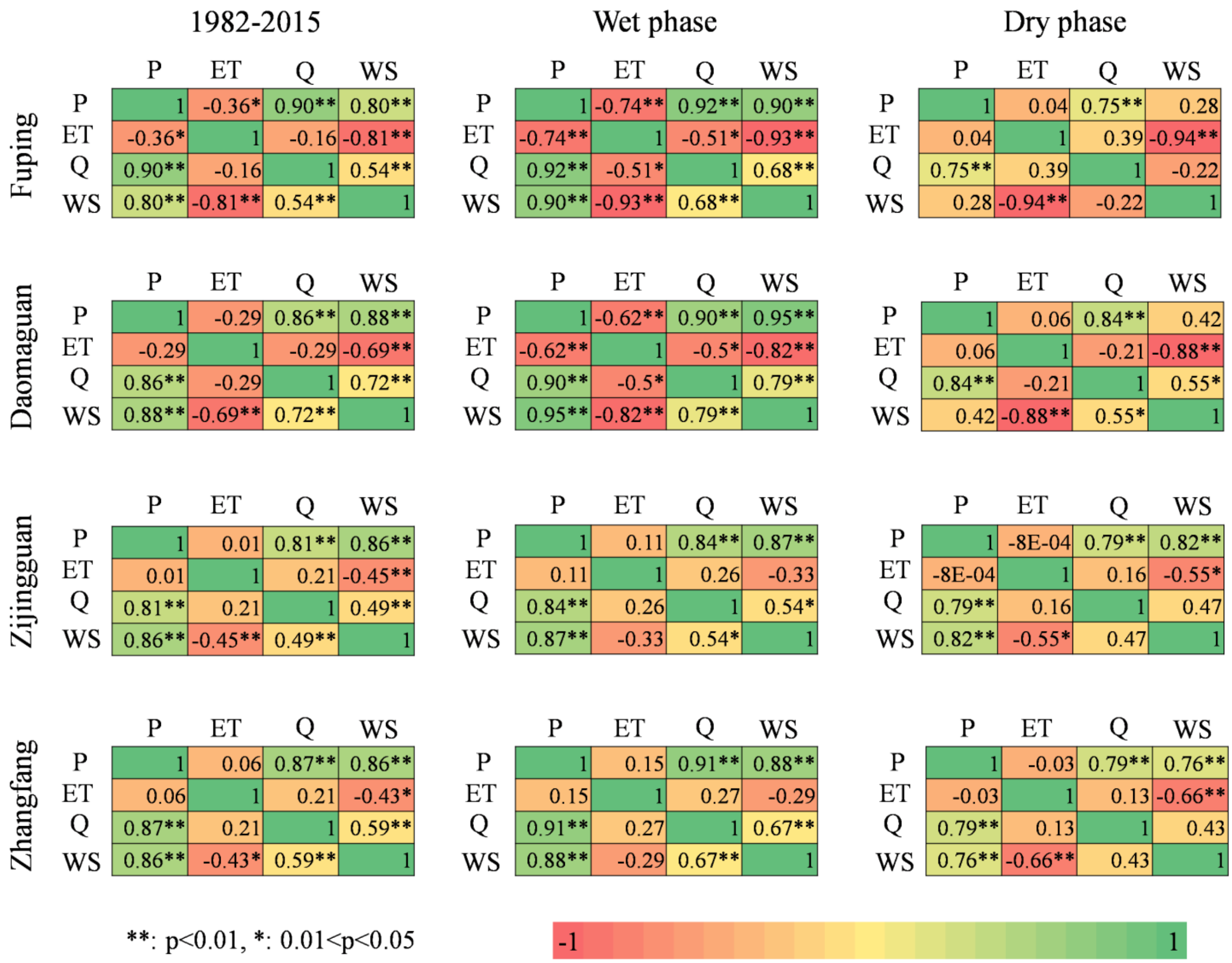

Figure 8: Annual correlation matrices for the four variables for the whole study period, the wet phase and the dry phase. The calculation is based on wavelet coefficients at a scale of 8.

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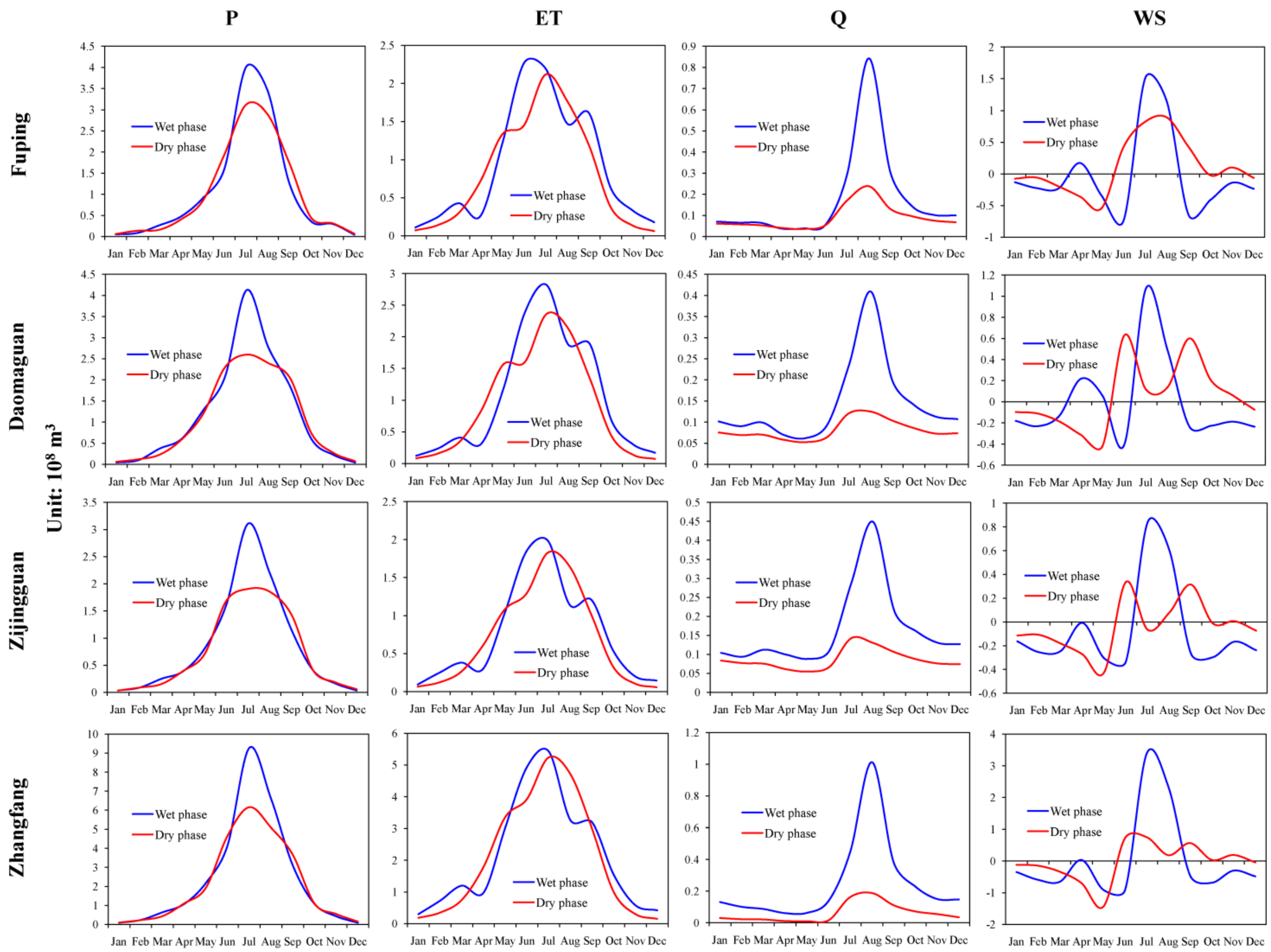

555 **Figure 9: Seasonal variations in rainfall, ET, streamflow, and water storage in the wet phase and dry phase in all the four catchments.**

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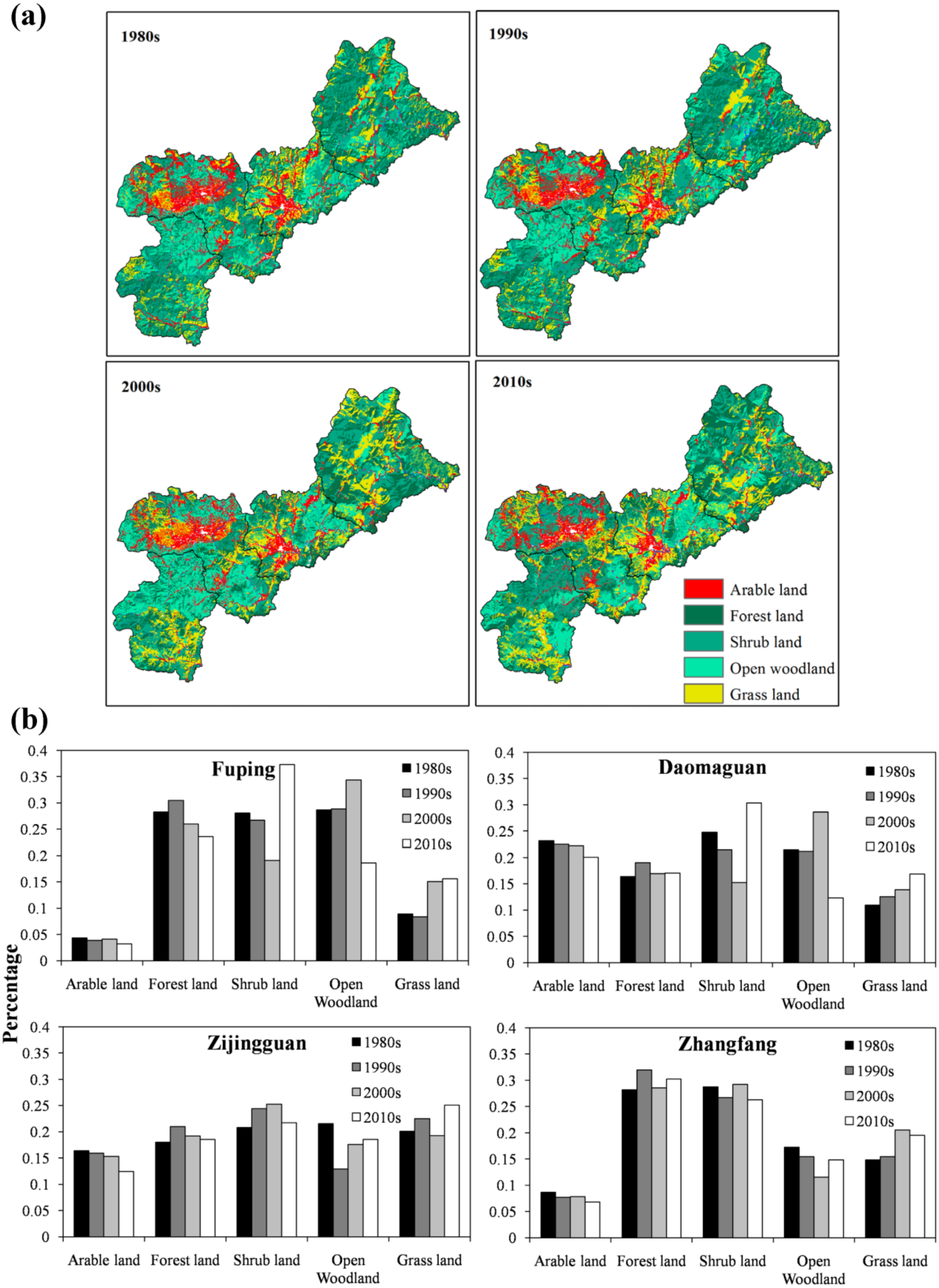

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Figure 10: The spatial distribution and temporal change of land use in four catchments of the headwater of Baiyang Lake.