Variations in the key hydrological elements of the Yarlung Zangbo River basin
Dian Li, Jia Li, Linglei Zhang, Yun Deng and Yaowen Zhang

ABSTRACT

Based on the monthly water level, runoff, precipitation and evaporation data from the four main hydrometric stations in the middle section of the Yarlung Zangbo River basin from 1956 to 2000, the periodic oscillations, trends and transformation characteristics at different time-scales are investigated via wavelet analysis. Moreover, the main periods of each time-series are identified by estimating the wavelet variance. The results show that the transformation scales of the monthly variation of the key hydrological elements over the last 44 years were 80–120, 40–70 and 16–24 months and that a high level of consistency was maintained at 16–24 months, where the periodic oscillation was the most significant. In addition, the first and second main periods of all hydrological elements were 18 and 9 months, respectively.

Key words | key hydrological elements, wavelet analysis, Yarlung Zangbo River

INTRODUCTION

The Tibetan Plateau, also named the Qinghai-Xizang Plateau, is the highest and largest plateau in the world, covers 2.5 million km² and is known as ‘the roof of the word’ (Shi et al. 2011). The Yarlung Zangbo River, which originates and flows across the southern Tibetan Plateau, is an important cross-boundary river (Cai et al. 2017). This river has a total length of 2,840 km (including a tributary length of 3,848 km) and a basin area of 935,000 km², represents the main source of fresh water for Tibet, and is a high-priority protection area for national ecological security and biodiversity. The ecosystem structure of this basin is relatively simple, and the ecological environment is fragile; thus, the basin is sensitive to climate change and represents an area where ecosystem responses to climate change will likely be initially observed. The length between the Lhaze and Nuxia gauging stations is 941 km, and the average elevation ranges from 2,911 m to 3,996 m. In recent years, the laws governing the temporal and spatial variations of the key hydrological elements of the Yarlung Zangbo River have been of increasing interest to researchers. Studies have shown that precipitation in this basin increased non-significantly at a rate of 6.32 mm/10 years and the air temperature significantly increased at a rate of 0.32 °C/10 years (Li et al. 2015). Moreover, the range-of-variability approach revealed that the hydrologic regime of the Yarlung Zangbo River was altered over 1961–2000 and the annual flow decreased by more than 10% and even up to 30% (Chen 2012). From ensembles of coupled general circulation models, Yang et al. (2012) projected that warm nights will increase and heavy precipitation events for single days and pentads (five days) will increase in intensity over most parts of the Tibetan Plateau in the 21st century. These studies have preliminarily described the variations in several hydrological elements of the Yarlung Zangbo River; however, the hydrological cycle and the evolution mechanism of runoff at multiple time-scales require further investigation.

Many studies have shown that changes in weather have not only global but also local characteristics, with diverse layers in their temporal structure and effects on multiple time-scales. Previous studies analyzing the hydrological
features in the Yarlung Zangbo River basin have mainly focused on interannual and interdecadal scales (Li et al. 2008; Qian et al. 2010; Shao et al. 2010). Based on monthly water level, runoff, precipitation and evaporation data from the four main meteorological stations in the middle section of the Yarlung Zangbo River basin from 1956 to 2000, the main periods at the month-scale and the tendency and transformation characteristics at different time-scales are investigated by adapting the wavelet analysis method in this study.

MATERIALS AND METHODS

Study site and data acquisition

Considering the integrity and representation of the hydrological elements at each station, the Lhaze, Nugesha, Yangcun, and Nuxia hydrometric stations in the middle section of the Yarlung Zangbo River were selected as representative stations that are distributed evenly in terms of geographical position (Figure 1). Few land-use disturbances were observed in the watersheds above the control section of the selected monitoring stations before the year 2000; thus, the natural flow status of the river can be sufficiently reflected by the measured flow data. We collected the daily data of the key hydrological elements from the four basic national hydrometric stations, whose measuring methods strictly follow the standard rules of the department of hydrology. The selected hydrological elements are precipitation, runoff, water level and evaporation, and the length of the data series is from 1951 to 2000. The arithmetic mean values of the measured daily hydrological data are calculated as monthly data.

Methods

The observed hydrological series are affected by many factors, including system noise and measurement noise. The existence of noise directly affects the real variation characteristics of hydrological series. Therefore, to improve the reliability and accuracy of the data analysis, noise must be removed from the hydrological series before multi-time-scale analysis. Noise reductions were performed using MATLAB (The MathWorks, Inc., USA) to extend both ends of the hydrological series to eliminate the boundary effect. Then, the Morlet Wavelet was applied for wavelet transform analysis. To calculate the results, the previously extended data were cut at both ends. The remaining real parts of the calculated wavelet coefficients were processed with Surfer 8.0 software (Golden Software, LLC, USA), and we obtained the wavelet coefficients of the monthly hydrological elements. The wavelet coefficient values at different scales and the wavelet variances were processed using Microsoft Excel and MATLAB, respectively. The transformation rules governing the hydrological elements were revealed according to the real part of the wavelet coefficients and the wavelet variances.

Mathematically, a wavelet transform is a convolution of a signal with an analysis window (mother wavelet) shifted in time and dilated by a scale parameter (Ouyang et al. 2017). Continuous wavelet analyses have been widely and maturely
applied in various geographic basins and regions worldwide to reveal the complex characteristics of hydrologic processes under multi-temporal scales (Sang 2013).

For a given hydrological time-series \( f(t) \in L^2(\mathbb{R}) \) and wavelet function \( \psi (t) \), the continuous wavelet transform (CWT) is expressed as follows:

\[
W_f(a, b) = |a|^{-\frac{1}{2}} \int_{\mathbb{R}} f(t) \psi \left( \frac{t - b}{a} \right) dt
\]

where \( W_f \) denotes the wavelet transformation coefficient, which can be used to recognize the transformation characteristics and abrupt changes at different time-scales of hydrological series; \( a \) represents a scaling factor that reflects the period length of the wavelet; and \( b \) represents a shifting factor that reflects time translation. In the isograms of the real part of the wavelet coefficients, the positive real part (solid line) and negative real part (dashed line) indicate increasing and decreasing values of the hydrological elements, respectively. In addition, zero represents a point of abrupt change.

Selection of an appropriate wavelet function is challenging and largely dependent upon the problems at hand and the properties of the wavelet function (Maheswaran & Khosa 2012; Ouyang et al. 2017). In this study, the Morlet wavelet is selected to analyze hydrological elements, and the formulation of the Morlet wavelet is as follows:

\[
\psi (t) = e^{jw_0 t} e^{-t^2/2}
\]

where \( t \) is a non-dimensional time parameter and \( W_0 \) is a non-dimensional frequency and has a value of 6 to satisfy the admissibility condition (Farge 1992; Niu & Sivakumar 2013).

The wavelet variance can be determined if we integrate all wavelet coefficients (squared) that correspond to \( a \). The equation is as follows:

\[
Var(a) = \int_{-\infty}^{\infty} |W_f(a, b)|^2 db
\]

The process by which the wavelet variance changes with a change in the scale of \( a \) is called the wavelet variance plot, which reflects the intensity of the periodic fluctuation of the hydrological series at a certain time-scale. In addition, the scale of the peak in the wavelet variance plot is the main time-scale, which is the first main period.

**RESULTS AND DISCUSSION**

Transformation characteristics of the key hydrological elements at the Nuxia station

To identify significant and insignificant trends of the hydrological elements, the Mann–Kendall (MK) nonparametric test was applied before wavelet analysis. A significance level of 0.05 was selected in this study, and the critical value of the standardized variable was 1.96. According to the MK test results (shown in Table 1), runoff and water levels in the Yarlung Zangbo River basin show overall decreasing trends. The evaporation series results show an increasing trend, and the growth trends in the Nugesha and Nuxia stations are significant.

Because of the limited space and high representativeness of the hydrological series in the Nuxia station, which is located in the middle and lower Yarlung Zangbo River, only the hydrological elements in the Nuxia station are analyzed in detail in this paper; the analysis results of the remaining stations will only be listed.

**Long-term variations in the hydrological series**

The isograms of the real part of the wavelet coefficients for monthly precipitation, runoff, water level and evaporation at the Nuxia station are shown in Figure 2, where the horizontal axis represents the time-scale (in months), with January 1956 as the start time, and the vertical axis represents the frequency scale.

**Table 1** Mann–Kendall test results for hydrological element trends at different stations

<table>
<thead>
<tr>
<th>Hydrological element</th>
<th>Lhaze</th>
<th>Nugesha</th>
<th>Yangcun</th>
<th>Nuxia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>0.10</td>
<td>–0.39</td>
<td>–0.46</td>
<td>–0.74</td>
</tr>
<tr>
<td>Water level</td>
<td>0.87</td>
<td>–2.29*</td>
<td>–0.75</td>
<td>–0.71</td>
</tr>
<tr>
<td>Precipitation</td>
<td>1.35</td>
<td>–2.28*</td>
<td>–1.22</td>
<td>1.37</td>
</tr>
<tr>
<td>Evaporation</td>
<td>1.69</td>
<td>5.71*</td>
<td>0.41</td>
<td>2.10*</td>
</tr>
</tbody>
</table>

* * indicates that the confidence level of the significance test is higher than 95%.
Based on these results (shown in Figure 2), the water level was correlated with the runoff at the Nuxia station (correlation coefficient of 0.9777). At the scale of 80–128 months, the water level and runoff experience 17 cycles of highs and lows, and at the scale of 40–70 months, 29 cycles are observed. For monthly precipitation, the transformation
Periodic characteristics of the hydrological elements

Figures 2 and 3 show that the main periods of the historical monthly water-level, runoff, precipitation and evaporation data are 18 months, and these cycles are distributed over the time domain. In addition, for the water-level series, periodic oscillation is obvious before 1964 and after 1976 at the scale of 40–70 months, and the cycles at the scale of 80–128 months are distributed evenly over the time domain. For runoff, the cycles at the scales of 40–70 months and 80–128 months are also distributed evenly, and the transformation trends correspond with the water-level trends. For precipitation, periodic oscillation is obvious before 1972 and after 1985 at the scale of 40–60 months and the cycles at the scale of 80–128 months are also stable after 1972. Before 1985, cycles are observed at the scales of 40–60 months and 80–120 months in the evaporation series, although the cycle at the latter scale is more obvious; however, both cycles are not notable after 1985, when the slopes of the curves are more gradual.

All of the maximum peaks in the wavelet variance plots of the key hydrological elements (shown in the Supplementary Material, available with the online version of this paper) are separated by 18 months, indicating that this periodic oscillation is the greatest and that 18 months is the first main period. However, periodic oscillations of 9 months and 50–90 months also occur for these elements.

Transformation characteristics of the key hydrological elements in the Yarlung Zangbo River basin

Based on the results from the wavelet coefficient plots for the four meteorological stations (omitted for brevity), the water-level and runoff series essentially have the same transformation scales (shown in Table 2), the cycles at different scales are consistent, and the correlation coefficients (shown in Table 3) for the water level and runoff data are high and increase with the downstream flow of the river. Although the precipitation and evaporation series have approximately the same long, intermediate, and short scales as the other hydrological elements, the correlation is not strong.

Focusing on the transformation cycles of the hydrological elements along the river as shown in Table 1, we can see that the range of the longest time-scales of the water-level and runoff series increases, with the longest time-scales at 110–128 months at the Lhaze station and 80–128 months at the Nuxia station. Moreover, small changes are observed at intermediate time-scales, which is consistent with the changes at short time-scales for water level and runoff. Compared with the results of other studies (Li et al. 2008; Shao et al. 2010), based on an interannual scale, the present work obtained a more accurate conclusion based on the monthly scale, and the main period of transformation in the Yarlung Zangbo River is 18 months. The time-scales of the precipitation series are nearly equivalent to those of the four meteorological stations along the river. The evaporation series has the same longest scales at the Lhaze, Nugesha and Yangcun stations but not at the Nuxia station, whereas the intermediate scales at the four stations are different. The study of historical data by Zhang (2011) shows that the potential evaporation decreases from upstream to downstream along the Yarlung Zangbo River, and the transformation scales of the evaporation series at different stations differ under the influence of the local relative humidity, wind speed, daylight duration and temperature.

The first main transformation periods of the key hydrological elements are 18 months (shown in Table 4), and the second periods are more complicated, including a short period of 9 months and a long period of 80 to 120 months, with the 9-month period accounting for a large proportion of the periods observed.

The last sets of isolines in the wavelet coefficient plots of the water level and runoff at the four meteorological stations are not closed at any time-scales, and the curves of the real part of the wavelet coefficients are solid lines (positive numbers) from which we can predict that runoff will be high in the Yarlung Zangbo River basin in the future (from 2000
Figure 3 | Wavelet coefficients at different scales of various hydrological elements at the Nuxia station: (a) runoff; (b) water level; (c) precipitation; and (d) evaporation.
Climate oscillations are the main driver of spatial and temporal variability in the hydrologic cycle at global and regional scales (Sheffield & Wood 2008; Räätänen & Kummu 2013; Liu et al. 2017). The results show that the cycles of 16–24 months in the transformations of the various hydrological elements are significant, the cycles of 40–70 months are relatively strong, and the cycles of 80–120 months have obvious local features in the time-frequency domain. Based on the identified climatic patterns and related astronomical phenomena, we preliminarily assume that the annual climate changes in the Yarlung Zangbo River basin are mainly affected by atmospheric circulation, the El Niño–Southern Oscillation (ENSO), periodic variations in solar activity over 2 years and semi-sunspot cycles of 5–6 years, and these factors result in the actual cycles of 16–24 and 40–70 months. These changes are also influenced by basic sunspot cycles over 11 years, although the effect is relatively weaker. According to Briciu & Mihală (2014), the influence of climatic teleconnection variations and sunspots on river flows occurs via rainfall and temperature variations. Some studies support our assumptions. Qi et al. (2012) believed that natural climate changes in southwestern China are primarily caused by the combined effects of solar activity, sea-surface temperature, atmosphere circulation and ice and snow cover. A close relationship is also observed between interdecadal climate variations of the Qinghai-Tibet Plateau and sunspot activity as well as the rotation rate of the Earth and other astronomical factors (Cai et al. 2005). However, Sang et al. (2016) proposed that the interannual nonstationary fluctuations of precipitation are caused by the periodic variability of the Indian monsoon. Therefore, further research and verification are still needed.

The transformation properties and development trends of key hydrological elements in the Yarlung Zangbo River basin were investigated at multiple time-scales in this study. Because of increasing water demands, water resource managers can predict the uncertain characteristics of river runoff (Zhang et al. 2017). Accurately determining the periodic hydrological processes in the Yarlung Zangbo River basin will help reveal the inner evolutionary mechanisms

### DISCUSSION

<table>
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<tbody>
<tr>
<td>Runoff–water level</td>
<td>0.8614</td>
<td>0.9675</td>
<td>0.9723</td>
<td>0.9777</td>
</tr>
<tr>
<td>Runoff–precipitation</td>
<td>0.7769</td>
<td>0.7701</td>
<td>0.7668</td>
<td>0.7183</td>
</tr>
<tr>
<td>Runoff–evaporation</td>
<td>0.0141</td>
<td>0.1311</td>
<td>0.0000</td>
<td>0.1783</td>
</tr>
<tr>
<td>Precipitation–evaporation</td>
<td>0.0374</td>
<td>0.0678</td>
<td>0.1775</td>
<td>0.3351</td>
</tr>
</tbody>
</table>

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</tr>
</thead>
<tbody>
<tr>
<td>Water level</td>
<td>9, 18$^b$, 70$^b$, 9, 18$^b$, 120$^b$</td>
<td>9$^b$, 18$^b$, 70</td>
<td>9$^b$, 18$^b$, 70</td>
<td>9$^b$, 18$^b$, 70</td>
</tr>
<tr>
<td>Runoff</td>
<td>9$^b$, 18$^b$, 70</td>
<td>9$^b$, 18$^b$, 68</td>
<td>9$^b$, 18$^b$, 70</td>
<td>9$^b$, 18$^b$, 70</td>
</tr>
<tr>
<td>Precipitation</td>
<td>9$^b$, 18$^b$, 48</td>
<td>18$^b$, 48, 120$^b$</td>
<td>18$^b$, 56, 120$^b$</td>
<td>18$^b$, 60, 90$^b$</td>
</tr>
<tr>
<td>Evaporation</td>
<td>9$^b$, 18$^b$, 58</td>
<td>9, 18$^b$, 42$^b$</td>
<td>9, 18$^b$, 80$^b$</td>
<td>18$^b$, 50, 90$^b$</td>
</tr>
</tbody>
</table>

*First main period. *Second main period.

on), which is consistent with the study of Li et al. (2008). In addition, the Lhaze and Yangcun stations will experience a period of heavy rains, whereas the Nugesha and Nuxia stations will experience a period of low precipitation at a scale of 40–70 months. Notably, the trend analysis of the MK test could not be compared with the wavelet analysis because the former results indicate the general pattern of 44 years of historic data, whereas the prediction of the latter analysis is based on the month-scale.
and development trends of the key hydrological elements. Associated analyses can be performed to generate preliminary predictions of the change trends of hydrological elements at different time-scales. Because watersheds were less affected by human disturbances before the year 2000, the rules presented for hydrological series from 1956 to 2000 can provide a reference to measure variations in the water basin under the effects of climate change and runoff regulation after the year 2000. Furthermore, the results can also provide a reference for ecological restoration. Other characteristics, such as abrupt changes and increases in the transformation of hydrological elements, require further study, as well as the inner evolution mechanism that resulted in the first main period of 18 months. In addition, the areal values of rainfall and evaporation could accurately represent the components of the hydrological cycle in the entire watershed and should thus be used in future studies.

The analyses of hydrological elements present a number of uncertainties, such as the length and integrity of the hydrological series and the selection of wavelet functions and parameters.

CONCLUSIONS

A wavelet analysis was applied in this study to uncover information hidden in hydrological series data. The frequency characteristics of the hydrological series during the time domain were determined, and the strengths of different time-scales as well as the distributions, trends, and main transformation periods were clearly described.

In the middle and lower reaches of the Yarlung Zangbo River, the transformation periods for evaporation, precipitation and runoff are highly consistent at the short time-scale of 16–24 months, and the corresponding cycles cover the whole analysis period while remaining relatively stable. The intermediate and long-term scales are similar at approximately 40–70 and 80–128 months, respectively. The first main periods of the transformations are 18 months, and most of the second periods are 9 months. We can predict that runoff in the Yarlung Zangbo River basin will be high at each time-scale in the future, the evaporation at the four meteorological stations will decrease at the scale of 40–70 months, the Lhaze and Yangcun stations will experience a period of heavy rains, and the Nugesha and Nuxia stations will experience a period of little precipitation at the same scale.

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