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Baseflow Separation and Its Response to Meteorological Drought in a Temperate Water-limited Basin, North China

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Abstract: Baseflow, a component of the total streamflow, plays a key role in maintaining aquatic habitats, particularly during extreme drought events. This study investigated baseflow response to a prolonged and extreme meteorological drought event in the Baiyangdian Basin (BYD basin), a temperate water-limited basin in North China. Applying a precipitation series, piecewise regression was used to determine this extreme meteorological drought event, while the Automatic Baseflow Identification Technique (ABIT) was used to estimate a recession parameter (α), which was used to isolate baseflow from total streamflow. Results showed that: 1) annual precipitation exhibited significant decreasing trends ($P < 0.05$) with an average change of -1.81 mm/yr^2. The precipitation deficit revealed that the start and end date of the extreme meteorological drought event was from August 1996 to May 2011, respectively, persisting for a total of 178 months (roughly 15 yr); 2) hydrological drought (including streamflow and baseflow) lagged behind meteorological drought while predictably persisting longer than extreme meteorological drought (i.e., precipitation); and 3) baseflow decreased dramatically under meteorological drought at both seasonal and annual scales, resulting in significantly decreasing trends during drought periods. Findings from this study confirmed that hydrological events caused by extreme meteorological drought can alter the magnitude and duration of baseflow and total streamflow, which will have an inevitable influence on aquatic ecosystems.

Keywords: baseflow; extreme drought; recession parameter; Baiyangdian Basin

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1 Introduction

Baseflow is defined as the water flow that derives from groundwater and other delayed sources, thus sustaining streamflow during dry periods (Smakhtin, 2001; Gnann et al., 2019). Hence, baseflow plays a vital role in the perennial maintenance of aquatic habitats (Fan et al., 2013). Climate change (e.g., pertaining to an extreme meteorological event in the context of this study) in combination with anthropogenic activities have altered the hydrological processes of global river systems, inevitably resulting in changes to baseflow regimes (Yang et

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al., 2017). Rising global temperatures have also led to a more energized hydrologic cycle. This has been particularly apparent in semiarid regions due to their fragile ecohydrological nature (Seager et al., 2010; Wu et al., 2019; Yang et al., 2019). Such precipitation redistribution has unexpectedly caused spatial and temporal reductions in global terrestrial precipitation variance whereby drier climates have become wetter and wetter climates have become drier on average (Sun et al., 2012).

In this context, studies have attempted to separate baseflow from total streamflow and to describe its role using flow duration curves (FDC) during different hydrological events (e.g., Ficklin et al., 2016; Yang et al., 2017; Zhang et al., 2017). Numerous approaches have been developed to quantify baseflow. These include applying hydrograph separation, numerical simulations, water balance equations, chemical mass balance (CMB) models as well as software such as the Hydrograph Separation Program (HYSEP) (Wu et al., 2019). All these approaches can be categorized as either tracer-based or non-tracer-based methods (Zhang et al., 2017). Non-tracer-based methods can overcome disadvantages inherent to tracer-based methods, such as the time required to collect samples and conduct analysis (Zhang et al., 2017). Moreover, another advantage is the ease of operation of non-tracer-based methods, which also avoid problems associated with subjectivity and the arbitrariness of manual separation methods. Non-tracer-based methods are also suitable for long–term hydrologic series (Xu et al., 2016). Moreover, digital filtering has widely been used to isolate baseflow and quickflow from total streamflow by applying the method developed by Lyne and Hollick (1979). Zhang et al. (2017) used the Automatic Baseflow Identification Technique (ABIT) to estimate the recession constant (α), which they asserted is critical to obtain the appropriate parameters prior to the application of digital filtering methods.

Recently, baseflow response to meteorological drought has also been explored to better understand runoff generation under different hydro-climatic conditions. For example, Aryal et al. (2020) reported a potential increase in baseflow drought during an extreme meteorological drought event in Australia. Yang et al. (2017) and Liu et al. (2020) investigated the response of hydrological drought intensity and severity (i.e., streamflow and baseflow drought) to meteorological drought in Australia and Northeast China, respectively. It has been observed that longer drought durations and a lower number of drought events have correlated to baseflow drought rather than to runoff drought (Sutanto and Van Lanen, 2020). Although the response of hydrological drought is dependent on meteorological conditions, it is also dependent on land-based hydrological processes and catchment properties, which are potentially correlated to physical catchment properties (e.g., catchment size, slope and soil properties), vegetation behavior and changes in hydrological conditions during drought events (Mishra and Singh, 2010; Van Loon and Laaha, 2015; Barker et al., 2016). However, different climate conditions and geographical characteristics will result in regional differences in hydrologic response, for which there are no systematic quantitative indicators. Accordingly, the objectives of this study were: 1) to investigate extreme meteorological drought at a basin scale using precipitation deficits; 2) to explain hydrological drought following extreme meteorological drought in both streamflow and baseflow; and 3) to assess baseflow response to drought under different hydro-climatic conditions, such as those related to pre-drought and drought periods in the Baiyangdian Basin (BYD Basin), China. Results from this study cloud offer insight into our understanding of the impacts of catchment properties on drought propagation and hydrological conditions under a background of changing climate.

2 Materials and Methods

2.1 Study area and data

Being the largest freshwater lake in the North China Plain, Baiyangdian Lake plays an important role in water resource management, flood control initiatives and regulatory regimes in the basin. The BYD Basin belongs to a temperate continental monsoon climate with an annual precipitation of 510 mm and an average annual pan evaporation of 1746 mm. The annual mean daily air temperature is –2.6℃. Historically, nine rivers flowed into Baiyangdian Lake; however, in recent years climate change and anthropogenic activities (e.g., through water transfer initiatives and irrigation activities) have caused most of these rivers to dry up. Moreover, extreme climate events (e.g., rainstorms and drought) have led to changes in hydrological regimes

(Wang et al., 2019). The BYD Basin is particularly sensitive to changes in hydrological regimes, which include 94 km^2 of raised fields and greater than 3700 ditches that subdivide the basin into 140 small shallow lakes. To preserve the water ecology of Baiyangdian Lake, ecological water transfer projects have been implemented since the 1980s to maintain its integrity (Liu, 2014). Specifically, the planning outline of the Xiong'an New Area, which has jurisdiction over Baiyangdian Lake, included an ordinance for its ecological restoration. Inevitably, alterations in hydrological regimes will result in changes to aquatic ecosystems (Zhao et al., 2012; Wang et al., 2014; Li et al., 2016). This study used a daily precipitation time series that spanned from 1959 to 2016, constructed from data obtained from eight local meteorological stations (Fig. 1), to explore extreme climate events in the region. Corresponding daily streamflow data of four hydrological stations (i.e., Daomaguan Station, Zhongtangmei Station, Fuping Station, Dongcicun Station) representing four sub-basins in the upstream that are less subject to human interference were used to investigate the hydrological response to an extreme drought event in the BYD Basin, China (Fig. 1).

2.2 Method

2.2.1 Quantifying drought

According to Yu and D'Odorico (2014), drought can be described as 'inputs with the recognition that this meteorological definition may lead to a variety of responses depending on ecosystem hydrology', which can be divided into meteorological, hydrological, agricultural and socioeconomic drought.

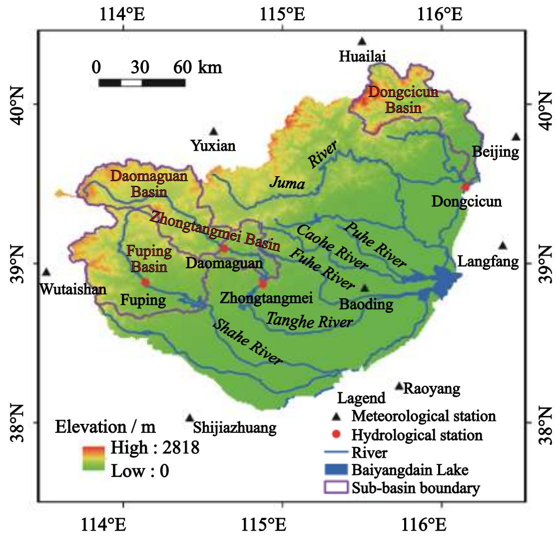

Fig. 1 The location and key features of the Baiyangdian Basin, China and the meteorological stations and the hydrological stations used in this study

Drought can be quantified through a two steps process. Firstly, annual precipitation anomalies were calculated. In order to avoid individual wetter years that can be interspersed between long and pronounced dry periods, results are smoothed with a three year moving window. Secondly, the exact start and end months of dry period were determining based on the accumulated monthly precipitation anomalies. This method has been successfully used to quantify drought, and details can be found in Yang et al. (2017). The piecewise regression model used to detect potential turning points in the cumulative monthly anomaly series.

$$y = \begin{cases} \beta_0 + \beta_1 + \varepsilon & t \le \delta \\ \beta_0 + \beta_1 t + \beta_2 (t - \delta) + \varepsilon & t > \delta \end{cases} \tag{1}$$

where t is the month, and y is the accumulated monthly precipitation anomaly; b_0, b_1 and b_2 are the regression coefficients; δ is the assumed turning point based on annual anomaly analysis. The range of the δ value was set to 12 months prior to and following the start and end year, which was determined through annual anomaly analysis. Linear least squares (LLS) regression was used to estimate the three regression coefficients, and a t-test was used to determine whether β_2 equates to zero.

Drought duration, severity, and intensity were used to describe characteristics for a drought event. Drought duration was the time difference between the start and end months. Drought severity presented as the accumulative precipitation anomaly during the drought event. And drought intensity was defined as the ratio of drought severity over drought duration. Hydrological drought was calculated respective to streamflow and baseflow using the above procedures.

2.2.2 Isolating baseflow from total streamflow

The Chapman-Maxwell method (i.e., the CM filter) used to separate baseflow from streamflow is a new algorithm of the digital filtering method (Zhang et al., 2017). The CM filter was developed to eliminate uncertainties, and it regards baseflow as a constant after quickflow has ceased (Chapman and Maxwell, 1996; Chapman, 1999; Graszkiewicz et al., 2011). The CM filter algorithm is determined by the following equation (Zhang et al., 2017):

$$Q_{b(i)} = \frac{\alpha}{2-\alpha} Q_{b(i-1)} + \frac{1-\alpha}{2-\alpha} Q_i \tag{2}$$

where Q and Q_b is total streamflow and baseflow (mm/d), respectively; i is the time step; and α is the recession constant (1/day). Considering the prevalence of this linear scenario within natural river systems, baseflow can be expressed as follows (Brutsaert, 2005):

$$\frac{dQ}{dt} = \frac{1}{\kappa} Q \tag{3}$$

where t is the length of time (d), and κ is the characteristic drainage time scale (d). The α can be inferred as follows:

$$\alpha = e^{-\frac{1}{\kappa}} \tag{4}$$

The default recession constant (α) was 0.925, which was defined by Nathan and McMahon (1990) using Germann's six watershed characteristics (Caissie and El-Jabi, 2003; Liu et al., 2020). In this study, the recession analysis method proposed by Brutsaert and Nieber (1977) (denoted as the BN77 method) was employed to estimate parameter α of the catchment. The BN77 method derives α from the lower envelope of a logarithmic plot of the recession rate (dQ/dt) that is plotted against the corresponding drought flow data Q. The lower envelope is the locus of points of the slowest recession rate determined by maintaining roughly 5% of the data points below it. This study adopted the Automatic Baseflow Identification Technique (ABIT) method developed by Cheng et al. (2016), which is considered a more rapid and objective method (i.e., the BN77 method) to estimate α (Tallaksen, 1995; Vogel and Kroll, 1996).

3 Results

3.1 Quantifying meteorological drought using the precipitation deficit

Results showed a decreasing trend in precipitation with an average annual change of –1.81 mm/yr^2. Moreover, a downward abrupt change was detected in 1971, and the average annual precipitation prior to and following this abrupt change was 588 and 509 mm/yr, respectively (Fig. 2).

Extreme drought was assessed according to monthly precipitation anomalies (Fig. 3). The duration of extreme drought covered 178 months (roughly 15 yr), from August 1996 to May 2011, namely, when precipitation was below the average of the BYD basin and its surrounding area (Fig. 3).

At the basin scale, precipitation deficits were observed to have occurred as early as the 1960s or the 1970s at three meteorological stations located in the southern region of the study area (Table 1), which were earlier than that observed in the other stations. Furthermore, half of the meteorological stations (i.e., 4/8) detected two occurrences of extreme drought, while a precipitation deficit was detected at most meteorological stations around the 1990s (except for the Shijiazhuang meteorological station). Extreme drought ranged from 49 mon (Yuxian) to 301 mon (Wutaishan), with an average value of 129 mon.

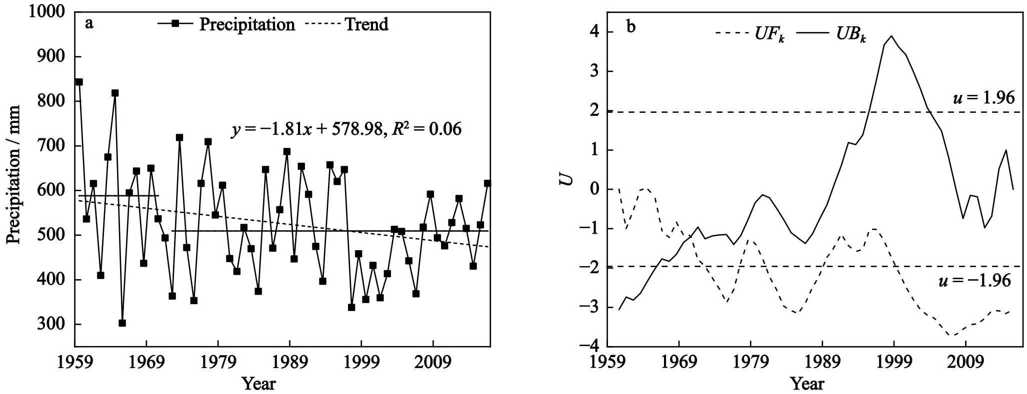

Fig. 2 Variation and temporal trends (a) and abrupt changes determined by the Mann-Kendall method (b) of the annual precipitation averaged from eight meteorological stations throughout 1959–2016 in Baiyangdian Basin and its surrounding area. The u represents statistics variables in the Mann-Kendall method, UF_k and UB_k is statistics variables calculated from normal and invert series to obtain timing of abrupt change according to the cross point. Details for Mann-Kendall method can be seen in Mann, 1945; Kendall, 1948; Liang et al., 2010

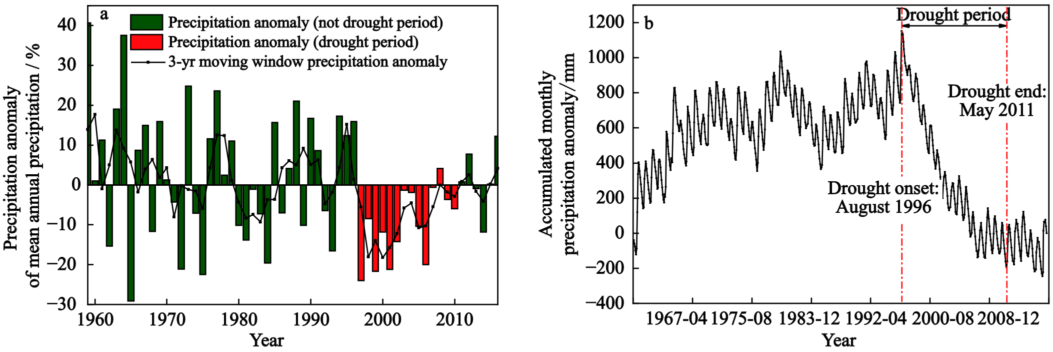

Fig. 3 Ascertainment of extreme meteorological drought in Baiyangdian Basin. a) annual precipitation anomaly and b) the exact start and end months of meteorological drought

Table 1 Extreme meteorological drought events detected in Baiyangdian Basin and its surrounding area

Meteorological station	Huailai	Yuxian	Wutaishan	Shijiazhunag
Meteorological drought	1980-08–1994-05 (165 mon) 1998-07–2007-08 (107 mon)	1998-07–2002-08 (49 mon)	1990-04–2015-08 (304 mon)	1965-04–1976-06 (134 mon) 1979-07–1998-04 (105 mon)
Meteorological station	Raoyang	Langfang	Beijing	Baoding
Meteorological drought	1977-07–1984-07 (84 mon) 1996-08–2004-08 (96 mon)	1995-09–2007-09 (137 mon)	1998-07–2010-07 (144 mon)	1979-08–1988-04 (104 mon) 1997-04–2007-07 (123 mon)

3.2 Baseflow separation and quantification of hydrological drought

Accounting for deviations from the default value (0.925), the ABIT method was used to obtain the recession constant α for all four sub-basins (Table 2), which Zhang et al. (2017) validated using the baseflow index (BFI) (i.e., the ratio of baseflow to total streamflow) obtained by applying tracer-based methods. Parameter κ ranged from 48.8 d in the middle reaches of the Tanghe River catchment to 161.3 d in the upper reaches of the Tanghe River catchment. The value of α ranged from 0.9797 to 0.9938 with an average of 0.9886, which was noticeably higher than the default recession constant value (0.9250). The recession constant α calculated with the ABIT method was used to separate baseflow from streamflow.

To explore the impact of extreme meteorological drought (i.e., extremely low precipitation), this study endeavored to detect the occurrence of hydrological drought in the BYD basin (Table 3). Hydrological drought was detected in both streamflow and baseflow in the BYD basin. It is noteworthy that except for the onset time (wherein the onset time of streamflow was earlier than that of baseflow), hydrological drought in streamflow and baseflow remained roughly consistent. Hydrological drought lagged behind meteorological drought; namely, the onset of the hydrological drought event was detected from October 1996 to June 1997, which lagged behind the onset of the meteorological drought event (start time: August 1996). Furthermore,

Table 2 The time scale (κ) and recession constant (α) obtained from four sub-basins within Baiyangdian Basin using the Automatic Baseflow Identification Technique (ABIT) method

Hydrological station	River	Recession day (κ) / d	Regression constant (α)
Zhongtangmei	Tanghe River	48.8	0.9797
Daomaguan	Tanghe River	161.3	0.9938
Dongcicun	Baigouyin River	97.1	0.9898
Fuping	Shahe River	111.1	0.9910

Table 3 Detection of hydrological drought (both streamflow and baseflow) in Baiyangdian Basin

Hydrological stations	River	Catchmentarea / km^2	Total streamflow drought			Baseflow drought		
			Start-end time	Start-end lag time/ mon	Period/mon	Start-end time	Start-end lag time / mon	Period / mon
Zhongtangmei	Tanghe River	3480	1996-10–2013-05	2–24	200	1997-06–2015-12	7–67	225
Daomaguan	Tanghe River	2770	1997-01–2014-08	5–39	212	1997-06–2015-12	9–54	236
Dongcicun	Baigouyin River	2249	1997-03 (end)	7–67	238	1997-05 (end)	8–67	237
Fuping	Shahe River	2210	1996-10–2016-06	2–61	237	1997-05–2016-06	5–61	234

hydrological drought recovery (i.e., the end of hydrological drought) also lagged behind meteorological drought recovery with an average lag time of 55 mon. Additionally, the duration of hydrological drought exceeded that of meteorological drought, which was determined by means of precipitation deficits, ranging from 200 to 238 mon.

3.3 Baseflow response to meteorological drought at seasonal and annual scales

The response of baseflow to drought varied at both seasonal and annual scales (Fig. 4). Compared to pre-drought periods, the precipitation deficit during the drought period significantly reduced baseflow both at both seasonal and annual scales in the four sub-basins. Therefore, baseflow exhibited decreasing trends at both seasonal and annual scales. This was especially the case for the similar patterns exhibited in baseflow at a seasonal scale. In other words, seasonal scale baseflow increased from spring (from March to May) to autumn (from September to November) before decreasing during winter (from December to February of the follow-

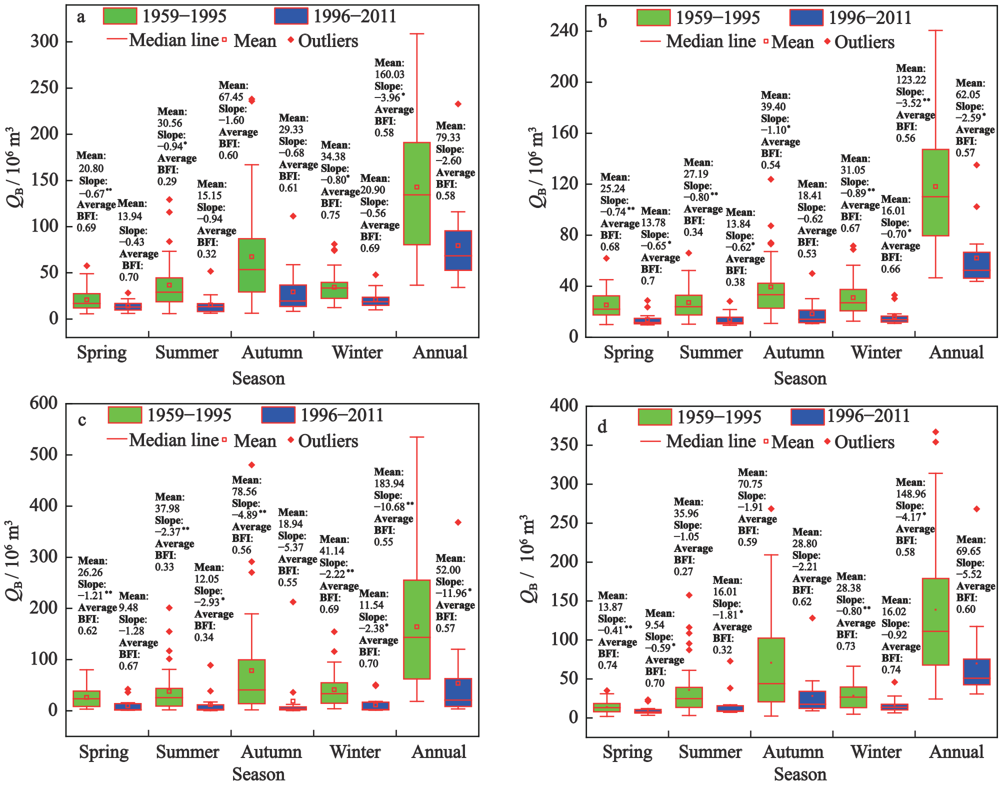

Fig. 4 Seasonal and annual baseflow in the four sub-basins during meteorological drought prior to the extreme meteorological drought event: a) Zhongtangmei, b) Daomaguan, c) Dongcicun and d) Fuping. The green box plots show the time prior to the extreme meteorological drought event (i.e., 1959–1995); the blue box plots show the time of meteorological drought (i.e., 1996–2011). The average baseflow volume, linear regression model slopes and the average baseflow index (BFI) values are shown at the top of the pillars. ** and * indicate significant correlation at 99% and 95% confidence levels, respectively

ing year). It is interesting to note that we detected more rapid decreases during both the pre-drought and drought periods, which varied at a seasonal scale in the four sub-basins. During the pre–drought period, autumn yielded the highest decreasing rates with values of -1.60×10^6 (Zhongtangmei), -1.10×10^6 (Daomaguan), -4.89×10^6 (Dongcicun) and -1.10×10^6 (Fuping) $\times 10^6$ m^3/yr. During the drought period, the highest decreasing rates in the sub–basins occurred during different seasons, namely, -0.94×10^6 (summer), -0.70×10^6 (winter), -5.37×10^6 (autumn), and -2.21×10^6 m^3/yr^2 (autumn) for Zhongtangmei, Daomaguan, Dongcicun and Fuping, respectively. In all, baseflow rapidly decreased during drought periods, and mean annual baseflow decreased by 50.4%, 49.6%, 71.7% and 53.2% in the Zhongtangmei, Daomaguan, Dongcicun and Fuping sub–basins, respectively. Especially, compared to the other sub–basins, baseflow in the Dongcicun sub-basin exhibited a significant decreasing trend ($P < 0.01$) with a rate of -6.12×10^6 m^3 at an annual scale. The BFI confirmed that the decrease in baseflow remained consistent with that of streamflow during both pre-drought and drought periods in the Dongcicun sub-basin. The prolong drought in the Dongcicun sub-basin significantly affected both streamflow and baseflow, which resulted in an extended hydrological drought period compared to the other three sub-basins.

4 Discussion

4.1 Using precipitation to detect extreme meteorological drought

Climate change not only involves changes in mean climate conditions but also changes in weather extremes (Fischer and Knutti, 2015). Increases in the frequency and magnitude of climate extremes have been predicted by global climate models, which are also supported by evidence pertaining to an increase in precipitation extremes (Knapp et al., 2015). As summarized by Knapp et al. (2015), such weather extremes are evident from studies that reported on record high yearly rainfall, extensive and extended periods of meteorological drought and shifts in intra-annual rainfall patterns. As shown in Figs. 2–3 and Table 1, precipitation exhibited a significant decreasing trend ($P < 0.05$) in the BYD basin, a subbasin of the Haihe River basin, China, which is consistent with results reported in previous studies (i.e., Zhang et al., 2012; Du et al., 2014; Qin et al., 2015). As expected, extensive and extended periods of meteorological drought are characterized by increased heavy rainfall events from high energy convective systems, fewer overall rainfall events (resulting in an increase in dry days) and longer intervening dry periods between such events (Janssen et al., 2014; Knapp et al., 2015). Interestingly, Du et al. (2014), who explored both annual maximum precipitation series and peaks over a threshold series, found that decreasing trends in extreme precipitation were detected at most meteorological stations in the Haihe River basin. Prein et al. (2016) reported that scaling rates between extreme precipitation and temperature events were strongly dependent on the region as well as temperature and moisture availability, and their results revealed that extreme precipitation events have caused temperatures to increase in moist, energy–limited environments and to abruptly decrease in dry, moisture-limited environments. Our study confirmed the existence of an extended extreme meteorological drought event of approximately 178 months (roughly 15 yr) that occurred between August 1996 and May 2011 (shown in Fig. 3). This extreme meteorological drought event, determined using precipitation deficits, was similar to that determined through multiscalar drought indices, namely, three typical inter-annual drought events that occurred between 1980–1985, 1999–2003 and 2005–2008 in the Haihe River Basin (Liu et al., 2016). Furthermore, drought, defined by precipitation deficits, varied in different stations and exhibited distinct spatial patterns (Table 1), which inevitably influence hydrological processes. These findings indicated that changes in the BYD basin have dramatically altered water allocation from precipitation, which will inevitably alter hydrological processes and influence aquatic ecosystems in the region.

4.2 Alterations in baseflow response to climate change and anthropogenic activities

Climate change is intensifying hydrologic cycles and is predicted to increase the frequency of extreme wet and dry years (Knapp et al., 2015). As expected, the decreasing trend in precipitation resulted in a decrease in streamflow (Table 1 and Table 3), which other studies have also confirmed (e.g., Bao et al., 2012; Yang et al., 2018). The impact of extreme meteorological drought has resulted in an increase in hydrological drought in the form of a reduction in baseflow and total streamflow (Table 3). It is interesting to note that a time lag commonly exists for hydrological recovery from meteorological drought, wherein the time lag for baseflow recovery is generally longer than that of streamflow recovery, which is similar to results reported by Yang et al. (2017). Baseflow is the last step in drought propagation from the atmosphere to the land surface, and its recovery typically requires catchment water storage to exceed a certain threshold. In contrast, streamflow responds directly to precipitation, and consequently undergoes a shorter lag time following a precipitation event. Furthermore, the hydrological response to meteorological drought was affected by the spatial variability of precipitation. Longer and more frequent meteorological drought events can cause a sharp decrease in baseflow and a delay in hydrological recovery, especially in the Dongcicun basin (Table 1 and Fig. 4). In point of fact, baseflow is correlated to climate and landscape properties, such as soil, geology, topography and vegetation; however, a universal relationship or a general theory has yet to be determined (Price, 2011; Gnann et al., 2019).

Complex response mechanisms in baseflow variability also exist (Gnann et al., 2019). Such baseflow variability can result from: 1) climate change, namely, extreme meteorological drought can lead to a reduction in baseflow (Yang et al., 2017); 2) changes in terrestrial characteristics resulting from overgrazing and excessive afforestation (Wu et al., 2019), namely, the impact of the Grain for Green program on the Chinese Loess Plateau has altered its hydrologic cycle through increased vegetation cover, leading to increasing rates of actual evapotranspiration that subsequently intensifies soil desiccation (Zhang et al., 2018); 3) the excessive exploitation of groundwater, leading to a reduction in the lateral discharge of groundwater which subsequently reduces baseflow (Wang et al., 2006); and 4) the construction of large reservoirs, which has dramatically altered hydrological processes associated with both total streamflow and baseflow (Kobierska et al., 2015). Given that baseflow plays an important role in sustaining the health of river ecosystems, other studies have also assessed suitable ecological water practices (Beatty et al., 2010; Ficklin et al., 2016), which will help to address problems associated with extreme climate change and anthropogenic activity.

5 Conclusions

Baseflow variability, which plays a vital role in sustaining the health of river ecosystems, reflects the impacts of extreme climate events. This study investigated baseflow response to an extreme meteorological drought event in the BYD basin, a temperate water-limited basin in North China. Several conclusions can be drawn from our findings:

We detected a precipitation deficit from August 1996 to May 2011 which was consistent with a corresponding decrease in annual precipitation, a period that resulted in an extended extreme meteorological drought event that lasted for a total of 178 mon (roughly 15 yr). In all four sub-basins investigated, we found that hydrological drought (including streamflow and baseflow) that followed the extreme meteorological drought event lagged behind its start and end dates. Moreover, the duration of hydrological drought exceeded that of metrological drought, which confirmed the existence of a time lag in the recovery from meteorological to hydrological drought.

Compared to pre-drought periods, baseflow response to meteorological drought varied at both seasonal and annual scales. Influenced by precipitation deficits, baseflow rapidly decreased during drought periods. For example, mean annual baseflow decreased by 50.4%, 49.6%, 71.7% and 53.2% in the Zhongtangmei, Daomaguan, Dongcicun and Fuping sub-basins, respectively. Particularly, hydrological drought reflected the complex interactions between catchment characteristics (i.e., catchment area, terrain, vegetation and water status) and climate change, which can cause different hydrological responses (i.e., such as that observed in the Dongcicun sub-basin). Investigating baseflow response to extreme climate events will help us to better understand alterations in hydrological regimes, ultimately mitigating climate change-induced impacts.

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