Response of hydrological processes to permafrost degradation from 1980 to 2009 in the Upper Yellow River Basin, China

Li Niu, Baisheng Ye, Yongjian Ding, Jing Li, Yinsheng Zhang, Yu Sheng and Guangyang Yue

ABSTRACT

Watersheds in cold regions are undergoing climate warming and permafrost degradation, which result in quantitative shifts in surface water–groundwater interaction. Daily discharge, annual maximum frozen depth (AMFD) of seasonal frozen soil, precipitation and negative degree-day temperature were analyzed to explore changes and correlations of climate, runoff and permafrost in the Upper Yellow River Basin from 1980 to 2009. Plausible permafrost degradation trends were found at two of the stations, but an unsubstantiated trend was found at Huangheyan Station. The winter recession processes slowed down gradually from 1980 to 2009 at three stations but had little relation to AMFD. Meanwhile, the ratio of monthly maximum to minimum discharge reduced significantly. It is clear that permafrost degradation and runoff variations have already occurred in the basin, particularly in zones where the permafrost coverage is above 40%. It is proposed that the variations in the hydrological regimes were caused by permafrost degradation which enlarged infiltration and sub-surface water contribution to winter discharge. The differences of changes in runoff generation and confluence in various regions were thought to be affected by different permafrost coverage and changes because the exchange of groundwater and surface-water mediated by permafrost.

Key words | China, climate warming, hydrological processes, permafrost, response, Upper Yellow River Basin

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INTRODUCTION

Changes in discharge are currently being observed in many river basins across the colder and higher-latitude regions, which have been linked to recent climate warming (Woo & Thorne 2008; Oberman & Busygina 2009; He *et al.* 2010; Niu *et al.* 2010). The well-documented changes include: (1) increase of winter runoff (Liu *et al.* 2003; Ye *et al.* 2009; Rennermalm *et al.* 2010); (2) increase of total discharge (Yang *et al.* 2004; Rawlins *et al.* 2009a, 2009b); (3) changes of recession processes (Lyon *et al.* 2009; Niu *et al.* 2010); and (4) increasing groundwater runoff (Walvoord & Striegl 2007; Ge *et al.* 2011; Cheng & Jin 2012). These changes are considered by several studies to be induced by permafrost degradation (Bense *et al.* 2009; Liu *et al.* 2011; Frampton *et al.* 2012) but are heavily debated since it is difficult to distinguish the impacts of permafrost degradation from other hydroclimatological influences (McClelland *et al.* 2004; Stocker & Raible 2005; Quinton & Baltzer 2012; Sjöberg *et al.* 2012). Therefore, the variation of hydrological processes due to permafrost degradation has become one of the most important issues in the field of climatology and hydrology, especially in cold region hydrology research (Ma & Jin 2008; Woo *et al.* 2008).

Hydrological regimes in permafrost zones have specific characteristics induced by impermeability, water storage

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capacity and evaporation (Sun *et al.* 2008) because of the moisture movement and heat transfer in the freezing–thawing processes of the active layer. Components of the hydrological regimes in the cold regions of China have already been affected by climate change (Liu *et al.* 2007). Previous studies have indicated that permafrost degradation affects basin hydrological processes mainly by influencing subsurface hydrology of cold regions (Camill 1999; Liu *et al.* 2003; Gong *et al.* 2006; Walvoord & Striegl 2007; Ye *et al.* 2009; Niu *et al.* 2010; Camill & Clark 2014). It is suggested that discharge and recession flow characteristics in cold regions potentially have a closer relationship with permafrost dynamics. However, river drainage in the basin can be affected by many factors during the warm seasons, such as rainfall, evapotranspiration and snowmelt, but is controlled mainly by subsurface water during the winter (Woo 1986). Therefore, winter discharge detected in some cold regions has been considered to be related to permafrost degradation (Liu *et al.* 2003; Ye *et al.* 2009; Obyazov & Smakhtin 2013; Watson *et al.* 2013). However, the variation of winter discharge can be caused by factors other than permafrost degradation, such as autumn runoff, precipitation, snow cover and so on. Some studies have shown that winter discharge recession processes slowed down, with a clear decrease in surface water runoff (Zhang 2005; Wang *et al.* 2006; Cheng & Wu 2007). By analyzing the relationship between precipitation and runoff, Yamazaki *et al.* (2006) suggested that the direct runoff coefficient increased with the attenuation of the active layer, and the recession rate decreased. Therefore, the variation of recession processes of winter discharge, indicated by recession coefficient (*RC*), can successfully index the runoff response to permafrost change (Ye *et al.* 2009; Niu *et al.* 2010). However, a fundamental understanding of the nature and controls of permafrost degradation is still lacking. Part of the lack of progress is due to limited information on permafrost distribution and conditions, and a lack of demand for water-resource information in this sparsely populated region.

In this paper, variations in discharge behavior induced by hydrological changes can be conceptually described as follows: (1) the variations in the freezing–thawing processes of the active layer in this study are mainly the results of climate warming; (2) the increasing thawing depth of permafrost enlarges the water storage capacity of the basin, allows more water to be released into the baseflow in winter and causes changes in evapotranspiration; (3) hydrological regimes become flat in most of the permafrost regions which means that the differences between peak flow and winter flow are reduced; and (4) the recession processes are slowed down in permafrost regions.

When measuring the *RC* in winter as a key parameter, the following two main assumptions were made. First, all discharge measured in winter was regarded as the drainage of groundwater because there was no liquid water supply (rain or snow/ice melt water) in the basin in winter. Second, the winter recession reflected the groundwater storage capacity when groundwater storage was treated as a linear subsurface storage reservoir. Based on the two premises above, RC in winter can be used to reflect the subsurface storage reservoir capacity of the Upper Yellow River Basin (UYRB).

Using UYRB (regions above Tangnaihai Hydrometric Station) as the study area, this article focuses on exploring hydrological trends and permafrost variability to gain more comprehensive knowledge of the responses of discharge to permafrost degradation induced by climate warming.

STUDY AREA

The UYRB is located in the northeastern Qinghai–Tibet Plateau at latitudes between 31 and 36 °N (Figure 1) with an average elevation of 4,000 masl. The spatiotemporal distribution and variation of water resources in the UYRB is significant for the entire basin because, as the 'water tower' of the basin, it accounts for approximately 57.5% of the water resources and 20% of the total area of the Yellow River Basin (Zhao *et al.* 2008). Permafrost is extensive in the basin (Cheng & Jin 2012).

The UYRB belongs to the Qinghai–Tibet Plateau climate system. The mean annual air temperatures at the four meteorological stations considered are between −0.6 and −4.2 °C with lower temperatures in the catchments spanning higher elevations and latitudes. Precipitation, subjected to Bengal Bay and the Pacific Ocean, is mainly concentrated in the summer and is sparsest in the winter, ranging from 250 to 750 mm/a. The streamflow is dominated by baseflow

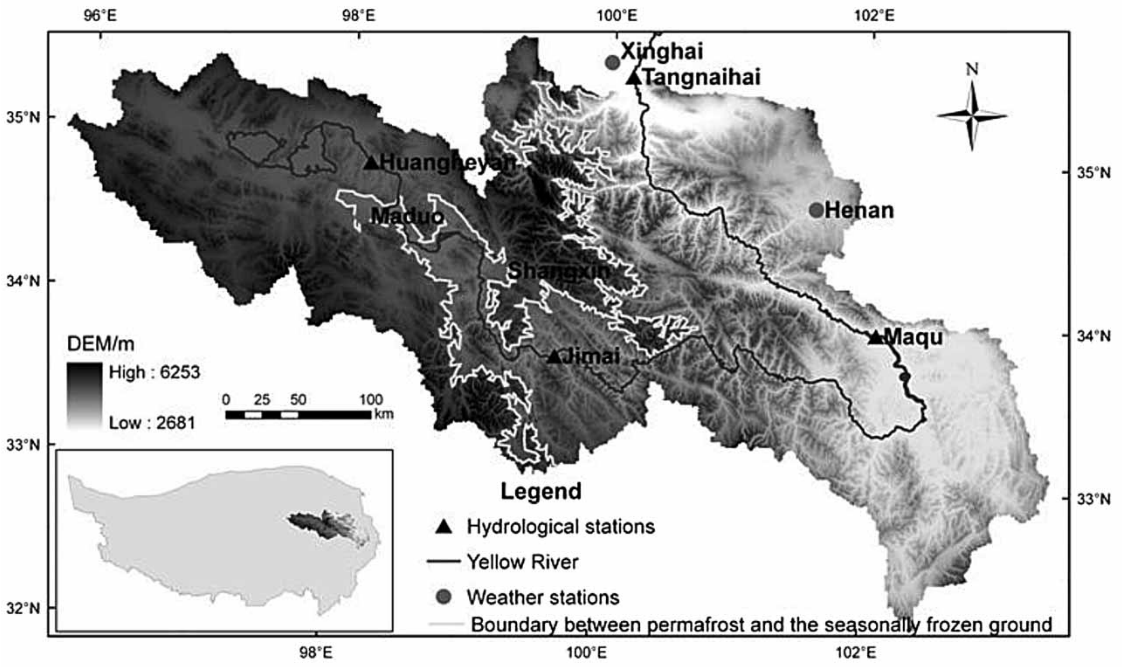

Figure 1 | Distribution of the hydrological and meteorological stations in the UYRB.

during October–April because precipitation falls as snow (Cuo *et al.* 2013). The spring peak discharge accounts for nearly 40% of the total runoff at the four hydrological stations used in this study. Climate changes have major impact on the hydrological regimes and environment of the UYRB (Wang *et al.* 2001), especially in recent years (Zhang *et al.* 2004; Cao *et al.* 2006; Chen *et al.* 2007; Cheng & Wu 2007; Lan *et al.* 2010). The annual mean precipitation has been approximately 200–600 mm with an annual runoff of 58 billion m^3 (Yang & Li 2004). Further investigation is required to determine the reasons for the variations of the hydrological regimes in the UYRB.

DATA

Based on the considerations that (1) the time series of hydrological and meteorological data are the same and uninterrupted, (2) the geographical environment of the hydrometric and meteorological stations of a sub-basin are almost the same or similar, (3) the data used in this paper is the most representative for each sub-basin, and (4) the stations selected are distributed across different parts and can represent the different attributes of a basin, we selected four hydrometric and four meteorological stations in the UYRB (Figure 1). The annual maximum frozen depth (AMFD) of seasonal frozen soil was obtained from National Meteorological Center to represent permafrost conditions because there were no direct and long-term observations of the permafrost active layer depths in the basin. The frozen soil depth is directly measured by using frozen soil apparatus at the meteorological stations. Daily discharge was obtained from years 1980 to 2009 at Jimai, Maqu, and Tangnaihai hydrometric stations, and from 1980 to 2004 at Huangheyan Hydrometric Station. Based on the distribution of the hydrometric stations, data of AMFD, temperatures, and precipitation from the nearest weather stations was obtained from the China Meteorological Administration. AMFD from 1980 to 2009 was obtained from Maduo, Shangxin, Henan, and Xinghai meteorological stations. Air temperature and precipitation from 1980 to 2009 were collected from Maduo, Dari, Jiuzhi, and Xinghai meteorological stations. The AMFD above the Jimai Hydrometric Station was not considered in this article because the data series from the Shangxin Meteorological Station were too short (from 1991 to 1996). The locations of the study area, boundary between permafrost and seasonal frozen soil, selected hydrological and meteorological stations are shown in Figure 1. Information of the UYRB and the selected gauging stations is listed in Table 1.

METHODS

The permafrost distribution shown in Figure 1 was calculated by using an empirical-statistical model, which expressed variations of the altitudinal permafrost lower limit with latitude in the northern hemisphere as the Gaussian distribution curve function (Cheng & Wu 1983; Cheng 1984; Cheng & Dramis 1992):

$$H = 3,650 \times \exp\left[-0.003 \times (\varphi - 25.37)^2\right] + 1,428 \tag{1}$$

where H (m) is the lower limit of the permafrost and φ is the latitude (°).

The permafrost distribution in the UYRB was defined using this model based on the digital elevation model data. First, the distribution patterns of permafrost in the Qinghai–Tibet Plateau were mapped based on the Gaussian distribution curve function. Then, permafrost area was divided by basin area to get the permafrost coverage as a result. Previous research has verified that the Gaussian curve is suitable for the plateau scale (Wu *et al.* 2010; Li *et al.* 2012) especially when there is no other data to support the calculations. The calculated results show that the coverage of permafrost (CP) is around 90%, 80%, 46% and 42% in the areas above Huangheyan, Jimai, Maqu and Tangnaihai hydrometric stations, respectively, and is considered to be a constant in this article. The 'boundary between permafrost and seasonal frozen soil' means the boundary between the zones where CP > 90% and those CP < 90%, not the boundary between CP > 0 and CP = 0. In addition, the AMFD of seasonal frozen soil was analyzed to represent permafrost changes because there were no direct and long-term observations of permafrost active layer depth.

To analyze the trends and variation of the hydrological regimes and frozen soil from 1980 to 2009, a common linear regression method was applied with the statistical significance test.

Certain representative and sensitive parameters of discharge can be used to express the relationship between the hydrological process and permafrost degradation (Gong *et al.* 2006). In this study, RC in winter and the ratio of monthly maximum to minimum discharge ($Q_{\max}/Q_{\min}$) were measured as appropriate representatives and sensitive parameters.

There is an exponential behavior which can represent the recession process (Tallasken 1993):

$$Q_t = Q_0 \cdot e^{-kt} \tag{2}$$

where Q_t is the discharge at time t (March in this paper), Q_0 is the discharge at the onset of the recession period, which is November, and k is a recession constant. In this paper, yearly recession constant is the RC. $Q_{\max}/Q_{\min}$ was also calculated in this article as it reflected the modulability of the groundwater on discharge.

To understand the impact of permafrost degradation on hydrological processes, the relationship between the two hydrological parameters and AMFD was comprehensively analyzed. However, permafrost degradation is a long-term and sluggish process and lags behind climate change. It was therefore assumed that the responses of the hydrological processes may also lag behind the permafrost degradation. Therefore, the correlation coefficients of the 1-, 3-, 5-, and 7-year moving averages between RC, $Q_{\max}/Q_{\min}$, and AMFD were calculated, except for Jimai Station because the AMFD time series there was too short.

Table 1 | Geophysical position, control area and permafrost coverage of the hydrological and meteorological stations in the UYRB

Hydrometric station	Meteorological station nearby	Longitude (°)E	Latitude (°)N	Basin area (km^2)	Permafrost coverage
Huangheyan	Maduo	98.17	34.88	20,930	100%
Jimai	Dari/Shangxin	99.65	33.77	45,019	80%
Maqu	Jiuzhi/Henan	102.08	33.97	86,048	46%
Tangnaihai	Xinghai	100.15	35.50	121,972	42%

RESULTS AND DISCUSSION

Trend analyses on the time series of annual precipitation and negative degree-day temperature (NDDT) were carried out. The increase rate of NDDT was 14.3, 9.1, 8.6, and 4.9 °C/a at the 99%, 99%, 98%, and 96% significance levels for Huangheyan, Jimai, Maqu, and Tangnaihai stations, respectively, from 1980 to 2009 (Figure 2). As a result, significant warming was detected in the UYRB that increased gradually from downstream to upstream, which might be one of the most important reasons for environmental changes, especially for the variation of underlying surface of the basin. However, there was no distinct variation in the basin for precipitation (Figure 3), which meant that precipitation had little effect on the trends of permafrost and hydrology. The effects of seasonal precipitation and extreme precipitation events were not analyzed here, although they might also affect the processes and relationships between hydrology and permafrost. Besides, evapotranspiration, an important component of the water cycle, is not detected here because of inadequate data, so it is difficult to determine how it affects the total amount of water available for discharge.

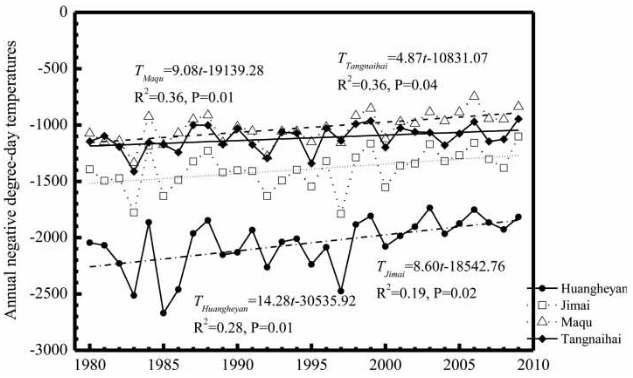

Figure 2 | Annual negative degree-day temperatures for the UYRB from 1980 to 2009.

The sporadic or discontinuous permafrost zones are below the boundary between permafrost and seasonal frozen soil as shown in Figure 1. The permafrost accounts for about 42% of the area above Tangnaihai Station, 46% above Maqu Station, 80% above Jimai Station, and 90% above Huangheyan Station based on the results of Equation (1), which decreased downstream as shown in Figure 1 in the UYRB. It will be more reliable if there is direct observation on permafrost distribution in UYRB, although the methods we used to calculate the permafrost coverage were verified to suitable for mountainous areas of Western China. The average AMFD was 219.1 cm (deepest in the UYRB) for the regions above Huangheyan Station, 193.7 cm above Jimai Station, 123.9 cm above Maqu Station (thinnest in the UYRB), and 161.8 cm above Tangnaihai Station. The AMFD above Tangnaihai (the lowest station

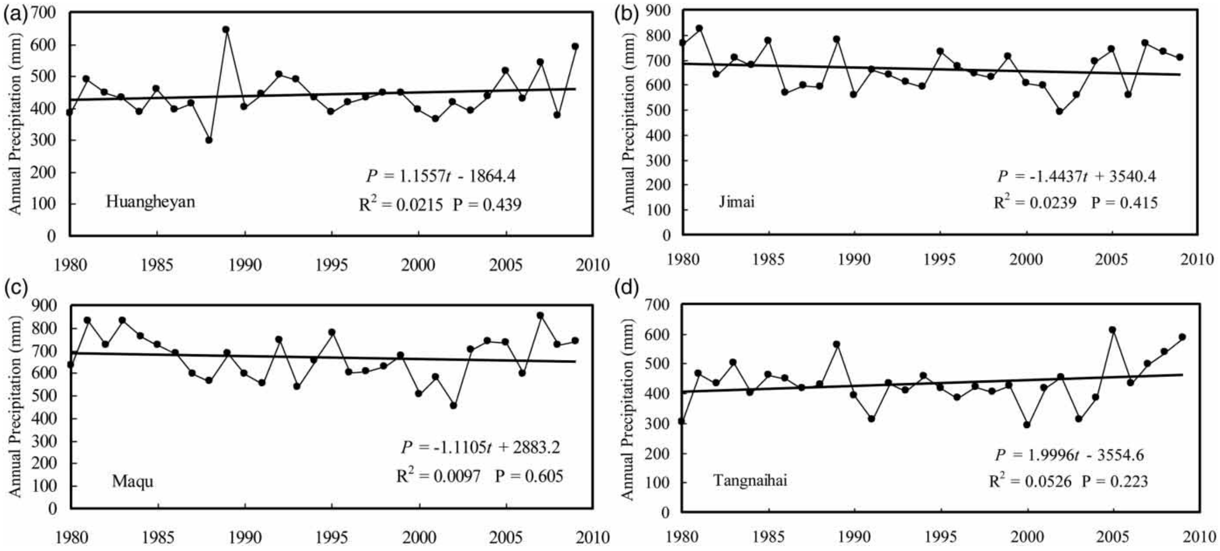

Figure 3 | Annual precipitations in the UYRB from 1980 to 2009.

in the UYRB) was deeper than that above Maqu Station because the former lies to the north of the latter. The decreased rate of AMFD was 0.99 cm/a at the 99% significance level above Maqu Hydrometric Station and 0.79 cm/a at 98% significance level above Tangnaihai Hydrometric Station as shown in Figure 4. AMFD showed an indistinct increase trend at Huangheyan Stations, which was 0.12 cm/a at the 16% significance level. The AMFD trend at Jimai Station was not evaluated because of a lack of data. In general, AMFD was stable above Huangheyan Station, while decreasing obviously for other areas in UYRB.

As a result, it was concluded that: (1) permafrost degraded evidently in the regions where permafrost coverage was equal to or less than 46%, but stable in the regions around Huangheyan Station; and (2) the permafrost changes were ambiguous around Huangheyan Station although the warming amplitudes there were the greatest in UYRB. It is found that: (1) the permafrost situation was relatively stable in the regions where the permafrost coverage was around 90%; and (2) the most unstable zones were the regions where permafrost coverage was around 45%. Because of the lack of data at Jimai Station, permafrost changes are unclear in the regions where permafrost coverage was between 45 and 90%.

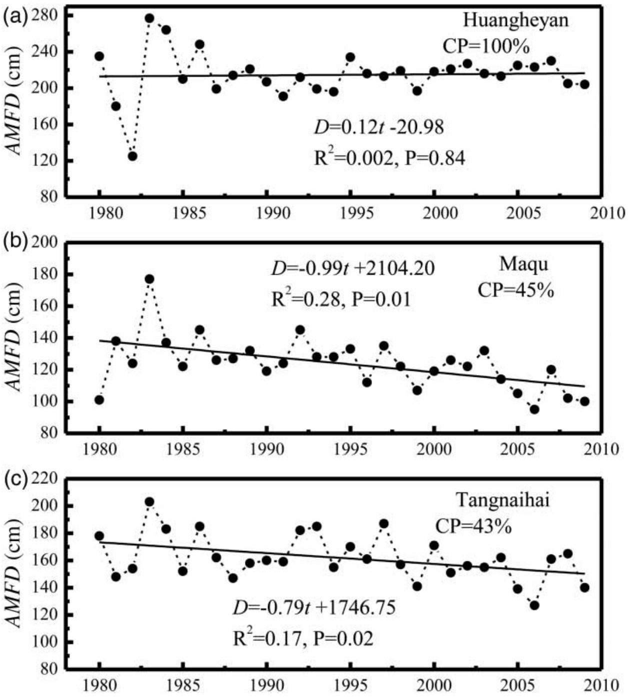

Figure 4 | AMFD in the UYRB: (a) Huangheyan Hydrometric Station; (b) Maqu Hydrometric Station; and (c) Tangnaihai Hydrometric Station.

The analysis of $Q_{\max}/Q_{\min}$ suggests different trends for the four sub-basins from 1980 to 2009 in the UYRB, as shown in Figure 5a(1)–5d(1). The decreased rates were 0.21/a, 0.20/a and 0.15/a at the 98%, 99%, and 99% significance levels at Jimai, Maqu and Tangnaihai stations, respectively. $Q_{\max}/Q_{\min}$ did not obviously increase for Huangheyan Station. It is clear that $Q_{\max}/Q_{\min}$ decreased markedly in the regions below Huangheyan Station. The results indicate that the hydrological regime became flat over the past decades in UYRB except the regions where the permafrost coverage was around 90%. In general, the difference between peak flow and winter runoff were reduced.

For RC in winter, the decreasing trends were 0.01, 0.004, 0.003 and 0.001/a for Huangheyan, Jimai, Maqu and Tangnaihai stations at the 95%, 98%, 96%, and 60% significance levels, respectively (Figure 5a(2)–5d(2)). RC decreased distinctly in the regions above Maqu Station. The decrease of RC can be considered to be caused by a reduction of drainage water volume and/or an increase of groundwater reservoir capacity. Therefore, the variations in these two parameters indicated that the changes in hydrological processes had already occurred in the UYRB under climate warming.

Furthermore, it is proposed that: (1) variations of hydrological processes occurred in UYRB regardless of whether the regions had high or low permafrost coverage; (2) that hydrological regimes became flat in most of the regions in UYRB which meant that the differences between peak flow and winter flow were reduced; and (3) the recession processes slowed down in most regions of UYRB.

The relationships between the two hydrological parameters and AMFD are shown in Figures 6–8. For the Huangheyan Hydrometric Station, neither hydrological parameters showed a distinct relationship with AMFD, which was also the case for all (1-, 3-, 5- and 7-year) moving averages (Figure 6). Significant increasing trends occurred when the moving average time was 3 years for Maqu Hydrometric Station (Figure 7). RC decreased obviously only when the moving average was 7 years at Tangnaihai Hydrometric Station (Figure 8). In general, $Q_{\max}/Q_{\min}$ had a positive

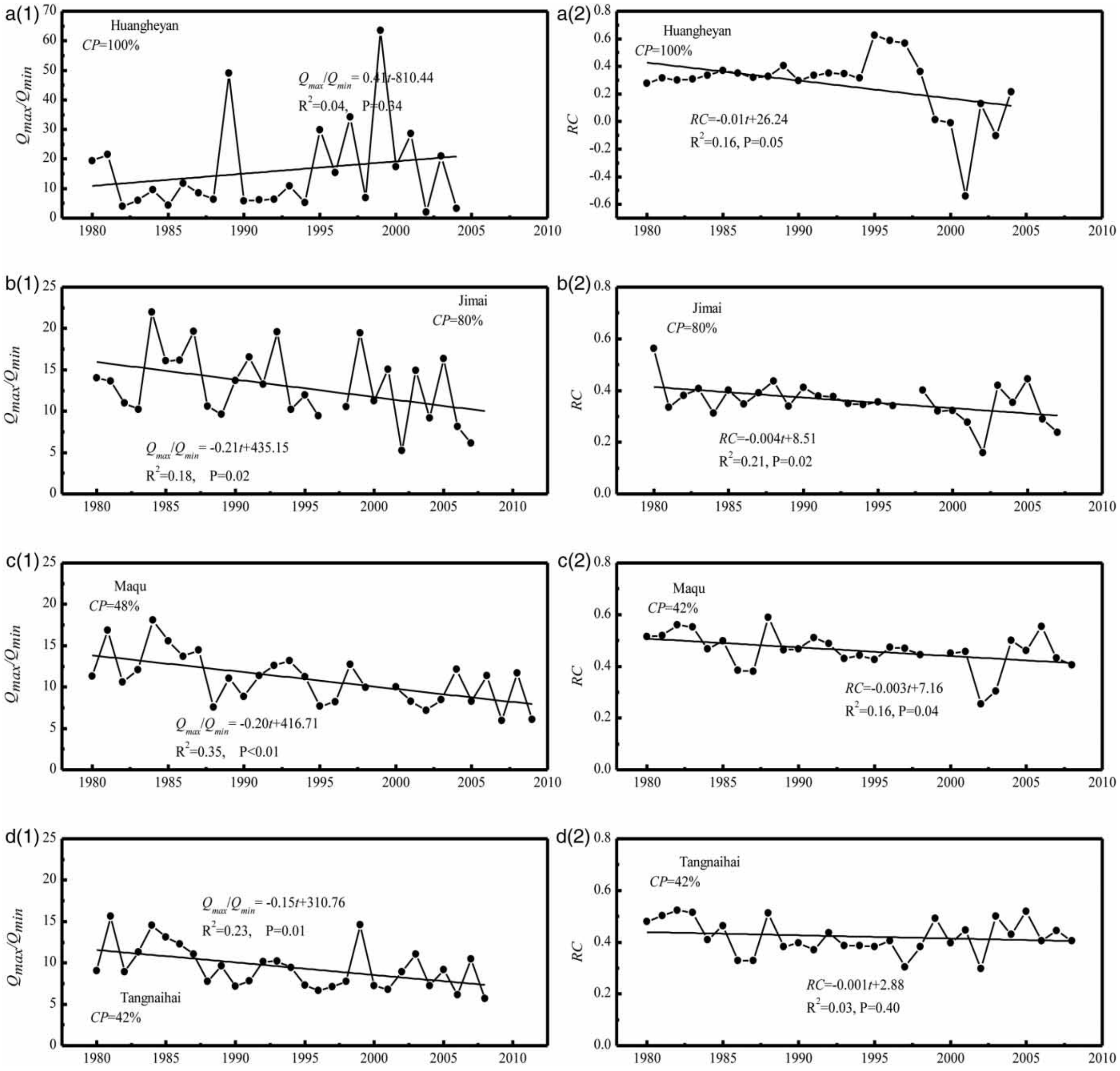

Figure 5 | Trends of *Q*max/*Q*min shown in a(1), b(1), c(1) and d(1) and RC shown in a(2), b(2), c(2) and d(2) from 1980 to 2009 for the UYRB.

correlation with the increasing of AMFD, especially when the moving average was 3 years for Maqu Station. However, RC displayed little correlation with AMFD.

Variations in hydrological parameters are thought to be affected by permafrost degradation as it leads to an enhanced percolation area and enlarges ground water storage capacity. As shown in Figure 7, hydrological processes were affected most obviously in the regions where the permafrost coverage was between 80% and 45%. For Huangheyan Station, where the permafrost coverage is about 90%, it seemed that changes in hydrological regime were not induced by permafrost degradation, because the permafrost was relatively stable there as shown in Figure 4(a). For Maqu and Tangnaihai stations, when the average moving time was long enough, the relationships between hydrological parameters and AMFD would become clear. It was suggested that the response of the hydrological process was a slow and long-term progression. However, the trend of $Q_{\max}/Q_{\min}$ was not clear in the areas with extremely high permafrost coverage, while the trends of RC were not distinct in the regions

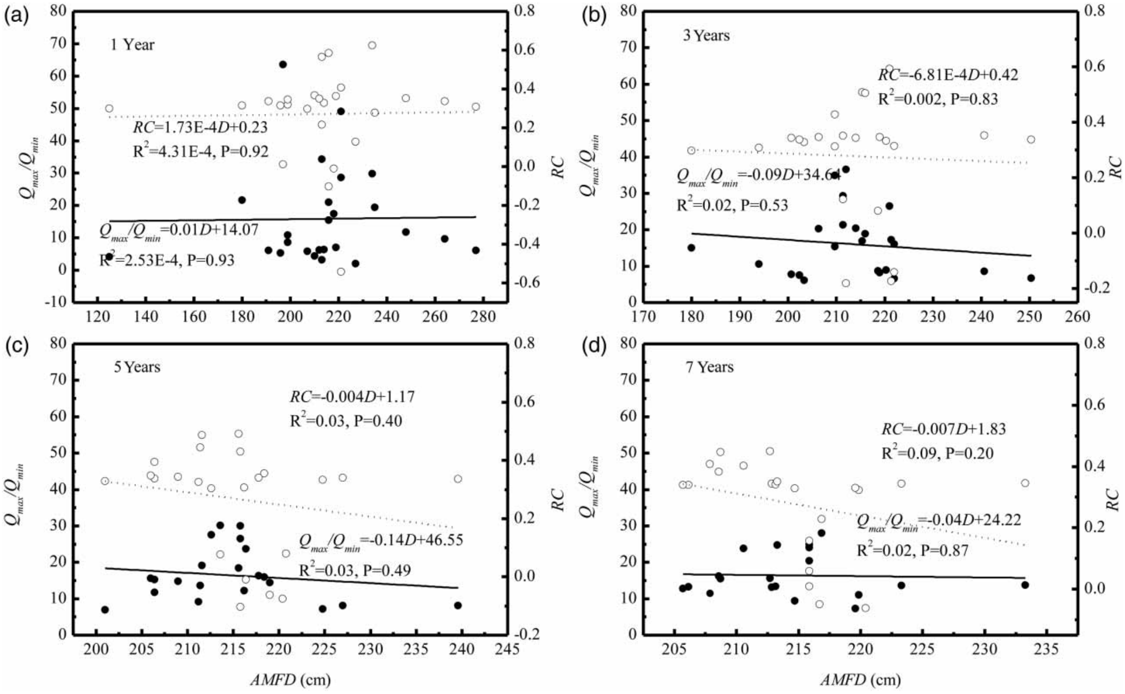

Figure 6 | RC in winter vs. AMFD (solid circle and lines) and *Q*max/*Q*min vs. AMFD (open circles and dashed lines) based on the (a) 1-year, (b) 3-year, (c) 5-year and (d) 7-year moving average methods at the Huangheyan Hydrometric Station.

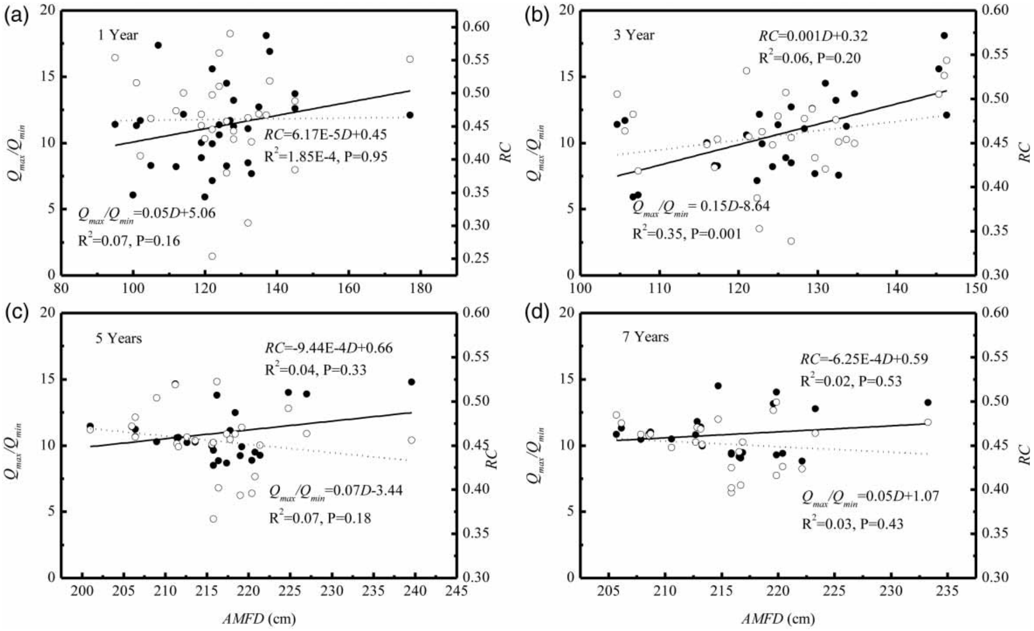

Figure 7 | RC in winter vs. AMFD (solid circles and lines) and *Q*max/*Q*min vs. AMFD (open circles and dashed lines) based on the (a) 1-year, (b) 3-year, (c) 5-year and (d) 7-year moving average methods at the Maqu Hydrometric Station.

with relatively lower permafrost coverage. Because it is much colder in the basins with higher permafrost coverage, permafrost changes caused by warming have less of an immediate impact on the hydrological processes. Conversely, the frozen ground in basins with relatively low permafrost coverage is sensitive to climate change but has

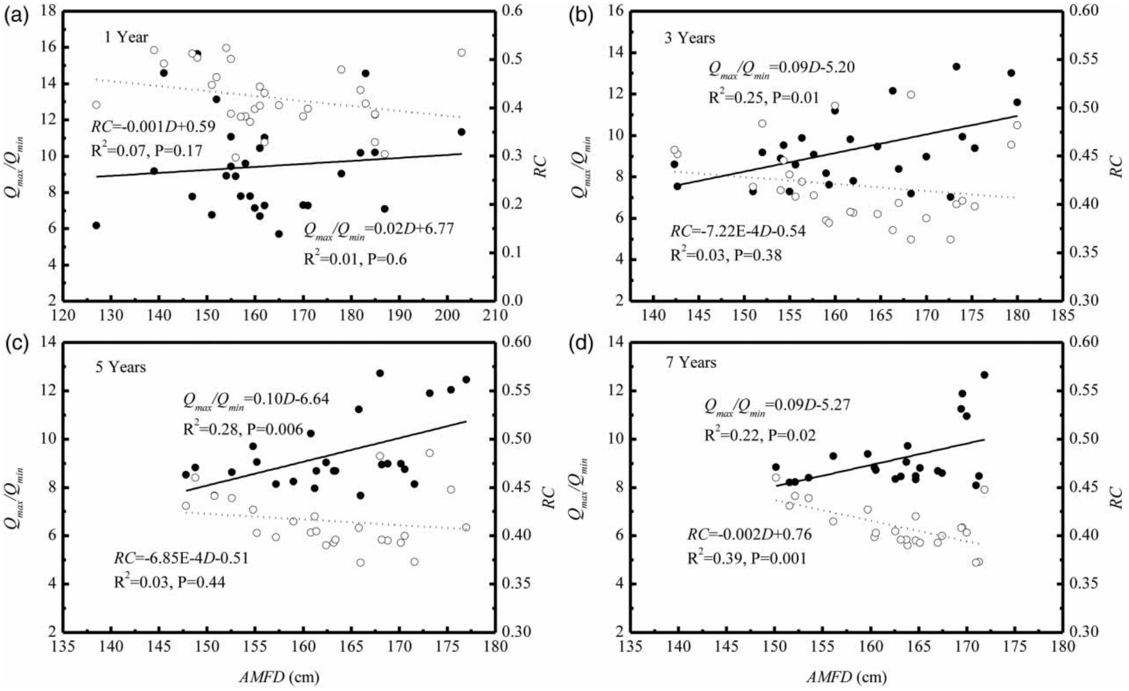

Figure 8 | RC in winter vs. AMFD (solid circles and lines) and *Q*max/*Q*min vs. AMFD (open circles and dashed lines) based on the (a) 1-year, (b) 3-year, (c) 5-year and (d) 7-year moving average methods at the Tangnaihai Hydrometric Station.

limited influence on hydrological processes. Drawing conclusions about the regions where the permafrost coverage is between 100% and 45% is not possible because of the data deficiency at Jimai Station. Furthermore, the response and relationships between hydrology and permafrost in the UYRB can be very different from those in other basins because of the different basin characteristics including ice content, active layer depths, vegetation, geographical positions, and evapotranspiration.

Limited by inadequate data, it was difficult for us to fully understand the changes in hydrology processes. The changes in hydrology regimes could also be induced by other environmental factors and required further investigation. For example, changes in land-use, lakes, vegetation coverages, evapotranspiration and so on.

CONCLUSIONS

The hydrological processes of the UYRB, which is an important runoff generating region of the Yellow River, have great significance for the entire river basin. Global warming has affected the study area significantly, especially in regards to permafrost, the existence and change of which would profoundly influence the regional environment.

It has been suggested that permafrost degradation caused by climate change has induced the thickening of the active layer and growth of groundwater storage capacity. This has led to a decreased maximum monthly discharge in the summer due to more surface water infiltrating groundwater, and a high minimum monthly discharge in winter caused by more groundwater supplied by rivers (Kane 1997). Previous research has verified that $Q_{\max}/Q_{\min}$ has a positive relationship with permafrost coverage (Ye *et al.* 2009) and is therefore reduced with permafrost degradation (Niu *et al.* 2010).

In this case study of the UYRB, the following have been indirectly demonstrated: (1) a warming trend; (2) distinct degradation of the permafrost except for the regions around Huangheyan Station; and (3) hydrological regimes changed to a gradual flat.

However, the relationship between hydrological parameters and AMFD in regions where the permafrost coverage was above 90% were not significant, which suggests that in these type of zones, hydrology regimes were not affected mainly by permafrost degradation, although the warm spell was stronger than that in other areas. Because the increase of soil permeability and water storage capacity induced by permafrost degradation in the UYRB can be considered to affect runoff production and concentration, the regulation of permafrost on discharge will likely increase as well. Our results suggested that hydrological processes are likely to be affected by climate warming, and are sensitive to permafrost changes, although the response of different basins varies considerably because of different permafrost coverage and other environmental factors. Accordingly, this study from a typical basin of the Qinghai–Tibet Plateau represents an indication of how NDDT changed, and permafrost degradation in particular may cause gradual changes in the geophysical environment with important effects on hydrological processes.

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