Complex response of runoff–precipitation ratio to the rising air temperature: the source area of the Yellow River, China

Jiongxin Xu

Received: 12 April 2013 / Accepted: 5 April 2014 / Published online: 4 May 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract The impact of climate warming on the water cycle and water resources is an important issue in science and for sustainable socioeconomic development. The drainage area above Tangnaihai station is the source area of the Yellow River, which is located in the Qinghai–Tibet Plateau and yields 41.3 % of the river’s total natural runoff. Thus, it is known as the “water tower of the Yellow River.” Based on climate and hydrometric data from 1956 to 2008, the purpose of this study is to deal with the influence of climate warming on the water cycle in this region and thereby to provide some knowledge for sustainable water resources management of the Yellow River. The statistical analysis shows basically no trend in annual precipitation, but a significant rising trend in air temperature. Hence, this area is ideal to study the response of the water cycle system to climate warming. We found non-linear variations in annual runoff (Q_w) and the runoff–precipitation ratio (R_{rp}): they increased to a peak and then decreased. According to the response of R_{rp} to rising temperature, we established a three-stage descriptive model for the complex response of runoff generation to the rising air temperature. The mechanism of the complex response is explained based on the evidence of environmental changes

previously reported in the study area, driven by rising temperatures.

Keywords Water cycle · Climate change · Runoff generation · Complex response · The Yellow River’s source area · Qinghai–Tibet Plateau

Introduction

The impact of climate warming on the water cycle and water resources is an important issue in science and for sustainable socioeconomic development. The increased temperature has important consequences for the hydrological cycle, particularly in regions where water supply is currently dominated by melting snow or ice (Barnett et al. 2005). By the synthesis of river-monitoring data, Peterson et al. (2002) found that the average annual discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean increased by 7 % from 1936 to 1999. Milly et al. (2005) studied the global pattern of trends in streamflow and water availability in a changing climate, using an ensemble of 12 climate models. They pointed out that regional patterns of warming-induced changes in surface hydroclimate are complex and less certain than those in temperature because both regional increases and decreases in precipitation may occur, and therefore, the trend in runoff is uncertain and complex. If we select a region where the temperature rises while the precipitation remains unchanged, the hydrological response to warming may be isolated and better revealed.

The Qinghai–Tibet Plateau is regarded as one of the most sensitive regions of the world to global climate change, and many results concerning hydrological response have been reported (e.g., Singh and Kumar 1997;

Editor: Wolfgang Cramer.

Electronic supplementary material The online version of this article (doi:10.1007/s10113-014-0617-9) contains supplementary material, which is available to authorized users.

J. Xu (✉)
Key Laboratory for Water Cycle and Land Surface Processes,
Institute of Geographic Sciences and Natural Resources
Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: xujx@igsnrr.ac.cn

Immerzeel et al. 2012). The Yellow River has a serious water shortage and more than a third of its natural runoff comes from the drainage area above Tangnaihai station, the river's source area located in the Qinghai–Tibet Plateau. Thus, this area is called “the water tower of the Yellow River.” Due to its importance in science and for the national strategy of sustainable water resources development, many studies have been made of the changes in climate, environment, water cycle and water resources in this area in the recent 10 years. These studies show that in the past 40 years, air temperature significantly increased. Consequently, the glaciers melted (Liu et al. 2002), the permafrost thawed and became degraded (Wang et al. 2001; Yang et al. 2004; Jin et al. 2010), the lakes and wetlands shrank (Lu et al. 2005; Li et al. 2009), ground-water levels declined (Peng et al. 2003), and vegetation degradation (Zeng and Feng 2009; Kang et al. 2011), land degradation and desertification occurred (Zeng and Feng 2007). The river runoff showed a decreasing trend after 1989 (Liu and Chang 2005; Chang et al. 2007). However, some questions still remain unanswered: How does the rising air temperature influence the ratio of precipitation to natural runoff? Is the response linear or more complicated? What is the pathway of the water cycle adjustment after climate warming? To address these questions, we conducted a study based on climate and hydrometric data and the facts of environmental changes reported previously by other researchers and found a complex response phenomenon. The results are reported here.

Study area

Natural settings

In this study, the Yellow River source area (YRSA) is considered as the drainage area above Tangnaihai station (Fig. 1), which is 122,000 km² and accounts for 16 % of the Yellow River's total. The YRSA is located in the northern part of the Qinghai–Tibet Plateau between the Buqing and Bayankala Mountains. Above Huangheyan station, the landforms are wide valleys and basins filled by fluvial and lacustrine sediments. Between Chali in Maduo county and Tangnaihai in Gonghe county, high mountains and deep gorges are the dominant landforms. In the study area, wide valleys, alpine meadows, lakes and marshy swamps, and cold deserts are found (Editorial Committee of “A Physical Geography in China” 1981). According to the investigation in 1970, there are 58 glaciers with a total area of 192 km² and mainly located in the eastern slopes of the Animaqing Mountains. The elevation of the snow line ranges from 4990 m to 5190 m (Yang 1991; Liu et al. 2002). According the investigation in 1978, there were

5,300 lakes with a total area of 1,271 km², and the largest are the Eling Lake and the Zaling Lake.

Environment changes

Since the findings of the present study are based on environmental changes induced by climate warming in the past 50 years as previously reported, a brief review is given below.

Melting and retrogression of the glaciers

The rising temperature causes the melting and retrogression of the glaciers. This is supported by many studies made on the changes in glaciers in the YRSA based on a comparison of satellite images and field observations (Wang 1987; Liu et al. 2002; Yang et al. 2004).

Degradation of permafrost

The rising air temperature increases the soil temperature, and therefore, the permafrost that has degraded its distribution has contracted and its area decreased. In the meantime, the distribution of seasonally frozen soil has expanded (Wang et al. 1991; Jin et al. 2010). Based on observations at 46 meteorological stations in the Qinghai–Tibet Plateau, Wang et al. (2001) found that since the 1990s, the thickness of seasonally frozen soil showed a decreasing trend. Another indicator of permafrost degradation is the rising of its lower limit. The two surveys of permafrost in 1970 and 1990 indicate that the lower limit rose 50–70 m at the edge of permafrost distribution (Yang et al. 2004).

The observations at Maduo meteorological station show that the maximum seasonally frozen depths in the 1980s and 1990s were 2.35 and 2.23 m, a decrease of 0.12 m (Jin et al. 2010). Jin et al. (2010) studied the temporal variations in soil temperature measured at different depths (5, 10, 20, 40, 80, 160 and 320) from 1981 to 2004, and all curves show an increasing trend, with the total increase ranging from 0.3 to 0.7 °C during the 24 years. The groundwater temperatures measured from wells in Maduo town also show an increase. The average August temperature in the 1980s ranged from 0.8 to 1.3 °C, and in 2007, it ranged from 1.5 to 2.0 °C, indicating an 0.5–0.7 °C increase in the shallow groundwater temperature (Liang et al. 2007).

Due to the rising temperature, the pingos (or frost-heaving mounds) near the upper limit of the permafrost began thawing and collapsing. In the meantime, in localities at higher elevations, many new pingos have developed (Zhang et al. 2004). The large and continuously distributed permafrost has become patchy, the area greatly decreased and the thickness much thinner, and part of the patchy

Fig. 1 The Yellow River basin. The area enclosed by the dotted line is the YRSA

permafrost thawed and became seasonal frozen earth (Jin et al. 2010).

Lowering of groundwater level

The melted permafrost and seasonal frozen earth caused the lowering of groundwater levels. Due to the melting, the impermeable, frozen layers moved downward, and the groundwater system was transformed from a type of “suprapermafrost-water plus frozen water” to a type of “non-frozen water with free surface” (Peng et al. 2003).

Degradation of lakes and wetlands

In the YRSA, there are 5,300 lakes with a total area of 1,270.77 km². The largest two are Eling and Zaling Lakes, their areas are 614 km² and 528 km² and average water capacities are 4.7 and 10.8 billion m³, respectively. The other lakes are very small and distributed in the low-lying swampy zone near the rivers (The Yellow River Institute et al. 2009). Based on the comparison of satellite images, the lakes were found to be shrinking. Three causes are identified for the shrinking or drying out of the lakes: the release of water in lakes to the river, the rising air temperature that enhanced evaporation where precipitation remains basically unchanged and the land degradation that has increased infiltration (Peng et al. 2003; Lu et al. 2005).

Based on satellite images, the changes in wetlands have been studied by many researchers. Pan et al. (2007) studied

the changes in wetlands in an area of 6.5×10^4 km² in the YRSA during the period from 1986 to 2000 and found that the wetland area decreased by 585.48 km² (10 %). The area of wetlands also shrank continuously. Based on a comparison of three satellite images from 1990, 2000 and 2004, Li et al. (2009) found that in Maduo county (25000 km² in area), from 1990 to 2004, the wetland shrank decreased by 4,002.65 km², a rate of 28.64 km²/year. The areas of swamps, lakes and rivers decreased by 9.45, 9.82 and 22.19 %, respectively.

Vegetation degradation and desertification

The decrease in soil moisture and the thawing of frozen soils may further result in vegetation degradation and land desertification. The existence of multi-annual frozen soil layers reduces the seepage of water and increases soil moisture, favoring the growth of vegetation. After the permafrost degradation, the groundwater level lowered, soil moisture decreased, the grassland degraded (Zeng and Feng 2009) and then land desertification occurred. Using satellite images, Zeng and Feng (2007) studied the desertification in an area of 37,000 km² in the YRSA for the 15-year period from 1986 to 2000 and found that the area of desertification increased by 2,045 km², of which the area of the types of slight, moderate, severe and very severe desertification accounts for 46.3, 30.6, 19.1 and 4.0 %, respectively. There is a close relationship between vegetation cover and the buried depth of the frozen soil, given

other conditions. Based on the field observations in Dayematan, Liang et al. (2007) found that the higher the vegetation cover (%) is, the deeper the frozen soil layer is buried. For places with different vegetation covers, the soil temperature decreases with the sampling depth, and the rate of the decrease positively correlates with the vegetation cover. When vegetation degradation occurs, the soil temperature may increase and the permafrost degradation occurs.

Concept, methods and data sources

The conceptual hypothesis

Based on the fact of rising temperature, the resulting environmental changes as reviewed above and the observed changes at the hydrometric station, a conceptual hypothesis is formed for the present study. The theory of the water cycle is based on the concept of the water balance:

$$P = Q_w + ET + \Delta S_w \quad (1)$$

where P is precipitation, Q_w is runoff, ET is evapo-transpiration, ΔS_w is the change in water storage in the drainage basin. For the study area, the ΔS_w may be divided into many components:

$$\begin{aligned} \Delta S_w &= \Delta S_{wi} + \Delta S_{wl} \\ &= (\Delta S_{w,glacier} + \Delta S_{w,permafrost}) + (\Delta S_{w,lake} + \Delta S_{w,swamp} \\ &\quad + \Delta S_{w,soil} + \Delta S_{w,ground}) \end{aligned} \quad (2)$$

where ΔS_{wi} is the change in the storage of ice, including that in glaciers (ΔS_{wg}) and permafrost ($\Delta S_{w,permafrost}$). ΔS_{wl} is the change in the storage of liquid water, including that in lakes ($\Delta S_{w,lake}$), swamps ($\Delta S_{w,swamp}$), the soil ($\Delta S_{w,soil}$) and groundwater ($\Delta S_{w,ground}$). Therefore,

$$\begin{aligned} Q_w &= P - ET - \Delta S_w \\ &= P - ET - (\Delta S_{w,glacier} + \Delta S_{w,permafrost} + \Delta S_{w,lake} \\ &\quad + \Delta S_{w,swamp} + \Delta S_{w,soil} + \Delta S_{w,ground}) \end{aligned} \quad (3)$$

If the temperature (T) increases and P remains unchanged, the changes in ET and ΔS_w may change Q_w . The melting of glaciers and thawing of permafrost will reduce $\Delta S_{w,glacier}$ and $\Delta S_{w,permafrost}$, and part of the resultant water will be released to the river, increasing the river flow. Thus, the runoff per unit of precipitation may increase, which is expressed by the ratio of runoff to precipitation (R_{rp}). Here R_{rp} is equivalent to the normally used “runoff coefficient,” but is somewhat different because a certain part of the runoff does not come from precipitation, but from the water released from storage. Therefore, we

use the runoff–precipitation ratio in the place of the runoff coefficient. The thawing of permafrost will lower groundwater level and reduces $\Delta S_{w,ground}$. The reduced $\Delta S_{w,ground}$ is then released to the river and Q_w and R_{rp} increases. The decline of the groundwater level causes wetland degradation and lake shrinkage, whereby $\Delta S_{w,lake}$ and $\Delta S_{w,swamp}$ decreases, also increasing Q_w and R_{rp} . In the meantime, the increased ET due to climate warming will reduce Q_w and R_{rp} . However, compared with the increase in Q_w and R_{rp} due to ΔS_w reduction, this is a minor factor. Hence, at this stage, Q_w and R_{rp} may have an increasing trend.

Over time, however, the amount of storage of solid and liquid water becomes smaller and smaller and so does the water released to the river. Thus, the increase in Q_w and R_{rp} becomes weaker and weaker and finally stops. In the meantime, temperature continues to rise, further changing the condition of the land surface. Degradation of wetlands, grasslands and alpine meadows as well as land desertification becomes more serious. Land surface evaporation is therefore enhanced, soil moisture further decreases, further reducing R_{rp} and Q_w . Finally, the trend of Q_w and R_{rp} is reversed, and the whole path of the adjustment of the water cycle is characterized by a complex response. In the present study, this hypothesis will be tested by data from the YRSA.

In general, to isolate the runoff variation caused by climate change, the influence of human water diversion should be added back to the measured river runoff to get the natural runoff. Fortunately, water diversion is negligibly small in the study area. According to data from 1956 to 2000, the annual mean measured runoff and the natural runoff (calculated as measured runoff plus water diversion) at Tangnaihai station is 660.3 and 664.5 m³/s, respectively, showing a difference of 0.6 %. Thus, the measured runoff at Tangnaihai station can be used in the place of natural runoff, and R_{rp} may be used for the natural runoff ratio. R_{rp} is calculated as:

$$R_{rp} = (Q_w \times L_t) / (P_m \times A \times 1000) \quad (4)$$

where Q_w (m³/s) is the measured annual runoff at Tangnaihai station (m³/s), P_m (mm) is the average annual precipitation over the drainage basin above Tangnaihai, A is the drainage area (km²), and L_t (s) is the length of a year.

Data sources and methods

The annual runoff data (1950–2008) at Tangnaihai station are provided by the Yellow River Water Conservancy Commission. The annual air–temperature (1957–2008) and precipitation (1958–2008) data from 8 county meteorological stations are provided by the National Meteorological Bureau of China, and the arithmetic mean is used for the precipitation and temperature over the study area.

Fig. 2 Temporal variations in Q_w (a) and R_{rp} (b)

Based these data, time series analysis, regression analysis, double-mass analysis and Mann–Kendall analysis, etc., are performed. The software package STATISTICA 5.5 is used to carry out the calculations.

Results, analysis and discussion

Temporal variations in annual runoff, the runoff to precipitation ratio and climate variables

The temporal variations in Q_w and R_{rp} at Tangnaihai station and annual P and T over the YRSA are shown in Fig. 2. Although the points are scattered, a trend can be seen that Q_w increases first and then decreases.

The variation in R_{rp} is also nonlinear, increasing first, attaining a peak around 1983 and then decreasing. In the rising limb, the increase before 1972 was slow, and afterward, the increase became more rapid. The points before and after 1983 are fitted by linear regression separately. The former is positive correlation ($p = 0.10$), while the latter is negative ($p = 0.0044$).

The temporal variation in annual P and T is shown in Fig. 3, where linear regression equations are fitted. The t test is performed at the hypothesis [H_0] that “the regression coefficient of the equation is equal to 0”. The

Fig. 3 Temporal variations in annual P (a) and air T (b)

result shows $p = 0.38$ for P and $p = 1.76 \times 10^{-9}$ for T . Thus, there is no trend in P , but a significant increasing trend in T . The increase in T is nonlinear (Fig. 3b): after 1984, T increased more rapidly.

The relationship between R_{rp} and climate variables

To reveal the influence of climate change on R_{rp} , the relationships of R_{rp} with P and T are plotted, given in the Online Resource (see ESM.pdf) as Supplementary material 2 (Fig. S1-1). The R^2 between R_{rp} and T is 0.22, but the R^2 between R_{rp} and P is 0.041, indicating that the variation in T can explain 22.0 % of the variation in R_{rp} and that the variation in P can explain only 4.1 % of the variation in R_{rp} . Figure 3 shows remarkable fluctuations in the variation in P and T , roughly in a quasi-period of 3–5 years. To offset these fluctuations and better represent the trend, a 5-year moving average is used. After this treatment, R_{rp} is plotted against of P and T , shown in the Online Resource (see ESM.pdf) as Supplementary material 2 (Fig. S1-2). The R^2 between R_{rp} and T increases to 0.4727, but the R^2 between R_{rp} and P is 0.020, still very low. Therefore, the trend in T determines the trend in R_{rp} , and P makes very little contribution to it.

Fig. 4 Temporal variations in R_{rp} and T (a) and in Mann-Kendall's UF_k of R_{rp} and T (b)

Response of R_{rp} to the rising T

Because there is no trend in annual P in the study area, the prerequisite of unchanged precipitation is satisfied. To reveal the complex response of R_{rp} to the rising T , we show the temporal variations in R_{rp} and T in the same ordinates (Fig. 4a). As mentioned previously, R_{rp} increases first and then decreases, while T continuously rises. The Mann-Kendall analysis is often used to detect the trend and abrupt change in a time series (Kendall 1975; Mudelsee et al. 2006). We calculated the Mann-Kendall's UF_k for R_{rp} and T and show the temporal variation in Fig. 4b. The UF_k of R_{rp} increases first and then decreases, and the variation is well fitted by a parabolic curve. The UF_k of T shows a significant increasing trend. Before the 1980s, it increased relatively slowly with some fluctuations, and afterward, it increased more rapidly.

For further comparison, the periods before and after 1983 are differentiated. Temporal variation in the cumulative R_{rp} is shown in Fig. 5a. The line turns to the right from 1983, indicating that the R_{rp} becomes smaller. Linear regression equations for the two periods are given, and the slope for the period before and after 1983 is 0.325 and 0.272, respectively, indicating a decrease. The double-mass plot between annual Q_w and P is shown in Fig. 5b. From 1983, the line turns to the right, which indicates a decrease after that year, given the

Fig. 5 The changes in the Q_w - P relationship before and after 1983. a Temporal variation in the cumulative R_{rp} . b Double-mass plot between Q_w and P . c $Q_w - P$ plot

P . The slopes of the linear regression equations for the periods after and before 1983 are 1.28 and 1.06, respectively, also indicating a decrease. The Q_w is plotted against P in Fig. 5c, where linear equations are fitted. The two straight lines are almost parallel, the slopes being 1.70 and 1.74, respectively, and the line for the first sub-period is much higher than that for the second, meaning that the Q_w in the second sub-period is smaller than Q_w in the first. Based on the two equations, we may roughly estimate the reduction in Q_w . By omitting the difference in the slope and subtracting the two sides of the second equation from those of the first gives $138 \text{ m}^3/\text{s}$, which means that on average the reduction in Q_w is $138 \text{ m}^3/\text{s}$.

Fig. 6 A flowchart describing the response of water cycle to the temperature rising in the YRSA

A conceptual model for the response of R_p to rising temperature

In essence, the change shown in Fig. 4a reflects the response of the water cycle system of the YRSA to the environmental changes induced by climate warming. The interactions between the climate warming, the resulting environmental changes and the response in the water cycle are generalized as a flowchart (see Fig. 6), which explains the mechanism of the complex response. Supporting information, such as glacier melting, permafrost thawing, wetland degradation, lake shrinkage, lowering of groundwater level, grassland degradation and land desertification, in the flowchart has been discussed in “[Environment changes](#)” section. Based on the flowchart, a descriptive three-stage model can be established, which is composed of the following three stages.

Stage I

Stage I was from 1958 to 1983. Due to rising temperature, shrinkage and recession of glaciers occurred. Based on a comparison of satellite images between 1966 and 2000, Liu et al. (2002) found that of the 57 glaciers in the Amaniqing Mountains, 52 retreated, 3 advanced and 2 remained unchanged. From 1966 to 2000, the total area of the glaciers decreased 17.3 %, from 125.5 to 103.8 km². For example, the length of the Yehelong Glacier decreased by 1500 m, 23.2 % of its length in 1966, 8,400 m (Wang 1987; Liu et al. 2002; Yang et al. 2004). In the meantime, the permafrost degraded and melted. For example, before

1970, Huangheyuan and Maduo were both within the area of permafrost. In the 1990s, the area of these two towns became a seasonally frozen area. The permafrost limit in Maduo moved 15 km to the west and that in Huanheyuan moved 2 km to the north (Wang et al. 1991; Jin et al. 2010). Between the 1970s and 1990s, the lower limit in Maduo rose from 4220 to 4270 m and that in southwest slope of the Amaniqing Mountains rose from 4,180 to 4250 m, going up by 50 and 70 m, respectively. As a result, the area of the permafrost shrank (Yang et al. 2004). Based on a modeling study simulating the decadal permafrost changes in the Qinghai–Tibet Plateau over the past 50 years, Cheng et al. (2012) found that permafrost was 1.60×10^6 , 1.49×10^6 , 1.45×10^6 , 1.36×10^6 and 1.27×10^6 km² in the 1960s, 1970s, 1980s, 1990s and 2000s, respectively, and the rate of permafrost loss has accelerated since the 1980s. Compared with the area in the 1960s, the area in the 2000s decreased by 26 %.

Permafrost layers play an important role in runoff generation in the water cycle system of the YRSA. The degradation of the permafrost caused the impermeable, frozen soil layers to move downward, and thus, the groundwater level declined. According to the data collected from 17 wells in Maduo during the period from 1992 to 2001, the decline of groundwater level ranges from 0.36 to 1.68 and 0.36 m, averaging 1.0 m. The ice stored in glaciers and permafrost is the solid water storage in the drainage basin water balance. The glacier and permafrost melting reduced the solid water storage and thereby increased the river flow. The water stored in lakes and wetlands is the liquid water storage. Close hydraulic relations exist between rivers,

lakes, wetlands and groundwater aquifers. With the decline of groundwater levels, the water stored in lakes, wetlands and groundwater aquifers was released to the river. This process is observed in the lakes and wetlands degradation. The comparison of satellite images shows that in Maduo, around 2,000 small lakes became dry up to 2003. The water level of lakes declined, e.g., the water level of the Eling and Zaling Lakes declined by 3.08 and 3.48 m, respectively (Peng et al. 2003; Lu et al. 2005).

The release of the previously stored solid water in glaciers and permafrost and liquid water in lakes and wetlands increased the river flow. Consequently, the R_{rp} increased from 1958 to 1983, as can be seen from Fig. 4a. The runoff is also influenced by evaporation. The result of this is given in the Online Resource (see ESM.pdf) as Supplementary material 2.

Stage II

Stage II started at the maximum of R_{rp} in 1983 (Fig. 4a) and extended to 2008. With the further rising of temperature and the degradation of glaciers, permafrost, lakes and wetlands, the previously solid and liquid water storages in these units became almost exhausted. The warming-induced runoff increase became weaker and weaker. In the same time, the rising temperature increased evaporation, which enhanced land desertification and grassland degradation, further reducing soil moisture. The decline of groundwater levels increased the thickness of the aeration zone, a factor that increases infiltration and reduces the generation of saturation-excess overland-flow. As a result, the runoff per unit of precipitation became less. As can be seen from Fig. 5c, the reduction in Q_w during Stage II is 138 m³/s or 4.35 billion m³ annually. Therefore, R_{rp} decreased. The transition from Stages I to II is characterized by the reversal of the trend in R_{rp} .

Stage III

When the adjustment goes further, the water cycle system may enter Stage III. A new equilibrium may be re-established among the components of the physico-geographical system and the components of the water cycle system. The R_{rp} may finally tend to a constant, if the increasing trend of temperature does not continue.

The influence of human activity

Under the conditions that T increases while P remains unchanged, the influence of human activity also plays a role in controlling the variation in R_{rp} . The land degradation caused by overgrazing may also reduce R_{rp} . The

results of the analysis on this issue are given in the Online Resource (see ESM.pdf) as Supplementary material 3.

Implications of the results

The present study first shows that, as a complicated water system where many sub-systems couple with each other, the response behavior of the YRSA to temperature rise is nonlinear and complex. It can be expected that for many large rivers, especially for those that are located in high latitudes or high altitudes and get multiple water sources including rain, snow, glaciers and frozen soils, a complex response to temperature rise is not unusual. Revealing this nonlinear behavior in depth may help get a new insight into better decision-making in water resources management. At the first stage of the expected complex response, the increased river flow due to higher R_{rp} may significantly increase the available water resources. However, with the response going toward the second stage, some reverse trend may occur and the available water resources may go down. At the third stage, the available water resources may become even smaller than the beginning of the first stage. With this picture of complex response in mind, some measurements can be prepared in advance to adapt to the changes and maintain the sustainability of water resources development.

Conclusions

The precipitation in the YRSA remains unchanged, while air temperature has risen markedly in the past 50 years. Located in the northeastern part of the Qinghai–Tibet Plateau, a region sensitive to climate change, the YRSA is an ideal location to study the response of the water cycle system to climate warming. The R_{rp} shows some nonlinear variation: it increased to a peak and then decreased. The variation in T explains 22.6 % of the variation in R_{rp} , but the variation in P can explain only 4.10 % of the variation in R_{rp} .

Based on the response of R_{rp} to rising temperature, a three-stage descriptive model for the complex response of runoff generation to rising temperature has been established. In Stage I, glaciers and permafrost melt, lakes shrink and wetlands degrade. The previous water storages, both in solid and liquid forms, are released, resulting in an increase in R_{rp} . In Stage II, the effects of the releases from storage cease, while evaporation induced by rising temperature is enhanced, which results in a decreasing trend in R_{rp} . In Stage III, a new equilibrium may be re-established, and the R_{rp} tends toward a constant value.

Acknowledgments The financial support from the Natural Science Foundation of China (Grant No. 41371037), the National Major Basic Research Program of China (Grant No. 2011CB403305) and Chinese Academy of Sciences is gratefully acknowledged. All hydrometrical data were provided by the Yellow River Water Conservancy Commission and data of air temperature and precipitation by the China National Bureau of Meteorology. I am grateful to Professor B. Finlayson and another anonymous reviewer, whose comments and suggestion are valuable for the improvement of the manuscript; to Professor B. Finlayson, who polished the English of the manuscript.

References

- Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309. doi:[10.1038/nature04141](https://doi.org/10.1038/nature04141)
- Chang GG, Li L, Zhu XD, Wang ZY, Xiao JS, Li FX (2007) Changes and influencing factors of surface water resources in the source region of the Yellow River. *Acta Geogr Sin* 62(3):312–320 (in Chinese)
- Cheng WM, Zhao SM, Zhou CH, Chen X (2012) Simulation of the decadal permafrost distribution on the Qinghai–Tibet Plateau (China) over the past 50 years. *Permafrost Periglacial Process* 23:292–300 (in Chinese)
- Editorial Committee of “A Physical Geography in China” (1981) A physical geography in China (Geomorphology Volume). Science Press, Beijing (in Chinese)
- Immerzeel WW, van Beek LPH, Konz M, Shrestha AB, Bierkens MFP (2012) Hydrological response to climate change in a glacierized catchment in the Himalayas. *Clim Change* 110:721–736
- Jin HJ, Wang SL, Lu LZ, He RX, Chang XL, Luo DL (2010) Features and degradation of frozen ground in the sources area of the Yellow River, China. *Glaciol Geocryol* 32(1):10–17 (in Chinese)
- Kang Y, Li ZC, Tian H, Liu R, Shi XK, Zhang JH, Wen J (2011) Trend of vegetation evaluation and its responses to climate change over the source region of the Yellow River. *Clim Environ Res* 16(4):505–512 (in Chinese)
- Kendall MG (1975) Rank-correlation measures. Charles Griffin, London
- Li FX, Chang GG, Xiao JS, Zhou BR, Fu Y (2009) Relationship between wetlands changes and climate change in the Yellow River source region. *J Nat Resour* 24(4):683–689 (in Chinese)
- Liang SH, Wan L, Li ZM, Cao WB (2007) The effect of permafrost on alpine vegetation in the source regions of the Yellow River. *J Glaciol Geocryol* 29(1):45–52 (in Chinese)
- Liu XY, Chang XH (2005) A summary of study on runoff variations in source region of the Yellow River. *Yellow River* 27(2):7–14 (in Chinese)
- Liu SY, Lu AX, Ding YJ, Yao TD, Ding LF, Li G, Hooke RL (2002) Glacier fluctuations and the inferred climate changes in the A'nyemaqen Mountains in the source area of the Yellow River. *J Glaciol Geocryol* 24(6):701–707 (in Chinese)
- Lu AX, Yao TD, Wan LH et al (2005) Study on the fluctuations of typical glaciers and lakes in the Tibetan Plateau using remote sensing. *J Glaciol Geocryol* 27(6):783–792 (in Chinese)
- Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438:347–350. doi:[10.1038/nature04312](https://doi.org/10.1038/nature04312)
- Mudelsee M, Deutsch M, Börngen M, Tetzlaff G (2006) Trends in flood risk of the River Werra (Germany) over the past 500 years. *Hydrol Sci J* 51(5):818–833
- Pan JH, Wang J, Wang JH (2007) Dynamic change of frigid wetlands in source region of the Yangtze and Yellow Rivers. *Wetl Sci* 5(4):298–304 (in Chinese)
- Peng XM, Wu QB, Tian MZ (2003) The effect of groundwater table lowering on ecological environment in the headwaters of the Yellow River. *J Glaciol Geocryol* 25(6):667–671 (in Chinese)
- Peterson BJ, Holmes RM, McClelland JW et al (2002) Increasing river discharge to the Arctic Ocean. *Science* 298(5601):2171–2173. doi:[10.1126/science.1077445](https://doi.org/10.1126/science.1077445)
- Singh P, Kumar N (1997) Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *J Hydrol* 193:316–350
- Wang WY (1987) Surveying of glacier variation in the northeastern part of Qinghai–Xizang Plateau. In: JH Vermann, WY Wang. Reports on the Northeastern Part of the Qinghai–Xizang (Tibet) Plateau by Sino-W. German Scientific Expedition. Science Press, Beijing, pp 22–37
- Wang SL, Luo XR, Guo PF (1991) The distributive characteristics of frozen ground in the east of Qinghai–Xizang Plateau. *Glaciol Geocryol* 13(2):131–140 (in Chinese)
- Wang CH, Dong WJ, Wei ZG (2001) The feature of seasonal frozen soil in Qinghai–Tibet Plateau. *Acta Geogr Sin* 56(5):523–531 (in Chinese)
- Yang ZN (1991) Water resources of glaciers in China. Gansu Publishing House for Science and Technology, Lanzhou (in Chinese)
- Yang JP, Ding YJ, Shen YP (2004) Permafrost change and its effect on eco-environment in the source regions of the Yangtze and Yellow Rivers. *J Mt Res* 22(3):278–285 (in Chinese)
- The Yellow River Institute of Hydraulic Engineering and Water Resources, Hydrologic Bureau of The Yellow River Water Conservancy Commission, Construction and Management Bureau of the Xiaolangdi Dam (2009) A study of incoming water and sediment conditions for the Xiaolangdi Reservoir. Research Report XLDYX0710 (in Chinese)
- Zeng YN, Feng ZD (2007) Spatial and temporal changes of desertification in the headwater area of the Yellow River using remote sensing. *Acta Geogr Sin* 62(5):529–536 (in Chinese)
- Zeng YN, Feng ZD (2009) Analysis of cause mechanism of desertification in headwater area of Yellow River. *J Nat Disasters* 18(1):45–52 (in Chinese)
- Zhang SQ, Wang YG, Zhao YZ, Huang Y, Li YG, Shi WD, Shang XG (2004) Permafrost degradation and its environmental sequent in the source regions of the Yellow River. *J Glaciol Geocryol* 26(1):1–6 (in Chinese)