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Evolution of the freeze-thaw cycles in the source region of the Yellow River under the influence of climate change and its hydrological effects

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Abstract: As an important water source and ecological barrier in the Yellow River Basin, the source region of the Yellow River (above the Huangheyan Hydrologic Station) presents a remarkable permafrost degradation trend due to climate change. Therefore, scientific understanding the effects of permafrost degradation on runoff variations is of great significance for the water resource and ecological protection in the Yellow River Basin. In this paper, we studied the mechanism and extent of the effect of degrading permafrost on surface flow in the source region of the Yellow River based on the monitoring data of temperature and moisture content of permafrost in 2013–2019 and the runoff data in 1960–2019. The following results have been found. From 2013 to 2019, the geotemperature of the monitoring sections at depths of 0–2.4 m increased by 0.16°C/a on average. With an increase in the thawing depth of the permafrost, the underground water storage space also increased, and the depth of water level above the frozen layer at the monitoring points decreased from above 1.2 m to 1.2–2 m. 64.7% of the average multiyear groundwater was recharged by runoff, in which meltwater from the permafrost accounted for 10.3%. Compared to 1960-1965, the runoff depth in the surface thawing period (from May to October) and the freezing period (from November to April) decreased by 1.5 mm and 1.2 mm, respectively during 1992–1997, accounting for 4.2% and 3.4% of the average annual runoff depth, respectively. Most specifically, the decrease in the runoff depth was primarily reflected in the decreased runoff from August to December. The permafrost degradation affects the runoff within a year by changing the runoff generation, concentration characteristics and the melt water quantity from permafrost, decreasing the runoff at the later stage of the permafrost thawing. However, the permafrost degradation has limited impacts on annual runoff and does not dominate the runoff changes in the source region of the Yellow River in the longterm.

Keywords: Runoff; Permafrost degradation; Climate change; Source region of the Yellow River

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Introduction

Permafrost, especially located at the high-altitude and distributed in the middle and low latitudes, has degraded extensively due to global climate change (Oliva et al. 2018; Czerniawska and Chlachula, 2020; Gao et al. 2020; Sheng et al. 2020). Permafrost is a key geological factor in maintaining the hydrological cycle in alpine regions, and its degradation will cause the transition of solid water into liquid water to participate in the hydrological cycle. In addition, the water-holding capacity of permafrost is reduced accordingly, which will alter the hydraulic connection between surface water and groundwater and affect the runoff generation process, thus significantly disturbing the surface hydrological process and regional water balance (Dai et al. 2018; Ma et al. 2019; Song et al. 2020; Qiao et al. 2022; Wang et al. 2020; Han et al. 2021; Shen et al. 2022; Zeng et al. 2022). As shown by the hydrological monitoring data of major rivers in the Arctic, the runoff of most rivers in the Arctic permafrost region tends to increase continuously. This result is not significantly related to the precipitation trend in the Arctic but has a strong

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correlation with the temperature trend (Frampton et al. 2013). The comparative analysis of remote sensing data indicates that the size and water level of most inland lakes in the permafrost region of the Qinghai-Tibet Plateau shows an upward trend in recent years as an result of climate change (Zhu et al. 2021; Zhang et al. 2022). An extreme example is that the Zhuonai Lake located in the hinterland of the Qinghai-Tibet Plateau has experienced continuous water level rise and burst (Liu et al. 2016). These changes are closely related to the formation of new water sources originating from underground ice melting in permafrost. The active layer thrally, the groundwater storage in the Qinghai-Tibet Plateau had increased from 2003 to 2012 with an average annual rate of 9.7 mm recipitation also increases. Generally, the groundwater storage in the Qinghai-Tibet Plateau had increased from 2003 to 2012 with an average annual rate of 9.7 mm (Zhang et al. 2019; Wu et al. 2020), which has augmented the base flow discharge in winter, leading to more even seasonal distribution of surface runoff (Walvoord et al. 2012; Xu et al. 2019; Bai et al. 2021).

The source region of the Yellow River is located at the eastern margin of the permafrost region of the Qinghai-Tibet Plateau, where the permafrost has a higher temperature and smaller thickness and is very sensitive to climate change. The elevation of the lower boundary of the permafrost throughout the plateau has generally increased by 50–80 m since the 1980s. The morphology of the permafrost has gradually changed from large sheets into thin islands and patches. Some permafrost islands on the plateau have completely disappeared and become seasonally frozen soil (Jin et al. 2009). The simulation results of a heat-conduction model show that the degradation rate of permafrost in the source region of the Yellow River could reach 22%–50% by 2100 under different climate change scenarios (Cao et al. 2021). With the climate change and the continuous degradation of permafrost, the river runoff in the source region of the Yellow River shows a fluctuating but general downward trend (Wang et al. 2020). Continuous flow interruption had occurred from 1997 to 2000, especially in 1998, when the interruption between two lakes lasted for half a year. As an important water conservation area in the Yellow River basin, the source region has attracted wide attention for its runoff change. Domestic and international researchers have discussed the factors influencing the runoff generation process in the source region, such as meteorological conditions, human factors, and permafrost degradation. However, they couldn’t reach a common understanding of the cause of the runoff changes in the source region since different runoff data and analysis methods were used in different studies. In particular, the mechanisms and degree of permafrost degradation on the runoff change in this region are still unclear and controversial.

Another noteworthy issue is that the runoff data used in most studies at present are the measured runoff data from the Huangheyan Hydrologic Station. There are two problems with these data. First, these data include anomalous runoff data for some years. For example, due to torrential rains in 1981 and 1989, the loose sediments of the Quaternary in the estuary of the Eling Lake were eroded and down cut by floods, and a large amount of lake water was discharged. As a result, the total runoff and winter base flow of the lake in 1981 or 1989 and the following year were 10 times those of the previous year. Moreover, there was an inconsistency between the decrease in precipitation and the increase in runoff. Second, these data do not exclude the impacts of water conservancy projects on runoff variations. The Huangheyuan Hydropower Station, located at the mouth of the Eling Lake, started to be constructed in 1998 and ceased operation at the end of 2017 (but the dam was not dismantled). Therefore, the runoff after 1998 was greatly affected by the regulation of the hydropower station. Ma (2019) considered that the average annual runoff hydrograph from 2010 to 2015 was flatter than that from 1961 to 1965 was caused by permafrost degradation. In fact, this change may be more closely related to the water storage and regulation of the hydropower station during the flood season. Therefore, study results may not represent the actual situation if the influence of special hydrological years and anthropogenic regulation on runoff variations is ignored.

Based on the variations of the water storage above the frozen layer during a freeze-thaw cycle (FTC) reflected by the monitoring data of permafrost temperature and moisture content, as well as the seasonal variation characteristics of runoff in typical time periods before and after permafrost degradation, this paper analyzed the influencing mechanisms of permafrost degradation on the runoff generation process in the source region of the Yellow River at different spatial scales and further clarified the degree of the influence of permafrost degradation and subsurface ice melting on the runoff change in the source region. The results of this study will help to improve the understanding of hydrological effects of permafrost degradation in the source region of the Yellow River.

1 Study area and data

The section of the Yellow River above the Huangheyan Hydrologic Station in Maduois regarded as the river source section, with a length of 285.5 km. The river passes through the Zhaling and Eling lakes from west to east, with a drainage area of 2 0930 km^2 and geographical coordinates of 95°53'–98°23'E and 33°55'–35°30'N. The source region of the Yellow River has an average elevation of over 4200 m, and more than 80% is covered with permafrost. This region has a plateau continental semi-arid alpine climate, with an average annual precipitation of 326.4 mm and average annual evaporation of 797.7 mm (E601). The Huangheyan Hydrologic Station has an average annual runoff of 6.8×10^8 m^3. The central and northern parts of the Yellow River Basin extend from the Zaling Lake Basin and the Eling Lake Basin to the alluvial-proluvial plain of the Yellow River, with agently undulating terrain. The region has widely distributed lakes, rivers, and streams. The Bayan Har Mountain in the south is high and covers a large area, with the center scattered with marshes in the sheet pattern (Fig. 1). The permafrost (rock) with a certain thickness in the area forms a relatively uniform aquiclude, and the thickness of the permafrost decreases with the elevation going down. Partly dominated by the permafrost, several special types of groundwater have occurred, such as groundwater above the frozen layer, below the frozen layer, and in the melting area, groundwater above the frozen layer is the most common type. Some occurs in bedrock fissures, which are widely distributed in the northern and southern mountainous areas and vast hilly areas, and it can also present in Quaternary loose rocks, which are distributed in the mountains and piedmont plain. Affected by tectonic faults and permafrost degradation in local areas, the water-holding capacity of permafrost has weakened and there is no strict distinction between the water above and below the frozen layer.

The data used in this study mainly included meteorological and hydrological data from 1960 to 2019 and monitoring data of the geotemperature and moisture content at permafrost monitoring points from 2013 to 2019. Among them, the temperature and precipitation data originated from the China Meteorological Data Network (http://data.cma.cn/), runoff data were the measured runoff from the Huangheyan Hydrologic Station, and geotemperature and moisture content data were the average daily monitoring data from 2013 to 2019 along four monitoring sections at the depths of 0.2 m, 1.2 m, 2.0 m, and 2.4 m at the permafrost monitoring points deployed in the valley-type loose layer at the northern foot of the Bayan Har Mountain by the Chinese Academy of Sciences.

2 Results and discussion

2.1 Variation characteristics of precipitation, temperature, and runoff

The precipitation from 1960 to 2019 generally showed a fluctuating upward trend (Fig. 2). The

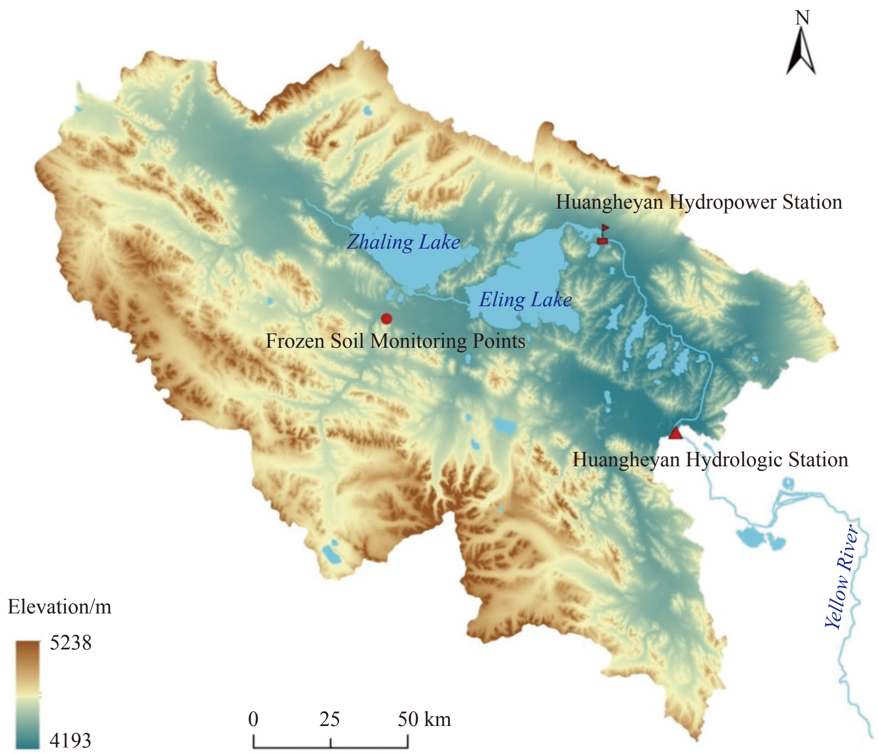

Fig. 1 Overview of the study area

cumulative precipitation departure curve from 1960 to 2003 generally showed a fluctuating downward trend, indicating that the precipitation in most years during this period was less than the average annual precipitation and there were consecutive dry years. The cumulative precipitation departure curve from 2003 to 2019 showed a fluctuating upward trend, indicating that the precipitation in most years during this period was greater than the average annual precipitation and there were consecutive wet years. The average precipitation from 2004 to 2019 (374.2 mm) was 65.2 mm higher than that from 1960 to 2003 (309.0 mm).

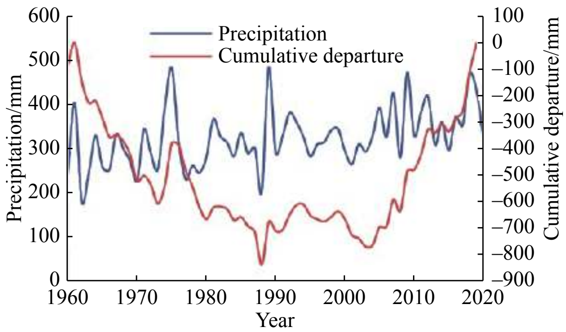

Fig. 2 Precipitation variation in the source region of the Yellow River from 1960 to 2019

From 1960 to 1985, the source region of the Yellow River showed a relatively stable temperature variation range, with the average annual temperature fluctuating between −2.81°C and −5.49°C. From 1985 to 2019, the temperature in the region continued to increase with a rate of 0.6°C/10a on average (Fig. 3), which was slightly higher than the temperature change amplitude in the entire Qinghai-Tibet Plateau in the past 50 years (0.4°C/10a; You et al. 2021).

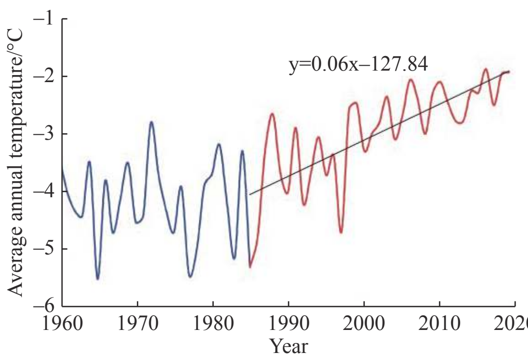

Fig. 3 Average annual temperature variation at the Maduo Meteorological Station from 1960 to 2019

From 1960 to 2020, the average annual runoff depth at the Huangheyan Hydrologic Station was 35.6 mm, and the average annual runoff coefficient was 0.11, which was much less than the runoff coefficients of the three adjacent sub-watersheds, i.e. Huangheyan-Jimai (0.31), Jimai-Maqu (0.37), and Maqu-Tangnaihai (0.38; Sun et al. 2021). The runoff shows a downward trend in the long term, which is inconsistent with the upward trend of precipitation. However, the runoff fluctuation is consistent with the precipitation fluctuation in most years, indicating that precipitation is still the most significant factor affecting the runoff (Yang et al. 2019). The years with inconsistency of precipitation and runoff (Fig. 4) are mainly related to human activities and special meteorological conditions (Li et al. 2018; Lu et al. 2020). As shown by the remote sensing interpretation results, the surface areas of Zhaling and Eling lakes have increased by 72.7 km^2 and the water storage has increased by 17.8×10^8 m^3 since 2000 due to the impact of water storage at the Huangheyuan Hydropower Station. Thus, the decrease in the runoff after 2000 is directly related to the increase in lake water storage. Therefore, when considering the influence of permafrost degradation on runoff, it is necessary to exclude the influence of special hydrological years and human factors, which are usually ignored in most studies of the runoff change in the source region of the Yellow River. This study elaborated on the effects of permafrost degradation on runoff variations through the comparative analysis of precipitation-runoff changes during 1960-1965 and 1992-1997, which were used as the typical periods before and after permafrost degradation, respectively by making reference to the long-term precipitation series-runoff variation characteristics in the source region of the Yellow River and excluding the influence of special hydrological years and the anthropogenic regulation since the construction of the Huangheyan Hydrologic Station in 1998 on the runoff variation.

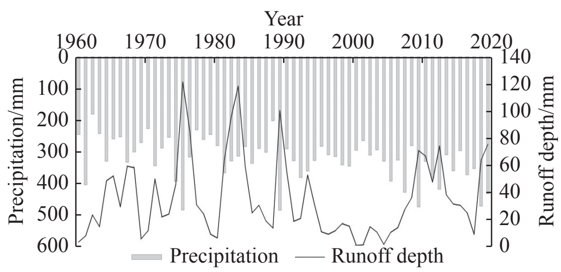

Fig. 4 Variation trends of precipitation and runoff in the source region of the Yellow River from 1960 to 2020

Affected by factors such as climate, hydrology, and permafrost, the runoff in the source region of the Yellow River is relatively complex. The surface runoff is mainly from rainfall and melting snow, while the baseflow is from the groundwater above the frozen layer recharged by precipitation infiltration and seasonal thawing of frozen soil and the water below the deep frozen layer. The average monthly precipitation-runoff hydrograph from 1960 to 1965 (Fig. 5) shows that: (1) the runoff was stable from February to March and then began to rise slowly from April to May with a rise in temperature and the melting of snow cover; (2) the runoff gradually increased from June and peaked in August with an increase in precipitation. However, the peak of runoff was one month behind the peak of precipitation; (3) the runoff began to decline in September at the end of the rainy season, but the recession curve showed a stable runoff period from September to October. Afterward, the runoff began to decline again and was roughly stable in February. Compared with the period from 1960 to 1965, the period from 1992 to 1997 showed roughly similar overall trends in the average monthly precipitation and runoff process, except for two significant differences. First, the peak runoff in August decreased instead of increasing when the precipitation increased in the rainy season. Second, the stable runoff period from September to October disappeared, while a less stable runoff period appeared from December to January.

2.2 Variation characteristics of freeze-thaw cycles

Affected by temperature rise, the permafrost degradation in the source region of the Yellow River has intensified. As shown in the geotemperature curve from 2013 to 2019 (Fig. 6), the average annual geotemperature showed an upward trend on the monitoring sections at depths of 0.2 m, 1.2 m, 2 m,

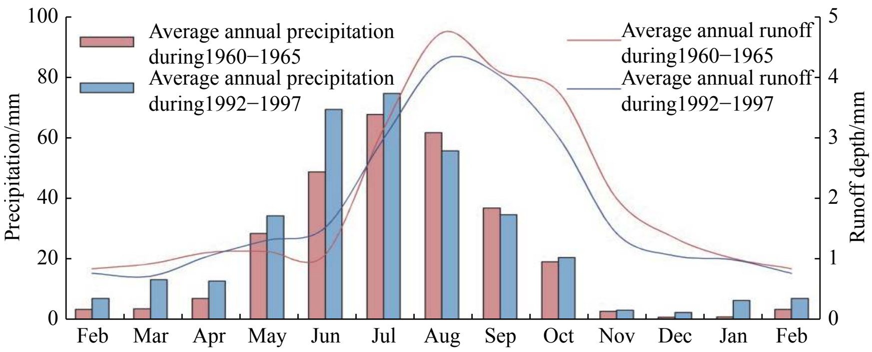

Fig. 5 Comparison of average monthly precipitation and runoff process in different years

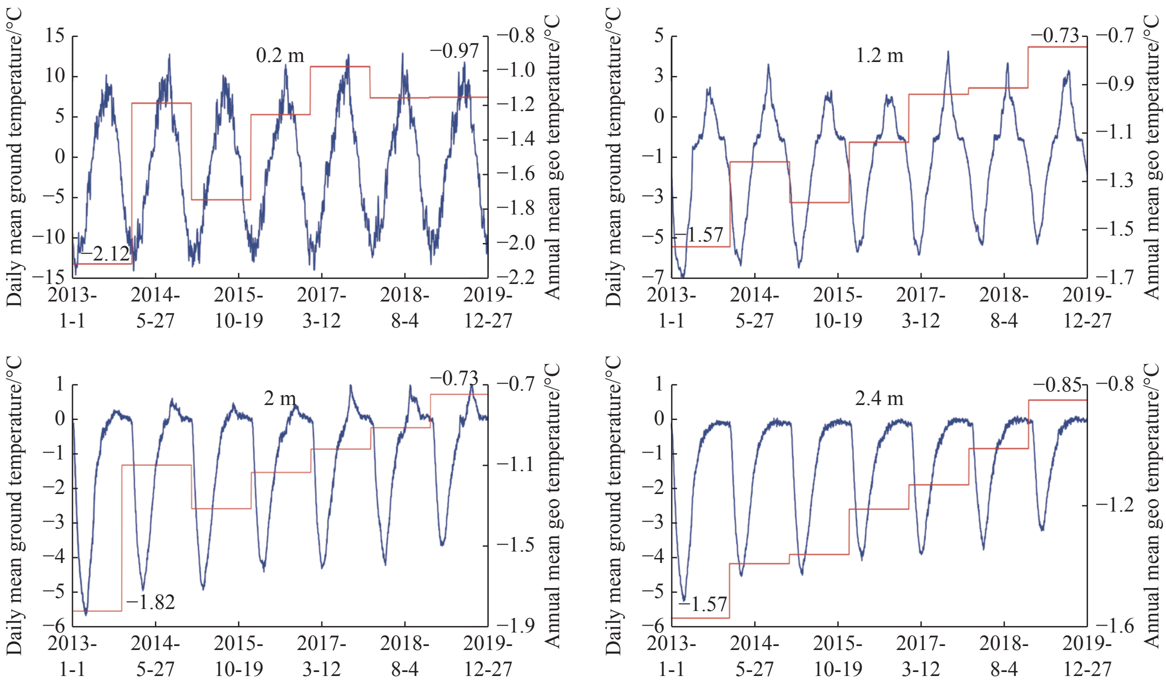

Fig. 6 Geotemperature curves of monitoring sections at different depths

and 2.4 m, increasing by 1.15°C, 0.84°C, 1.09°C, and 0.72°C, respectively, with an average of 0.95°C and an average annual increase of 0.16°C/a. With regard to depth, the shallow geotemperature showed steep increase with strong fluctuations, while the deep geotemperature showed a gentle increase with a continuous upward trend. Regarding the annual fluctuations of geotemperature at different layers, the trough and peak of geotemperature appeared later with an increase in depth. Among them, the trough and peak of geotemperature along the measuring section at a depth of 0.2 m appeared in January and August, respectively, and the geotemperature decreased rapidly due to the decrease in air temperature after the peak. The trough and peak of geotemperature along the measuring section at a depth of 2.4 m appeared in March and November, respectively, and the high temperature near the peak lasted for nearly 3 months. These results indicate that the surface geotemperature is more sensitive to surface air temperature, while the deep geotemperature is not only affected by the air temperature change but also related to other factors such as the geotemperature gradient and formation temperature (Zhang et al. 2013). Therefore, the thawing cycle of frozen soil includes not only the time of thawing at a certain depth, but also the period from the of thawing in the top layer to the beginning of freezing at the bottom layer. Regarding the variations in freeze-thaw days at different depths (Table 1), the freeze-thaw days of the monitoring sections except for the one at the depth of 1.2 m all increased to different degrees. Among them, the freeze-thaw days of the monitoring section at a depth of 2.4 m increased continuously from 0 days to 48 days, and the permafrost was transformed into an active layer, explicitly indicating permafrost degradation.

The temperature of frozen soil determines the freeze-thaw process and further significantly affects soil moisture and the water above the frozen layer. This is reflected in the soil moisture content curves of monitoring sections at different depths (Fig. 7). The soil moisture content of monitoring sections at different depths peaked at different time every year, with the peak values from shallow to deep sections gradually decreasing with time, which is closely related to the freezing and thawing time of soil at different depths. Regarding the variation characteristics of soil moisture content in different years, the soil moisture content of the monitoring section at a depth of 0.2 m fluctuated between 10% and 15% during the freeze-thaw period, indicating unsaturated soil moisture, which was significantly affected by precipitation infiltration. The soil moisture content of the monitoring section at a depth of 2 m was roughly stable at 36%–37% during the thawing period and was not related to the change in precipitation. For the sandy soil in the source region of the Yellow River, this moisture content range represents saturated soil. Therefore, the water level above the frozen layer always had a depth of less than 2 m during the thawing period from 2013 to 2019. The soil moisture content of the monitoring section at a depth of 1.2 m generally showed a downward trend. Specifically, the moisture content had a peak value ranging from 31% to 35% during the freeze-thaw period from 2013 to 2016. However, the peak value of the moisture content dropped to approximately 20% and fluctuated under the influence of precipitation infiltration after 2017. In other words, the soil changed from a steady saturated state into a fluctuating unsaturated state. This result indicates that the depth of water level above the frozen layer gradually increased from less than 1.2 m to between 1.2 m and 2 m during the thawing period from 2013 to 2019. In particular, 2017 was a critical time point in the depth drop of water level above the frozen layer. However, the precipitation curve in Fig. 4 shows that the precipitation in 2017 was higher than that in 2016. Therefore, the precipitation did not prevail in the decrease in the water level above the frozen layer. The soil thawing time of the monitoring section at a depth

Table 1 Variations in annual thawing days of monitoring sections at different depths

Year	0.2 m	1.2 m	2 m	2.4 m
2013	165	150	141	0
2014	177	148	150	2
2015	174	157	159	4
2016	170	158	143	5
2017	171	157	157	29
2018	184	155	152	43
2019	180	146	190	48

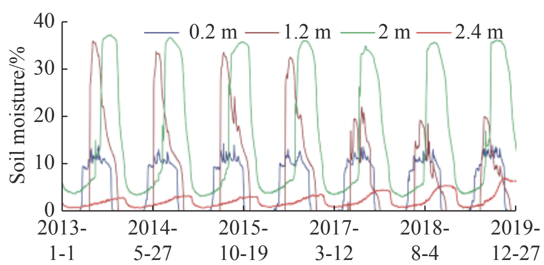

Fig. 7 Soil moisture content variation of monitoring sections

of 2.4 m constantly increased (Table 1) and the peak value of the moisture content also showed an upward trend. When other conditions remain unchanged, the continuous increase in the depth of the upper interface of the permafrost (i.e. the aquiclude roof) will inevitably cause the water level above the frozen layer to decrease. Therefore, permafrost degradation is the main reason for the decrease in water level above the frozen layer.

To more closely observe the permafrost degradation at the monitoring points and the variation in the water above the frozen layer under the influence of permafrost degradation, the freezing and thawing processes of the frozen soil at the monitoring sections and the changes in the depth of water level above the frozen layer in 2013 and 2019 were plotted, as shown in Fig. 8. The following processes in 2013 can be discovered from Fig. 8a. From January to April, the subsurface was completely frozen. From May to July, the frozen soil gradually began to thaw but the aquifer above the frozen layer was still dry. In June, a small amount of water above the frozen layer appeared above the upper interface of the frozen soil with an increase of recharge from atmospheric precipitation. From July to September, the aquifer above the frozen layer continuously thickened with a further increase of recharge from precipitation. However, with the increasing freeze-thaw depth (i.e. an increase in the depth of the aquiclude roof), the water level above the frozen layer showed a downward trend. In October, the aquifer above the frozen layer still thickened due to the recharge from the melting of ice in the frozen soil layer, although the recharge by precipitation decreased. In November, the aquifer became thinner as the temperature decreased, the freezing depth increased, and the water above the frozen layer was continuously discharged. By January of next year, the melting layer formed in the previous year was completely frozen and the water above the frozen layer was transformed into solid underground ice, which could melt and form an effective recharge source of water above the frozen layer in the next year and thus was significant for maintaining the transient stable runoff in the recession curve.

Regarding the freeze-thaw processes and the depth of water level above the frozen layer in 2019 (Fig. 8b), their overall trends were consistent with those in 2013, except that the melting depth in 2019 was greater than the deepest monitoring section (2.4 m) and that the melting depth of each month during the melting period in 2019 was also greater than that in 2013. Moreover, the depth of water level above the frozen layer increased and the aquifer was thinner in 2019 compared to 2013. In other words, the water level and amount of the water above the frozen layer showed a downward trend with the permafrost degradation process. Owing to the decreasing water level, the depth of the solid underground ice formed in the saturated zone increased during the freezing period, leading to a time lag in the initial melting of the solid underground ice. Accordingly, the transient stable runoff in the recession curve maintained via recharge by melted underground ice appeared later. These results are consistent with the delay of the stable runoff in the two typical periods before and after permafrost degradation in the annual runoff hydrograph in Fig. 5.

2.3 Hydrological effects of freeze-thaw cycle evolution

2.3.1 Control effect of the freeze-thaw process on the precipitation-runoff process

As shown in the precipitation-runoff hydrograph in Fig. 5, the weak snowmelt runoff from April to May was roughly consistent with the melting time

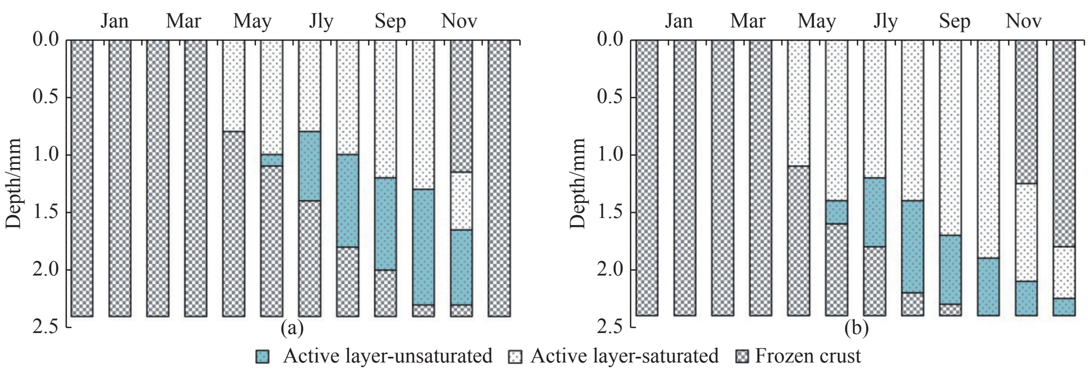

Fig. 8 Comparison of annual changes in the freeze-thaw processes and the depth of water level above the frozen layer between 2013 and 2019

of the snow cover, while the runoff peak in August lagged behind the precipitation peak for approximately one month. The reasons are analyzed as follows. When the temperature rose and the ice and snow began to melt from April to May, the geotemperature did not significantly increase, and the subsurface part was still frozen mostly. Meanwhile, the surface still acted as an impermeable interface. As a result, only a small amount of ice- and snowmelt water vertically infiltrated into soil, while most of the melted water flowed downstream along the terrain towards the Yellow River, leading to a short-term runoff generation. After May, with a further rise in temperature, the frozen soil began to thaw from top to bottom, and the freeze-thaw depth constantly increased, providing an effective vertical infiltration path for precipitation and increasing the buffering capacity for runoff generation and concentration (Wang et al. 2017). The outcrops in the regional river-lake basins and wide valleys among mountains mainly consists of Quaternary glacial, fluviatile-lacustrine, and aeolian sediments, which are favorable for precipitation infiltration. A large amount of runoff from the mountainous area began to infiltrate downward to recharge the groundwater at the mountain pass. Then, the runoff was intensively discharged in the overflow zone and finally recharged the surface water in the river. Moreover, the average multiyear monthly precipitation was up to a maximum of only 73.1 mm and a single precipitation event generally had a low intensity, while the evaporation intensity was high. Therefore, under the combined effect of meteorological, frozen-soil, and hydrogeological conditions, most of the precipitation went through multiple transitions before finally drained to Yellow River, causing a time lag of the runoff peak. Marshes and alpine meadows are widely distributed in the wide valleys among mountains in the source region of the Yellow River. Moreover, numerous lakes are presented along the main stream and tributaries of the Yellow River, such as Zhaling, Eling, Xingxinghai, and Galalacuo. Most of these lakes are water-carrying lakes, which provide a strong runoff regulation function in the rainy season. Therefore, the conservation and regulation of wetlands and lakes are also a factor that causes the lag of runoff.

Approaching the end of the rainy season, the precipitation gradually decreased from August, and the surface runoff began to decrease from September accordingly. As shown in the relationship between the freeze-thaw process and the depth of water level above the frozen layer (Fig. 8), the frozen soil roughly began to thaw and formed an effective recharge of underground runoff in June. However, compared with the surface runoff recharge by precipitation, the recharge by melt water from the frozen soil was limited at that time, which could not be clearly reflected in the runoff hydrograph from June to September. At the end of September, the surface began to freeze as the temperature gradually dropped below 0°C. Accordingly, the recharge of surface runoff by precipitation further decreased. However, under the influence of the accumulated soil temperature and geotemperature gradient, the thawing depth of the frozen soil further increased, increasing the recharge by melt water from the deeper ice-rich frozen soil. Therefore, under the superposition of the decreased precipitation recharge and increased recharge from frozen soil thawing, a transient stable runoff appeared in the regression curve, fully reflecting the recharge of runoff by melt water from the frozen soil. The difference is that the transient stable runoff process appeared from September to October during 1960–1965 and appeared from December to January during 1992–1997. This time lag is closely related to the change in the freeze-thaw process caused by permafrost degradation.

2.3.2 Influencing mechanisms and degree of permafrost degradation on runoff generation capacity

Frozen soil is generally composed of a shallow active layer and lower permafrost. Since frozen soil is impermeable or hardly permeable, it is difficult for water to penetrate permafrost to recharge the deeper part. As indicated by the law of change in the soil temperature and moisture content of the monitoring sections, the soil moisture content gradually increases from top to bottom and then reaches a saturated state as the thawing depth of frozen soil increases in the thawing period. Owing to the barrier effect of permafrost, soil moisture accumulates near the upper interface of the permafrost and forms water above the frozen layer. As the thawing of the permafrost goes deeper, water in the saturated soil migrates downward under the action of gravity, causing a decrease in the water level above the frozen layer and an expansion of the aeration zone. Therefore, the soil moisture migration and the change in the water level above the frozen layer are a distinct response to the increase in the thawing depth of the permafrost.

The runoff generation under saturated conditions is the main runoff generation mechanism of precipitation in the source region of the Yellow River (Zhang et al. 2004). The expansion of the aeration zone prolongs the process under saturated conditions, and more precipitation infiltration at the surface reduces the surface runoff generation capacity. Therefore, the runoff depth from July to September during 1992–1997 was 0.67 mm, lower than that during 1960–1965, although the precipitation from June to August increased by 21.2 mm for the same comparison period. Moreover, the expansion of the aeration zone increases the migration time of water in unsaturated soil toward the deeper aeration zone. With the rise of geotemperature, the evaporation of soil water increases, leading to a decrease in the effective recharge intensity of groundwater. The hydraulic gradient decreases as the groundwater level decreases, thus reducing the groundwater discharge toward the lower reaches of the Yellow River. In addition, unevenly distributed permafrost may degrade into the island-like permafrost forms of "skylights", through which the water above the frozen layer that was previously confined above the permafrost seeps into the deeper part. Overall, permafrost degradation changes the regional and local hydrogeological structure. Specifically, the expansion of the aeration zone leads to more water exchange at the ground-air interface, which directly wenkens the surface runoff generation in the rainy season. Moreover, the decrease in water level delays the discharge of the water above the frozen layer, and the local "skylights" increases the water seepage into the deep part. As a result, the surface water flow system above the frozen layer transitions into the groundwater flow system in the non-frozen area, which eventually reduces the runoff. The pattern that permafrost degradation changes runoff by changing hydrogeological conditions is shown in Fig. 9.

In addition to the above, the long-term runoff variations in the source region of the Yellow River are the result of comprehensive factors including meteorology, permafrost, underlying surface, and human activities. In this study, the average multi-year precipitation-runoff hydrograph was plotted based on the measured data from 1960 to 2019, and the baseflow was segmented using the linear segmentation method (Zhu et al. 2021) according to the annual runoff variation characteristics. From February to March, the soil was completely frozen, there was no other recharge source of runoff except groundwater, and the hydrograph of this period was very stable. Therefore, the average runoff from February to March could be regarded as the baseflow of groundwater below the frozen layer and in the thawing area. From March, some ice- and snow-melt water contributed to the runoff with a rise in the temperature. From June, the surface runoff enhanced in the wet season as the precipitation increased and ice- and snow-melt water recharged the river. In October, the precipitation significantly decreased, the monthly average temperature decreased below 0°C, and the surface began to freeze. Moreover, the recharge via precipitation infiltration was interrupted, and the river flow decreased accordingly. An obvious inflection point appeared in December in the depletion curve. Until January of the following year, the runoff became relatively gentle, and by February the runoff decreased. Therefore, the inflection point in December in the flow hydrograph was likely caused by the delayed recharge by the incompletely frozen water above the frozen layer. Based on the above ana-

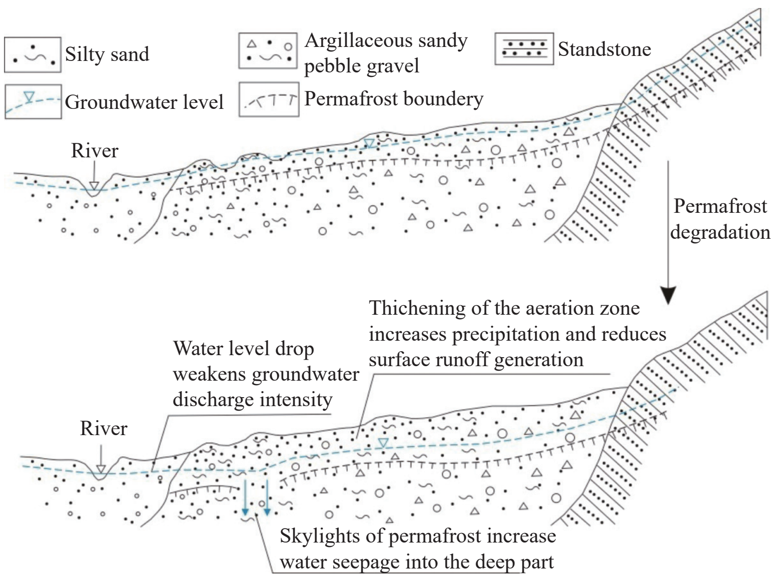

Fig. 9 Change pattern of runoff caused by the changes in hydrogeological conditions in the permafrost region

lysis, the baseflow can be divided into two parts. One part is the melt water from frozen soil, and the other is the groundwater below the frozen layer and in the thawing area (Fig. 10). In other words, the runoff of parts A, B, and C were recharged by rainfall and snowmelt, the melt water from frozen soil, and water below the frozen layer and groundwater in the non-frozen area, respectively. According to the calculation results of the baseflow segmentation of the average annual precipitation-runoff process, the baseflow of the Huangheyan Hydrologic Station was 4.4×10^8 m^3 during 1960–2019, accounting for 64.7% of the average multiyear runoff (6.8×10^8 m^3). The baseflow included 0.7×10^8 m^3 of recharge by the melt water from the frozen soil, which accounted for 10.3% of the average annual runoff. The proportion of the runoff recharge by groundwater calculated through the baseflow separation approximates to that calculated based on isotopic data (59.2%; Wan et al. 2019) and is slightly greater than that of the Tuotuohe Station in the source region of the Yangtze River (51%; Li et al. 2020). The calculated proportion of runoff recharged by melt water from the frozen soil is slightly lower than that of Ma (2019) (14.4%) and is roughly equal to the runoff analysis result of the permafrost distribution area in the source region of the Yellow River issued by China's National Tibetan Plateau Data Center (http://data.tpdc.ac.cn; 11.2%). Although there are some differences between the results calculated using different methods, all results show that groundwater is the most important recharge source of runoff in the source region of the Yellow River, and the proportion of melt water from the frozen soil to groundwater is small.

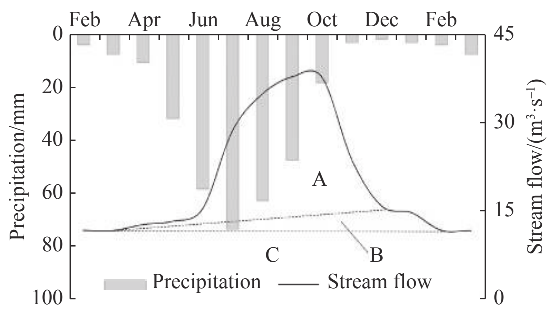

Fig. 10 Average annual precipitation-runoff process

Generally, the melt water from the frozen soil consists of two parts. One part is the melt water from solid underground ice formed by the frozen groundwater during the freezing period of the previous year. This part of the water participates in the recharge-freezing-thawing cycle. When the active layer thickens, it generally changes with the precipitation recharge which could be weaken to some extent. Therefore, this part of water is not subject to absolute decrease. The second part is the melt water from the permafrost and consumes absolute solid water in the alpine region. In the context of permafrost degradation, the sheet-like permafrost in the source region of the Yellow River has been degraded into island-like permafrost and even disappeared. Therefore, this part of the water shows a continuous downward trend and will disappear if the permafrost completely degrades. As revealed by the above analysis, there are mainly two influencing mechanisms of permafrost degradation on the runoff. Regarding the first influencing mechanism, the degradation of the permafrost as an aquifer (i.e. the change in the hydrogeological structure) changes the hydraulic connection between the surface water and the groundwater, which eventually changes the runoff generation process by reducing the runoff generation capacity. However, the runoff generation is also controlled by the precipitation, thus, this process has uncertain effects on runoff. The second influencing mechanism is that the decline in the permafrost area causes the recharge by the melt water from the permafrost to continuously decrease. However, the melt water from the permafrost in the runoff represents a small proportion.

Overall, permafrost degradation mainly affects the runoff in two ways in the source region of the Yellow River. One way is that permafrost degradation changes the runoff generation and concentration during the surface thawing period by changing hydrogeological conditions, which is mainly reflected by the runoff variations during the surface thawing period (from May to October). The other way is that permafrost degradation changes the melt water quantity from the frozen soil and is mainly reflected by the runoff variation during the surface freezing period (from November to April). The average runoff coefficient during this period decreased from 0.07 in 1960–1965 to 0.06 in 1992–1997. The runoff generation capacity of precipitation during the surface thawing period also weakened in 1992–1997 compared with the same period in 1960–1965. Specifically, the runoff depth decreased by 1.5 mm, accounting for 4.2% of the average annual runoff depth (35.6 mm). The average runoff depth during the surface freezing period decreased from 7.2 mm in 1960–1965 to 6.0 mm in 1992–1997, the difference of which accounted for 3.4% of the average multiyear runoff depth. As revealed by the comparison of runoff variations between two typical periods, the permafrost degradation caused the decrease of runoff by 7.6%. Therefore, permafrost degradation has a limited impact on runoff in the source region of the Yellow River and will not greatly impact the runoff in the long term.

3 Conclusions

(1) The permafrost degradation in the source region of the Yellow River has changed the seasonal variation characteristics of runoff, resulting in decreased runoff in the late stage of permafrost thawing (from August to December). With an increase of the thawing depth in the later stage of permafrost thawing, the permafrost degradation causes the water level above the frozen layer to decrease and "skylights" form locally. Meanwhile, the vertical exchange of water between the aeration zone and aquifer system increases, while the horizontal migration capacity of water decreases, thus provides a buffering for the runoff generation and concentration anddelaysthe horizontal discharge of water above the frozen layer. As a result, the runoff during the rainy season decreases. Moreover, the depth of the underground ice formed by the freezing of water above the frozen layer increases as the water level decreases, delaying the underground ice melting in the following year. Correspondingly, the regression curve showed the time lag of the appearance of the transient stable runoff process maintained via the recharge by meltwater from the solid underground ice.

(2) The decrease of runoff due to permafrost degradation does not soly dominate the runoff variations in the source region of the Yellow River. There are two influencing mechanisms of permafrost degradation onthe runoff. The first is that permafrost degradation changes runoff generation and concentration during the surface thawing period by changing hydrogeological conditions. The second is that permafrost degradation change the meltwater quantity from frozen soil. As compared between two typical time periods before and after permafrost degradation (i.e. 1960–1965 and 1992–1997), the runoff depth decreased by 7.6% inthe latter period. Therefore, the runoff changes in the source region of the Yellow River are the result of comprehensive factors including underlying surface, climate, and human activities, and permafrost degradation only has a limited impact on the runoff variations and does not fundamentally change the runoff variation trend in the area.

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