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Cryospheric Hydrology: Decode the Largest Freshwater Reservoir on Earth

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Abstract

The cryosphere is solid reservoir, and the meltwater of cryosphere affects hydrology, water resource, and water cycles in the watershed, regional, even global scale. The article reviewed on the current research results on the hydrological function, hydrological processes of meltwater and runoff and their effect, the impact on ecosystem and environment of cryosphere from hydrology view. The hydrological function mainly includes the water conservation, runoff supply, and regulation on water resource. The hydrological processes have significantly changed under the background of climate change, the onset of glacier melting period starts earlier and the volume of melting water has increased, and the snow melting period starts earlier, the permafrost degradation has led to winter runoff increasing, which increases the regulation function of watershed runoff. The projected glacier meltwater will continuingly decrease under the future climate change, which will bring greater challenge on the water resource management of Northwest China. The changes in hydrological process of cryosphere also have important impact on the ecosystem and ecological engineering, flood hazard and sustainability, and geopolitics in cold regions.

Keywords

cryosphere; cryospheric hydrology; hydrological function; change; impact

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Cryospheric Hydrology: Decode the Largest Freshwater Reservoir on Earth

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More than 70% of the global freshwater resources are stored in glaciers and ice sheets. The annual maximum water equivalent of snow cover in the northern hemisphere is about 3×10^6 km^3. Therefore, the cryosphere is the largest freshwater reservoir in the world. The interaction between the cryosphere and the hydrosphere is an important hydrological process in the climate system and even the earth system, including the liquid water released from the cryosphere elements (such as glacier, ice sheet, snow cover, permafrost, river ice, lake ice, and sea ice) and its hydrological, water resource, ecological, and environmental effects, which is not only the focus and hotspot of people's attention but also the main research content of cryospheric hydrology. Cryospheric hydrology is a new discipline developed to meet the practical needs of sustainable utilization of regional water resources in accordance with the development trend of international cryospheric science.

Traditionally, hydrological research on different elements of the cryosphere is mainly carried out separately for individual elements. For example, the research on glacier hydrology is mainly conducted from the aspects of glacier ablation, runoff formation, and the role of glacial runoff in the watershed, so is the research on the hydrology of permafrost and snow cover [1]. With the increasing impact of global climate change on the cryosphere, the hydrological processes and impacts of cryospheric elements have been widely concerned. The cryospheric elements often act together at the watershed scale. Thus, the processes and impact of water problems related to the cryosphere can no longer be understood from the perspective of traditional single cryospheric element, and the water problems need to be examined from the perspective of cryospheric science. For example, there are not only glaciers and snow but also permafrost and seasonally frozen soil in the watershed where the cryosphere is distributed. Coupled with rainfall, the hydrological processes become complicated. The hydrological processes of the watershed and the hydrological functions of different cryospheric elements can be accurately understood only if the hydrological processes of each cryospheric element and rainfall hydrology are considered comprehensively in addition to the single hydrological impact of glaciers, snow cover, and permafrost. The holistic view of different hydrological elements in cryosphere is the core idea of cryospheric hydrology.

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1 Cryospheric hydrology

Briefly speaking, cryospheric hydrology is a discipline that studies hydrological processes and mechanisms of cryospheric elements, as well as their hydrological functions and impacts. Cryospheric hydrology was proposed with the development of cryospheric science. It is a new discipline with special hydrological attributes and also a science first proposed and completed in its discipline system construction by Chinese scientists [2]. At present, there are few studies on cryospheric hydrology (or cryo-hydrology) in the world. The term of "cryospheric hydrology" or "cryo-hydrology" is only mentioned in some literature [3–6], without the scientific connotation of the discipline itself involved.

The main feature of cryospheric hydrology is that the water is stored in solid form and released in liquid form. The ice-water transformation process and its impact on resources and the environment are the focus of cryospheric hydrology. The study of cryospheric hydrology includes two aspects: ① to study the hydrologic mechanism and change process of cryospheric elements; ② to study the impact of cryosphere change on hydrological processes and water cycles in the watershed, regional, or even global scale. For example, the impact of glacier change on river runoff may involve the water resources problem of the whole watershed, and the influence of cryosphere change on sea level is related to the global water cycle.

Under the background of climate warming, great changes have taken place in the global cryosphere, which are mainly manifested in glacial recession, snow cover reduction, permafrost degradation, sea ice range fading, and temperature rising of the cryosphere itself leading to an increase in its instability [7]. The change of cryosphere exerts a significant influence on hydrological processes and then has an important impact on water resources, ecology, and disasters. It can be seen that although the cryosphere is distributed in high altitude and high latitude areas, the downstream, middle- and low-latitude whole watershed and a wide range of areas are affected under its hydrological impact. Research on the impact of glacier meltwater on water resources demonstrated that the risks of water from distant cryosphere impacting future water resources are enormous, and water resources in the cryosphere are closely related to human sustainable development [8–13]. From the perspective of cryospheric hydrology, the role and impact of cryospheric hydrology were briefly introduced in this paper.

2 Basic hydrological function of cryosphere

The hydrological function of the cryosphere is mainly manifested in three aspects, namely, water conservation, runoff supply, and regulation on water resources.

(1) The function of water conservation is mainly manifested in two aspects of water sources and the cold island and moisture island effects. ① Cryosphere is developed in high-altitude and high-latitude areas, and is the birthplace of many major rivers in the world. The cryosphere with the Qinghai-Tibet Plateau as its main body is the source of famous rivers such as the Yangtze River, the Yellow River, the Tarim River, the Nujiang River, the Lancang River, the Ili River, the Irtysh River, the Yarlung Zangbo River, the Indus River, and the Ganges River (Figure 1), as well as the "Asian water tower." The cryosphere, as a water source, is different from the rainfall-type source, which forms water resources by transforming solid water into liquid water, releasing the accumulated water in the past. Even in the dry period, the cryosphere could continue to supply water, and the water source will not be depleted until it has experienced large and long-term climate fluctuations. ② The high mountain system in which the mountain cryosphere is located can directly intercept the water vapor rising along the hillside due to the terrain uplift and that moving in the main wind direction. Since the cryosphere is a huge cold source, it can effectively condense this water vapor to form precipitation. Especially in the arid inland river watershed, the cryosphere not only stores the external water vapor but also transports the internal water vapor to the high cold cryospheric regions through the internal circulation in the watershed. Because of this, the difference of precipitation between plain area and cryospheric region of arid inland river watershed can be 5–10 times.

(2) The well-known hydrological function of the cryosphere is the runoff supply. As a solid reservoir, the cryosphere itself is important water resources. Its resource attributes are shown in two aspects of total reserves and annual recharge. The annual recharge of rivers by cryosphere is an important part of surface runoff. In 2010, the annual meltwater volume of glaciers in China is about 7.8×10^{10} m^3, which is more than the total annual water inflow of the Yellow River (6×10^{10} m^3). The national glacial runoff is about 2.2% of the national river runoff, equivalent to 10.5% of the river runoff of Gansu, Qinghai, Xinjiang, and Tibet in Western China.

(3) Compared with the functions of water conservation and runoff supply, the regulation on water resources of cryosphere is more crucial. In the watersheds without glaciers, the rivers are mainly supplied by the precipitation, and the annual variation of runoff is very large, which indicates that the runoff process is extremely unstable. However, in the watersheds covered by cryosphere, due to the much precipitation in the watersheds in wet years and the low temperature in the glacier area distributed in extremely high mountain areas, the amount of glacier meltwater supply to rivers is reduced, and the increase in runoff caused by excessive precipitation is weakened. On the contrary, when the precipitation in the watersheds is less, the relatively high temperature in the glacier areas leads to the increase in glacier meltwater, which makes up for the insufficient supply of precipitation to the river [1]. Therefore, the river runoff in the watersheds with glaciers will be relatively stable because of the existence of

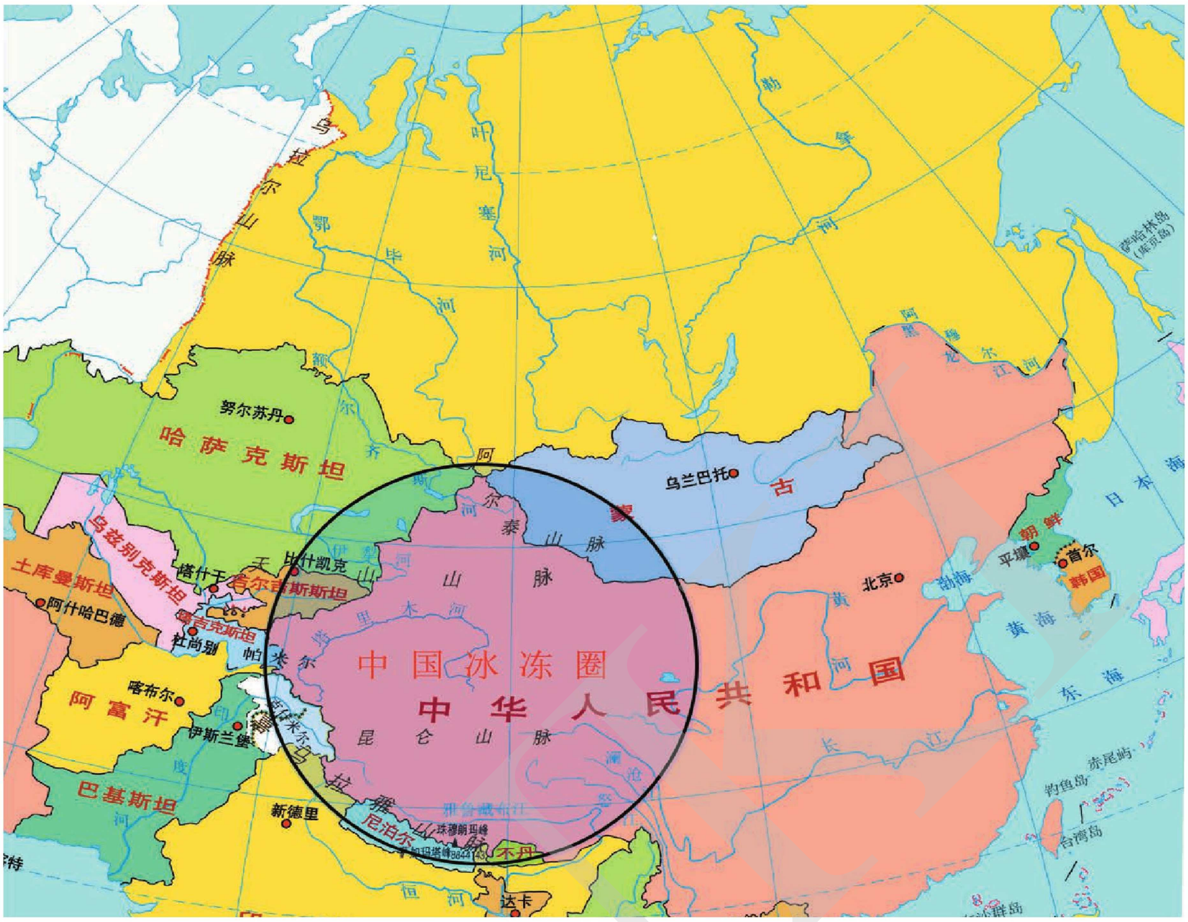

Figure 1 Cryosphere in Western China is the birthplace of many rivers in Asia

glaciers, indicating that glaciers, as solid reservoirs, play a significant role in regulating the runoff changes in wet and dry years, which is very beneficial to the utilization of water resources in oasis in arid areas. The regulation effect of permafrost hydrology is mainly manifested by the increase in the active layer thickness through the permafrost ablation (Figure 2). The storage space of soil water is enlarged, and the water released by summer precipitation through the soil active layer increases. As a result, the summer precipitation prolongs the runoff generation time in the active layer, which often leads to an increase in winter runoff in permafrost area [1,14,15].

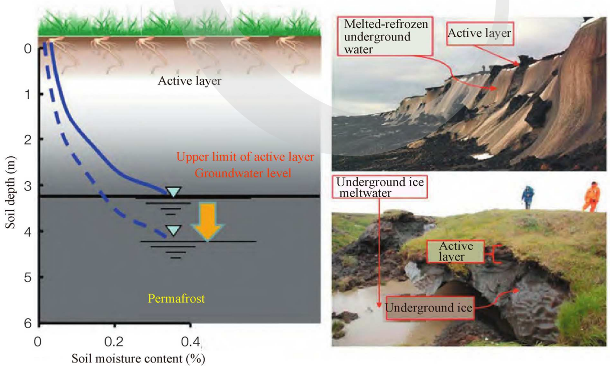

Figure 2 Effect of permafrost changes on runoff

The blue solid line and dotted line on the left indicate the relative positions of upper limit of permafrost active layer and groundwater level before and after the thawing of permafrost, respectively.

3 Runoff change in cryosphere and its impact

The change of cryosphere has led to the increase in glacier meltwater runoff, the advance snowmelt runoff, and the increase in winter runoff in permafrost regions, which are the basic characteristics of the runoff change of glacier meltwater since 1960s.

3.1 Impact of glacier meltwater on runoff

Global warming leads to the increase in river runoff which is greatly affected by glacial replenishment and has a significant impact on surface water resources, especially in arid and water-deficient areas. Taking China as an example, since 1980, the runoff from Xinjiang mountainous areas has increased significantly, with the highest increase of 40%. Seventy percent of the runoff increase in the source area of Urumqi River comes from the accelerated melting of glaciers. About

1/3 of the runoff increase in Aksu River in southern Xinjiang comes from the increase in glacial runoff in recent ten years. In the source area of the Yangtze River, the river runoff has decreased by 14% in the past 40 years, while the glacial runoff has increased by 15.2%. If there is no glacial runoff supply, the reduction of river runoff will be more significant. The increase in river water volume caused by glacier ablation is favorable at present [16,17].

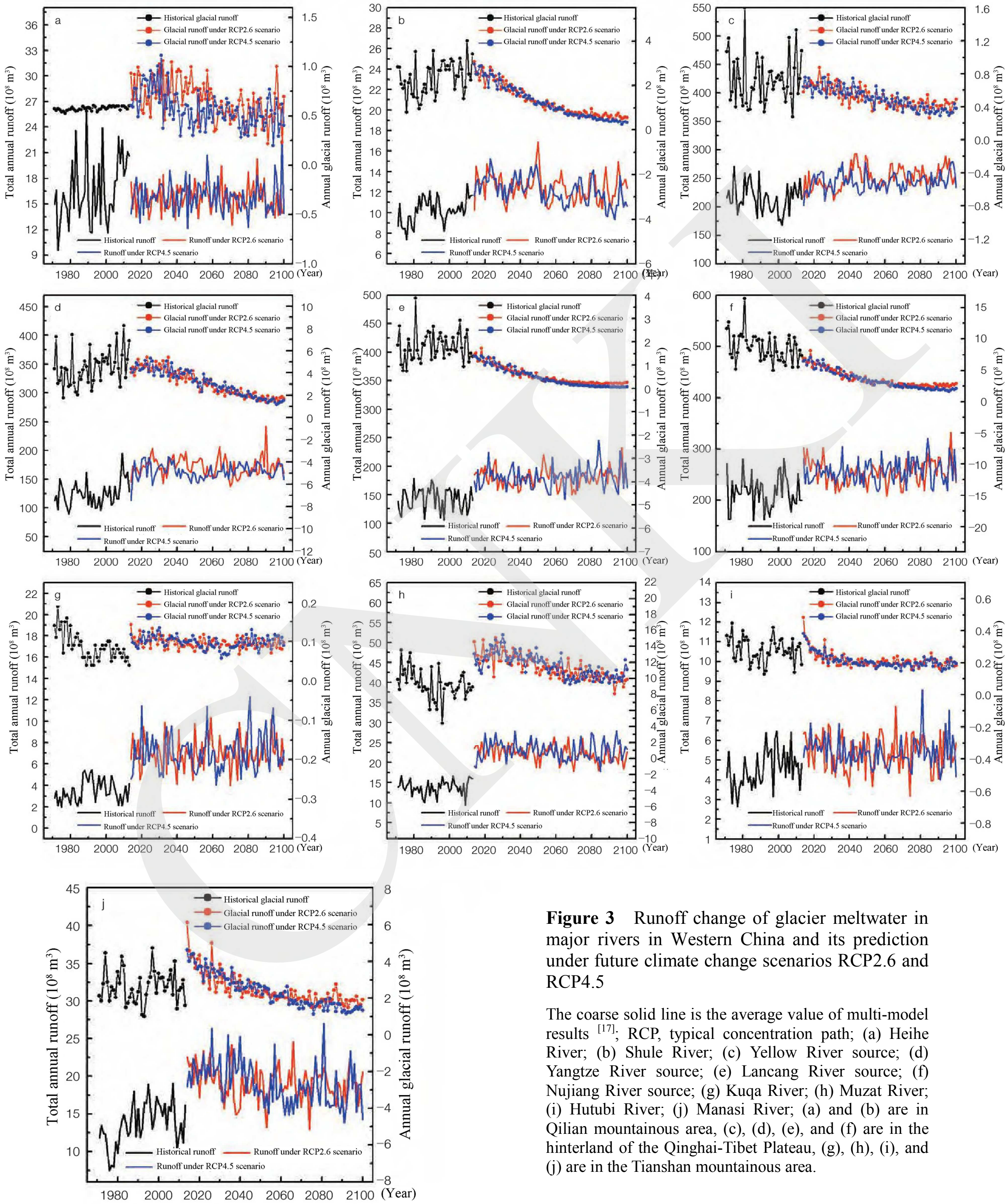

Figure 3 Runoff change of glacier meltwater in major rivers in Western China and its prediction under future climate change scenarios RCP2.6 and RCP4.5

The coarse solid line is the average value of multi-model results [17]; RCP, typical concentration path; (a) Heihe River; (b) Shule River; (c) Yellow River source; (d) Yangtze River source; (e) Lancang River source; (f) Nujiang River source; (g) Kuqa River; (h) Muzat River; (i) Hutubi River; (j) Manasi River; (a) and (b) are in Qilian mountainous area, (c), (d), (e), and (f) are in the hinterland of the Qinghai-Tibet Plateau, (g), (h), (i), and (j) are in the Tianshan mountainous area.

With the decrease in glacier area, the amount of glacier meltwater will decrease in a certain period of time. The inflection point of glacier meltwater from increase to decrease is the focus of attention. The results demonstrated that the glacial runoff increases first and then decreases with the increase in temperature. The occurrence time of the inflection point is mainly related to the size and quantity of glaciers in the watershed. ① In the watershed with low glacier coverage and dominated by small glaciers, the inflection point has appeared, such as the Shiyang River Basin in Hexi Corridor, which is greatly affected by the East Asian monsoon [18], Manasi River and Hutubi River basins in the northern slope of Tianshan Mountains in the region of westerlies, and the sources of Nujiang River, Yellow River and Lancang River in the Qinghai-Tibet Plateau [19,20]; ② in the next 10–20 years, there will be an inflection point in the watersheds dominated by large glaciers, such as Kuqa River and Muzat River on the southern slope of Tianshan Mountains, Heihe River and Shule River in Qilian Mountains, and Yangtze River source in Qinghai-Tibet Plateau [19,20]; ③ in watershed with large-scale glaciers, the inflection point of glacier meltwater appears late or will not occur in the late 21st century. For example, the inflection point in the Aksu River Basin on the southern slope of Tianshan mountains may come after 2050 (Figure 3). According to the seasonal distribution of glacier meltwater, the beginning date of glacier ablation is advanced, and the ending date is delayed.

3.2 Hydrologic effect of snow cover variation

From 1965 to 2015, the measured snow cover variation in Eurasia showed a trend of warming, thickening, and strengthening, which is manifested in delay of the first day of snow accumulation, the earlier last day of snow accumulation, the reduction of the snow accumulation period, the distinct increase in the average snow depth, and the intensified snowfall at 90% of stations. Besides, the days of light snow decreased; those of moderate snow increased slowly before 2000 and decreased after 2000; those of heavy snow increased as a whole; blizzard days decreased before 1990 and increased after 1990 [21].

The proportion of snow/snow cover meltwater in Western China is generally 15%–25%, and they are the main sources of water in northern China. Climate warming, the ratio of snowfall to rainfall (rainfall-to-snowfall ratio), and the snow cover variation have changed the annual runoff process of watersheds, leading to the advance snow melting and the shortened ablation period, especially for some rivers mainly supplied by snow cover meltwater. For example, the maximum runoff month of Kelan River is advanced from June to May every year (Figure 4). Since 1960, the snowmelt runoff in high-altitude and high-latitude watersheds in the northern hemisphere has shown an increasing trend, while that in other regions is mainly decreasing (Table 1). From 1960 to 2014, the snowmelt runoff in China generally shows an increasing trend, with significant increases in the southern Tianshan Mountains, the western Qilian Mountains, the source area of the Yangtze River, and the Changbai Mountains. In the future, the overall snowmelt runoff in western China will show little change or an increasing trend, and the temperature rise in high-altitude areas is not enough to cause qualitative changes in the rainfall-to-snowfall ratio. The main reason is the increase in snowfall in alpine regions caused by the increase in precipitation [16]. With the shrinking of the glacier area in western China, the glacier meltwater runoff decreases, and the snowmelt runoff plays a more important role in the western region, especially in the northwest region.

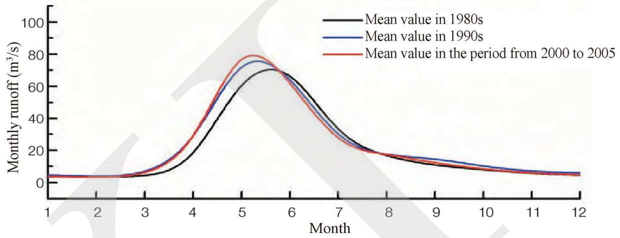

Figure 4 Annual variation of snowmelt runoff at Altay hydrological station of Kelan River, Xinjiang

Table 1 Snowmelt runoff variation of main rivers in the northern hemisphere since 1960 [17]

Watershed	Snowmelt runoff trend	Significant or not
Colorado River	Decrease	Significant
Rhine River	Decrease	Significant
Ob River	Increase	Significant
Yenisei River	Increase	Significant
Lena River	Increase	Significant
Syr Darya	Decrease	Not significant
Amu Darya	Decrease	Not significant
Indus River	Decrease	Significant
Indus River source	Decrease	Not significant
Tarim River	Decrease	Not significant
Amur River	Decrease	Not significant
Yangtze River source	Increase	Not significant
Yellow River source	Decrease	Not significant
Yarlung Zangbo River	Increase	Not significant
Mekong River	Increase	Not significant
Ganges River	Decrease	Not significant

Note: the confidence level of significance is 0.05.

3.3 Hydrologic effect of permafrost

The permafrost freezing-thawing process affects hydrology in many aspects. Soil freezing can increase runoff, retard soil water supply, increase snow cover runoff in spring, and delay the transportation of solute to deep soil. Due to the close relationship between snow cover and permafrost, the hydrological relationship between them is also highly concerned. Due to the phase change of water, the process of snowmelt infiltration is affected by many factors, including soil temperature, freezing depth, previous soil moisture content, snow thickness, and the complex interaction among these factors. The studies about the process on a small scale demonstrated that the existence of pore ice in soil usually reduces the infiltration capacity of soil, forms large surface snowmelt runoff, and reduces groundwater recharge.

The existence of permafrost mainly affects the process of surface runoff generation and concentration. The annual runoff process (i.e., annual runoff distribution) of watersheds with different permafrost coverage is significantly different [13,21,22]. The influence of interdecadal variation of permafrost on runoff mainly occurs in the watersheds with high permafrost coverage, and the degradation of permafrost leads to the change of underlying surface and water storage conditions, and then results in the increase in winter runoff (Figure 2). The analysis and simulation of runoff change in Russia indicate that due to the decrease in freezing front and the change of melting process of permafrost, the surface runoff in European Russia in winter increases significantly, and the increase in runoff reaches 50%–120% [23]. For example, for the four main rivers (Lena River, Yenisei River, Ob River, and Mackenzie River) flowing into the Arctic region, the runoff increases significantly in winter and spring but decreases in summer, which is closely related to the thawing of permafrost and the advance snow cover melting in spring [23].

The degradation of permafrost and seasonally frozen soil has caused the increase in river runoff in winter (dry season), the decrease in runoff in summer, and the slowing down of annual runoff process in corresponding regions of China. The intensity of runoff change is related to the permafrost coverage. In the future, with global warming, the permafrost will continue to degrade, and the underlying surface with vegetation will change, which may lead to the decrease in runoff system of watersheds in cold regions. Climate warming can lead to the expansion of alpine grassland and shrub meadow in high-altitude permafrost; with the degradation of swamp meadow and alpine meadow, more of the precipitation is subjected to evapotranspiration caused by the expansion of underlying surface; the increase in the proportion of regional evapotranspiration in precipitation would lead to the decrease in the future runoff coefficient of the watersheds in cold regions [16].

4 Ecological and environmental effects of cryospheric hydrology

4.1 Hydrological process change and ecosystem in cryosphere

The hydrological change of the cryosphere not only affects the river runoff but also influences the ecosystem through the change of the water cycle. In the inland river basins of arid areas in China, the glacier change plays an important role in regulating and stabilizing the oasis and lake in the watershed ecosystem composed of alpine glacier, piedmont oasis, and terminal lakes (Figure 5). Glaciers are the source of life for the stability and development of oases in arid regions of China. In fact, it is the existence of glaciers and snow cover that makes many oases formed in the arid areas in the hinterland of China for human survival, which makes the arid areas in China different from other zonal arid areas in the world. Glaciers and oases are the cores for the stability and persistent existence of glacier and snow cover–oasis scenery and its related hydrological and ecosystem. If there are no glaciers and snow cover, there is no oasis, and people cannot survive for thousands of years.

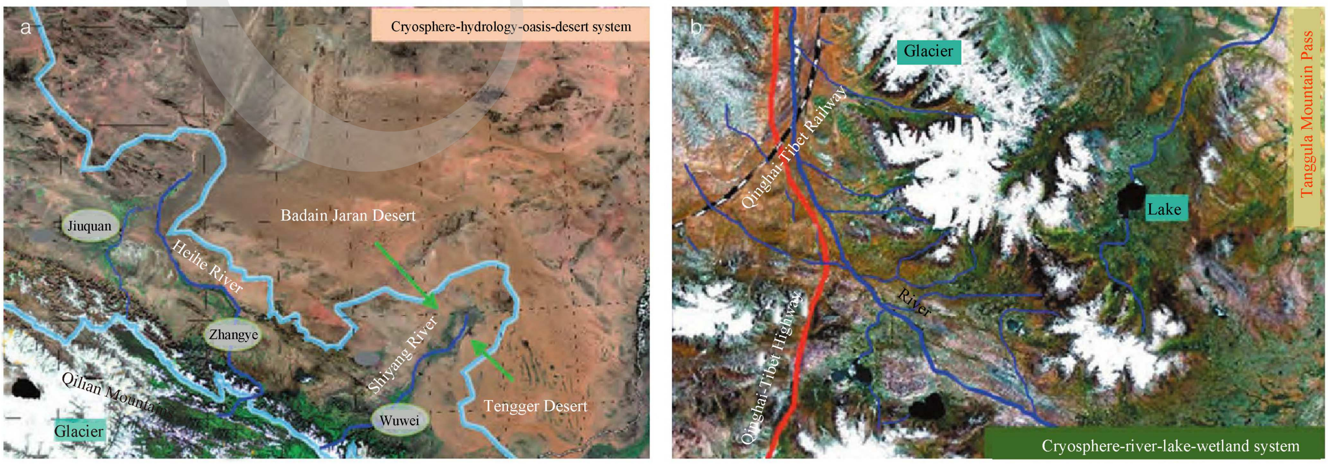

Figure 5 Cryosphere-hydrology-ecology relationship in inland river basin (a) and Qinghai-Tibet Plateau (b)

In high-latitude and high-altitude areas, the change of cryosphere not only directly affects the hydrological situation of source areas of some major rivers but also has a close relationship with the changes of lakes and marshes. Glacier changes affect the water cycles in the surrounding area and then influence the ecology and environment of the source areas. The special water-heat exchange of permafrost active layer is the key to maintaining the stability of alpine ecosystem. The alpine marsh and alpine meadow ecosystems in permafrost area have significant water conservation function and are important factors to stabilize water cycle and river runoff in the source areas of rivers. The change of permafrost is the main reason for the degradation of alpine meadow and marsh wetland in the source areas of rivers. In a word, in high-altitude and high-latitude areas, cryosphere, river, lake, and wetland are closely connected. In arid inland river basins, cryosphere, river, oasis, and terminal lake are inseparable. The change of cryosphere has an important effect on the ecosystem in cold regions. Major projects of ecological construction and water source protection in western China, such as Three-river-source National Park, Tarim River Comprehensive Treatment Project, Tibet Ecological Barrier Project, Qilian Mountain Ecological Protection Project, and Tianshan Nature Reserve, are closely related to the hydrological impact of the cryosphere.

In the Antarctic and Arctic regions, the cold freshwater melted from the cryosphere has a significant impact on marine ecology. The cold effect of the water melted from the cryosphere can change the temperature of high-latitude ocean, and the freshwater effect can also affect ocean temperature. Under the background of global warming, the continuous meltwater from the cryosphere flows into the ocean, which changes the living environment of the marine ecosystem, thus affecting the marine ecosystem. In high-altitude watersheds on land, the changes in the cryosphere have the same impact on lake ecosystems.

The meltwater in the alpine cryosphere also has an important impact on the biogeochemical process of watersheds. A large number of loose deposits in the cryosphere area, which are strongly eroded and weathered, and the physical, chemical, and biological substances accumulated on the surface of glaciers for a long time are transported into the lakes, farmlands, and grasslands along with the glacier meltwater, which will affect the temperature, turbidity, and nutrients of lakes, as well as the soil and nutrients of farmland and grassland. Actually, the physical, chemical, and biological composition of soil in oasis farmland is closely related to the material composition of the upper cryosphere area in the inland river basins. One of the important sources of biogeochemical composition in oasis soil is the result of long-term transportation and accumulation of materials eroded and accumulated in the cryosphere under the impact of cryospheric hydrology.

4.2 Hydrological disasters in cryosphere

Glaciers and snow meltwater can form floods, which affect the economy, traffic, life and property safety of human gathering lowlands. ① Snow-melted flood. In the snowmelt period, the snow cover at high-latitude and high-altitude areas will often form snow-melted floods and cause disasters because the active layer of permafrost has not melted yet and the amount of snow cover in the early stage is large, or the warming is fast and high. Snow-melted floods can be divided into mountain type and plain type. Mountain-type flood often forms in high-altitude areas. For example, Tianshan Mountains, Himalayas, Altai Mountains, and other places are prone areas of the mountain-type snow-melted floods. In March 2010, the temperature rose and the rainfall and snowfall were repeatedly staggered in northern Xinjiang, resulting in frequent snow-melted floods in Ili, Altay, Tacheng, and other places, and the traffic in some areas was blocked repeatedly. Abnormal weather changes have caused great losses to people's production and life, resulting in 310,000 people suffering from disasters in Ili River Valley, the collapse of more than 10,000 greenhouses and more than 20,000 houses, and the death of more than 40,000 livestock. In high-latitude areas, in addition to mountain-type snow-melted floods, there are also plain-type snow-melted floods, which have a more extensive impact. In Europe, this situation also occurs from time to time [23]. ② Glacier ablation flood. Generally, it occurs in July and August with the largest degree of ablation. Under the influence of continuous high temperature in the early stage, glacier ablation accelerates and floods are formed. Due to the thawing of permafrost, the ability of ice-melted flood to transport sediment is also greatly enhanced. Therefore, the ice-melted flood often forms mud-rock flow, which is harmful to the downstream areas. ③ Mixed flood. Snow-melted flood, together with ice-melted flood and precipitation flood, often forms mixed flood, and the impact is more serious. ④ Glacial lake outburst flood. It is characterized by burstiness, rapidity, and large energy, which is more threatening to the downstream areas. Since the formation mechanism of the flood is complicated, and it is difficult to predict and prevent, the disaster degree is often large.

4.3 Geographical effect of water resources in cryosphere

There are many cross-border rivers affected by the cryosphere. How to systematically understand the hydrological and water resources effects of cryosphere changes is not only related to the sustainable development of the host country but also associated with the utilization of water resources by neighboring countries. Once an inflection point appears in the change of water resources in the cryosphere, it can lead to significant changes in river runoff, which will cause international issues. This problem has drawn extensive attention from the international community, and some international organizations have issued warnings. For example, the Human Development Report 2006 issued by the United Nations

Development Programme points out that the glacier ablation in Central Asia, South Asia, and the Qinghai-Tibet Plateau in the next 50 years may be one of the most serious threats to human progress and food security. The World Bank also pointed out in the World Development Indicators 2005 that glacier changes in the Himalayas (Qinghai-Tibet Plateau) in the next 50 years will seriously affect the river runoff there. The key question is how much the water resources of the cryosphere in the host countries affect the downstream areas, that is, how long the time scale of the impact and how wide the space range are. It is very important to understand the quantitative impact. Otherwise, it will lead to a series of suspicion and misunderstanding between upstream and downstream countries and even lead to international disputes. On the one hand, much glacier meltwater in China flows out of the country; on the other hand, some rivers in China are also supplied by the glacier meltwater from other countries. Therefore, it is the core for gaining the speaking right and initiative of international "water negotiation" to master the process, quantity, and spatio-temporal scale of hydrological changes in the cryosphere.

5 Conclusions and prospects

The main feature of hydrological processes in the cryosphere is that the runoff generation and concentration are closely related to temperature. Under the background of climate warming, the hydrological processes have changed greatly, which has an important impact on the safety of "Asian water tower." The main conclusions are as follows:

(1) The hydrological function of the cryosphere is mainly manifested in three aspects of water conservation, runoff supply, and regulation on water resources, especially for "Asian water tower."

(2) Under the background of climate warming, the hydrological processes of the cryosphere have changed, which is mainly manifested by the increase in glacier meltwater runoff, the decrease in glacier reserves, the advance snowmelt runoff peak, and the change of annual runoff distribution caused by permafrost degradation. It is estimated that the water resources in the cryosphere will decrease in the future, and its regulating function will also decline.

(3) The future changes of hydrological processes of the cryosphere have significant impacts on the "Asian water tower," ecological processes, sustainable development, and disasters in cold regions.

With the rapid change of the cryosphere, the meltwater in the cryosphere is also changing rapidly, which will lead to many potential consequences in the water supply and water cycle of the cryosphere. At present, for most people, the understanding of the change of cryospheric hydrology is kept at the description of the phenomenon of cryosphere meltwater, and there is no sufficient understanding of the deep, systemic, and extensive influence brought by cryospheric hydrology. For example, the in-depth understanding of the water conservation and regulation of glacier meltwater, the water supply and regulating-storing function at different time scales of permafrost, water cycle of the large-scale cryosphere and its impact on ocean hydrology, ecology, and circulation is not only the basic problem of accurately understanding the runoff change of watersheds and clarifying the global water cycle but also the important scientific problem about sustainable utilization of watershed water resources, scientific conservation of regional ecology, and quantitative identification of global hydrological impacts. Therefore, the future research on cryospheric hydrology not only needs to carry out the mechanism and process research based on observation and simulation for the basic problems of cryospheric hydrology but also requires comprehensive and systematic cryospheric hydrology studies focusing on the actual needs of watershed, regional, and global water problems from a new perspective with a holistic view.

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