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# Permafrost and groundwater on the Qinghai-Tibet Plateau and in northeast China

Guodong Cheng · Huijun Jin

**Abstract** The areal extent of permafrost in China has been reduced by about 18.6% during the last 30 years. Due to the combined influences of climate warming and human activities, permafrost has been degrading extensively, with marked spatiotemporal variability. Distribution and thermal regimes of permafrost and seasonal freeze-thaw processes are closely related to groundwater dynamics. Permafrost degradation and changes in frost action have extensively affected cold-regions hydrogeology. Progress on some research programs on groundwater and permafrost in two regions of China are summarized. On the Qinghai-Tibet Plateau and in mountainous northwest China, permafrost is particularly sensitive to climate change, and the permafrost hydrogeologic environment is vulnerable due to the arid climate, lower soil-moisture content, and sparse vegetative coverage, although anthropogenic activities have limited impact. In northeast China, permafrost is thermally more stable due to the moist climate and more organic soils, but the presence or preservation of permafrost is largely dependent on favorable surface coverage. Extensive and increasing human activities in some regions have considerably accelerated the degradation of permafrost, further complicating groundwater dynamics. In summary, permafrost degradation has markedly changed the cold-regions hydrogeology in China, and has led to a series of hydrological, ecological, and environmental problems of wide concern.

**Keywords** Permafrost degradation · Ecological environment · Groundwater dynamics · Climate change · China

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## Introduction

Heat and moisture transfer and the potential greenhouse effects of the carbon pools in the permafrost interact with the climate systems and hydrogeological cycles. Due to the increasing development of natural resources and land use in the cold-regions environments, escalating demands for water resources and the subsequent water pollution have become the foci of research on the local geocryology and hydrogeology.

In permafrost regions, watershed hydrogeological conditions are controlled by the distribution of frozen ground and taliks, as well as the freeze-thaw processes of aquifers (White et al. 2007). Monitoring indicates that since the late twentieth century, the thermal state of shallow permafrost has changed remarkably (Christiansen et al. 2010; Romanovsky et al. 2010; Smith et al. 2010; Zhao et al. 2010a). However, ground and surface warming alone cannot sufficiently account for the several degrees of permafrost warming; cyclic changes in snow cover might also have a significant contribution (Osterkamp 2007). Consequently, cold-region hydrologic and hydrogeologic environments have changed remarkably under an extensive degrading permafrost and changing snow-cover dynamics (Serreze et al. 2000; Hinzman et al. 2005; White et al. 2007).

Although research in cold-regions hydrology has seen significant and rapid growth during the last few decades, the associated advances in permafrost hydrogeology have been limited to only a few research attempts in groundwater chemistry and modeling (e.g., Clark et al. 2001; Woo et al. 2008; Carey and Quinton 2005; Bense and Person 2009), changes in the hydraulic connections as a result of thawing permafrost (Carey and Woo 2000), and impacts of changing permafrost on watershed hydrologic processes in major rivers such as those in Siberia and Alaska (Ye et al. 2003; Yang et al. 2004a, b; Zhang et al. 2012). In these studies, interactions of groundwater and permafrost have been taken into account. These scholars observed that thin permafrost has greater impact on ice formation in the freezing season and the base flows in the thawing season, and the mutual influences of groundwater and surface waters are significant in discontinuous permafrost regions, providing more supplies to the winter base flows of rivers.

Although new technology and methods have provided more powerful means to study permafrost hydrogeology,

many problems remain unsolved for coupled surface and groundwater systems. In particular, temporal changes and migration of soil moisture in the active layer and changes in surface evapotranspiration have not been adequately studied at scales smaller than the watershed scale (Woo 1986, 2000; Woo et al. 2008). Although rapidly improving technologies have provided powerful tools to study flow processes related to freezing and thawing of soils, the hydraulic connections between various small watersheds are still inadequate in the source areas of major rivers in discontinuous permafrost regions. Woo (2000) called for more modeling studies on the roles of spatial changes of ground freezing and thawing in modifying the groundwater dynamics.

During the last few decades, climate warming and subsequent permafrost degradation have reshaped cold-regions hydrogeologic environments (Peterson et al. 2002; Bense and Person 2009; Zhang et al. 2012). This is evidenced in changing groundwater flow patterns, lowering water tables, shrinking wetlands, and worsening ecological environments (Wang GX et al. 2000; Jin et al. 2000, 2009; Ye et al. 2003; Yang et al. 2004a; Zhang et al. 2012). Permafrost degradation has been shown to smooth out the seasonal distribution of runoff at the watershed scale, which clearly affects groundwater dynamics and resources volumes (Woo 1986; Michel and van Everdingen 1994; Hinzman et al. 2005; White et al. 2007). However, significant uncertainty remains in the interpretation of observations and models due to inadequate field measurements and the need for consideration of many terrestrial processes (McClelland et al. 2004; Zhang et al. 2012). To date, most of these models have focused on hydrology in North America and northern Eurasia (e.g., Berezovskaya et al. 2004; Bense and Person 2009; Muskett and Romanovsky 2009; Zhang et al. 2012).

The permafrost and hydrogeologic regimes in southern permafrost regions (relative to the Arctic) such as the boreal wetlands and forests, and areas of elevational permafrost in south-central Alaska and Mongolia, on the Qinghai-Tibet Plateau (QTP), and in the mountains in central and high Asia, are more sensitive to climate change than other permafrost regions. Therefore, more reliable evidence and rapid changes could be anticipated in these regions in response to climate change. Unfortunately, there have been very limited observational studies conducted in these areas.

In the early 1960s, research programs and engineering practices related to geocryology and hydrogeology were initiated and have since been intermittently implemented on the QTP, in northeast China, and in mountains in northwest China. Various types of maps for geocryology and hydrogeology were compiled at different periods (e.g., Guo et al. 1981; Dai 1982; Wang et al. 1994; Li et al. 1996; Wang 2006; Li et al. 2012). In some areas the relationships of groundwater and permafrost were more intensively studied such as in far northern northeast China (Wang et al. 1988; Guo et al. 1989) and along the Qinghai-Tibet Highway (QTH, see Fig. 1) (Bi 2003). However, the studies have not been sustained and thus

yield data that are inadequate for more systematic interpretations for the resources volumes, trends, sensitivity, and vulnerability of groundwater dynamics in permafrost regions.

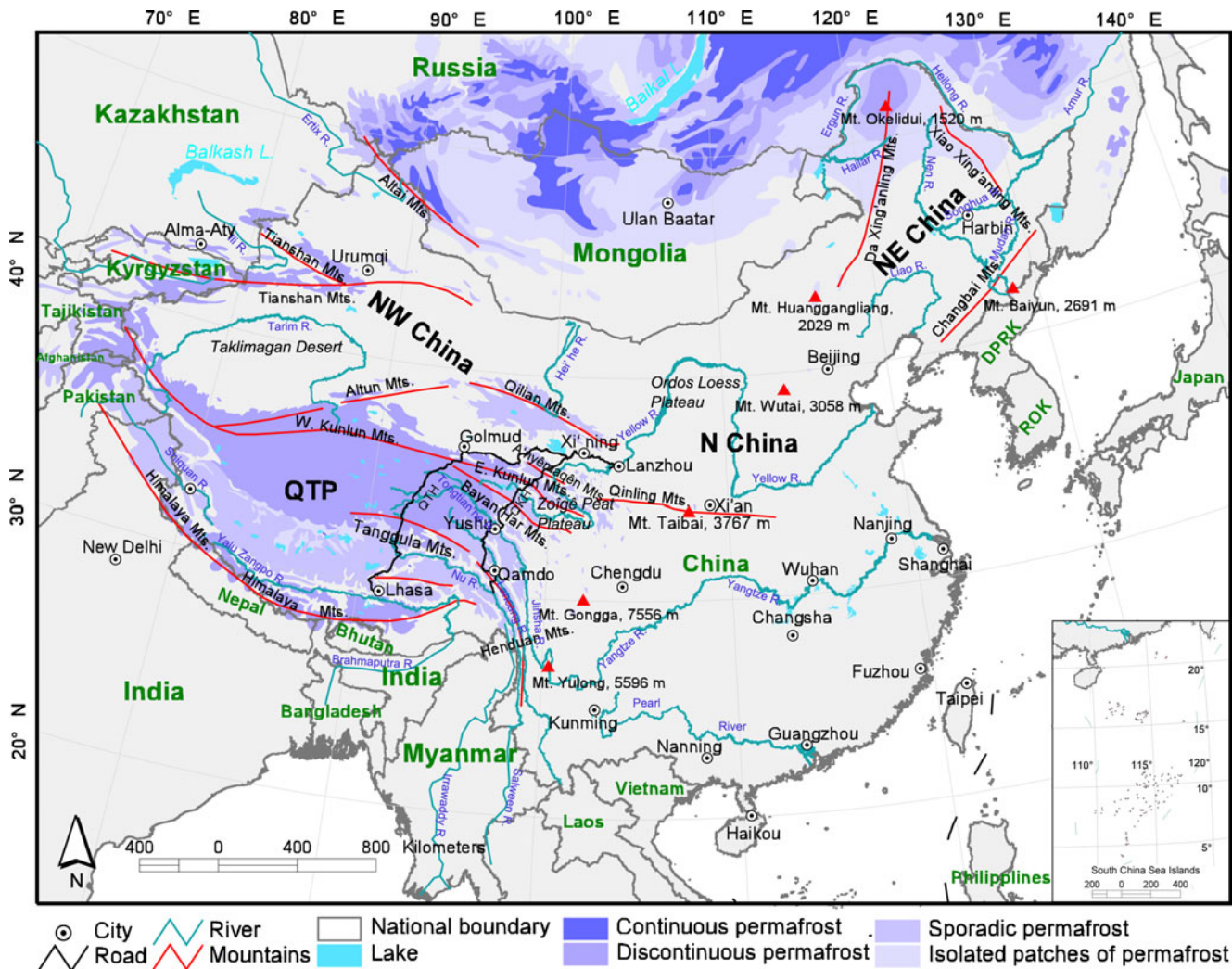
Research on interactive processes between permafrost and groundwater are important for management of cold-regions water resources, ecological environments, and engineering construction as China continues its dynamic economic growth. Studying the permafrost-groundwater interactions and their changes in China, and understanding the impacts of climate warming on cold-regions water cycling, are important for the prediction of changes in water resources, and for developing adaptive strategies and policies. Some programs on groundwater and permafrost research have been resumed in the permafrost regions in China, and this paper summarizes the progress of this research during the last three decades.

### Distribution and degradation of permafrost in China

China used to have 68.6 % of its land territories occupied by permafrost ( $2.15 \times 10^6 \text{ km}^2$ , or 22.4 %) and seasonally frozen ground (46.2 %) (Zhou et al. 2000), but it might have changed significantly since the late 1980s when the monitoring of the thermal state of permafrost started. Permafrost is mainly found on the QTP, in the Xing'anling and Changbai mountains in northeast China, in the Tianshan and Altai mountains in northwest China, and in some high mountains in central China such as the Taibai and Wutai mountains (Fig. 1) (Zhou and Guo 1982).

Permafrost degradation has led to a decline in permafrost areal extent in China, from  $2.15 \times 10^6 \text{ km}^2$  in the 1970s to  $1.75 \times 10^6 \text{ km}^2$  in 2006 (Zhou and Guo 1982; Wang 2006), and possibly to  $1.59 \times 10^6$  in 2012 (Li et al. 2012). This suggests a permafrost reduction of about 18.6 % during the 30 years between the 1970s and 2000s, but this must be confirmed with systematic surveys and mapping (Table 1). After several decades of monitoring of permafrost changes in China, it is evident that climate warming is the basic cause for permafrost degradation, and human activities such as deforestation for agriculture and overgrazing, have accelerated permafrost degradation in some regions (Jin et al. 2000, 2007, 2009, 2011). The response time and affected depths of permafrost to climate change depend on extents, duration, amplitudes, and rates of climate warming and are closely related to soil types, surface coverage, ice content, groundwater occurrence, geothermal anomalies, and human activities. Because the occurrence and evolution of permafrost fundamentally control the water cycling in permafrost regions, permafrost degradation may have initiated substantial changes in the groundwater dynamics in cold regions.

Jin et al. (2011) closely examined the spatiotemporal variability of permafrost degradation in relation to the rates of temperature changes in the air, at the ground



**Fig. 1** Map of permafrost in China (Wang 2006). Note 1: *QTH* is the Qinghai-Tibet Highway from Golmud, Qinghai Province to Lhasa, Tibet Autonomous Regions of China. In some studies, the *QTH* also includes the segment from Xi'ning to Golmud, Qinghai Province. *QKH* is the Qinghai-Kang Highway from Xi'ning, Qinghai to Jinghong, Yunnan Province. In most permafrost studies, the *QKH* mainly includes the segment from Xi'ning to Yushu (Gyêgu), Qinghai Province. *DPRK* is the Democratic People's Republic of Korea (North Korea). *ROK* is the Republic of Korea (South Korea). Note 2: Ephemeraally frozen ground is that which is frozen for less than 3 months, whereas seasonally frozen ground lasts for more than 3 months but less than 1 year. Permafrost is defined as the frozen state for more than two consecutive summers; that which lasts for more than 1 year but less than 2 years is defined as *pereletok*. However, the *pereletok* is not well observed due to its limited presence and minor significance, and therefore it is not marked on the map. Note 3: China is traditionally divided into several regions: NE China, NW China, N China, QTP, SW China, Central China, E China and S China. In this map, those regions free of permafrost are seldom mentioned. Permafrost in China is mainly found on the *QTP*, *NE China* and *NW China*. However, in (very) high mountains in N China and SW China such as *Mt. Taibai*, *Mt. Wutai*, *Mt. Gongga*, and *Mt. Yulong*, alpine permafrost occurs. The *Qilian Mountains* are also regarded as the northern part of the *QTP*. Permafrost also presents in the joint mountains of the *East Kunlun Mountains* and *West Qinling mountains*. Note 4: Permafrost in Mongolia and southern Russia includes that in the *Altai*, *Sanya*, *Hangayn*, *Stanovy* and *Yablonovy mountains*. However, they are not marked out in this map because permafrost there is not discussed in this paper. It shows up because of their southern-most locations in Eurasia and regional relationships with permafrost in China

surface, and in the ground (subsurface) on the QTP (Table 2). Their results indicate that plateau permafrost was relatively stable during 1976–1985; a regional degradation of permafrost occurred during 1986–1995; an accelerated degradation of permafrost has been observed since then; and permafrost degradation is anticipated to continue or accelerate during the next few decades. In the meantime, permafrost degrades more rapidly on the eastern and northeastern margins, and less rapidly in the interior of the QTP. Based on the measurements of ground temperatures in northeast China, soil

temperatures at depths shallower than 20 m have been rising at rates of 0.02~0.06 °C/year during the last few decades (Jin et al. 2007).

As a temperature-dependent aquitard, frozen ground can obstruct or significantly reduce hydraulic connections between groundwater, surface water, and other water sources. The occurrence and evolution of permafrost and the active-layer dynamics thus define the formation, migration, distribution, and cycling of groundwater in cold regions. The degradation of permafrost, therefore, will inevitably alter the storage and flow conditions, and



**Table 1** Permafrost areal extents ( $\times 10^6 \text{ km}^2$ ) in China: changes from 1970s to 2012

Types of permafrost	Year				
	1970s	1988	2000	2006	2012
Latitudinal <sup>a</sup> permafrost in NE China	0.382	0.388	0.390	0.356	0.240
Alpine permafrost in central and NW China	0.268	0.268	0.261	0.300	0.300
Elevational <sup>b</sup> permafrost on the QTP	1.500	1.500	1.500	1.100	1.050
Sum	2.150	2.156	2.151	1.754	1.590
References	Zhou and Guo 1982	Shi and Mi 1988	Qiu and Cheng 1995; Zhou et al. 2000	Wang 2006	Li et al. 2012

<sup>a</sup> Latitudinal permafrost is permafrost occurring primarily as a result of proximity to the poles

<sup>b</sup> Elevational permafrost occurs primarily as a result of high elevation. Notes: Li et al. (2012) compiled the latest permafrost map by updating and integrating the existing maps of permafrost in China using grid-based modeling results instead of the previous mapping methods, i.e., using the correlations of permafrost distribution with other environmental variables. Therefore, the values in this table are generally smaller, but perhaps more accurate, than previously published values which also include the areal extents of glaciers and lakes generally free of permafrost. However, it might be too early to conclude that permafrost has degraded extensively just by these comparisons because the changes of permafrost extent could have resulted from technical or methodological differences

modulate groundwater and surface waters, and may lead to deterioration of ecological environments.

## Permafrost region of the Qinghai-Tibet Plateau (QTP)

### Distribution of groundwater

As the “water tower of Asia,” the QTP each year receives  $850 \text{ km}^3$  of water from atmospheric precipitation, and exports about  $690 \text{ km}^3$  of water (Lu et al. 2004). Data indicate that on the QTP there are 36,793 modern glaciers with a total ice-surface of  $49,873 \text{ km}^2$  and total ice volume of  $4,561 \text{ km}^3$ , which account for 79.4, 84.0, and 81.6 %, respectively, of the national total glacier number, ice-surface areal extent, and ice volume in China (Pu et al. 2004). In central and high Asia, glacier-melt is one of the major water supplies for inland rivers and groundwater. There are extensive expanses of wetlands on the QTP, with a total areal extent of about  $1.33 \times 10^5 \text{ km}^2$ , among which tussock wetlands are mainly identified in the source areas of the Yangtze and Yellow rivers and on the Zoigé Peat Plateau. By areal extent, 43.5 % of wetlands on the QTP are clustered in the source areas of the Three Rivers (SATRs), i.e., the Yangtze, Yellow, and Lancang-Mekong rivers (Niu 1999). There are also thousands of lakes on the QTP, with a total water

surface of  $36,889 \text{ km}^2$  and total water volume of  $546 \text{ km}^3$  (Xie et al. 2003). Such a significant presence of lakes and wetlands substantially modulates the water resources.

The QTP is also the primary permafrost zone in China. The presence of permafrost significantly limits moisture exchanges among the surface, the permafrost layer(s), and the underlying unfrozen soils. Thus, permafrost plays a significant role in water cycling and has important influence on the generation and modulation of the hydrology in alpine regions, and directly affects groundwater formation and its hydrochemistry. In particular, spatiotemporal features of vegetation in alpine paludal meadows may facilitate the development and preservation of permafrost and can maintain the so-called “water tower” function by storing and modulating large amounts of water resources.

In summary, regional hydrologic and hydrogeologic systems in permafrost regions are formed by interactions and interdependence of glaciers, lakes, wetlands, vegetation, permafrost, and groundwater. They participate in atmospheric circulations and water-vapor cycles on the QTP, and further affect larger-scale climate and hydrological cycles.

The hydrogeology on the QTP is complicated by the extensive occurrence of permafrost and intensive geologic structures and tectonic movements. The distribution and

**Table 2** Change rates ( $^{\circ}\text{C}/\text{year}$ ) of mean annual air temperature (MAAT), mean annual ground-surface temperature (MAGST), and mean annual ground (subsurface) temperature (MAGT) on the QTP during the last 30 years

Thermal types of permafrost	Years			
		1976~1985	1986~1995	1996~2008
Cold permafrost (MAGT < $-2^{\circ}\text{C}$ )	MAAT	$-0.01 \sim +0.02$	$+0.01 \sim +0.04$	$+0.02 \sim +0.06$
	MAGST	$-0.00 \sim +0.02$	$+0.01 \sim +0.04$	$+0.03 \sim +0.07$
	MAGT	0.00	$+0.00 \sim +0.02$	$+0.02 \sim +0.04$
Transitory permafrost ( $-2$ to $-1^{\circ}\text{C}$ )	MAAT	$-0.01 \sim +0.02$	$+0.01 \sim +0.04$	$+0.02 \sim +0.06$
	MAGST	$-0.01 \sim +0.02$	$+0.01 \sim +0.04$	$+0.03 \sim +0.07$
	MAGT	0.00	$0.00 \sim +0.02$	$+0.01 \sim +0.03$
Warm permafrost (MAGT $\geq -1.0^{\circ}\text{C}$ )	MAAT	$-0.01 \sim +0.02$	$+0.01 \sim +0.02$	$+0.02 \sim +0.06$
	MAGST	$-0.01 \sim +0.02$	$+0.01 \sim +0.04$	$+0.03 \sim +0.07$
	MAGT	$0.00 \sim +0.01$	$+0.01 \sim +0.02$	$+0.02 \sim +0.04$

Adapted from Jin et al. (2011)

thermal regimes of permafrost, the features of seasonal freeze-thaw processes, and the topography and geomorphology (active faults and associated geothermal anomalies and resultant talik formation) control the occurrence of groundwater and directly affect the groundwater depths and recharge and discharge conditions, as well as the groundwater hydrochemistry.

Intense tectonic movement and differential uplifts have shaped the framework of the QTP, which in turn determines large-scale landscapes. The graben basins and valleys are controlled by the nature, intensity, and modes of recent (neoid) tectonic movements, lithology (soil types), and sedimentary phases and structures. Hydraulically, they are directly linked with surface waters and nearby bedrock fissure water. They form complicated underground hydrological networks. Although the thickness, structures, textures, and ice contents of permafrost vary greatly in these graben basins and valleys of multifaceted sedimentary geneses, textures, and structures during the formative periods, the hydrogeology differs greatly from basin to basin, most of which are good for the storage of sub-permafrost water.

Vertically, permafrost serves as a relatively stable regional aquitard, forming a double- or even triple-layered structure of groundwater systems. Tectonic movement also plays an important role in the occurrence of groundwater. Various active faults and graben basins form frameworks controlling the flow and discharge of surface waters and groundwater. Active faults disturb and alter the latitudinal and elevational zonation of permafrost, and lead to the formation of numerous taliks such as the 24 taliks along the Qinghai-Tibet Highway (QTH; Wang et al. 1979; Qiu 1982; Jin et al. 2008).

Geothermal gradients in Tibet are relatively high ( $0.10\sim 0.35\text{ W/m}^2$ ), with large spatial variations (Wang and Huang 1990, 1996). On average, the geothermal gradient of unfrozen soils beneath permafrost on the QTP is about  $50\text{ }^\circ\text{C/km}$ ; average geothermal gradients in permafrost close to the base of permafrost vary from  $40$  to  $60\text{ }^\circ\text{C/km}$  along the QTH; and those in the Lunpola Basin on the Northern Tibet Plateau vary from  $50$  to  $70\text{ }^\circ\text{C/km}$  (Wang and Li 1983; Wang and Huang 1990). River and lake taliks disrupt the continuity and thickness of permafrost. These taliks also form important channels for recharge, flow, and discharge of groundwater. The integrated processes, history, and dynamics of permafrost, tectonics, and many other environmental factors control the distributive patterns of groundwater and determine the hydrogeology in permafrost regions, with great variations in different permafrost zones.

### **Features of permafrost hydrogeology: regional divisions of hydrogeologic conditions on the QTP**

Due to the close relationship of groundwater and permafrost, two hydrogeologic units are classified on the QTP on the basis of permafrost areal extent: continuous and discontinuous permafrost zones (Fig. 2). Patches of permafrost can also be found at the outer margins of the

discontinuous permafrost zone, but with much reduced influence on groundwater dynamics.

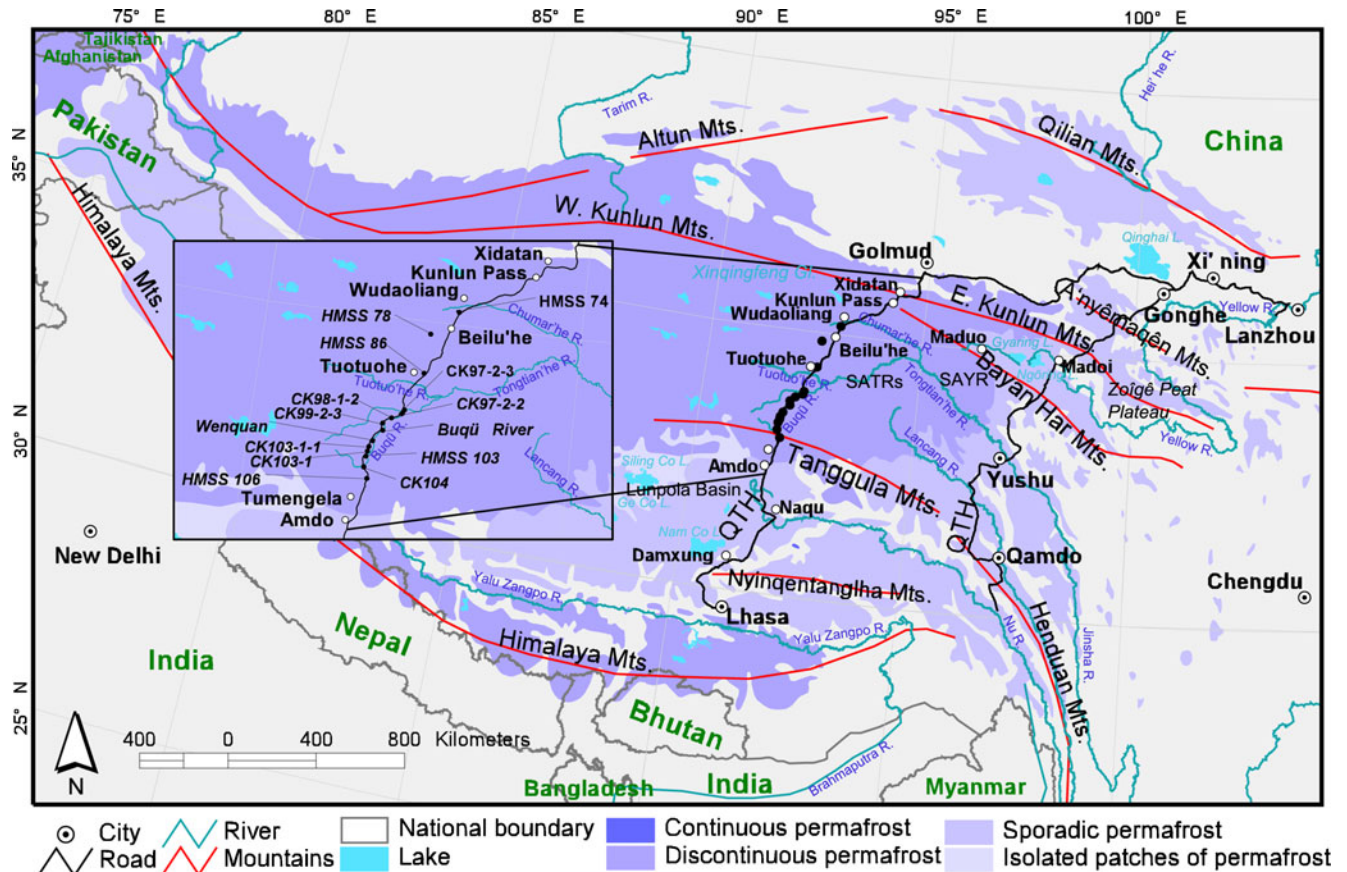
#### *Continuous permafrost zone*

The continuous permafrost zone includes the regions in the interior and western QTP to the south of the Kunlun Mountains, north of the Tanggula Mountains, and west of  $94^\circ\text{E}$  longitude (Fig. 2). Permafrost accounts for more than 75 % in areal extent and is generally thick and relatively cold. It serves as a relatively stable regional aquitard. As a result, vertical water percolation is poor, and atmospheric precipitation, surface waters, and shallow groundwater can only laterally or horizontally recharge deep groundwater through localized talik zones, or after penetrating through fault-fracture zones. Therefore, groundwater in this zone is characterized by long flow paths and poor recharge and discharge conditions due to limitations of the permafrost layer. The recharge volumes are also controlled by the extent of the supply areas. Therefore, the occurrence of groundwater is very uneven, and the burial depth of groundwater is generally controlled by the thickness of permafrost. Seasonal and longer-term variations in volumes, quality, and dynamics are apparent in shallow groundwater.

In contrast, the depths, volume, quality, and dynamics of deep groundwater are affected by geologic and tectonic structures, geomorphology, topography, and aquifer lithology (soil types). In alpine regions, well-developed frost cracks and tectonic fractures provide adequate space for groundwater storage, flow, drainage, and eventual discharge through fracture zones to ground surfaces or supply to nearby graben basins or valleys. The basins and valleys in the interior QTP such as the Tuotuo'he, Tongtian'he, and Chumar'he valleys along the upstream Yangtze River, were formed by subsidence related to intensive uplifts of the plateau during the Quaternary period. On their margins, active faults are generally well developed and are connected with nearby water-bearing systems, thus providing a sink for groundwater in mountainous areas. This large-scale storage structure is rich in water resources but it is limited by the permafrost layer and thus can only discharge through taliks or fracture zones. In summary, the hydrogeology in the continuous permafrost zone is characterized by extensive occurrence of aquifer, linear (point or strip) enrichment (accumulation) of groundwater (Fan 1979; Wang et al. 1994).

#### *Discontinuous permafrost zone*

In the southern and northern mountainous regions of the QTP, the landscapes are characterized by the mosaic distribution of permafrost and seasonally frozen ground, and deep gorges and steep slopes with reliefs of 1,000-2,000 m. Patches or islands of permafrost are generally found on the middle, upper parts, and tops (water divides) of high mountains, or in lowland or valley wetlands, with limited areal extents and thicknesses. Hydraulically, the



**Fig. 2** Map of permafrost on the Qinghai-Tibet Plateau. Note 1: *QTH* is the Qinghai-Tibet Highway from Golmud, Qinghai Province to Lhasa, Tibet Autonomous Regions of China. In some studies, the *QTH* also includes the segment from Xi'ning to Golmud, Qinghai Province. *QKH* is the Qinghai-Kang Highway. *SAYR* is the source area of Yellow River. *SATRs* are the source areas of the Three Rivers (Yangtze, Yellow and Lancang). *HMSS* is the highway-maintenance squad station along the *QTH*. *CK* is for marking the borehole positions. Note 2: Permafrost on the QTP and Pamir Plateau is one type of elevational permafrost far south to the main body of latitudinal permafrost on the Eurasian Continent. In China, it is regarded as a special type of permafrost, i.e., plateau permafrost. Therefore, in addition to elevational zonation, it also displaces latitudinal and longitudinal zonation of distribution and thermal regimes because of the large expanse of the QTP (more than 2.6 million km<sup>2</sup>). However, in its periphery mountains, permafrost is alpine because it occurs only on the summits of very high mountains alternating with deep gorges

permafrost zone is closely linked to groundwater in nearby areas free of permafrost. The conditions for groundwater recharge, flow, and discharge are generally good, with frequent conversions of groundwater and surface waters. In the *SATRs*, permafrost, taliks, and seasonally frozen ground have mosaic distributions; wetlands are widely distributed, and effective aquifers are deep and widespread. Therefore, the groundwater is generally good in quality and adequate in quantity. Snow- and ice-melt water and groundwater continually feed to the Yangtze, Yellow, and Lancang-Mekong rivers. Among these, 49 % of the water volume in the Yellow River watershed is provided by the *SATRs*; the Yangtze and Lancang-Mekong rivers have 25 and 10 %, respectively (Lu et al. 2004).

### Classification and types of groundwater on the QTP

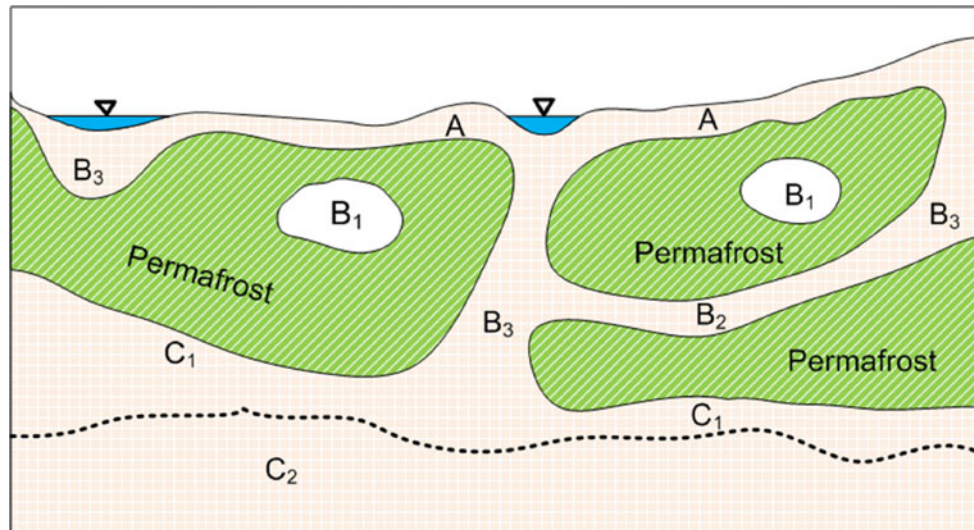
To date, there is no consensus on the classification of groundwater on the QTP; the standards, criteria, and bases for groundwater classification differ significantly

(e.g. Fan 1979; Guo 1989; Wang SL 1990a). Most of the environmental factors controlling or affecting the formation and distribution of groundwater need systematic consideration. Because of the predominant role of permafrost among those factors, the generally adopted classification system of groundwater in permafrost regions was based on the spatial relation of the aquifer(s) and permafrost layer(s), in which three types and six sub-types of groundwater are identified (Fig. 3; Zhou et al. 2000), and revised as the following:

Type A. Supra-permafrost water (also called “water in the seasonally thawed layer”): This is the water above the permafrost table, and the permafrost layer serves as an aquitard in the bottom.

Type B. In-permafrost water: This special type of groundwater generally occurs only in warm ( $> -1$  °C) permafrost. The groundwater is partially or entirely surrounded by permafrost and stays unfrozen throughout the year. This type of groundwater can be further divided into three sub-types by the





**Fig. 3** Schematic diagram of groundwater types in permafrost regions (adapted from Zhou et al. 2000). Notes: *A* supra-permafrost water, *B* in-permafrost water, *C* sub-permafrost water (see text for full details of these types and the sub-types)

position of the aquifer(s) in, between, or among the permafrost layer(s):

Sub-type *B*<sub>1</sub>: En-permafrost water: entirely surrounded by permafrost in all directions

Sub-type *B*<sub>2</sub>: Intra-permafrost water: only surrounded by permafrost at the top and bottom

Sub-type *B*<sub>3</sub>: Talik channel water: vertical aquifers only laterally surrounded by permafrost

Type *C*. Sub-permafrost water: groundwater under the base of the permafrost layer. This can be further divided into two sub-types by its relation to the base of permafrost:

Sub-type *C*<sub>1</sub>: The aquifer is directly beneath the base of permafrost

Sub-type *C*<sub>2</sub>: The aquifer indirectly contacts the permafrost base

The features of various groundwater types on the QTP are summarized in Table 3. According to the aquifer lithology, groundwater can be further divided into pore water, waters of bedrock, pore-bedrock, and vein-like fissures in structural zones, karst water, and others.

### **Recharge, flow, and discharge of groundwater**

Most major Asian rivers originate in the QTP. These watersheds are divided by major mountains such as the Kunlun, Bayan Har, Tanggula, Nyainqentanglha, Hengduan, and Himalayas. They form independent hydrogeologic units. In each unit, the recharge, flow, and discharge of groundwater are, to various degrees, controlled by permafrost, and are also affected by topography, geomorphology, tectonics, and surface hydrology. Air temperatures and precipitation increase eastward and southward, while landscapes change from periglacial to

fluvial environments and continuous permafrost is gradually replaced by isolated patches of permafrost and the increasing presence of seasonal frost. In each hydrogeologic unit, precipitation increases, air temperatures decrease, and the permafrost layer thickens with rising elevations. These changes further differentiate the groundwater dynamics.

In alpine regions above 5,000 m above sea level (a.s.l.) in the interior QTP, modern glaciers, snow cover, and permafrost are widespread. Snow- and ice-melt, and atmospheric precipitation provide relatively rich supplies for surface waters and groundwater. The supra-permafrost water in bedrocks is generally recharged by precipitation and melt water via weathered bedrocks and geological fissures, and then some of this water discharges in the form of depression springs. Other supra-permafrost water recharges the sub-permafrost water in bedrocks via talik channels, or feed to bedrock fissure water and loose-rock pore water without identifiable transport modes. The sub-permafrost water in bedrocks is recharged by precipitation and the supra-permafrost water, and can be stored in fracture zones along its flow paths. Some of the sub-permafrost water discharges as hypogene or rising springs, and the rest pools in adjacent basins or valleys.

In intermontane basins in the continuous permafrost zone, the relatively stable permafrost layer serves as a regional aquitard. The supra-permafrost water generally occurs in loose rocks or soils with groundwater dynamics similar to those in the alpine bedrock zone. The discharge modes are (1) vertical evaporation from alpine wetlands, (2) drainage into lakes or rivers as springs, and (3) recharge to the sub-permafrost water via talik channels. The sub-permafrost water also can discharge via talik channels. Because of great limitations by the relatively more extensive presence of permafrost layers, the recharge and discharge of sub-permafrost water are more difficult and are characterized by slow flow rates and long flow pathways and water-cycling time.

**Table 3** Classification of groundwater in permafrost regions on the QTP

Type of groundwater	Distribution, depths, lithology	Major hydrogeologic features
A	Supra-permafrost aquifer(s) generally consists of loose sediments	Aquifer is thawed, 1~2 m thick. Complicated in lithology, and variable in permeability. Flow rates from 0.2~1.5 L/s to more than 10 L/s. Has strong seasonality. Generally phreatic, can be weakly artesian.
B	B <sub>1</sub> In warm permafrost zones with coarse soils, or in pores or fissures in fractured bedrocks	Permeability and groundwater flow rates decline with temperatures. When soil warms, ice content decreases; permeability, flow rates, and water content increases. The en-permafrost water occurs only in certain environments and seasons. Its inflow rates are generally small.
	B <sub>2</sub> Between permafrost layers	Permafrost confines the aquifer. Generally limited in occurrence. Groundwater is limited in recharge, flow, and discharge, and generally is artesian, with small inflow rates.
	B <sub>3</sub> Generally along tectonic faults or rivers and lakes	In lake taliks or beneath major rivers, lacustrine or alluvial sandy soil aquifers 5~10 m in depths. Occasionally artesian, inflow rates of 1~10 L/m/s. Hydraulic channels for groundwater.
C	C <sub>1</sub> Sub-permafrost sediments or fracture zones of bedrock	Aquifers are widely and continuously distributed, stable, and thick, consisting of glacial till, glaciofluvial, alluvial, and fluvial deposits, and sands and gravels and mud pebbles. Generally artesian, water head -2.2~0.8 m, inflow rates of 0.3~5.2 L/m/s.
	C <sub>2</sub> Sub-permafrost fissures or pores of bedrocks	Aquifers consist of sandstone, slate, and some metamorphic rock veins, with burial depths at 40~120 m. Variable groundwater dynamics. Some locally artesian, but some phreatic. Inflow rates of 0.1~1.0 L/m/s.

In the patchy permafrost zone on the QTP margins, the permafrost is thin and patchy. Therefore, no large expanse of stable aquitard is present. Additionally, deeply incised gorges and large reliefs influence the development of almost all groundwater types. These groundwater types are generally connected, convertible, and have very complex hydraulic networks and very short cycling times. In permafrost regions, all of the groundwater and atmospheric precipitation feed to major rivers, forming a so called "plateau water tower." For example, the northern flanks of the Kunlun Mountains generate extensive slope runoff, where glacier- and snow-melt, and surface waters and groundwater in permafrost regions collect and feed the downstream oases in the Qaidam and Tarim Basins.

Wang et al. (1990) investigated the recharge duration and cycling of groundwater on the QTP using a tritium tracer. Their results indicated that (1) the cycling time for the supra-permafrost water is 1–4 years; (2) the sub-permafrost water has complex distribution patterns and burial depths, and its recharge and cycling are closely related to aquifer lithology, burial depths, and flow paths (deeply buried in basins or valleys generally cycle every 30 years or more, but that of shallow burials generally turns over within 30 years); and (3) the in-permafrost water has very complicated hydraulic links, and its cycling time is between those of the supra- and sub-permafrost water. Evidently, even the deeply buried sub-permafrost water on the QTP has relatively short cycles in comparison with those on the North China Plain (Zhang 1987) and in the Ordos Basin in North China (Yuan 1988), which generally have cycling periods of 100–200 years. This may be attributed to the high elevations, rugged terrains, steep groundwater gradients, and large flow rates on the QTP. Additionally, strong neoid tectonic movements have resulted in many active faults and fracture zones, which facilitate the flow of groundwater. In mountains, frost cracks are well developed, especially at

the joints of water networks. All these factors are conducive to groundwater movement, increasing flow rates, and shortening the cycle time of groundwater.

In summary, most of the groundwater in the QTP permafrost regions is recharged by precipitation and snow- and ice-melt water. Mountains are generally the recharging areas for groundwater, while basins and valleys are for flow and discharge of groundwater (Wang et al. 1994). In some segments along river valleys, groundwater and surface waters frequently convert based on the local topography. The sub-permafrost water has slow flow rates, while the bedrock fissure water has high flow rates. The fissure-pore water in fragmental rocks has poor recharge, flow, and discharge conditions, while those of pore water in loose rocks and sediments have better conditions.

### Hydrochemical features of groundwater of the QTP

#### Shallow groundwater

The hydrochemical features of shallow (<30 m) groundwater on the QTP, generally including the supra-permafrost water and some of the in-permafrost water, are affected by many factors such as permafrost, climate, topography, geomorphology, aquifer lithology, and groundwater dynamics of recharge, flow paths, and discharge. Overall, groundwater hydrochemistry is generally simple and has low mineralization. Table 4 summarizes the characteristics from 316 groundwater samples from the QTH from Golmud to Lhasa. With regard to Table 4:

- There are 21 types of groundwater chemistry, but three types predominate: HCO<sub>3</sub>-Ca, HCO<sub>3</sub>-Ca·Mg, and HCO<sub>3</sub>-Na.
- Horizontal zonation of groundwater hydrochemistry is evident due to a gradual northwestward decline in



**Table 4** Hydrochemical types of shallow groundwater in permafrost region on the QTP

Cations	Anions				
	HCO <sub>3</sub>	HCO <sub>3</sub> ·SO <sub>4</sub>	HCO <sub>3</sub> ·Cl	SO <sub>4</sub> ·Cl	Cl
Ca	90 <sup>a</sup>	8 <sup>a</sup> ,1 <sup>b</sup>	1 <sup>a</sup>		
*Ca·Mg	102 <sup>a</sup>	11 <sup>a</sup>			
Ca·Na	8 <sup>a</sup>	1 <sup>a</sup>	12 <sup>a</sup>	1 <sup>c</sup>	1 <sup>b</sup>
Mg·Na	1 <sup>a</sup>	1 <sup>a</sup>	2 <sup>a</sup> ,1 <sup>b</sup>		
Ca·Mg·Na	12 <sup>a</sup>		7 <sup>a</sup>	1 <sup>a</sup> ,1 <sup>c</sup>	
Na	42 <sup>a</sup> ,2 <sup>b</sup>	1 <sup>a</sup> ,1 <sup>b</sup>	2 <sup>a</sup>	1 <sup>b</sup>	1 <sup>a</sup> ,2 <sup>b</sup> ,2 <sup>c</sup>

Notes on mineralization rates of groundwater:

<sup>a</sup> <1 g/L

<sup>b</sup> 1~3 g/L

<sup>c</sup> >3 g/L. The numbers indicate the number of water samples in respect to the designated anions and cations

precipitation and drying in climate, and subsequent worsening conditions for groundwater recharge, flow, and discharge.

- The mineralization rates of groundwater increase northwestward from <0.3 to >1.0 g/L, while the hydrochemistry changes from HCO<sub>3</sub>-Ca and HCO<sub>3</sub>-Ca·Mg to HCO<sub>3</sub>·SO<sub>4</sub>-Ca·Mg, HCO<sub>3</sub>·Cl-Ca·Na, and Cl-Na. The inland lake watersheds in the Hoh Xil Mountains have the worst groundwater quality.

Within one hydrogeologic unit, vertical variations in hydrochemistry track with changes in geomorphology and lithology from recharge areas (mountains) to the discharge areas (basins, valleys and high plains) (Table 5). It is also evident that variation in the hydrochemical types and mineralization rates of groundwater increase and water quality worsens from recharge to discharge areas.

#### Deep groundwater

The permafrost layer has been considered the primary factor in determining the hydrochemistry of deep groundwater in permafrost regions. The sub-permafrost water from both bedrock and loose sediments is generally recharged and discharged through talik channels. Because of slow flow rates, this water is more difficult to supply and drain, and thus stays longer in aquifers. As a result, chemical elements and mineral components of the strata along the flow paths are dissolved into groundwater, worsening the groundwater quality as characterized by high mineralization rates. Data on groundwater quality from 18 deep boreholes in permafrost regions along the QTH indicate that only 31 % of deep groundwater has a mineralization <1.0 g/L, and most (61 %) of it has a mineralization rate >1.0 g/L, and it is dominated by Cl-Na

and Cl·HCO<sub>3</sub>-Na·Ca types. Mineralization rates of sub-permafrost water in bedrock increase and water quality apparently worsens with burial depths (Table 6).

In summary, groundwater hydrochemistry in the permafrost regions on the QTP is controlled or affected by numerous factors. It displays regional and marked vertical variations, and can be explained by changes in groundwater dynamics in recharge, flow paths, and discharge.

#### Hot groundwater

Hot groundwater is a special type in permafrost regions on the QTP, which is characterized by high temperatures and enrichment of rare chemical elements. On the QTP, hot groundwater occurs extensively; as many as 600 spots have been identified and more than half of them are in permafrost regions. Some even occur beneath glaciers or lakes such as those beneath the Xinqingfeng Glacier in the Kunlun Mountains, where the water temperature is >59 °C (some at 91 °C). In the Wenquan Valley along the QTH, spring water temperatures vary from 40 to 50 °C or higher such as the 72 °C temperatures of springs behind the highway maintenance squad station (HMSS) 103.

The intensity of hot water activities displayed on the QTP is comparable to those in Iceland, as marked by widespread water and heat explosions and intermittent geysers. The development of hot groundwater is greatly facilitated by active neotectonics and magmatism. Therefore, the occurrence of hot springs is generally controlled by geologic structures, and most of them occur linearly at the positions with overlapping geologic structures, or at the joints of primary and secondary faults, always in large groups of springs, and surrounded by talik zones.

**Table 5** Topographical changes in groundwater dynamics and hydrochemistry within one hydrogeologic unit

Geomorphology	High→mid-high mountains→	Low mountains and hills→	Basins or valleys→	Inland lake watersheds
Recharge, flow, and discharge conditions	Recharge→flow areas	Flow areas→	Flow→discharge areas	Discharge areas
Hydrochemistry	$HCO_3 \left\{ \begin{array}{l} Ca \\ Mg \rightarrow \\ Na \end{array} \right.$	$HCO_3 \cdot SO_4 \left\{ \begin{array}{l} Ca \\ Na \rightarrow \\ Mg \end{array} \right.$	$HCO_3 \cdot Cl \left\{ \begin{array}{l} Na \\ Cl \cdot HCO_3 \\ SO_4 \cdot Cl \end{array} \right. \left\{ \begin{array}{l} Mg \rightarrow \end{array} \right.$	$Cl \cdot SO_4 \left\{ \begin{array}{l} Na \\ Cl \end{array} \right. \left\{ \begin{array}{l} Mg \cdot Na \rightarrow \end{array} \right.$

**Table 6** Hydrochemistry of sub-permafrost water in bedrocks along the Qinghai-Tibet Highway (QTH)

Groundwater burial depths (m)	Well No.	Location	Parameters of deep aquifers			Mineralization rate (g/L)	Groundwater hydrochemistry
			Burial depth (m)	Thickness (m)	Geological age/lithology		
Shallow (<30 m)	8	2 km south of HMSS 78	12.56	2.84	Eogene/sandstone	0.75	HCO <sub>3</sub> -Na·Mg
	21	HMSS 106	25.00	3.20	Jurassic/shale	0.30	HCO <sub>3</sub> -Na
Deep (≥30 m)	7	2 km south of HMSS 74	60.00	67.67	Triassic/sandy slate	4.30	HCO <sub>3</sub> -Cl·Na
	11	3 km south of HMSS 86	70.02	18.20	Triassic /sandstone	5.07	Cl·HCO <sub>3</sub> -Na

HMSS highway maintenance squad station

Generally, the mineralization rate of hot spring water is low, and bicarbonate (HCO<sub>3</sub>) ions, resulting from atmospheric precipitation percolated through shallow soils, predominate. The major hydrochemical types include HCO<sub>3</sub>-Na·Ca and SO<sub>4</sub>·HCO<sub>3</sub>-Na·Ca, and generally have soluble silicic and metaboric acids, free CO<sub>2</sub>, and other chemicals. These features indicate a similar formation mechanism for these hot springs, i.e., by intensive and alternate cycling of atmospheric precipitation water into and out of deep strata. According to research by Wang SL (1990b) on dating, deposit extents, and thickness of sinter, the temperatures and flow volumes of hot springs are proportional to the intensity of tectonic activities.

### **Interactions between permafrost and groundwater on the QTP**

The presence of and changes in permafrost alter the hydrogeology and properties of aquifers. The distribution of groundwater is dependent on subsurface ground temperatures and is closely related to the ice-water phase changes. Permafrost mainly affects the permeability and dynamics of groundwater, but groundwater also affects many aspects of permafrost (Zhou et al. 2000).

Experimental research indicates that gravelly soils have a permeability of 12.8 m/day at 12.0 °C; this is lowered to 1.5 m/day after 7 h of staying at about -0.2 ~ -0.3 °C, and it becomes basically impervious after 11 h at -2.0 °C (Wang SL 1990a). In the patchy permafrost zone on the eastern QTP, rich liquid freshwater is still present in frozen sands and gravels with subsurface ground temperatures above -0.3 °C, i.e., the en-permafrost water (Wang SL 1990a). Therefore, the occurrence and movement of en-permafrost water is constrained by the porosity and permeability of the aquifer, and permafrost temperatures.

Under certain circumstances, the en-permafrost water can flow in forms of layers, veins, and pipes in permafrost. Groundwater exchanges heat with ambient soils and rocks along the flow paths, and cools while the ground warms due to the added heat from the flows. The en-permafrost water is thus sustained by the interactive and dynamic moisture and heat equilibria. When the ground cools, the permeability and groundwater flow rates decline, and eventually pores are fully filled with ice when all of the en-permafrost water is converted to ice; permafrost thus becomes an aquitard. Conversely, ground warming will

lead to higher permeability and a wetter aquifer, and it eventually thaws.

In the seasonally thawed layer, after repeated freeze-thaw cycles, sandy and gravelly soils are loosened, creating increased porosity and permeability. In mountainous regions, fracture zones formed by intensive frost weathering enhance soil permeability. This leads to better recharge, flow, and discharge conditions for the supra-permafrost water, resulting in the extensive occurrence of supra-permafrost water.

Permafrost greatly limits the horizontal and vertical movement and recharge of groundwater. The distribution patterns of permafrost control the occurrence, distribution, and hydrochemistry of groundwater, further complicating the regional hydrogeologic conditions. For example, seasonal variations have been observed with variation in aquifer thickness, flow rates, water temperatures, hydrochemistry, and dynamics of supra-permafrost water (Wang et al. 1994; Zhou et al. 2000). The hydrochemistry of sub-permafrost water is directly related to the thickness of permafrost (Table 6): the thicker the permafrost, the deeper the burial depth of sub-permafrost water, the longer the groundwater cycling time, and the worse the groundwater quality.

In permafrost regions, groundwater may release heat along flow paths, warming the ambient permafrost soils. The sub-permafrost water can warm or thaw the overburden permafrost soils, thereby thinning the permafrost and decreasing the thermal gradients. This has been observed on the Chumar'he High Plain and in the Tuotuo'he and Tongtian'he basins in the Interior QTP, where the artesian sub-permafrost water is well developed (Jin et al. 2008) and the permafrost is generally thin and warm (Table 7). On the other hand, when the permafrost is thick and cold, the sub-permafrost water in mountainous regions is generally deeply buried.

The hot water anomalies can result in an extensive expanse of talik systems such as the talik along the Buqū River Valley, which has anomalous geothermal fluxes (Table 8). There are many hot springs along the two sides of the valley; the largest measured outflow rate per spring was 720 m<sup>3</sup>/day and the highest observed water temperature was 72 °C. Because of the influences of hot springs, the development of permafrost is greatly limited, and a talik of 10~20 km in width and 70 km in length (along the QTH) has been identified.

**Table 7** Comparison of the permafrost table and artesian aquifer depth in major geomorphologic units along the Qinghai-Tibet Highway (QTH)

Location	Kunlun Pass	Chuamer'he High Plain			Beilu'he Basin			Tuotuo'he Basin		Tongtian'he Basin	Amdo Valley	Tumengela
Borehole No.	10	7	8	12	2	4	5	5	6	20	114-1	204
Permafrost table depth (m)	73	16.8	35.5	19.5	23	9	10	14.3	17.0	20	9	67
Artesian aquifer thickness (m)	75.8	16.8~48	39~80	25~50				14.3	19.5	39~44	10	187
MAGT (°C)	-2.7	+0.5	-0.5	-0.6	-0.4	+0.1	+0.1	-0.1	-0.4	-0.2	+0.3	-1.7

MAGT mean annual ground (subsurface) temperature

The effects of groundwater on permafrost are related to water content and groundwater movement. In fracture zones with aquitards, groundwater only has minor influences. In areas rich in groundwater, the permafrost is generally thin and variable in the thermal regimes. In areas lacking in groundwater, the permafrost is generally thick and thermally stable. Complicated hydrogeology generally results in variable permafrost distribution. Lithology largely determines the groundwater abundance in an aquifer. For example, in the Xidatan and Wenquan valleys along the QTH, fluvial-alluvial and glacio-alluvial sands and gravels are generally permeable and conductive to groundwater, and adverse for permafrost development (Guo 1989). Therefore, permafrost is generally absent there.

### Changes in groundwater dynamics and their ecological effects on the QTP

High elevations and regional atmospheric circulation control the QTP climate. Southeastern and southwestern monsoons prevailing in the warm seasons bring moisture and subsequent precipitation (400~800 mm/year, or more) to the southern and southeastern QTP from the South China Sea and the Bay of Bengal via valleys and gorges along the Nu, Lancang-Mekong, Jinsha, and Yalu Zangpo River valleys. The moisture carried in these air masses gradually depletes along the northwest climbing onto the QTP. In cold seasons, however, the QTP climate is controlled by the westerlies and is characterized by very limited and spatiotemporally variable precipitation declining northwestward. In particular, in the inland lake areas in the interior QTP, precipitation is rare and river networks are sparse, with minor runoff. All these features lead to a very uneven distribution of water resources on the QTP.

The climate in westerly prevailing regions has been transforming from dry and warm to moist and warm patterns (Shi 2003). This trend of climate change has been revealed by (1) increases in precipitation and glacier-melt water that have surpassed increases in evaporation in mountainous regions; (2) evident increases in river runoff; and (3) significantly rising water levels in inland lakes, as has been observed in the inland lake regions on the western QTP, including in Nam, Siling, and Ge Lakes in recent years. Accordingly, the water tables have risen and the worsening trends in surface ecological environments have slightly abated. However, the dry and warm climate pattern persists on the eastern QTP. Particularly in the source areas of the Yellow River (SAYR), precipitation patterns have shown no apparent trends but other water cycling parameters have clearly changed. They are characterized by (1) terrestrial evaporation that continues to increase and river runoff that continues to decline under a persistent warming climate, resulting in a negative water balance in local soils and lakes; and (2) water resources in the SAYR that are diminishing, as evidenced by continual lowering of water tables, extensive shrinking of lakes and wetlands, and increasingly frequent exposure of the Yellow River bed (Jin et al. 2009, 2012).

The most striking change has occurred in surface-water resources. Data indicate that the water surface extent of all lakes in the SAYR was 1,226.9 km<sup>2</sup> in the 1960s and 1,177.3 km<sup>2</sup> in 2000, a reduction of 49.6 km<sup>2</sup> in less than 40 years. The trends of lake shrinking, drying, and salinizing are evident. The water levels of Gyaring and Ngöring lakes lowered by 3.1~3.5 m from the 1950s to 2001; the 3-year period from 1999–2001 incurred a 0.6-m lowering of water level and a shrinkage of 12 % in areal extent of water surface in the Ayonggongma Co (Lake) (Zhang et al. 2009). During 1992–2001, the water table in

**Table 8** Ground temperatures of various geomorphologic units along the Buqü Valley (adapted from Guo 1990)

Borehole	Geomorphologic position	Ground temperatures (°C)				Geothermal gradient (m/°C)
		10 m	20 m	30 m	50 m	
CK103-1-1	Middle part of a fluvial-alluvial fan	7.8	10.2	12.0		5.0
CK103-1	Back of the second river terrace	1.0	1.9	2.8	4.2	13.0
CK98-1-2	Back margin of the first river terrace	3.2	3.5	3.8		3.3
CK97-2-2	Back margin of the first river terrace	2.6	4.2	4.9		9.0
CK97-2-3	High floodplain	1.9	2.9	3.6	5.2	13.0
CK99-2-3	On the first terrace 15 m above river	1.4	2.0	2.3		22.0
CK104	Middle part of a fluvial fan		2.1	5.2		3.0



river basins close to Madoi lowered by 0.5~1.7 m, with an average annual rate of 0.1 m/year (Zhang et al. 2009), and this lowering trend has been continuing in recent years. Most springs fed by the supra-permafrost water have dried up. Based on data on the percentage of reduction in the runoff modulus of single springs, total recharge from the supra-permafrost water declined by  $1.52 \times 10^8 \text{ m}^3$  (42 %) during 1989–2002, with an average annual decrease of  $1.1 \times 10^5 \text{ m}^3$  (Zhang et al. 2009).

Supra-permafrost water accounts for 88.3 % of the total water resources in the SAYR. Its recent sharp reduction has caused grave effects on local ecological environments. The lowland bogs mainly fed by the supra-permafrost water have clearly shrunk. Comparison of remote sensing images in 1990 and 2000 with field investigation data collected in 1976 indicates that wetlands shrank from 8,864 km<sup>2</sup> in 1976 to 8,005 km<sup>2</sup> in 1990, and sharply reduced to 5,743 km<sup>2</sup> in 2000 (Peng et al. 2003). These dramatic changes have led to successions from alpine paludal meadows to alpine meadows and steppes in most areas in the SAYR, as well as changes in vegetative coverage and root systems, declining modulation of vegetation on soil-moisture budgets, decrease in storage and modulation of surface-water resources, and great losses in surface soil moisture (Jin et al. 2009, 2012).

The lower water table alters the original hydraulic connections and conditions, and disrupts the water dynamics, i.e., the annual water equilibrium among recharge, flow, and discharge. Sometimes the relationships between recharge and discharge of groundwater and surface waters can be reversed. When the water table is lowered to below the local river levels, some of the river flows will decrease or even reach zero, exposing the riverbed. For example, there are clear variations in flow rates of the Yellow River in the SAYR. Normally, the average annual discharge at the Huang'he'yan (Madoi) hydrological station was 10~20 m<sup>3</sup>/s during 1991–2004, but this was reduced to 0.619 m<sup>3</sup>/s in 2000, the record low. During this period, several exposures of the Yellow River bed were observed.

Preliminary observations and research indicate that reduction of water resources in the SAYR may be attributed to the regional degradation of permafrost (Jin et al. 2009, 2012; Luo et al. 2012). The SAYR is in the region of patchy and discontinuous permafrost with thin and warm permafrost. When permafrost is thawed or warmed to the melting point of water, it can be changed from an aquitard to an aquifer in some areas, and (open) talik channels can be formed or enlarged. This can facilitate the recharge from surface waters and supra-permafrost water to deep groundwater such as the en-permafrost and sub-permafrost waters, resulting in a decline in surface waters and the supra-permafrost water. At present, the permafrost extent in the SAYR has been observed to be shrinking, and the areal extents of talik systems and seasonally frozen ground have been expanding, opening more space for groundwater storage. Even if

the recharge remained unchanged, the water table would be lowered.

Also, the combination of declining frequency and duration of effective precipitation, the uneven seasonal distribution of precipitation frequencies and amounts, and increasing evaporation from land and water surfaces have led to decreasing water resources in the SAYR (Cheng et al. 1998; Jin et al. 2009). The degradation of permafrost and the lowering tables of permafrost and groundwater have resulted in great losses in shallow soil moisture, which is drying the surface soils. This in turn destroys short-rooted plants and causes adverse vegetation successions, declining vegetative coverage, land degradation and desertification, and enhanced soil erosion. The ecological environment in the permafrost regions in the SAYR has been and is worsening (Wang 1998; Wang SL et al. 2000; Zhang et al. 2004; Jin et al. 2009, 2012), and this change is representative of the entire eastern QTP.

## Permafrost regions in northeast China

Permafrost in northeast China is mainly distributed in the Da and Xiao Xing'anling Mountains, on the northern Songnen Plain and the Hulun Buir High Plain, and in the Changbai Mountains (Fig. 4). The Xing'anling Mountains were formed by the Hercynian folding in the Paleozoic Era, with geosynclinal anticlinorium and synclinorium at each flank. The lithology includes large-scale invasions of granite, andesite, basalt, cinerite, and metamorphic rocks, with rich tectonic faults, fissures, and joints. After numerous uplifts and denudations, these mountains generally have thin (<3~5 m) Quaternary deposits, except in intermontane valleys and lowlands with sediments more than 10 m in thickness (Han 1982; Zheng 1989).

At the end of the late Pleistocene, an Ice Age climate prevailed and the Eurasia permafrost body invaded southward into the Xing'anling Mountains and as far south as 42~43°N in northeast China. In the Holocene, climate fluctuations have also resulted in several advances and retreats of the southern limit of permafrost, and subsequent changes in the permafrost table and thickness (Guo and Li 1981). Until the 1960s and 1970s, the southern limit of permafrost in northeast China took a shape of the letter 'W' between latitudes of 47~49°N, and the permafrost extent was about 390,000 km<sup>2</sup> (Guo 1990). However, permafrost has retreated by about 50~150 km northward during the last 50 years under the combined influences of climate change and anthropogenic activities; the permafrost has also thinned and the base of the permafrost has risen (Jin et al. 2007).

## Permafrost hydrogeology in northeast China

The hydrogeologic features and the groundwater storage in the Da and Xiao Xing'anling mountains are controlled or affected by the evolutionary processes in geologic



**Fig. 4** Map of permafrost in northeast China. Note 1: MDEC is the Mo'he-Daqing Engineering Corridor, which includes highways, railways, crude oil pipeline, power transmission lines, and other linear infrastructures. BHH is the Bei'an-Hei'he Highway. DPRK is the Democratic People's Republic of Korea (North Korea). Songnen Plain is the major plain in northern part of northeast China, which was formed by the alluvial and fluvial plains of the Songhua and Nen rivers, major tributaries of the Heilong-Amur River. The Hulun Buir High Plain is named after the sister lakes of Hulun and Buir lakes, which were formed by the tributaries of Hailar River. Note 2: Traditionally, permafrost in northeast China is regarded as latitudinal permafrost because of higher northern latitudes in northeast China. However, permafrost is mainly distributed in the northern Da Xing'anling Mountains, with Mt. Okelidui (1,520 m a.s.l.) as the highest peak, and Xiao Xing'anling Mountains. These mountains are generally low, with elevations of several hundreds of meters. In the southernmost Da Xing'anling Mountains, with the highest peak at Mt. Huanggangliang (2,029 m a.s.l.), and in the Changbai Mountains, with the highest peak at Mt. Baiyun (2,691 m a.s.l.), permafrost is generally classified as elevational. However, a unanimous understanding is not yet reached among Chinese geocryologists

structures, and changes in permafrost conditions in response to climate change. This is evidenced by the following:

- The areal extent of permafrost is about 60~70 % in the north, and gradually changes to 10~40 % in the south-central regions. The extensive presence of permafrost

greatly limits the recharge, storage, discharge, and exploitation of groundwater.

- The movement and recharge of groundwater have marked seasonal variability. In thaw seasons, some groundwater bodies can be hydraulically connected, but they are generally disconnected in freeze-up seasons. In cold seasons, some water wells have an

artesian head, but some groundwater becomes phreatic in warm seasons. Exploitable groundwater resources generally have seasonal patterns and longer-term periodic variations due to the lateral and vertical limitations of frozen ground on groundwater recharge, flow paths, and discharge. Groundwater quality also has seasonal variations paced with the freeze-thaw processes. This is particularly true for shallow groundwater. In cold seasons, pollution from surface sources is effectively obstructed by the frozen active layer, so groundwater is of good quality. In the warm season, however, groundwater can be contaminated by permeation of pollutants accumulated in the winter and spring seasons, and therefore can be of poor quality.

- According to Lin and Tu (1981), in many intermontane basins and depressions in the northern Da Xing'anling Mountains, the distribution of groundwater is characterized by "extensive occurrence and linear enrichment (storage)." This is mainly attributed to two causes. First, frequent climatic fluctuations caused changes in the positions of the permafrost table. Due to the freeze-thaw cycles in the active layer, shallow bedrock layers were intensively cracked and shattered, resulting in well-developed weathering fractures. They provide extensive spaces for groundwater storage in most places. Additionally, since the Paleozoic Era, many geologic and tectonic movements have occurred in this region, resulting in extensively developed geologic faults and fissures, providing an important basis for linear enrichment of groundwater. Although this rule of thumb has been confirmed in many places, the most representative is found in the better studied and understood Hola River Basin in the northern Da Xing'anling Mountains (Wang and Lin 1987; Wang et al. 1988).

### **Types and features of groundwater in northeast China**

There are three major types of groundwater in northeast China, based on their burial depths.

*Phreatic water in the active layer (supra-permafrost water).* This is mainly found in the seasonally thawed layer in permafrost regions, generally with a thickness of 1.0–2.5 m (sometimes less than several tens of centimeters to 1 m, or can be up to 4.0 m, or thicker). It is mainly recharged directly from atmospheric precipitation and indirectly from snow- and ice-melt water. Generally, inflow rates are large in summer and autumn but are greatly reduced in winter and spring, and occasionally there is no liquid water because of aquifer freeze-up. This type of groundwater is generally important for water supplies for local inhabitants.

*River and lake talik water (shallow groundwater).* This varies with the areal extent of surface-water bodies, with variable water supplies. Large rivers or

lakes have more extensive taliks and thicker effective aquifers, and therefore larger inflow rates. In addition, inflow rates are affected by geological structures. If active faults cut through talik networks, exploitable groundwater supplies increase greatly, sometimes up to 300–600 m<sup>3</sup>/day. This type of groundwater is generally of good quality, with the hydrochemical profiles being HCO<sub>3</sub>–Ca and SO<sub>4</sub>–HCO<sub>3</sub>–Ca·Mg. It is generally shallow and easy to explore and exploit, and therefore is widely used for water supplies for stations, towns, and forest farms along railways and highways in the Xing'anling Mountains.

*Bedrock fissure/pore water (sub-permafrost water, or deep groundwater).* Generally, this is buried beneath the permafrost layer at depths of about 30–40 to 100–150 m, and is one of the major water supplies in permafrost regions. In the Da Xing'anling Mountains, major water-storage structures for this type of groundwater are weathering and tectonic fissures developed in andesite, basalt, metamorphic rocks, and cinerite with extensive joints and fissures. The major recharge for this groundwater is atmospheric precipitation. Inflow rates are generally at 200–350 m<sup>3</sup>/day. The groundwater hydrochemical profile is CO<sub>3</sub>–Ca. It is generally artesian, usually with a hidden (unobservable) water head and with a confined water head located within the depths of the permafrost layer. Occasionally, the sub-permafrost water is revealed by a show head, where groundwater outflows above the ground surface. When the confined groundwater has a hidden head and is affected by the ground temperatures of permafrost, groundwater can freeze if the pumping is not frequent enough and can result in difficult pumping conditions, greatly affecting the normal water supplies.

### **Changing groundwater dynamics in the Hola River Basin**

The Hola River Basin (52°57'–53°03'N, 121°52'–122°04'E) is in the northernmost county (Mo'he) of northeast China, where the annual air temperature has averaged about –3.0 to –6.2 °C since the 1950s; the record low of –52.3 °C occurred on February 23, 1969 and the record high of +39.3 °C occurred on June 24, 2010. The river is completely frozen in winter, but the large thermokarst lake (Yueya (Crescent Moon) Lake), 15 m deep and 0.09 km<sup>2</sup> in areal extent, and 45,000–84,000 m<sup>3</sup> in water storage) cannot be frozen to the bottom, although the lake is not an open talik (Wang and Lin 1987; Wang BL 1990). The permafrost in this area thickens from about 10–20 m on the surrounding hills to about 28–40 m at the edge of the basin to about 98–134 m in the center (Wang and Lin 1987; Wang et al. 1988; Liang et al. 1991; Wang 1996; Zhao et al. 2001); generally it is 60–80 m. The permafrost is largely continuous and covered by dense vegetative mats consisting of forests, shrubs, and meadows. The loose sediments are generally 1–12 m in thickness with an



active layer about 0.6–1.5 m thick at sites with peat, clay, and sandy silts with good vegetative coverage (Liang et al. 1991). The active layer thickness enlarges radically from about 0.6–0.8 m at the basin center to 0.8–1.4 m at the hill slopes to about 2.2–2.3 m on the hilltops. Forest fires significantly affect the thaw depths by about 10–20 cm in the year immediately after the burning (Liang et al. 1991), but it gradually recovers with natural revegetation.

In hydrogeologic investigations in this basin in the 1980s, almost all of the boreholes revealed groundwater; the only differences were in the greatly variable inflow rates. For example, in boreholes close to fracture zones of active faults, the inflow rates were 2,000–3,000 m<sup>3</sup>/day, but some other wells had pump-outs less than 10 m<sup>3</sup>/day (Lin and Tu 1981). There are many isolated patches of tectonically controlled taliks on the edge of the basin, as well as the open talik of Yueya Lake, which serves as the supplying windows for sub-permafrost water (Zhao et al. 2001). On the northern edge of the thermokarst lake, massive ground ice layers with thicknesses of 16.15 and 22.2 m were revealed at depths of 46.15 m from the ground surface, probably an intrusive ice body formed by artesian groundwater between the mudstone and coal deposits (Wang BL1990).

However, the ice core of the Yueya Lake area is characterized by a hydrochemical profile of HCO<sub>3</sub>·Cl–Ca·Na, with a mineralization rate of 0.05 g/L (Wang BL1990). The latest data indicate a hydrochemistry of HCO<sub>3</sub>·SO<sub>4</sub>·Cl–Ca·Mg, with a mineralization rate of 30.4 mg/L (Li et al. 2010). In the Hola River Basin, the hydrochemistry is HCO<sub>3</sub>–Ca·Mg with a mineralization rate of 0.1 g/L for the supra-permafrost water and HCO<sub>3</sub>–Ca·Mg and HCO<sub>3</sub>–Na with mineralization rates <0.3 g/L for the sub-permafrost water (Wang BL 1990). The confined waterhead is about 64.74 m, with an inflow rate of 24.25 L/s, or 2095 t/day (Wang and Lin 1987). However, although the Yueya Lake is a talik, hydraulically it is disconnected from the sub-permafrost water as proved by monitored changes in groundwater head and hydrochemistry (Zhao et al. 2001). The sub-permafrost water can only be discharged through the Hola River fault and northeast-trending fault taliks at the basin edge.

It is interesting to note that the lake water has a δ<sup>18</sup>O of –13.99 ‰, the river water has –14.55 ‰, and the ground ice at 47 m in depth has –12.75 ‰ (Li et al. 2010), which is close to that for atmospheric water. This suggests that the ground ice was formed by rapid freezing of precipitation-fed water. The latest drilling in 2004 revealed an open talik in fragmented rocks under the lake (Li et al. 2004). This might reverse the former understanding of the sub-permafrost groundwater discharge route and the supply sources for the Yueya Lake; that is, the lake could serve as a discharge channel for the groundwater in the Hola River Basin. The tritium concentration was as high as 81.4 TU for the lake-water samples. The lake-water hydrochemistry of HCO<sub>3</sub>–Ca·Mg and pH <7 were also different from that of the groundwater. The lake has mixed supplies from precipitation, groundwater, and surface runoff.

A fault cut through the lake can become a channel for groundwater movement and can provide space for ground-ice-body formation. The lake is not the only discharge point for deep groundwater in the basin. This is evidenced by that fact that in the winter freeze-up, when discharge through the lake is greatly restricted, there is no observed elevation of the lake levels in the winter. Therefore, the groundwater must be discharging by other routes such as spring/icings or along fault sutures connected with the Yueya Lake.

In the Hola River Basin, the talik fault supplies water which is stored beneath the permafrost layer and later discharged through fault taliks. Due to climate and ground warming as a result of increasing mining activities in the area and declining forest coverage, the thaw depths and talik extents have been enlarging, thus increasing supplies to the sub-permafrost water. Therefore, groundwater inflow rates and the water head have risen, and its discharge has accelerated.

Although there have been many research attempts, the explanations of the genesis and continued presence of this massive ice body remain debatable. The nearby mining of coal deposits and pumping of lake water for a local power plant have further complicated the conditions of the thermokarst lake and the stability of the permafrost in the surrounding area. The lake was once drained and the lake bed was exposed, but later the power plant has been closed and the lake level has now been restored. The local government has been expending great efforts to restore the environment for recreational purposes, and possibly even build a permafrost and ground ice museum to draw tourists.

### **Effects of permafrost degradation on ecological environments in northeast China: causes and evidence of permafrost degradation**

In northern northeast China, the decadal average of mean annual air temperatures (MAATs) rose by 0.9–2.2 °C during 1961–2000 (Pan and Zhang 2003; Gao et al. 2007). Extensive and significant climate warming and increased human activities have resulted in ground warming and permafrost degradation (Jin et al. 2007; Li et al. 2008, 2012).

In the Xing'anling Mountains, the permafrost differs significantly in thickness, MAGT, and areal extent from north to south. Therefore, the degradation of permafrost also varies in response to a warming climate and anthropogenic activities. In the isolated patches of permafrost zone with MAGTs from –0.5 ~ +0.5 °C, the permafrost is thin (5–15 m) and sometimes less than the depth of annual amplitudes in ground temperatures. In the vicinity of the southern limit of permafrost such as in Da'yangshu, Jiagdaqi, and Yakeshi, intensive human influences began as early as the 1850 s, resulting in extensive degradation of permafrost as represented by continuous shrinkage and disappearance of permafrost islands. In the 1950s, when local towns began to be built, there were extensive islands of permafrost; after

30~40 years, these permafrost islands have largely vanished in response to diminishing forest coverage, from 94 to 10 % (Jin et al. 2007).

In the 1970s, during investigations to find the southern limit of the permafrost in the Da and Xiao Xing'anling mountains, five island permafrost sub-regions were identified north of the southern limit of permafrost, with an areal extent of 10~25 %. However, in August–September of 2000, during an investigation for the possible presence of permafrost at sections from posts (mileage) K42~K190 along the Bei'an-Hei'he Highway in the Xiao Xing'anling Mountains, the hand-dug pit excavations and ground penetration radar revealed 17 islands of permafrost with a total length of 3.16 km, or 2.1 % of the route length surveyed; the thickest permafrost was 7 m and the thinnest was only 1.5 m, but most were 4~5 m thick (Yuan 1989). The Bei'an-Hei'he Highway is about 230 km long from north to south, traversing three island permafrost subzones from the hills on the eastern flanks of the Da Xing'anling Mountains, via low hills in the Xiao Xing'anling Mountains, to the northern edge of the Songnen Plain. Therefore, the results from this survey are considered to be representative of the present distribution of permafrost in the three subzones of island permafrost regions. This suggests that, considering the effects from nearby engineering activities, the areal extent of permafrost along the Bei'an-Hei'he Highway is now only slightly higher than 1~3 %.

The degradation of permafrost in the northern Da Xing'anling Mountains is mainly characterized by the expansion of talik networks, a rise in ground temperature, and thinning of the permafrost. Most of the forestry farms and residential centers in the northern Da Xing'anling Mountains are located at the lower slopes or on the terraces of mid-sized and large rivers. The explorations indicate that the permafrost is generally thin and warm, and has taliks. During the last 40~50 years, because of climate warming and human influences, the permafrost in these regions has been degraded into taliks, and taliks have been expanding along the mid-sized and large rivers. For example, in 1975~1990, talik networks expanded from the river-banks to mountain slopes by 400~500 and 500~1,500 m in the vicinity of the Fuqingshan and Linzhong Forest Farms, respectively (Yuan 1989).

### **Changes in eco-environments caused by permafrost degradation in northeast China**

The degradation of permafrost can facilitate the percolation and recharge of groundwater by atmospheric precipitation. At the same time, it enhances hydraulic connections between surface waters and groundwater and water cycling.

In the vicinity of the southern limit of permafrost such as north of Nenjiang, Da'yangshu, Jiagdaqi, and in the southern Hulun Buir High Plain (between the Wurson and Hui'he rivers), field investigations have revealed that isolated patches of permafrost were generally present

beneath wet meadows dominated by *Carex tato* and tessellated meadows in the 1950s–1960s. However, since the 1960s and 1970s, the isolated patches of permafrost north of the edges of the Songnen Plain have degraded largely due to human cultivation of wetlands into farmland. After permafrost degradation, the aquitard largely disappears and the ground warms up, with ameliorated air permeability and heat-moisture conditions. These facilitate crop growth and thus the development of more and larger farms, in turn leading to more degradation of permafrost and the drying and degradation of more wet meadows and wetlands. These phenomena have been most striking on the southern Hulun Buir High Plain south of the Hailar River, east of the Hulun Lake and the Wurson River, and west of the Hui'he River. In the 1970s, the wetlands in this region were extensively distributed in large expanses. However, after 40 years, the wetlands have dried up and succeeded into semi-desert and steppes due to climate warming and permafrost degradation.

### **Conclusions and prospects**

In some regions of northeast and western China, cold climate and permafrost form special groundwater environments and hydrogeologic zones, where the types of groundwater, hydrogeologic structures, conversions of atmospheric and surface waters, and groundwater, and surface ecosystems are different from those in regions free of permafrost. Groundwater is one of the principal variables in the permafrost environment.

Groundwater in the permafrost regions on the QTP is a product of a unique geologic and geographical environment, where permafrost controls the distribution, recharge, flow paths, discharge, dynamics, and hydrochemistry of groundwater, and differentiates hydrogeologic conditions regionally. Neotectonics and lithology, and many other factors, further complicate the local hydrogeologic conditions. Intensive uplifts of the QTP accelerate groundwater cycling and exacerbate anomalous manifestations of geothermal fluxes. Groundwater and permafrost interact and interdepend on each other, forming a unique QTP hydrogeologic environment. At present, because of regional variations in climate change, the dynamics of groundwater and change trends in permafrost ecological environments also display significant regional variability.

On the QTP, the total volume of ground ice is estimated to be 9,528 km<sup>3</sup> (Zhao et al. 2010b), roughly 10 times that of the plateau groundwater resources defined by the Geological Survey of China (Zhang 1990). Because of great differences in the definitions of and computation methods for ground ice storage and groundwater resources, and in spatiotemporal scales for their participation in hydrogeologic cycles, it is not scientifically sound to quantitatively compare the ground ice storage and the groundwater resources. However, under regional warming and permafrost degradation, the lowering of the

permafrost table and the thinning and thawing of permafrost, the excess ice in permafrost can be partially converted into liquid water, precipitating short-term hydrological and hydrogeologic cycles and modulating groundwater dynamics. How large is the volume of this type of water? To what extent can it modulate regional water resources? To answer these questions, one has to understand many associated questions on climate change modes, amplitudes, rates and depths of permafrost thawing, local soil and rock types, drainage patterns, and hydrogeologic conditions. Further investigations, experiments, and long-term monitoring and observations are necessary, in addition to modeling of the coupled response of the permafrost-groundwater system to climate change at various spatiotemporal scales.

The permafrost hydrogeology in northeast China is characterized by extensive occurrence and linear enrichment (storage or collection) of groundwater, a feature closely related to the evolution of permafrost in this region on the southern edge of the Eurasian permafrost body. Since the end of the late Pleistocene, and affected by climate cooling and warming of various time-scales, permafrost has frequently advanced southward and retreated northward. These freeze-thaw cycles have led to well-developed joints and fissures due to frost weathering, providing extensive space for groundwater occurrence and storage. Since the Paleozoic Era, the region has also been under the influences of numerous geologic and tectonic movements. They resulted in well-developed faults and fissures, further providing a good basis for linear enrichment of groundwater along these joints and fissures.

In northwest China, very high mountains and inland arid basins have mosaic distributions, and therefore the occurrence and distribution channels of groundwater are complicated. However, an elevational zonation of geomorphology and soil types can be divided into five units: alpine snow-ice zone, middle and low mountain steppes, piedmont gobi deserts, fine-grained oases, and salt crust and lake-wetlands (salt marshes). A groundwater zonation can be delineated on the basis of these five units: (1) alpine snow and ice zone and middle and low mountain steppes → sub-permafrost and bedrock fissure water; (2) piedmont gobi deserts → phreatic, locally confined, water percolated into Quaternary sediments; (3) fine-grained oases → phreatic and confined artesian water in Quaternary sediments, and; (4) salt crust and lake-wetlands (salt marshes) → saline phreatic, karst, or artesian saline water. Therefore, it is evident that groundwater dynamics are closely related to geomorphology and lithology and/or soil types. The alpine snow-ice zone, rich in groundwater, generally serves as a recharge zone in an inland watershed. The piedmont gravelly gobi zone facilitates the flow of groundwater, and generally the flow paths are long and the burial depths of groundwater are deep. In the oases, lakes, and wetlands in basin centers, groundwater generally outflows onto ground surfaces and is lost to evapotranspiration in deserts or gobi.

At present, under a warming climate and degrading permafrost, the foci for research on permafrost hydrology and hydrogeology involve three key issues:

- The hydraulic properties of warm permafrost, especially the hydraulic permeability and conductivity of permafrost
- Predictions on the spatiotemporal processes of partially converting ground ice into groundwater resources in permafrost regions
- How anthropogenic activities have changed groundwater dynamics and permafrost regimes, and their relationships

The answers to these issues are critical in explicating the mechanisms of changes in cold-regions water resources, in forecasting the change trends of water resources in permafrost regions, in providing a basis for understanding the response mechanisms of permafrost hydrogeology to climate change, and in developing adaptive strategies. Therefore, these studies are important and applicable in China as well as in other northern countries and highlands.

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