Research process of groundwater in Qinghai-Tibet Plateau

Yongzhen Niu 1,2, Baisha Weng 2*, Xiaoyan Gong 2
1 School of Water Conservancy and Hydroelectric Power, Hebei University of Engineering, Handan 056038, China
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (IWHR), Beijing 100038, China

*Corresponding author: wengbs@iwhr.com

Abstract. Qinghai-Tibet Plateau, known as the "third Pole" of the world, is the birthplace of many great rivers, including the Yangtze River, the Yellow River, the Lancang River, the Nu River, the Yarlung Zangbo River and other world famous rivers. Under the background of global warming, the hydrogeological conditions of the Qinghai-Tibet Plateau have been changed to some extent. The degradation of frozen soil and melting of glaciers have a significant impact on the recharge and runoff discharge of groundwater, leading to changes in the dynamic characteristics of groundwater, and thus have a certain impact on the ecological environment of the Qinghai-Tibet Plateau. Therefore, it is of great significance to analyze the evolution law and development trend of groundwater resources in Qinghai-Tibet Plateau. This paper reviews the past research work on groundwater in Qinghai-Tibet Plateau, summarizes the technical methods used in groundwater research, and puts forward the development trend of groundwater research in the future.

1. Introduction
Groundwater is an important source of water for life, industry and irrigation, and plays an irreplaceable role in social and economic development [1, 2]. How to rationally develop and utilize groundwater resources is of great significance to guarantee the sustainable development of social economy, meet the needs of people's life and production, and protect the ecological environment. As the aptly named "Water tower of Asia", the Qinghai-Tibet Plateau covers an area of about $2.5 \times 10^6$ km$^2$. The outflow area and the internal flow area account for about half of the total area. The outflow area includes the Pacific and Indian Ocean water systems. The inland water systems consist of the Qiangtang, Qaidam Basin, Qilian Mountains and the inland water systems of Southern Xinjiang. There are 1,129 lakes above 1km$^2$ on the Qinghai-Tibet Plateau, accounting for 49% of the country's lake area. The glaciers and wetlands cover about $5.1 \times 10^4$ km$^2$ and $4.7 \times 10^6$ hm$^2$, respectively [3]. Under the background of global warming, the melting of glaciers on the Qinghai-Tibet Plateau and the deterioration of frozen soil and snow cover are increasingly aggravating, which, to a certain extent, have changed the hydrogeological conditions in this area, and the more complex hydrogeological conditions have had a significant impact on the burial, recharge and discharge conditions of groundwater, as well as the hydrodynamic and chemical characteristics of groundwater. The research on groundwater in The Qinghai-Tibet Plateau is summarized through the knowledge map, as shown in Fig. 1. In recent decades, the Qinghai-Tibet Plateau groundwater has been the focus of attention in academic circles at home and abroad, many
scholars through the field prototype test, indoor experiment analysis, numerical simulation of groundwater and technical means such as deduction hypothesis of the Qinghai-Tibet Plateau groundwater has carried out a series of studies [4-6], these studies have focused on climate change on the field of engineering geology and disaster prevention hamper, groundwater of the Qinghai-Tibet Plateau of important scientific problems in a certain degree of solutions, and puts forward the groundwater is facing new challenges. In this paper, the Qinghai-Tibet Plateau reviewed previous studies of groundwater, introduced the main technical means of some of the men in the study, and points out the trend of future research of groundwater, Qinghai-Tibet Plateau in order to study the change mechanism of Tibetan plateau groundwater provide certain theoretical basis, for reasonable exploitation and utilization of the groundwater resources to provide certain scientific basis.

Figure 1. Knowledge map of groundwater research on the Qinghai-Tibet Plateau

2. Progress in groundwater research in Qinghai-Tibet Plateau

2.1. Groundwater evolution
In recent decades, the climate of the Qinghai-Tibet Plateau has been shifting from warm and dry to warm and wet [7]. Climate change has a very adverse impact on the cryosphere of the Qinghai-Tibet Plateau, including glacier melting, snow cover reduction, permafrost degradation, active layer thickening, etc. [8], and directly or indirectly has a profound impact on the groundwater resources of the Qinghai-Tibet Plateau. Under such conditions, groundwater recharge sources in high-altitude areas will become more abundant in the future, and groundwater runoff and drainage paths will also change significantly. For example, there may be a "deep circulation" of groundwater in the Qinghai-Tibet Plateau. In the process of different migration paths, underground water and the surrounding frozen soil continuously exchange...
heat, which further aggravates the melting rate of permafrost. The reduction and degradation of permafrost have led to a series of changes in the hydraulic links between groundwater and surface water, leading to an increase in the frequency of surface water and groundwater exchange. The melting of glaciers and snow cover increases the recharge source of groundwater to a certain extent, and the freezing-thawing of permafrost provides space and place for the migration and storage of groundwater, so the amount of groundwater resources in the Qinghai-Tibet Plateau in the future may show a certain trend of increase.

2.2. Driving mechanism
As a typical representative of the high and cold region, the Qinghai-Tibet Plateau has a unique particularity and complexity of its groundwater system [9-12]. The melting of glaciers and permafrost caused by global warming has increased the supply of groundwater. Permafrost is one of the most active factors in groundwater circulation in Qinghai-Tibet Plateau. The freezing-thawing effect of permafrost will change the properties of soil and thus affect the conditions of groundwater recharge and discharge. During the freezing period of soil, liquid water in the soil gradually freezes into solid ice, the permeability channel is blocked gradually, and the permeability coefficient of aquifer decreases accordingly. Finally, it is transformed into a weak pervious layer or even an impermeable layer, thus affecting the recharge of groundwater by precipitation and glacial melt water. The accumulated freezing-thawing action of soil will also change the water permeability of aquifer. In the thawing layer of seasonal permafrost, repeated freezing-thawing action makes the structure of subsandy soil, gravel and other rock become loose, the number of pores increases, the porosity increases, and the water permeability also increases. To a certain extent, precipitation and meltwater from glaciers and permafrost increase the recharge of groundwater, and the runoff and discharge of water sources become more unimpeded, providing space and place for the migration and storage of groundwater, thus significantly increasing the water storage of groundwater [13].

2.3. Development tendency
With the increasing melting of glaciers and permafrost, the increase of groundwater reserves on the Qinghai-Tibet Plateau and surrounding areas will show a certain trend in the short term. From 2003 to 2012, the groundwater resources storage in the Qinghai-Tibet Plateau increased at a rate of 9.7mm/a, while the glacial snow water lost at a rate of 20.2mm/a [14]. Groundwater reserves in eight major regions of the Qinghai-Tibet Plateau increased from 2003 to 2009 on average, as shown in Table 1. It includes Jinsha River Basin $(24.6 \pm 22.4) \times 10^8$ m$^3$/a, Nu River source region $(17.7 \pm 20.9) \times 10^8$ m$^3$/a, Yangtze River source region $(18.6 \pm 16.9) \times 10^8$ m$^3$/a, Yellow River source region $(11.4 \pm 13.9) \times 10^8$ m$^3$/a, Qaidam Basin $(15.2 \pm 9.5) \times 10^8$ m$^3$/a, Qiangtang Nature Reserve $(13.6 \pm 15.2) \times 10^8$ m$^3$/a, upper Indus River Basin $(53.7 \pm 21.7) \times 10^8$ m$^3$/a, and Aksu River Basin $(27.7 \pm 9.9) \times 10^8$ m$^3$/a. This is mainly due to the increasing melting of glaciers and permafrost in the Himalayas and China's ecological conservation and construction projects in the Sanjiangyuan region.

| Region                      | Period (a)   | Groundwater storage changes (m$^3$/a) |
|-----------------------------|--------------|--------------------------------------|
| Jinsha River Basin          | 2003-2009    | $(24.6 \pm 22.4) \times 10^8$        |
| Source region of Nujiang    | 2003-2009    | $(17.7 \pm 20.9) \times 10^8$        |
| Source region of Yangtze River | 2003-2009     | $(18.6 \pm 16.9) \times 10^8$        |
| Source region of Yellow River | 2003-2009  | $(11.4 \pm 13.9) \times 10^8$        |
| Tsaidam Basin               | 2003-2009    | $(15.2 \pm 9.5) \times 10^8$        |
| Qiangtang Nature Reserve    | 2003-2009    | $(13.6 \pm 15.2) \times 10^8$        |
| Upper course of Indus        | 2003-2009    | $(53.7 \pm 21.7) \times 10^8$        |
| Aksu River Basin            | 2003-2009    | $(27.7 \pm 9.9) \times 10^8$        |
2.4. Ecological environment impact and measures

Mainly affected by the west wind circulation of the Qinghai-Tibet Plateau region, to transform from dry and warm to wet and warm climate, mainly reflected in is bigger than the precipitation and the glacier melt water evaporation, rivers runoff show obvious rising trend, inland lake water level also had a significant rebound, lake weeks underground water level rise obviously, vegetation coverage also gradually improve, from a certain extent, to curb the trend of the surface ecological environment. However, the climate in the east of the Qinghai-Tibet Plateau remains warm and dry [15]. Under the background of gradually rising air temperature, evaporation increases continuously while precipitation does not change significantly, which leads to gradual decrease of river runoff, large-scale shrinkage of lakes and wetlands, and significant decrease of groundwater level. This phenomenon in the Yellow River source area is most obvious, the Yellow River source area of permafrost and seasonal frozen soil in the degraded state for a long time, has made upper limit of permafrost is bigger, seasonal melt layer thickness increasing, the decrease of the groundwater recharge caused the water level drops, for the region's ecological environment has a significant influence [16]. It is mainly reflected in three aspects: wetland atrophy and desertification expansion, river disconnection, and indirect influence on climate change [17, 18]. Marsh area of the Yellow River source region from 8864 km² in 1976 fell to 1990 in 5743 km², swamp meadow ecosystem gradually to the evolution of alpine meadow ecosystem, vegetation coverage gradually decreases, and the root has become sparse, the role of vegetation for soil and water conservation, appear even the phenomenon of large area of desertification, leading to change of the underlying surface to produce. The decline of groundwater level weakens the connection between surface water and groundwater, and when the local water level is lower than the river water level, the river flow will decrease significantly, or even cut off. From 1991 to 2004, the Yellow River was interrupted several times with an annual runoff of only 0.619m³/s. The combined action of the underlying surface and groundwater level makes the distribution of precipitation in the source area of the Yellow River uneven and evaporation intensifies, which leads to a series of ecological and environmental problems. Therefore, measures such as ecological migration, wetland protection, artificial rainfall and scientific grazing policies can be adopted to reduce the exploitation and utilization of groundwater in order to protect the ecological environment of the region.

3. Review of groundwater research methods in Qinghai-Tibet Plateau

3.1. Field prototype test

Field prototype test is one of the important means to analyze the interaction between environment and groundwater. Many scholars have carried out researches on the influence of various environmental factors on groundwater. Dai et al. [19] found through field observation experiments that wind speed was the most important influencing factor on the change of groundwater level in the alpine meadow area of Haibei Station, Qinghai, while precipitation had a weak influence on the groundwater level. Ye et al. [20] systematically analyzed the permeability coefficient of aquifer in the freezing-thawing process of soil in the Fengshan Volcano Basin through pumping test, and found that the dynamic change of groundwater level and permeability coefficient presented similar change rules in the freezing-thawing process of soil. Zhu [21] in the early stage of the vegetation coverage and soil moisture content under the condition of different regions double ring infiltration experiments found that the soil infiltration rate and the dynamic changes of the shallow groundwater level in different seasons showed a trend of consistent, tallies with the activity and thawing cycle process, from the side reaction of the groundwater flow in different seasons of the differences between active. To some extent, these experiments reflect that environmental factors such as precipitation, wind speed and soil properties all have a certain influence on the dynamic change of groundwater.

3.2. Numerical simulation and 3S technique

Numerical simulation and 3S technology, as important means to solve groundwater problems, have been widely used in the study of groundwater in the Qinghai-Tibet Plateau, and can solve the problem of
difficult access to data to a certain extent. The current popular statistics of groundwater numerical simulation software are shown in Table 2. Wei [22] established a three-dimensional stratigraphic model based on GMS to realize visualization, divided the aquifer structure and established a groundwater model, verified the model by using the observed water level, and obtained the interaction relationship between groundwater and surface water. Zhang [23] analyzed the hydrogeological data of the western plain area of Yili Valley, and built a numerical model of underground water flow using Visual MODFLOW to analyze the total supplement and output of groundwater in this area. Huang [24] made a balance analysis of lake water storage using remote sensing data and found that from 2010 to 2017, the contribution of glaciers and permafrost to lake supply slowed down the decline rate of glacial lake water level to a certain extent, and analyzed the relationship between temperature change and lake water level change. Liu [25] made use of the functions of spatial analysis and expression in GIS software and combined with hydrogeological data to analyze and evaluate the spatial and temporal distribution characteristics and transformation rules of water resources components in Nagqu Basin.

| Model          | Function                                                                 | Feature                                           |
|----------------|---------------------------------------------------------------------------|---------------------------------------------------|
| Visual MODFLOW | Three-dimensional visualization of groundwater flow and migration          | Finite difference method discrete and powerful visualization function |
| GMS            | Simulation of flow and Solute transport in saturated flow and unsaturated flow with three-dimensional finite element coupling model | Finite difference and finite element methods make the interface more friendly |
| FEFLOW         | Three-dimensional simulation of subsurface flow and solute transport      | The space finite element mesh can be quickly generated |
| Processing MODFLOW | It can simulate the amount of aquifer compression due to groundwater extraction | The interface is simple and the post-processing function is not powerful enough |
| HydroGeoSphere | Three-dimensional processes of underground flow movement solute transport and heat transfer in continuous medium are simulated | Groundwater and surface water are coupled by physical mechanism |

### 3.3. Isotope technique

Compared with other technologies, environmental isotope technology has the advantages of simple, rapid, accurate and locatable, and has developed rapidly in recent years. This paper mainly analyzes the origin, formation conditions, recharge mechanism, discharge rule and circulating regeneration ability of groundwater by comparing the difference and variation rule of isotopic composition in water, and then evaluates the amount of groundwater resources, Fig. 2 is a schematic diagram. By studying the stable H and O isotopes of lakes, rivers, rain and snow in The Manasarowa Basin of Tibet, it was found that D and 18O in the river water were larger than the lake water, and the influence of altitude on D and 18O was not significant [26]. The interaction between groundwater and surface water was discussed by directly measuring the solubility of 222Rn on site [27]. Liu et al. [28] found that the chemical types of diving and confined water in Jianghan Plain were mainly HCO3-·Mg, and the cationic exchange and adsorption effect in confined water was less than that of diving. Using 14C isotope technology, He et al. [29] found that the upstream groundwater in Hexi Corridor is relatively young and the recharge cycle is faster, while the downstream groundwater presents an opposite trend. Li et al. [30] found that the groundwater circulation in the lower reaches of Aksu River is relatively rapid and has great development potential based on the test results of a large number of water environment isotope samples.
Wang et al. [31] found that the $^{14}$C age of Yongding River gradually increased from shallow to deep with the maximum variation of 19470a by using isotope technology. Nai et al. [32] found through research that the age of groundwater in Kashi Plain gradually increased from the pre-mountain flush-gravel plain to the fine soil plain area, and the variation range was 10a to 50a.

![Figure 2. The relationship between δ2H and δ18O among groundwater, river water and precipitation](image)

### 4. Future trends of groundwater research in Qinghai-Tibet Plateau

#### 4.1. Keep in touch with information technology

The hydrogeological conditions of the Qinghai-Tibet Plateau are relatively special and sensitive to climate change, which makes the process of filling and discharging groundwater more complicated. It is necessary to obtain data through field tests, conduct trial calculation combined with groundwater numerical model, and continuously conduct inference or inversion. When obtaining measured groundwater data, geological and geological radar technology [33], resistivity tomographic imaging technology [34], and high-density resistivity exploration method [35] should be used to reduce the difficulties and costs of hydrogeological exploration, thus improving work efficiency. In addition, groundwater numerical simulation technology should be closely combined with 3S technology.

#### 4.2. Research on groundwater mechanism

At present, the numerical model of groundwater is mainly based on Darcy’s law and the law of conservation of mass to simulate the situation of groundwater laminar flow and continuous media [36]. However, new problems will emerge in the study of groundwater, which need to be paid more attention to. The scale of hydrogeological parameters, water flow in fractured rocks, and multiple process coupling have put forward new requirements for numerical simulation methods, which have become a new hotspot in groundwater research and also a key problem to be broken through in the future [37-40]. At present, some progress has been made in the fields of variable density flow, fissure flow and hydrothermal coupling. In the future, these complex problems need to be unified in the same groundwater system model.
5. Conclusion

Some achievements have been made in the study of groundwater in the Qinghai-Tibet Plateau, which has improved people's cognition of the law of dynamic change of groundwater in the high and cold regions. However, due to the limitations of natural conditions and technical means, the current research on the theory of groundwater in the Qinghai-Tibet Plateau is relatively shallow. In the face of the emerging groundwater problems, it is necessary to further strengthen the research in this area and improve the theory of groundwater system in the Qinghai-Tibet Plateau.

Acknowledgement

The researchers would like to extend their thanks to the Second Comprehensive Scientific Study on the Qinghai-Tibet Plateau (grant NO.2019QZKK0207).

Reference

[1] Nematollahi M J, Ebrahimi P, Razmara M, Ghasemi A 2016 Environmental Monitoring & Assessment 2 188.
[2] Zheng QL, Ma T, Wang YY, Yan YN, Liu L, Liu L 2017 Procedia Earth Planet Sci 368 371.
[3] Yao ZJ, Liu J, Huang HQ, Song XF, Dong XH, Liu X 2009 Environ Geol 551 556.
[4] Dai CL, SUN S, DU XQ, YE Y 2011 Resources Science 286 293.
[5] Nan ZT 2016 Journal of Geography 318 327.
[6] Yu ZD 2012 Advanced Science 23 48.
[7] Song Ci, PEI T, ZHOU CH 1960 Advances in Geographical Sciences 91 97.
[8] Peijun A, Feng G, Liwei W 2016 Remote Sensing Technology & Application 6 31.
[9] Yong Y, Ren SC 2011 Advances in Earth Science 51 83.
[10] Liao Houchu, Zhang Bin, Xiao Difang 2008 Journal of Engineering of Heilongjiang 123 126.
[11] Guodong C, Huijun J 2013 Hydrogeology & Engineering Geology 58 93.
[12] Cheng G, Jin H 2013 Hydrogeology Journal 5 23.
[13] Ye RZ, Chang J 2019 Journal of Glacial Permafrost 183 196.
[14] Guo J, Mu D, Liu X, Guo B 2016 Acta Geophysica 463 476.
[15] Zhao XY, Zhang HY, Wan J 2002 Geographic Sciences 190 195.
[16] Zhang SQ, Li Y, Wang YG, Shi WD, Lu BC, Zhuang YC, Li YJ 2005 Hydrogeology and Engineering Geology 109 113.
[17] Peng XM, Wu QB, Tian MZ 2003 Glacial Permafrost 667 671.
[18] Zhang SQ, Wang YG, Zhu H 2003 Hydrogeological Engineering Geology 11 13.
[19] Dai LC, Ke X, Cao YF, Zhang FW, Du YG, Li YK, Guo XW, Li Q, Lin L, Cao GM 2016. Journal of Ecological Environment 1750 1757.
[20] Ye RZ 2019 Influence of freezing-thawing process of active layer in permafrost region in the hinterland of Qinghai-Tibet Plateau on the dynamic change of water above the frozen layer(Ph.D. thesis Lanzhou University).
[21] Zhu MZ, Wang GX, Xiao Y 2017 Journal of Glacial Permafrost 1316 1325.
[22] Wei SY 2018 Study on the Interaction between groundwater and surface water in The Crook Lake Area of Qaidam Basin (Ph.D. thesis China University of Geosciences).
[23] Zhang C 2019 Three-dimensional numerical simulation and Resource Evaluation of groundwater flow in the western Plain area of Yili River Valley (Ph.D. Changan University).
[24] Huang ZK 2018 Using multi-source satellite data to study the change of lake water reserves in Qinghai-Tibet Plateau and its influencing factors (Ph.D. Wuhan University).
[25] Liu N 2015 Discussion on evaluation methods of water resources in areas with little data (Ph.D. Hebei Agricultural University).
[26] Yao Z, Liu J, Huang HQ, Song X, Dong X, Xin L 2009 Journal of Environmental Geology 551 556.
[27] Yi P, Luo H, Chen L, Yu Z, Jin H, Chen X, Wan C, Aldahan A, Zheng M, Hu Q 2018 Journal of Environmental Radioactivity 257 266.
[28] Dong GQ, Weng BS, Yan DH 2018 China Rural Water Conservancy and Hydropower 20 25.
[29] He JH, Ling XX, Ma JZ 2018 Gansu Water Conservancy and Hydropower Technology 1 4.
[30] Li WP, Hao AB, Zheng YJ 2006 Geoscience Front 191 198.
[31] Wang XJ, Zhou X 2006 Geological Review 283 288.
[32] Wei H, Shi J, Wang WK 2018 Geology of Xinjiang 406 409.
[33] Ru RD, Zhang JC, Qi XJ 1996 Journal of Engineering Geology 51 56.
[34] Feng R, Li XQ 1997 Acta Seismologica Sinica 655 663.
[35] Wang SP 2000 Hydrogeology and Engineering Geology 52 56.
[36] Wang H, Lu CY, Qin DY, Sang XF, Li Y, Xiao WH 2010 Frontiers of Geology 1 12.
[37] Cheng QB, Chen X, Zhang ZC, Zhang RR, Qiu N, Huang RC, Cai LB 2018 Hydrogeology and Engineering Geology 7 14.
[38] Liu DD, Xiang YY 2020 Journal of Central South University 523 531.
[39] Xu ZP, Zhou X, Cui XF, Tu MM, Wang XJ, Zhang Y 2018 Karst of China 475 483.
[40] Liu P 2018 Journal of Drainage and Irrigation Mechanical Engineering 593 598.