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GROUNDWATER FLOW PROCESS IN FROZEN SOIL AREAS AND ITS RELATIONSHIP WITH SURFACE WATER TRANSFORMATION

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Abstract: In the study of groundwater flow process and its relationship with surface water transformation, the distribution characteristics of frozen soil and the impact mechanism of the thawing process on the groundwater system are less studied. By analyzing the contribution of groundwater in frozen soil areas at home and abroad to river runoff, groundwater flow path and groundwater-thermal coupling model, and reviewed the research on groundwater flow process and its transformation with surface water. It is believed that: ① Affected by the spatial heterogeneity of frozen soil in the soil, the impact of groundwater in different frozen soil areas on runoff The proportion of contribution is inconsistent; ② The use of hydrochemistry and isotope tracers to study groundwater flow paths is helpful for the construction of conceptual models of groundwater flow systems in permafrost areas, but only qualitative or semi-quantitative results can be obtained; ③ Underground multi-phase flow systems The water-thermal coupling model can couple the changes in frozen soil with its corresponding hydrological response process, achieving a quantitative depiction of the groundwater flow process and its relationship with surface water transformation. However, it still needs to be further improved in terms of practicality, which is the future main research directions.

Keywords: Frozen soil; groundwater flow; Surface water-groundwater interaction; Environmental tracer; Water-thermal coupling model

1 CONTRIBUTION OF GROUNDWATER IN PERMAFROST AREAS TO RIVER RUNOFF

The cryosphere is the water source area of many large rivers in the world. As an important component of it, frozen soil accounts for 50% of the exposed surface in the northern hemisphere [1], of which the permafrost area accounts for about 20% to 25% of the total land area. Mainly distributed in polar and near-polar areas, lower latitude alpine belts, and islands and mountainous areas in high latitudes [2]. Permafrost not only has an important impact on cryospheric hydrological processes [1, 3], but is also extremely sensitive to climate change [4-5]. Therefore, for many rivers originating from the cryosphere, research on hydrological processes in permafrost areas is the key to understanding their runoff formation mechanisms and transformation processes, and is also the basis for predicting the response of basin hydrological processes under the influence of climate change and human activities. As a key link in the hydrological cycle in permafrost areas, the groundwater flow process not only controls the water resources and runoff formation in the basin, but also affects the surface hydrological process in permafrost areas through interaction with surface water. Therefore, it is an important part of the hydrology in permafrost areas. One of the core contents of the research.

Compared with other areas, the groundwater flow process in permafrost areas is extremely complex and unique. On the one hand, the frozen soil layer has the characteristics of a relatively aquifer, and its existence affects the structure of the groundwater water-containing system, thereby controlling the groundwater flow system [6]. In discontinuous frozen soil areas, the combination of "lens-shaped" frozen soil layer and "skylight-shaped" non-frozen soil layer makes the above effect particularly significant, resulting in frequent transformation of groundwater between different aquifers and between the underground and the surface. The recharge, runoff and excretion processes are extremely complex [1,7]. On the other hand, frozen soil is not as stable as the underground rock formations that make up the water-bearing system and its boundaries. Seasonal changes and climate changes will cause changes in the water-heat storage and migration patterns in the frozen soil layer, causing periodic thawing and even freezing. Trend evolution[8-10]. This dynamic process of frozen soil will not only cause some groundwater to transform between solid and liquid phases, affecting the amount of water participating in the regional water cycle, but also lead to changes in the thickness of the frozen soil layer and its spatial distribution pattern [11-16], resulting in Structural changes in the water-bearing system, in turn, affect the structure of the groundwater flow system, making the dynamic changes in the groundwater flow process in permafrost areas more complex than in other areas. The discussion of the groundwater flow process in permafrost areas and its interaction with surface water not only helps to gain a deeper understanding of the formation mechanism and transformation process of runoff, but also reveals the response mechanism of hydrological processes in permafrost areas under the influence of climate change and human activities, providing new insights for the watershed. It provides a basis for scientific management of water resources, promotes the development of groundwater system theory, and enriches the knowledge system of hydrogeology.

In recent years, related research on groundwater flow processes in permafrost areas has gradually increased, but mainly focused on the simulation of groundwater flow processes in permafrost areas and the characterization of the transformation relationship between groundwater and surface water. The distribution pattern of permafrost and the thawing process There is a lack of in-depth discussion on the influencing mechanism of groundwater circulation. The author attempts to provide new ideas for the study of groundwater flow processes in permafrost areas and their relationship with surface water transformation by summarizing the research progress on the contribution of groundwater to river runoff in permafrost areas, groundwater flow paths, and groundwater-thermal coupling models.

The recharge of river runoff by groundwater in permafrost areas has been a hot topic in the research on the relationship between groundwater and surface water in recent years. Studies have shown that the average annual runoff coefficient in permafrost areas is higher than that in non-frozen areas, with the latter generally ranging from 0. 2 to 0. 3, and the former reaching or even exceeding 0. 7[2]. The main reason for this difference is that the contribution of groundwater to river runoff in permafrost areas is different from that in non-frozen areas [2, 9]. With climate warming, the degradation of permafrost may cause more groundwater to be discharged into rivers, leading to changes in runoff coefficient [9-11]. Therefore, as an important part of the cryosphere, it is of great significance to study the contribution of groundwater in permafrost areas to river runoff.

At present, the research on the contribution of groundwater to river runoff mainly uses the baseflow segmentation method [17-18]. Traditional research mostly uses direct segmentation methods (also called graphical methods), including straight-line segmentation methods, Kuterin methods, and regression curve methods. This method uses the connection between the rising point of the flow process line and the inflection point of the retreat section as the basis for dividing base flow and surface water, ignoring the differences in basin conditions and runoff composition, and is highly subjective and empirical. The accuracy is difficult to guarantee [18-21]. Under this condition, new baseflow segmentation methods emerged, mainly including water balance method, time series method, and tracer method. Among them, the water balance method includes parameter segmentation method and hydrological simulation method. It is a method to solve the groundwater outflow process based on the water balance principle. It has a certain physical basis, but its parameters are difficult to determine and lack applicability and reliability. Time series methods include base flow index method, digital filtering method, smooth minimum method, time step method, etc. Most of them are mathematical methods that imitate manual segmentation of flow hydrographs. They are easy to use computers to implement complex calculations and overcome the disadvantages of manual methods. Subjective, but without strict physical meaning, its application is limited [17-21]. The tracer law uses common environmental isotopes as natural tracers and combines them with water chemistry data to divide the composition ratios of different runoff components. This method is based on mass conservation and isotope concentration conservation, and overcomes the shortcomings of the above methods. It shows its unique advantages in both theoretical basis and practical operation [20, 22-24]. For this reason, the runoff segmentation method based on hydrochemistry and isotope tracers is currently the main method used to study the contribution of groundwater to river runoff in permafrost areas.

As early as the beginning of the 20th century, some studies believed that: frozen soil has low permeability, which usually limits the infiltration of precipitation and promotes the generation of slope flow; groundwater in frozen soil areas is mainly stored in the frozen soil layer in solid form, and only in recent years. Groundwater in the surface active layer may be discharged into rivers, but the amount of water is extremely small [25-26]. Therefore, these studies infer that river runoff in permafrost areas is mainly supplied by surface runoff converted from precipitation, and that underground runoff is also supplied mainly from the active layer, with very little recharge from deep groundwater [27]. However, this view has only been confirmed by a few field tracer studies of water chemistry and isotopes [28-29].

Since the introduction of hydrochemistry and isotope tracing methods in the 1970s, a large number of isotope runoff segmentation studies have been carried out, and a conclusion inconsistent with earlier studies was reached - groundwater in permafrost areas is the main component of river runoff. Research by Obradovic et al. [30], Gibson et al. [31], and Metcalfe et al. [32] found that during the entire snowmelt period, groundwater recharge in permafrost areas accounted for about 50% of the total river runoff; Carey et al. [33], Boucher et al. [34] found that groundwater contributes more than 70% to river runoff. The reason why groundwater in permafrost areas accounts for a higher proportion of river runoff is generally believed to be that as the permafrost gradually thaws, it releases water and changes the permeability of the soil layer, allowing more precipitation to infiltrate, thus increasing the The amount of groundwater discharged [30, 32-33]. Gibson et al.[31] pointed out that the main reason for the high contribution of groundwater to river runoff is the mixing of snowmelt water with infiltration and groundwater in the active layer. In addition, the pipe flow at the interface between the organic layer and the mineral layer may be another important reason. Some tracer studies also found that the contribution of groundwater to river runoff in permafrost areas changes with seasonal changes [35]. Many studies have also reported that under the background of global climate warming, the melting of permafrost has caused an increase in the contribution of groundwater to the runoff of large rivers, such as the Yukon River in Canada, the Ob River, the Yenisey River and the Lena River in Russia [36]. In the past 30 years, due to the melting of permafrost, the annual contribution of groundwater to the Yukon River in Canada has increased by 1%, and the winter base flow of many large rivers in the Northwest Territories of Canada has even increased by 0.5% to 272% [36 -37].

Carey et al. [27] and Boucher et al. [34] believed that the spatial heterogeneity of soil properties (especially ice content) in permafrost areas may be the main reason for the above differences. This heterogeneity leads to differences in the response patterns of hydrological processes in different basins, making them incomparable between basins. In addition, the inherent limitations of the tracer-based runoff segmentation method may be a deeper reason: the method treats the entire watershed as a "black box" and determines the contribution of groundwater to river runoff based only on the relationship between hydrological inputs and outputs. The groundwater flow process in permafrost areas has not been deeply explored, especially the supply source of groundwater, flow path and its transformation relationship with soil water and surface water. Therefore, it is impossible to accurately describe the discharge process of groundwater into rivers.

2 GROUNDWATER FLOW PATHS IN PERMAFROST AREAS

The study of groundwater flow paths is of great significance for identifying the structure of the groundwater system, understanding the groundwater flow process, and constructing a conceptual model of groundwater flow. However, in permafrost areas, the existence of permafrost makes the groundwater flow process extremely complex and unique. In continuous permafrost areas, the flow of groundwater is mainly controlled by the regional topography. Whether it is water above the permafrost layer or water below the permafrost layer, it generally flows from higher terrain to valley depressions in the form of horizontal runoff. However, in some areas, it is also controlled by micro-topography. Influence of landforms and frozen soil characteristics. In discontinuous or island permafrost areas, in addition to horizontal runoff, groundwater also has longitudinal runoff [38]. It can be seen that groundwater flow paths may be different in permafrost areas with different topographic and geomorphological backgrounds.

Most permafrost areas are remote and have difficult living conditions, and basic geological and hydrogeological data are often scarce [15], making it difficult to directly characterize the structure of groundwater water-bearing systems and flow systems. Relatively speaking, it is more advantageous to use the hydrochemical and isotopic characteristics of spring water and surface water to invert groundwater flow paths [39]. Therefore, existing studies on groundwater flow paths in permafrost areas mostly use hydrochemistry and isotope tracing methods. In permafrost areas, the water above the permafrost layer, interlayer water and substratum water have different supply sources, residence times, and contact with different strata. They also have different hydrogeochemical environments and experienced water-rock interactions. The same, so there are obvious differences in the chemical and isotope characteristics of groundwater in each layer, and they are also different from the characteristics of surface water and soil water [35]. This difference lays the foundation for the use of isotopes and reactive solute tracers to study groundwater flow paths. foundation.

Early groundwater flow path tracing studies in permafrost areas mostly used conventional chemical parameters such as pH value, conductivity, and major ions as tracers. Because some parameters are too "active", that is, a variety of processes in the watershed may affect their changes, there is no unique correspondence between these parameters and flow paths. There are often multiple solutions when indicating groundwater flow paths, making it difficult to analyze the results. Explanation[40-41]. Therefore, the use of tracers that uniquely mark the groundwater flow path has become the key to accurately depicting the groundwater flow path.

Among the tracers that meet the above conditions, soluble SiO2 is used earlier and more widely [36]. The concentration of soluble SiO2 is stable when it migrates with the water flow in the watershed. A chemical reaction will occur only when the water contacts the mineral soil, thereby changing the concentration. The reaction rate is fast and can reach equilibrium in a short time [42]. Therefore, soluble SiO2 can be used to indicate whether water flow passes through mineral layers and thus the flow path. The opposite is soluble organic carbon (DOC) [43]. In surface water and shallow soil water, the DOC concentration is high because the water flow contacts the organic layer in the near-surface soil; in relatively deeply buried groundwater, the water flow often flows through mineral matter before being recharged to the underground aquifer. Soil, the latter's chemical absorption and biological effects reduce the concentration of DOC in groundwater [27, 44-46]. When the frozen soil in the basin melts, it will cause the groundwater flow path to become deeper and increase the exchange time between water and minerals, thereby reducing the concentration of DOC and increasing the concentration of other ions. Therefore, DOC often combines with Ca2 +, Mg2 +, Na + plasma to indicate the flow path in permafrost areas [33-34, 36, 47]. Petrone et al. [47] conducted a comparative study on the groundwater flow paths of two basins in Alaska using DOC and Ca2 +, Mg2 +, K + and Na + concentrations observed in two hydrological years from 2000 to 2001. Wickland et al.[48] studied the Yukon River and its two tributaries in Alaska, USA. Based on the differences in the chemical composition of degradable dissolved organic carbon (BDOC) and dissolved organic matter (DOM), they indicated the components of the river runoff coming from different runoff pathways..

The weathering of the matrix usually weakens with increasing depth, but minerals with different elemental compositions have different resistance to weathering, so the ratio of soluble elements in the underground medium, such as Ba / Sr, Ca / Sr, Ca /Na and Ca /Ba usually shows a trend change with increasing depth, which can indicate the flow path of groundwater [43, 49-50]. For example, Land et al. [51] used the Ba/Sr ratio and Ca/Sr ratio to distinguish three flow paths of underground runoff during snowmelt. Ren Dongxing et al. [52] conducted relevant research in the Fenghuoshan watershed where permafrost develops in the source area of the Yangtze River on the Qinghai-Tibet Plateau, and found that the chemical composition of runoff water from melting snow and frozen soil meltwater is different, which can be used to distinguish the supply sources of river runoff.

Isotope methods have also been applied to varying degrees in the tracing study of water flow paths in frozen soil areas [39]. Mcintosh et al. [53] used isotopes such as D, 18 O and 14 C to distinguish groundwater released from permafrost melting and groundwater from other sources in Europe and North America. Bagard et al. [54] used main chemical components, trace elements, Sr and U isotopes to analyze seasonal changes in river runoff recharge sources in the Siberian permafrost region, and found that river runoff during spring floods was mainly recharged by surface runoff flowing in the soil organic layer., in summer and autumn it is mainly recharged by shallow underground runoff that experiences significant water-rock interaction, and in winter it is recharged by deep groundwater. Casanova et al. [55] used B isotopes as tracers to study the impact of the freezing process of groundwater on its recharge and discharge in different sites in the permafrost regions of Finland and Switzerland. In addition, reactive solute isotopes such as 34 S, 13 C, and 15 N can also be used to indicate the flow path of water in the basin. For example, due to active microbial action in the soil organic layer, the δ13C value of soluble inorganic carbon (DIC) in shallow underground runoff is often lower than that in deep groundwater, so it can be used to identify underground runoff at different depths in permafrost areas [56].

Although isotope and hydrochemical tracing methods have been widely used in hydrogeological research since the 1970s and have shown their unique advantages, they have been relatively rarely used in the study of groundwater flow paths in permafrost areas. It needs to be further strengthened. In addition, the method itself has some limitations, which are reflected in the fact that this method can only obtain qualitative or semi-quantitative results; due to the many factors that affect the hydrogeochemical process or isotope abundance in permafrost areas, the research results often have multiple solutions. Certain assumptions must be met when using it, otherwise the research results will be uncertain. For example, Sklash et al. [57] and Uhlenbrook et al. [58] pointed out that when using stable water isotopes to establish a binary mixing model for runoff segmentation, there are five potential error sources that will cause uncertainty in the segmentation results. At present, the uncertainty research of the tracer method has attracted the attention of scholars at home and abroad. Many scholars are committed to developing more accurate uncertainty evaluation methods, and some scholars are trying to eliminate or reduce this uncertainty by improving the runoff segmentation model. Based on the segmentation of snowmelt runoff using stable water isotopes, a new isotope input value correction method RunCE (runoff-corrected event water approach) was proposed. This method can reduce the error caused by the time history change of snowmelt water [59]. Overall, although hydrochemistry and isotope tracing methods have certain limitations in the quantitative identification of moisture sources, they are helpful in the construction of conceptual models (in remote high-altitude areas, they are even the only way to form conceptual understanding). means), thereby laying the foundation for the construction of numerical models.

3 GROUNDWATER-THERMAL COUPLING MODEL IN PERMAFROST AREAS

Constructing a numerical model of the underground multiphase flow system in permafrost areas can not only more accurately describe the groundwater flow process in permafrost areas, reflect the transformation relationship between groundwater and surface water, reveal the impact mechanism of permafrost distribution characteristics on the groundwater system, and thereby improve the watershed The level of understanding of the formation and transformation mechanisms of water resources can also provide support for research on the response mechanism of hydrological processes in permafrost areas under the influence of climate change and human activities, and provide a basis for the management of water resources in river basins [2, 60].

At present, hydrological experiments and observations in permafrost areas are gradually increasing, but there are still few numerical models based on physical processes and suitable for permafrost areas [15]. Existing hydrological models such as SHAW [61], COUP [62], and SWATMOD [63] focus on the simulation of surface runoff or soil water, and give less consideration to the underground flow process [64-66]. Although models such as HydroGeoSphere [65, 67] and GSFLOW [68] include the groundwater flow process, they ignore the physical phase change of water (the freezing and melting process of pore water) and the related changes caused by it.

In recent years, groundwater-thermal coupled numerical models in permafrost regions have become increasingly popular. Some models take into account the different phases of water and the changes in porosity and permeability caused by freezing and thawing of permafrost. For example, in order to analyze the hydrological response of permafrost to seasonal and long-term temperature changes, Ge et al. [11] used the SUTRA software developed by the United States Geological Survey to establish a two-dimensional profile groundwater flow and heat conduction coupling model in the permafrost mountainous watershed in the northern Tibetan Plateau.. The model considers the impact of physical phase changes of water on permeability. The simulation results show that as the climate warms, the discharge of groundwater from permafrost areas to river valleys increases. Bense et al. [12] established a hypothetical two-dimensional profile model of a multi-level loose sediment water-bearing system driven by topography, and used it to predict the impact of permafrost melting in high latitudes on hydrogeological processes under surface warming. The model takes into account heat transport and water flow migration under unsteady conditions, and takes into account permeability changes during the thawing process of frozen soil. The simulation results show that whether it is the increase in the permeability of the aqueous medium during the melting process of permafrost, or the release of aquifer water storage caused by the rise in water head under the permafrost layer, it will lead to an increase in the base flow of the river channel. Provost et al. [69] established a two-dimensional groundwater flow profile model with a length of 1,500 km for the Nordic permafrost region, and predicted the changes in groundwater flow processes caused by climate change in the next 140 ka. In the model, the simulation of frozen soil thickness changes is separated from the simulation of water flow, and the changes in permeability caused by the freezing and thawing process of frozen soil are not considered.

It should be pointed out that most of the water-thermal coupling models established in the above studies are hypothetical models under ideal conditions and are mainly used to infer the evolution of permafrost on a longer time scale under climate warming scenarios and its impact on groundwater circulation., but there is a lack of empirical calculations and simulations of actual groundwater systems in specific research locations, and the calibration and subsequent verification of the model are not in-depth enough. In order to better reveal the groundwater flow process in permafrost areas and accurately calculate the amount of groundwater resources and base flow recharge to river channels, more empirical research is needed to improve the practicality of the model.

4 DISCUSSION AND OUTLOOK

In summary, due to the harsh research conditions in permafrost areas and the limitations of traditional baseflow segmentation methods, hydrochemistry and isotope tracing methods are still the main means to study the groundwater flow process in permafrost areas and its relationship with surface water transformation.. However, the distribution characteristics of frozen soil and the impact mechanism of the thawing process on groundwater circulation and river runoff formation are extremely complex, which will not only cause part of the groundwater to transform between solid and liquid phases, but also cause changes in the thickness and distribution pattern of the frozen soil layer, that is, Causes changes in the structure of the groundwater aqueous system, thereby affecting the recharge, runoff, and discharge processes of groundwater. Therefore, the impact of frozen soil on the groundwater system is also a difficulty in the study of groundwater processes and effects in frozen soil areas. How to accurately characterize the distribution characteristics of frozen soil and the impact of the freezing and thawing process on the groundwater water-bearing system and flow system is what this research needs to solve. Key scientific issues. In the future, research should be strengthened in the following aspects:

a. Accumulation of basic hydrogeological data in permafrost areas. Permafrost areas are usually located in remote areas at high altitudes or low latitudes, making it difficult to carry out hydrological and hydrogeological surveys, and difficult to maintain long-term field monitoring [53]. This will inevitably lead to a lack of basic data, thereby limiting the groundwater flow process and The development of research on its relationship with surface water transformation. Therefore, it is recommended to improve from the following two aspects: ① Reasonably arrange new hydrogeological monitoring holes in permafrost areas, and integrate existing monitoring holes to build a groundwater monitoring network to conduct dynamic monitoring of water level, water temperature, water chemistry, and isotopes. ; ② Carry out a systematic hydrogeological survey. In addition to the regular content such as meteorology, hydrology, regional geology, hydrogeology, groundwater environment, special types of groundwater, etc., permafrost-related content should also be added, such as permafrost and seasonally frozen soil. The distribution characteristics of frozen soil, the thawing and freezing rules of frozen soil, the thickness of the active layer, the connection between water on the frozen soil layer, between layers and below the layer, etc.

b. Uncertainty analysis of water chemistry and isotope tracing results. Specifically, the first is to continue to improve the uncertainty evaluation model, consider the potential errors of all parameters and various links in the tracer study as comprehensively as possible, and analyze the satisfaction of the assumptions of the tracer method, so as to evaluate the tracer results. The second is to explore ways to reduce or eliminate uncertainty from the layout of sampling points, control of sampling and testing links, and improvement of runoff segmentation models, etc., to explore ways to reduce or eliminate uncertainty, such as through Correction of model inputs [70], reducing the uncertainty caused by time course effects [22], or using auxiliary tracers [71-72], temperature, water level and other multi-source data [73] to jointly constrain the segmentation model.

c. Practicality of water-thermal coupling model in permafrost regions. At present, research on groundwater-thermal coupling models in frozen soil areas that considers changes in water between different phases and permeability changes during the thawing process of frozen soil has just started [4, 10-11], and most models are extremely simplified processing of the actual situation. The latter ideal model [61-68] is mainly used to predict the possible impact of permafrost melting on groundwater flow processes and water resources under climate change. These models often have little or no correction, so they are difficult to use to simulate actual groundwater flow and calculate water resources in specific areas. Regarding the improvement of the practicality of water-thermal coupling models in frozen soil areas, there are two directions worth noting in the future: ①Constructing a three-dimensional actual model for specific research areas for groundwater flow process characterization, data integration and result prediction. In the process of building the model, the key scientific issue is the transformation of hydrological scale, that is, the parameters obtained at points (wells) are extended to the surface through spatial technology [74-75]. Accurate characterization of heterogeneity may be another major challenge. It will not only occur in watersheds with large simulation areas or large elevation differences, but also in smaller simulation scales where multiple types of groundwater (frozen soil layers) exist. Upper water, interlayer water, pressurized water under the layer, unpressurized water under the layer, etc.), different types of frozen soil areas (continuous permafrost area, discontinuous permafrost area, seasonal frozen soil area) or frozen soil It will also be encountered in watersheds where both frozen rock and frozen rock may constitute aqueous media [76]. A possible breakthrough direction is to establish a hydrogeological test site in permafrost areas, carry out multi-method, high-precision experiments, obtain relevant parameters required for the model, and form a theoretical understanding of the heterogeneity of aqueous media in permafrost areas. ② In the process of model construction and calibration, make full use of multi-source data to improve the reliability of the model. For example, a conceptual model of groundwater flow in permafrost areas is constructed based on the tracing results of groundwater flow paths, a small number of hydrogeological surveys and experiments are carried out to obtain the hydraulic and thermodynamic parameters required by the model, and the isotope segmentation results of river runoff are used as constraints on the model. The model is calibrated using field automatic monitoring data such as water level, flow rate, and water temperature.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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