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Review and Prospect of Hydrological Studies in Cold and Arid Regions of China*

(我国寒区和干旱区水文研究的回顾和展望)

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Abstract: For the hydrological studies in cold and arid regions of China, a comprehensive system of observation, experiment and investigation has been basically established in the areas of glaciers, snow cover, frozen soils, alpine cold watersheds and piedmont belts in northwest China. Numerous achievements have been obtained since the 1980's. Recently, some new progress has been achieved in the studies of hydrology and water resources. It might be expected that, in the next ten years or more, the studies of hydrology in cold and arid regions of northwest China will enter a new stage of comprehensive research, which will probe the spatial and temporal interaction among the hydrosphere, atmosphere, cryosphere, lithosphere and biosphere, with hydrosphere as a core. Furthermore, there may be some new breakthrough progress in the studies of water environment and water resources. All these will lay a foundation for making decisions in the sustainable economic development of arid northwest China.

Key words: cold regions; arid regions; hydrology; water resources; review and prospect
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1 INTRODUCTION

The hydrological researches in cold and arid regions of China have experienced a course of 40 years. Northwest China consists of vast plateaus, huge mountain systems and piedmont plains or basins, where drainage systems can be divided into interior and exterior ones. The cold alpine region in the southeastern part of the Tibetan Plateau is the source of several large rivers of China flowing into the Pacific Ocean and Indian Ocean. Water resources in arid northwest China are mainly distributed in a number of relatively independent inland river basins, of which the cold alpine areas are the runoff—forming regions, while the piedmont plains or basins are the runoff loss regions. Such topographic features and spatial distribution characteristics of runoff result in the unique hydrological and water resources systems in northwest China. In the inland river basins, the hydrological processes both in the arid areas and cold alpine areas are interrelated and interacted. From very beginning the studies of glaciology and geocryology in China have set the research objective as "Tapping the alpine ice and snow water resources to mitigate the drought in northwest China"[1]. Accordingly, hydrological studies in cold and arid regions of China were

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developed synchronously with the research of glaciology and geocryology. During the period from 1958 to1965, some pioneering achievements were obtained in such research fields as glacial radiation and heat balance, glacial accumulation and ablation, glacial hydrology, river hydrology in mountain regions, and the transformation between surface water and ground water. During this period, a hydrological and meteorological station was established at the Laohugou Glacier in the Daxueshan of the western Qilian Mountains, and the Tianshan Glaciological Station was established in the source area of the Urumqi River. The monograph entitled "Study of glaciers and hydrology in the Urumqi River" was published in 1965. The study of water resources in the Shiyang River, Gansu Province, was initiated and a hydrological research division of arid zone was set up during the period[1]. In most of the glaciological investigations at that time, hydrology was an important item[2]. Afterward, research of hydrology in cold and arid regions were suspended due to the "Cultural Revolution". Since 1978, studies of glacial hydrology, cold region hydrology and arid zone hydrology have been resumed[3, 4]. This paper intends to review the hydrological studies in cold and arid regions of northwest China since the 1980's, especially in the recent ten years. In addition, the future direction of research is also discussed.

2 RESEARCH PROGRESS SINCE THE 1980's

2.1 Researches on glacial meltwater runoff

With the progress and completion of the Chinese glacier inventory[5], the statistics reveal that China has a total glacier area of 59 406 km^2, equivalent to a water resources storage of $5\,031\times10^9 m^3$. Based on the systematic summarization of the available data, Yang Zhenniang analyzed the precipitation conditions responsible for the glacier development in the mountainous regions of west China, as well as glacier ablation, glacier meltwater runoff and glacier water resources, and then published a monograph entitled "Glacier Water Resources of China"[6]. In this book she defined the basic parameters of glacier meltwater runoff, such as glacier meltwater runoff modulus, glacier meltwater runoff depth and runoff coefficient. By means of comparative observation and experiment, discharge—temperature relation method and glacial meltwater runoff modulus method, she made a detailed regionalization for the glacier meltwater runoff in China and calculated the glacier meltwater runoff amounts in various mountain systems. According to her calculation, China has a glacier meltwater runoff volume of $60.5\times10^9 m^3$, of which 58% is distributed in the Autonomous Region of Tibet and 33% in the Xinjiang Uygur Autonomous Region.

For simulating the glacier runoff, a number of statistical models and stochastic models were adopted, such as time series analysis[7, 8], stochastic process simulation[9] and the multiple regression model[10] etc. It has been found from multiple regression analysis that besides air temperature, vapour pressure is also an important index to describe the water and heat conditions in high mountains, and plays an important role in the discharge simulation[10]. In addition, glacier ablation function was established from statistics and analyses[11]. In the studies of the physical processes of glacier melting, a method was developed to compute glacier runoff by glacier energybalance[12], and then a parameterized energy balance model of glacier melting was developed[13]. In addition, numerous observations and studies have been carried out on the englacial and subglacial drainage systems[14], as well as on the glacier water chemistry[15, 16].

2.2 Experimental studies of the formation of mountain runoff

Aiming at the understanding of runoff—generating in the mountainous areas, which are the runoff generation area of the inland river basins, a project "Studies of some problems of water resources in the Urumqi Prefecture" was jointly organized by the Chinese Academy of Sciences and the Xinjiang Uygur Autonomous Region Government. In this project comprehensive observations and experimental studies of runoff formation were carried out during the peri-

od from 1985 to 1987 in the mountatious watersheds of the Urumqi River, mainly supported by the Tianshan Glaciological Station, CAS, and the Runoff Experimental Station of the Water Resources Bureau of Xinjiang Uygur Autonomous Region[17]. The project includes precipitaiton features and its measurement, glacial hydrology, evaporation measurement ect. Through the observational and experimental studies, some new knowledge and new progress was obtained[17], such as precipitation measurement method and its systematic error correction, as well as precipitation distribution in a mountainous area[18], glacier energy balance, runoff—forming processes and glacial meltwater nourishing therivers[12, 19], river ice and its role in the formation of spring runoff[20], evaporation measurement at the source area of the Urumqi River[21], and evaporation estimation in a mountainous basin[22]. In addition, improved methods for water resources estimation and runoff simulation were put forward[10, 23, 24]. Of particular importance was the experimental study of the systematic error correction of precipitation measurement, which was first put forward in China and has attracted attention of international scholars. It has also been adopted and quoted in the World Meteorological Organization's publications[25]. Other work conducted in the period included such studies as the change of climate, glaciers and runoff and its future trend in the Urumqi River basin[26].

2.3 Study of the hydrological processes in the cold regions

In addition to glaciated areas, the hydrological phenomena of ground surface and the active layer of permafrost in vast cold regions is quite sensitive to climate change. For exploring the hydrological processes, runoff forming mechanism and runoff generating characteristics in the cold alpine regions, Yang Zhengniang *et al*. conducted hydrological observations and experiments in the Binggou basin at the upper Heihe River in the Qilian Mountains and in the Ice—free Cirque basin at the source area of the Urumqi River in the Tianshan Mountains[27]. Parts of these studies were conducted in cooperation with Professor Ming—Ko Woo, McMarster University of Canada. Through a series of field observations and experiments some new knowledge was obtained and some problems were discussed, such as runoff formation and runoff generating patterns in the coldregions[28], runoff analysis and estimation[29], hydrological processes in frozen soils[28], relationship between runoff and meteorological elements[30], spatial and temporal distribution ofprecipitation[31], water balance and waterresources[32, 33], and water chemical properties in the cold regions[34]. Studies of the runoff—generating mechanism in the cold alpine regions show that it can be expressed by quantitative mathematical models, and the runoff generation results from the infiltration and transformation of surface water and ground water on frozen layer[35]. In addition, from the chemical composition study of snowmelt runoff in the Ice—free Cirque basin in the source area of the Urumqi River, it has been found that there exists the "Ion pulse" phenomenon in the snowmelt runoff[36].

2.4 Interrelationship between hydrological processesand atmospheric processes in the glacierized basins

During the period from 1985 to 1989, the Tianshan Glaciological Station conducted a series of observations and experimental studies of the energy balance, mass balance, water balance and runoff—forming processes in the glaciated basin of the source area of the Urumqi River, of which the field observations and studies of glacial energy balance and glacial climate were conducted in cooperation with Professor Atsumu Ohmura, Swiss Federal Institute of Technology[37, 38]. Based on the above—mentioned work, Kang Ersi *et al*. developed a hydrological discharge simulation model by means of combination of energy balance with water balance and the association of atmospheric processes with hydrological processes in a glacierized basin[39, 40]. The model not only can be used in the runoff process simulation but also can be used in the simulation of runoff change in a decade to century time scale in glacierizted basins[38]. With conventional meteorological ele-

ments measured at standard meteorological stations as the initial inputs, the model was used in the simulation of energy balance of snow and ice surface, snow accumulation, runoff generation and hydrological processes in the glacierized basin at the source area of the Urumqi River[41].

2.5 Studies of some problems of water resources in the Urumqi Prefecture

"The studies of some problems of water resources in the Urumqi Prefecture" is a subject put forward by the Chinese Academy of Sciences to meet the demand of economic development in the arid regions of northwest China and the westward migration of the state's future construction priority. Supported by the Xinjiang Uygur Autonomous Region Government, Shi Yafeng and Qu Yaoguang, in cooperation with relevant local institutions, directed this project and organized many multidisciplinary and comprehensive studies, such as water shortage issue in the Urumqi City, city development scale, rational distribution of water resources among industry, agriculture and inhabitants, water resources formation and variation, water quantity and quality, broadening the water sources and economizing the water consumption, water resources exploitation and utilization extent and their bearing capacity etc.[42]. The main research results have been summarized in severalmonographs[17, 42~44]. This research project represents China's first systematic multidisciplinary research in a mountainous area and piedmont belt in an inland river basin in arid northwest China. These studies have increased our understanding and yielded fruitful results in the following aspects: region's runoff formation and transformation processes, geo-chemical features of water environment, water resources exploitation and utilization, water conservancy, status of industrial and agricultural structure, future demand and distribution of water, water pollution and environment protection, and water resources bearing capacity etc..

2.6 Impact of climate change on water resources

As for the research project "The Impact of Climate Changes on Water Resources in Northwest and North China", directed by Professor Shi Yafeng, the Lanzhou Institute of Glaciology and Geocryology, CAS, undertook its sub-project "Impact of Climate Change on Water Resources in Northwest China and their Trend Evaluation". The institute carried out studies of the change of water resources of arid northwest China from various angles, and a wide range of information was used, such as paleoclimate information recorded in the ice cores, glacier change and its trend, seasonal snow cover change and its trend as well as river runoff change and its trend etc.[45, 46]. In the studies of the river runoff change, the main climatic factors influencing the runoff changes were analyzed, then the regional distribution of runoff change was revealed, and the influences of climate change on the mountain runoff was simulated. It was found that the 1970's was a turning period of climate change in northwest China. From then on, the summer temperature has been gradually rising. From the late 1960's to the early 1980's, the precipitation reduced significantly in most of the region. During the late 1980's, a positive precipitation departure occurred in the whole region. The runoff change also showed a feature of positive departure during the late1980's[47]. In addition, a water balance model was used in the simulation of runoff change and its influence on the water resources under different climatic scenarios in the Urumqi River basin[48] and the Ili River basin[49]. Furthermore, the greenhouse effect on river runoff in west China was also discussed[50]. Based on the studies above mentioned, the futurechanging trend of surface water resources was predicted under various climate change scenarios in arid northwest China[45].

2.7 Hydrological studies of the high-altitude Asian cryosphere

As a part of the project "Response of High-Altitude Asian Cryosphere to Climate Change and Its Effect on Environment" supported by the Chinese Academy of Sciences, the research of "Response of High-Altitude Asian Glaciers and River Runoff to Climate Change" was carried out. According to available records, the energy and mass balance pro-

cesses of the high — altitude Asian cryosphere wereaddressed[51]. Theories and methods concerning glacial system as well as energy — water balance runoff model were employed in the simulation of possible change of glacier system and runoff on the northern slope of Mount Tianger, Tianshan Mountains, owing to climate change[52]. The response of hydrology to climate change in the cold area on the northern slopes of the Qilian Mountains was also studied, and the runoff and environment changes in the cold area were preliminarily predicted in accordance with their periodical variation[53]. Studying the influence of climate change on runoff of the major rivers in the Tibetan Plateau found a declining tendency of runoff owing to climate warming and the desiccation since the mid 1960's. Nevertheless, the early 1970's was a turning point, since then, precipitation has been increasing in different degrees in various basins, but the annual river runoff volumes still fluctuated below the normal values[54]. In addition, through field investigations and observations, the following research has been also carried out: ablation features of the continental glaciers in China[55], the evaporation of winter—accumulated snow in mountainous areas[56], the glacier hydrology in the Gongga Mountains[57], the hydrological processes in the Dongkemadi River basin in the Tanggula Range of the TibetanPlateau[58], the climate change in the Qinghai Lake basin together with its influence on water balance and its changing tendency over the past 30 years[59].

2.8 Glacier Meltwater Flood and Snowmelt Runoff

During the period from 1985 to 1987, the Lanzhou Institute of Glaciology and Geocryology, CAS, and the Water Conservancy Bureau of Xinjiang Uygur Autonomous Region jointly organized a scientific investigation of glacier meltwater flood in the Yarkant River[60, 61]. The studies showed that sudden flood events of the Yarkant River were due to the outburst of the glacier—dammed lakes, especially the rapid expansion of the subglacial drainage channels. The Kyagar Glacier and Singhi Glacier at the upper reaches of the Shaksgam River are the main source areas of such floods. It was concluded from the investigation that the two glaciers will significantly retreat and become thinner by the end of the 20th century under global warming, hence the flooding scale of the glacier—dammed lakes will become smaller[60]. This research result not only enriches China's hydrological studies, but also provides a scientific basis for the planning and management of the Yarkant River and the economic development of the southern part of the Xinjiang Region[62]. In addition, some dangerous glacial lakes and their outburst issues were studied in the Himalayas[63], and comprehensive studies were also carried out on the flood disasters caused by the outburst of glacier—dammed lakes in other regions of China[64].

In the snowmelt runoff research, emphasis was on the analysis and prediction of spring runoff in the upper Yellow River[65, 66] and in the Hexi corridor, Gansu Province[67]. In the prediction of snowmelt runoff, a regression method with biasedestimation[68] and a method of gray systemanalysis[69] were employed, and as a result, a good result of prediction was obtained. In addition, the processes of flooding and sediment transportation were also studied in small watersheds in some mountainous regions[70].

2.9 Hydrological studies in the arid areas

In the hydrological studies in the arid piedmont plains and basins, some new progress has been achieved, such as water resources transformation and water quality variation, stages of exploitation and utilization of water resources, potential capacity of water resources, water relating to oases, and the simulation and prediction of water resources. The studies in the Urumqi River basin indicate that an inland river basin can be divided into several independent but interrelated hydrogeological units, groundwater movement and circulation processes are closely related to the surface water, while recoverable and renewable groundwater mainly comes from the conversion of surface river water[71]. Water quality varies obviously with altitude, and the lower reaches of rivers are the accumulated areas of variouspollutants[71]. According to the development history, present status and future trend of exploitation and utilization of water resources in arid northwest China, the stages of exploitation and utilization of water resources can be divided into, firstly, the stage of exploitation and utilization of

surface water, secondly, the stage of joint exploitation and utilization of surface water and ground water, and thirdly, the stage of economical utilization of water resources. These three stages reflect the level and rationality of exploitation and utilization of water resources[72]. In the studies of water relating to oases in the Hexi corridor, the formation and evolution of oases and their relations with water resources were explored, and the future development scale and direction of oases were inferred[73]. In the simulation studies of water resources transformation in the Urumqi River basin, with water balance as the basic principle, great efforts were made to resolve the problems in the present exploitation and utilization of water resources. Through the simulation of transformation mechanisms among the river water, ground water and spring water, a model with predictable functions was developed[74].

2.10 Research on some other aspects

In addition to the work described above, many other associated institutions also conducted a lot of field investigations, observations, experiments and studies of hydrology and water resources in the cold and arid regions of China. For example, the Lanzhou Institute of Desert Research, CAS, conducted studies of rational exploitation and utilization of water resources in the Heihe River basin[75]; the Xinjiang Geographical Institute, CAS, conducted studies of water resources in central Asia; the Xinjiang Bureau of Hydrology and Water Resources conducted studies of hydrology and water resources in arid areas; the Integrated Scientific Investigation Team of Taklimakan Desert, CAS, conducted studies of the evaluation and utilization of water resources in the Taklimakan Desert; Commission for Intergrated Survey of Natural Resources, CAS, conducted investigations of water resources in the Tibetan Plateau and Xinjiang Region; and Institute of Geography, CAS, conducted studies of water resources in the Tibetan Plateau and northwest China, and so on. A lot of related monographs and papers have been published, and all these studies have made a great contribution to the studies of hydrology and water resources in the cold and arid regions of China.

The above described studies and achievements indicate that a comprehensive observational, experimental and studying system has been preliminarily established in China to study hydrology and water resources in the cold and arid regions, including the areas of glaciers, snow cover, frozen soils, alpine watersheds, piedmont plains and basins. Numerous encouraging research results have been achieved. During the 9th five—year planning period of the state, more attention is paid to the studies of hydrology and water resources in the cold and arid regions of China and these studies are taken to be priority projects. For this reason, the Cold and Arid Regions Environmental and Engineering Research Institute, CAS, which is a new institude reorganized based on the three institutes of Chinese Academy of Sciences——Lanzhou Institute of Glaciology and Geocryology, Institute of Desert Research and Lanzhou Institute of Plateau Atmospheric Physics, should strengthen its ties with international research plans[76]. Now the director of the institute, Academician Cheng Guodong, has organized relevant scientists of the institute to undertake studies in the state's key project in the 9th five—year planning period "Studies of rational exploitation and utilization of water resources and eco—environment protection in northwest China". Two special subjects the institute undertook were "Studies of rational exploitation and utilization of water resources and their harmonious development with society and eco—environment in the Heihe River basin" and "Studies of the changes of snow and ice water resources and mountain runoff and their trend prediction". In addition, the institute is now implementing the National Natural Science Foundation's key project "Basic studies of water resources formation and changes in the inland river basins of arid northwest China".

In these studies, new progress has been achieved. A model has been developed for simulating the response of runoff from the mountainous watersheds of inland river basins to climate change in the arid areas of northwest China[77]. Change of water resources of glaciers and snow was investigated in the arid area of northwest China[78, 79]. Response of the snowmelt and glacier runoff to the climate warming in the Xinjiang Uygur Autonomous Region in the last 40 years has also been discussed[80]. In the inland river basins, the variation of precipitation[81], runoff[82], glacier meltwater runoff[83], forest hydrology[84] and runoff chemistry[85] have been further

studied. Research on the runoff variation and trend forecast has also been carried out at the upper reaches of the Yellow River[86]. Furthermore, new progress has been achieved on the multi-criteria decision analysis of water resources[87], current problems of waterresources[88,89], the relationship among the ecological system, environment and waterresources[90~93]. The rational utilization and exploitation of water resources have been studied in the inland river basins of the arid area of northwestChina[94~96]. Research has also been carried out on the carbon cycle of sandy lands in China and its global significance[97].

3 TREND AND PROSPECT

Water is a life giver, and also the largest limiting factor to economic development. Fresh water resources on the Earth are limited. With the increasing human demand for water, the contradiction between water demand and water supply is becoming increasingly acute. In the 21st century, water crisis has become a matter of worldwide concern. China is one of the severest water-deficient countries in the world, while northwest China is the driest region of the country. In the present-day hydrological studies, much attention is paid to the impact of global change on the hydrology and water resources, aiming at predicting the long-term change of water resources. For this reason, great efforts are being made to study the relations between climate change and water resources, and this also includes the forefront subjects of hydrological research, such as hydrological process interface and scale conversion issues. At present, hydrological studies have entered such a stage that, with the hydrosphere as a core, great attention is being paid to the studies of the interactions among the atmosphere, cryosphere, lithosphere and biosphere, thus we can conduct a dynamical model of the water cycle. In addition, how to make the most optimal use of limited water resources, and the influence of water resources exploitation on the environment are also the problems facing us in the sustainable utilization of water resources. In view of this, the author is making a prospect to the studies of hydrology, water environment and water resources from the present-day up to 2010.

3.1 Cryosphere hydrology and water resources in high-altitude Asia

The physical models concerning energy and water exchange among glaciers, frozen soils, snow cover, vegetation cover and atmosphere and runoff-generating mechanism should be established, which will contribute to the understanding of distribution of water resources and their change in space and time. The relations between water resources variations and climate change and their affecting processes on the plateau eco-environment will be numerically simulated and analysed, and thus we can further predict future water resources change and their environmental effect.

3.2 Systems of hydrology and water resources of the inland river basins of the arid area of northwest China

The energy and water transmission models at snow and ice-atmosphere interface, ground-atmosphere interface, soil-atmosphere interface and soil-plant-atmosphere interface should be established and a scale conversion scheme should be put forward. Furthermore, distribution parameter hydrological models of inland river basins should be established and coupled with regional climate models as well as GCMs models to predict the outflow runoff from the mountainous watersheds and its long-term changing trend. Great progress should be achieved in the basic theories, concerning the influence of human activities in the exploitation and utilization of water resources on the water resources and eco-environment, and then we can establish a decision-making system for a high-effective sustainable use and scientific management of water resources in the inland river basins.

3.3 Water cycle in the arid area of northwest China

Study of systematic error correction for precipitation measurement should be continually carried out, and computational methods of land evaporation should be improved. Therefore, the calculation accuracy of the water balance has to be improved. The water budget and renewal rate should be studied for both the glacial water and ground water, then the water cycle in different peri-

ods can be revealed. A numerical modeling should be carried out for the transformation among atmospheric water, snow and ice water, surface water, soil water and ground water in the inland river basins. Centered around water, interactions should be studied among water, atmosphere, snow and ice, frozen ground, land surface and vegetation, then a dynamic model of water cycle will be preliminarily developed for the arid area of northwest China.

3.4 Water environment of arid northwest China

Through studying the SPAC (or SVAT) system, factors affecting mass migration in the hydrological system, the main characteristics of mass migration processes, the water chemical dynamical processes and the relations between water quality change and environment change should be revealed, thus a model of hydrological mass migration can be established in arid northwest China.

The studies mentioned above require us to strengthen field observations and experiments, especially systematic and long-term studies in selected typical experiment basins. Field observations also require to continuously improve measurement techniques and data collection, to strengthen international cooperation studies and to adopt advanced academic views and research methods. Ground observation systems must be combined with 3S systems, and special attention should be given to the application of microwave remote sensing. In addition, there is also a need to extend the climate and hydrological time series using ice core and tree ring methods. It may be expected that in the next ten years or more, the hydrological studies in the cold and arid regions of China will reach a comprehensive stage, during which much work will focus on the spatial and temporal interactions among the atmosphere, cryosphere, lithosphere and biosphere with hydrosphere as a core. And there will be some new breakthrough progress in the studies of water resources and water environment, providing a basis for decision-making for the sustainable economic development in the cold and arid regions of China.

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