Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.24214

168 (2019) 394–404
November

Regionalization of cryosphere water resource service

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Received 22 October 2018; Accepted 21 January 2019

ABSTRACT

The cryosphere water resource service (CWRS) is the most significant cryosphere service (CS) to directly affect human societies. Regionalization of CWRS is an important prototype for the comprehensive regionalization of CSs. It is also a crucial cutting-edge exploration of interdisciplinary work across cryospheric science, physical geography and human geography. We constructed a quantitative indexing system for the regionalization of CWRS along the dimensions of base–supply–demand informed by the characteristics of cryosphere resources and human use of CSs. Different levels of regionalization are subdivided using cluster analysis, the importance index of CWRS, and a location entropy model. A region in Northwest China with significant CWRS use was the study area. From the joint effects of nature and human activity, there emerge principles of regional differentiation that govern the regionalization of CWRS. The study area was first divided into three high level service regions according to the availability of stored cryosphere water in snow cover, frozen ground and glaciers, indicating the regulatory function of cryosphere components. Second-level regionalization subdivided each region into three sub-regions based on the supply of CSs, determined by the different quantities of snow melt and glacial runoff. The study area was finally subdivided into 63 third-level regional units based on land use and socio-economic indicators, which reflect differences in demand for the CSs. This study provides practical scientific guidance for the future use of CSs, such as the Belt and Road Initiative and new urbanization, and protection of the cryosphere by sustainable development and ecological improvement.

Keywords: Cryosphere; Water resource service; Regionalization; Northwest China

1. Introduction

Past studies of the relationships between the cryosphere and humanity have ignored the positive influences of the cryosphere on human societies and economies, concentrating instead on natural attributes, such as cryospheric processes and mechanisms, and the damage caused by rising sea levels and cryospheric disasters. The cryosphere is a vital component of the earth's climate and is of great significance to humanity in terms of climate regulation, ecosystem maintenance, engineering services, tourism and leisure, and support for natural resources.

CSs have not received sufficient attention due to the remote locations and lack of public awareness of the cryosphere [1,2]. Rapid economic and social development has led to people's understanding of CSs gradually deepening. In 2016, General Secretary Xi Jinping said "Not only green

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mountains and clear water, but also snow and ice are golden and silver mountains," which increased the importance and awareness of CSs for the general public. The climate regulation function of the cryosphere is the basis of CSs, which focus on the natural properties of the cryosphere. For example, cryosphere water resources have three functions: water conservation, runoff regulation, and replenishment.

CSs include all the benefits that humanity directly or indirectly obtains from the cryosphere, such as natural resource use, products, and wellbeing [3]. Broadly speaking, CSs include provisioning (e.g., freshwater, clean energy, and germplasm), regulation (e.g., climatic regulation, runoff regulation, and ecological regulation), social and cultural services (e.g., an aesthetic, tourism, sports, religion, and culture), habitat, and engineering services [2,4]. Water is the most significant component of the cryosphere ecosystem, and is the foundation of human social development, as it provides the fundamental resources to maintain socioeconomic development and plays a major part in maintaining ecosystem structure, processes, and stability [5].

The cryosphere is the sub-zero temperature layer of the earth's surface. Although the cryosphere is not contiguously distributed and is of a certain thickness, it stores 75% of the earth's freshwater as a solid water reservoir [6,7]. The major constituents of the cryosphere are glaciers (mountain glacier, ice sheets, and ice shelves), frozen ground (temporary frozen ground, seasonal frozen ground, and permafrost), snow cover, solid precipitation, sea ice, river ice, and lake ice [8]. The cryosphere is not only a solid water tower for rivers in arid and semi-arid regions but also effectively the source point of many of Asia's major rivers [9].

Global warming has caused changes in the cryosphere, directly affecting about 45% of the world's population. The effects of glacial shrinkage in the Qinghai–Tibet Plateau on river runoff endanger the food security of about 2 billion people [10]. The IPCC Fifth Assessment Synthesis Report states that increased snow cover melting has influenced the net flow of ephemeral streams [11]. A temperature rise of 2°C may lead to the frequent occurrence of snowless years. Melting glaciers in Central Asia, South Asia and the Qinghai–Tibet Plateau may be one of the most serious threats to local human development and food security in the next 50 years [12,13]. A temperature rise of 2°C could cause a reduction of 20%–30% in total runoff from the Qinghai–Tibet Plateau.

Climate change is influenced by natural events and change in human activities. As a source of water, the cryosphere has changed in major ways. Oases and cities that depend on the meltwater from glaciers and snow cover are rapidly increasing in size, giving rise to more challenges to regional water security and conflicts in human–water relationships [14,15]. The cryosphere is a solid reservoir, and there are significant differences in water conservation, runoff regulation, and replenishment practices between watershed guardians and other regional authorities. The spatial and temporal distribution of cryosphere water is complicated by differences in local water resource utilization. The Paris Agreement requires sophisticated responses to cryosphere changes caused by climate change, and this requirement will inevitably affect the socio-economic development of areas affected by changes in the cryosphere, especially arid regions. However, there is little understanding of the relationships between cryosphere water resources and socio-economic development [16,17]. The cryosphere has not been assessed scientifically as a source of water resource services, and there is no clear holistic understanding of its behaviour.

The issue of how to cope with major issues caused by changes in the cryosphere due to climate change, such as rising sea levels and the exploitation of marine resources, needs to be settled. Building on China's initiative by voicing opinions in international diplomatic negotiations and assigning rights and responsibilities between areas that benefit and adversely affected areas is also an urgent task. Providing scientific support for the Belt and Road Initiative, the Winter Olympics, ecological progress, regional economies, and coordinated regional development, is also of great importance.

Cryospheric science must become part of the overall framework of earth system science. Studies of the changing cryosphere and adaptation strategies belong in the fields of climate, ecological, and environmental science [8]. Cross-disciplinary, integrated methods, and high-end technologies are indispensable for comprehensive research of the cryosphere. CSs combine natural supply with human demand and thus form a dynamic structure in which humans and the earth interact through the cryosphere. Exploring the law of territorial differentiation in the cryosphere, a special kind of man–earth areal system in earth surface science, can identify causal relationships between CSs and regional socioeconomic development [18,19]. Regional differentiation and synthesis, known as regionalization, have become an established part of geographical research [20]. The main goal of regionalization is to reveal common phenomena within regions and differences between regions by using the scientific research paradigm [21].

Comprehensive regionalization can reveal the underlying causes of regional differentiation and the man–earth areal system that have developed. It has been important in social and economic development and it incorporates the attributes and interconnections of geographical features in the environment [22,23]. Existing regionalization structures have not adapted to the 21st century situation that has resulted from in-depth research in earth system science and worldwide emphasis on sustainable development. Thus, comprehensive regionalization must confront the trends of increasing recognition of human–natural world systems, the synthesis of qualitative and quantitative approaches to understand the planet, and multi-scale global-through-local analysis [24,25].

Current cryosphere research on regionalization is mainly concerned with the supply side of the cryosphere as a resource. It emphasizes cryosphere change, processes, causal relationships, and negative socioeconomic impacts, such as rising sea levels and cryosphere-induced disasters. It studies various CSs, such as freshwater resources, ecological regulation, ice and snow tourism, and cultural services, but it lacks a systematic analysis of the positive impacts of the cryosphere on human wellbeing. This shortcoming has led to a gap between cryospheric science and sustainable socio-economic development and thus there is limited practical guidance. Research into both the supply and the demand sides that investigates practical needs is fragmented and the results are difficult to be effectively implemented [8].

Comprehensive regionalization of CSs will fill in the blanks in cross-disciplinary investigation and, more importantly, it will help geographers to develop better national and regional development strategies. Such studies are at present preliminary but are considered to be at the leading edge of cryospheric science. Cryosphere water resource service (CWRS) is prominent and direct service provided by the cryosphere and represents an important breakthrough for the application-oriented regionalization of CSs. They provide the necessary scientific basis for identifying regional characteristics and implementing socio-economic development plans. A full scientific understanding of CSs and their spatial differentiation is fundamental to sustainable socio-economic development and ecological progress in cold and arid regions for both the scientific growth and forward-looking strategy development.

2. Materials and methods

2.1. Study area

This study takes part of Northwest China as a typical case area. The study area includes three provinces, Xinjiang, Gansu, and Qinghai as well as Ejina Banner in the Inner Mongolia Autonomous Region. It is in a mainly semi-arid and arid region. Local water resources are greatly dependent on high mountain cryosphere areas, making the CWRS of great importance to local socio-economic development. Runoff from glacial meltwater accounts for more than 30% of Xinjiang province's total runoff. The study area is 2,951,300 km^2, accounting for 30.6% of the land area of China. In 2014, the total gross domestic product (GDP) reached 1,805.8 billion yuan, 2.8% of China's GDP. The per capita GDP was 32,989.3 yuan, drastically lower than the national average of 47,202.8 yuan. Total population of the area was 56.04 million, 4.1% of the country's population. Remarkably, the population density was 19 inhabitants per km^2, showing that the study area was sparsely populated over a vast land area.

Water resources in the study area in 2014 were 163.94 billion m^3, accounting for only 6% of the country's total. Nevertheless, the per capita water resources of Northwest China were only 2,291 m^3, only slightly higher than the national level of 1,999 m^3. The intra-regional discrepancy is comparatively large. The per capita water resources of Qinghai, Xinjiang, and Gansu are 13,676; 3,187; and 767 m^3, ranking them 2nd, 5th, and 22nd in China. Regional differences were also quite large. The total amount of water resources was only 117,000 m^3, whereas, in other areas of China, Nangchen county, Chindu county, and Yushu city each exceeded 7.5 billion m^3. The Tibetan Autonomous Prefecture of Yushu is the source of the three major rivers, the Yangtze River, the Yellow River, and the Lantsang River, and is also the largest prefecture-level administrative division unit in terms of water resource in Northwest China.

The study area stretches across the arid region of Xinjiang province, the semi-arid region of Qinghai–Gansu–Ningxia–Inner Mongolia, and the Alpine region of the Qinghai–Tibet Plateau. The cryosphere services animal husbandry in the alpine region, oasis agriculture, forestry in mountainous areas, and animal husbandry in grasslands. Also, it provides conditions necessary for the growth and expansion of areas where populations are concentrated, such as the urban aggregation on the north slope of Tianshan mountain, the Kashgar and Lhasa urban clusters, and the urban belt along the Yellow River in Ningxia. It also serves as an ecological protective screen for the Qinghai–Tibet Plateau and the Three Rivers Headwaters region.

2.2. Principles

The success of regionalization depends on the underlying principles which provide the basic rules and guidelines for regionalization [26]. We propose the following six principles, which recognize the natural characteristics of the cryosphere and emphasize the occurrence, development and genesis of cryosphere connections, for the regionalization of CWRS [27,28].

2.2.1. Principle of occurrence

The cryosphere is closely linked to human survival. We must understand the cryosphere as a natural ecosystem, determine the current distribution of resources and the factors that influence that distribution, and analyze the causal connections between the cryosphere and socio-economic activities. These requirements reflect the differences in the formation and development of the cryosphere across different regions.

2.2.2. Principle of hierarchy

Regional differences shown in different levels of regionalization must be consistent or logically related, for example, by sequential ordering or by having similar primary and secondary levels. Thus they will form a hierarchy that reflects the territorial differentiation of CSs. As regionalization levels go from high to low, the similarities between regions gradually increase while the differences gradually decrease.

2.2.3. Principle of relative uniformity

At equivalent hierarchical levels of regionalization, the simultaneous intra-regional similarities and inter-regional differences are as large as possible. The regularity and integrity of spatial differentiation in the cryosphere is maintained by choosing the large over the small in recognizing spatial distributions and merging fragmented regions.

2.2.4. Principle of multi-scale integration

Watersheds, administrative divisions and the observation grid are the main scale units. Point elements (e.g., cities), line elements (e.g., rivers), and surface elements (e.g., alpine grassland) are cross-scale units. Multi-scale integration is achieved by creating combinations of different scale units.

2.2.5. Principle of synthesis and dominance

Synthesis consists of all possible primary factors that differentiate the regional CSs and the dominant factors identification for each level of regionalization. This is necessary to maximize the feasibility and rationality of the proposed regionalization.

2.2.6. Principle of combining top-down and bottom-up

A top-down perspective provides a better understanding of general trends, whereas a bottom-up perspective is more suitable for quantitative analysis at a relatively small spatial scale. The combination of top-down and bottom-up perspectives produces a more accurate and realistic delineation and less fragmentation.

2.3. Indicators

Regionalization of CSs consists of three levels: target, factor, and layer indicators. These are shown in Table 1. The target classes are the natural environment, cryosphere resource, and social and economic activity. The factor layer further subdivides these classes. For example, the natural environment includes terrain, climate, soil, and vegetation. The layer level further refines the factor classification. For example, the specific terrain elements are altitude, terrain classification, and land surface relief. In all, 36 quantifiable indicators that constitute the indexing system for the regionalization of CWRS were chosen.

2.4. Data sources

The data for specific indicators are primarily from statistical yearbooks, government bulletins, model calculations, and remotely sensed image interpretation. The data for the natural environment come mainly from the Resource and Environmental Data Cloud Platform of the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences and the National Earth System Science Data Sharing Infrastructure. Terrain data are mainly derived from the digital elevation model (Shuttle Radar Topography Mission 90 m) and the map of landform types in China (1:4,000,000).

Climate data were monthly data obtained directly from meteorological stations (1951–2014). Land coverage data for forests and grass is mainly from the map of vegetation types in China (1:4,000,000). The type, amount, and area distribution data for the cryosphere were derived from the map of snow, ice, and frozen ground in China (1:4,000,000) from the Cold and Arid Region Science Data Center [29] and the map of frozen ground in China (1:10,000,000) [30], the Second Glacier Inventory Dataset of China [31], the long-term snow depth dataset of China (1979–2016) [32], the long-term surface soil freeze/thaw states dataset of China using the dual-indices algorithm (1987–2009) [33]. The reserve, regulation, and runoff of the cryosphere were all calculated by hydrological model equations for glaciers and snow cover [34–37].

Land use data were derived from the Remote Sensing Monitoring Database of Land Use Status (1:100,000). The economic and demographic data were derived from the China County Statistical Yearbook, China Statistical Yearbook for Regional Economies, China's sixth national census in 2010, statistical yearbooks and government bulletins of provinces and cities, and the spatialization of population and GDP based on 1 km × 1 km grids (1995–2015).

2.5. Technical processes

The natural environment has a fundamental influence on CSs. The cryosphere includes glaciers, frozen ground, and snow cover which can profoundly affect socio-economic development, including agriculture, animal husbandry, and population distributions. The most important natural

Table 1
Indexing system for the regionalization of CWRS

Target class	Factor classification	Layer indicator
Natural environment	Terrain	Altitude, terrain classification, land surface relief
	Climate	Aridity, rainfall, accumulated temperatures (≥10°C)
	Soil	Agrotype
	Vegetation	Coverage of forest and grass
Cryosphere resource	Type, amount, distribution	Area and volume of glacier
		Area and depth of snow cover
		Area and active layer thickness of permafrost
	Reserve, regulation, runoff	Glacier water storage, water equivalent of snow cover, amount of ice maintained in permafrost
		Glacier regulation function, snow cover regulation function, frozen ground regulation function
		Proportion of runoff from glacial meltwater, proportion of runoff from snow cover meltwater
Social and economic activity	Land use type	Arable land, woodland, grassland, water area, urban and rural construction land, unused land
	Economy	GDP, economic density, added value of agriculture, added value of animal husbandry, added value of industry, total grain output
	Population	Resident population, urban population, rural population, population density, ice and snow tourism population

features of the cryosphere are resource reserves, its regulatory capacity with respect to other weather and climate variables, and the runoff from glacial and snow cover meltwater, and understanding these is the basis for understanding how the cryosphere affects human society and the supply side of the economy. Human factors, such as urban services, industrial services, and ecosystem services, influence CWRS on the demand side and are the building blocks of regionalization. Thus regionalization is determined by attending to base, supply, and demand, which are discussed in more detail below.

The process of regionalization combines qualitative and quantitative analysis, theoretical and empirical study, static and dynamic analysis, comparative and systematic research, guided by the basic concepts of top-down sequential regionalization and bottom-up stepwise combination. Techniques used include cluster analysis with spatial and attribute constraints, determining the importance index of CSs (Eq. (1)), location entropy modelling, and other spatial identification and regionalization methods. Regionalization also includes making uniform of the multi-scale grids, watersheds and administrative divisions. Three-level regionalization reflects the spatially interactive relationships between cryosphere resources, ecological concerns, and socio-economic factors.

2.5.1. Base

The critical point in first-level regionalization is to ascertain the dominant factors that influence the macro-distribution patterns of cryosphere resources and identify overall differences in the essential features of the water resource. The area and volume of a glacier, the area and depth of snow cover, and the thickness of the active layer of permafrost are core indicators. Natural environmental factors such as terrain, climate, soil and vegetation are auxiliary indicators. The regionalization scale is the primary or secondary watershed, which ensures that altitude, terrain conditions, climate conditions, and dry–wet differences are relatively consistent within the region while intra-regional differences are as large as possible. Cluster analysis with spatial and attribute constraints is used to classify areas with similar attributes and spatial proximity [38].

Cluster analysis considers natural geographical divisions, land surface system regionalization, climate regionalization, ecological regionalization, population geographic regionalization, economic regionalization, comprehensive agricultural regionalization, new urbanization regionalization, and other topics. The results of the cluster analyses are compared, analyzed, and amended to create a reliable regionalization. Following the principle of choosing the large over the small in terms of spatial distribution, and merging excessively fragmented regions to reflect the regularity and unity of spatially differentiated CSs, the regionalization schema is finally adjusted by comparing it with watershed boundaries and county-level administrative divisions [39].

2.5.2. Supply

Second-level regionalization examines the supply side features of cryosphere resources. The regionalization scale is the tertiary watershed, ensuring relative uniformity among the type, reserve, regulation capacity, and runoff percentage within the region and maximum discrepancy among the regions. The regionalization method is based on the importance index of CWRS, which considers the runoff percentage from the glaciers and snow cover, and combines county-level administrative divisions and watershed boundaries to ensure that the boundary of a second-level regionalization does not cross a first-level regionalization boundary. By choosing the large over the small in terms of spatial distribution, we divided the CWRS regions into several sub-regions from top to bottom. The calculation of the importance index I of CWRS is as follows:

$$I = \sum_{n=1}^{3} a_i \times P_i \tag{1}$$

where P_1 is the glacier water storage capacity, snow cover water equivalent, and the amount of ice maintained in permafrost; P_2 is the proportion of runoff from glacier and snow cover meltwater; P_3 is the regulation capacity of the cryosphere water resource; and a_i is a weight. P_2 only takes the glacier and snow cover into consideration because the recharge time and the amount of runoff replenishment for frozen ground are both small. The coefficient a_i is determined by the Delphi method, and it should be ensured that $a_1 + a_2 + a_3 = 1$. Data were normalized to render them more accessible and comparable because of large discrepancies in dimensions.

2.5.3. Demand

Third-level regionalization represents the needs of human society for different kinds of CWRS. Land use, economy, and population are used as the principal indicators. The regionalization scale is the administrative divisions of district and county. Third-level regionalization mainly shows the geographical differentiation between the service elements of the cryosphere, and it ensures that the intra-regional similarities and inter-regional differences between land use, population density, industrial structures, and water utilization are as large as possible. The services are not mutually exclusive; two or more CSs may be required in one area. Thus it is crucially important to ascertain the specific type of service, such as agricultural service, animal husbandry service, industrial service, urban service, tourism service, or ecosystem service. A location entropy model is used to ascertain the major types of CWRS in each county and district in addition to a comparative analysis of indicators such as land use and industrial added value. The regionalization is finally adjusted and checked for conflicts with legal redlines (e.g., ecological conservation redlines, basic farmland redlines and forest protection redlines) and relevant boundaries (administrative divisions of district and county, watershed zones) to ensure that the boundaries of the third-level regionalization do not cross those of the second-level regionalization. The principle of choosing the large over the small in terms of spatial distribution was followed, and the CWRS sub-region is further divided into several CWRS units [40].

There are many regionalization scales because data for the quantitative index system have many metrics. For example, socio-economic data, ecological data, and remote sensing image data are based on administrative divisions of district and county, watersheds, and observational grids. Ensuring a uniform scale for different data is one of the most important and difficult task in regionalization. We used a combination of top-down deduction and bottom-up induction. First- and second-level regionalization divides the study area into different regions and sub-regions by top-down and uses the watershed scale as the unit. Third-level regionalization uses the grid scale of remotely sensed land use data with a spatial resolution of 30 m, which provides accurate boundaries for bottom-up regionalization. In the end, the administrative division of district and county is used as the uniform unit for multi-scale assimilation and a spatial statistical method is used to achieve scale uniformity. This process follows the principle of choosing the large over the small in terms of spatial distribution, and excessively fragmented regions were merged to reflect the regularity and integrity of spatial differentiation in the cryosphere, so that regionalization boundaries fit in with the administrative divisions (Fig. 1).

3. Results

3.1. Regionalization scheme

Top-level regionalization divides the study area into three regions, those that are strongly affected, moderately affected, and weakly affected regions. These divisions represent the controlling effect and potential for development of the total cryosphere resources on the supply side. Second-level regionalization divides each top-level category into three sub-regions, high-supply, medium-supply, and low-supply regions, which reflect differences in the percentage runoff from glacial and snow cover meltwater, essentially the actual water supply capacity of CWRS. Third-level regionalization results in the study area being divided into sixty-three units, which represent the supply-side effects of the cryosphere on the demand side at specific locations. The final regionalization schema is shown in Fig. 2.

The naming of the three levels of regionalization (regions, sub-regions, and units) is an important part of the regionalization of CWRS, because it should indicate the hierarchy and characteristics of the regionalization. The naming should abide the following principles:

It accurately reflects the degree of influence and the main service features of the cryosphere.

- It indicates the geospatial location.
- CWRS should be accurately named and the name should reflect the service.
- The names at the same regionalization level should correspond to each other.
- The names should be concise and easy for readers to assimilate.

The specific names given to the regions, sub-regions, and units can be found in Table 2.

3.2. Case analysis

We use Xinjiang province as an example of regionalization that incorporates elements of the local cryosphere and the spatial distribution of cryosphere resources.

The Tianshan mountains are in the inland arid region of Central Asia and contain one of the largest glaciated areas in China [41]. The area surrounding the Tianshan glacier is strongly influenced by the glacier. The glacier services the northwestern Tianshan mountain agricultural unit, the

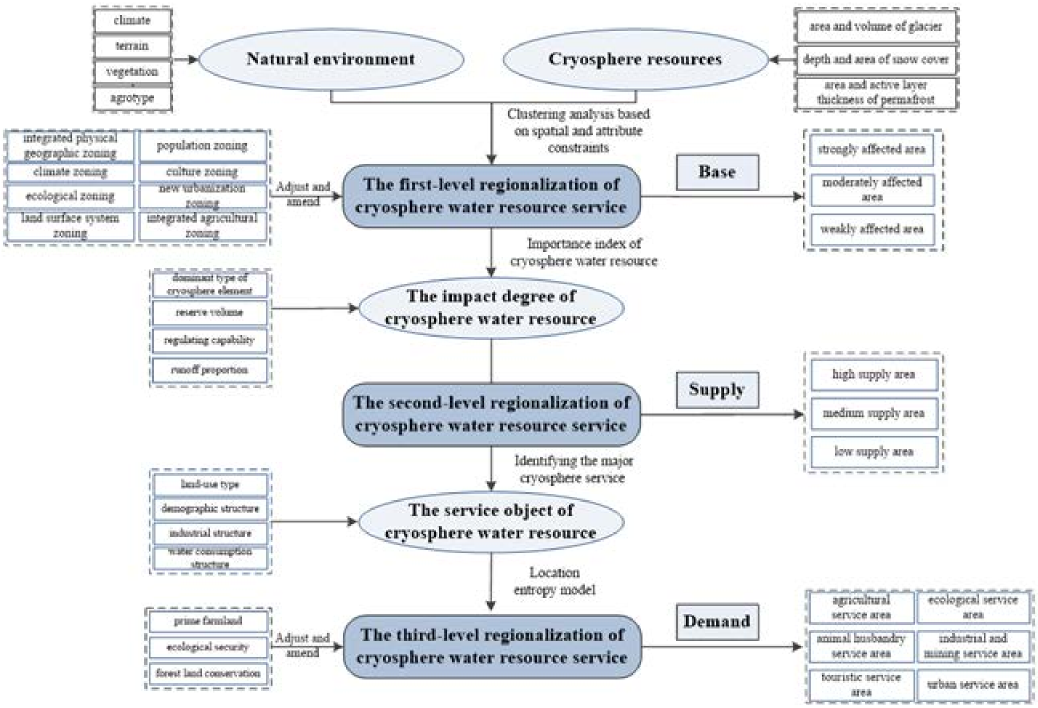

Fig. 1. Regionalization levels.

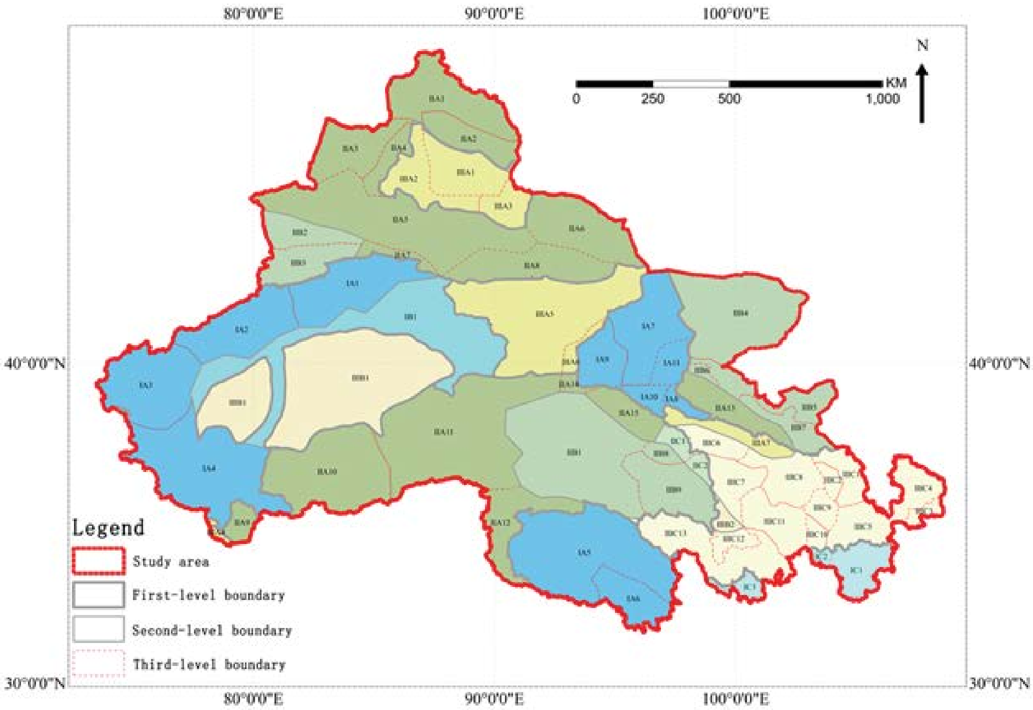

Fig. 2. Regionalization of CWRS.

Table 2
Regionalization naming

I-Strongly affected region	II-Moderately affected region	III-Weakly affected region
IA–High supply sub-region	**IIA-High supply sub-region**	**IIIA-High supply sub-region**
IA1-South of the middle reaches of the Tarim River agricultural and industrial unit	IIA1-Altay Mountain front animal husbandry unit	IIIA1-Northeastern Tianshan Mountain industrial unit
IA2-Lower reaches of Tarim River agricultural and industrial unit	IIA2-Kanas tourism and urban unit	IIIA2-Northeastern slope of Tianshan Mountain urban agglomeration unit
IA3- Kashgar urban cluster unit	IIA3-Emin basin animal husbandry unit	IIIA3-Western Turpan-Hami basin agricultural, industrial and urban unit
IA4-Northwest foot of Kunlun Mountain animal husbandry and ecological unit	IIA4-Northwestern slope of Tianshan Mountain urban agglomeration unit	IIIA4-Northeast foot of Kunlun Mountain ecological unit
IA5-Southern Qinghai animal husbandry unit	IIA5-Northwestern Tianshan Mountain agricultural unit	IIIA5-Northern Turpan-Hami basin ecological unit
IA6-Zadoi animal husbandry and ecological unit	IIA6-Eastern Turpan-Hami basin agricultural, industrial and urban unit	IIIA6-Western Dunhuang tourism unit
IA7-Subei industrial unit	IIA7-North of middle reaches of Tarim River agricultural and industrial unit	IIIA7-Northern slope of Qilian mountain ecological unit
IA8-Northern slope of Qilian mountain animal husbandry and ecological unit	IIA8-Northern Turpan-Hami basin industrial service and ecological unit	**IIIB-Medium supply sub-region**
IA9-Eastern Dunhuang tourism unit	IIA9-Northeast foot of Kunlun Mountain animal husbandry and ecological unit	IIIB1-Taklimakan desert ecological unit
IA10-Subei ecological unit	IIA10-Northeast foot of Kunlun Mountain animal husbandry unit	IIIB2-Eastern Dulan agricultural and industrial unit

(*Continued*)

Table 2 Continued

IA11-Yumen urban unit	IIA11-Ruoqiang river agricultural and ecological unit	**IIIC-Low supply sub-region**
IB–Medium supply sub-region	IIA12-Southwestern Qinghai animal husbandry unit	IIIC1-Southern slope of Qilian mountain animal husbandry and industrial unit
IB1-Taklimakan desert agricultural and ecological unit	IIA13- Northern slope of Qilian mountain animal husbandry unit	IIIC2-Lanzhou-Yongjin urban cluster unit
IC-Low supply sub-region	IIA14-Southern Dunhuang tourism unit	IIIC3-Southern Qingyang agricultural unit
IC1-Longnan agricultural unit	IIA15-Subei industrial service and ecological unit	IIIC4-Northern Qingyang industrial unit
IC2-Southern Tianshui agricultural unit	**IIB-Medium supply sub-region**	IIIC5-Northern Tianshui agricultural unit
IC3-Southern Maqin animal husbandry and ecological unit	IIB1-Da Qaidam urban and industrial unit	IIIC6-Eastern Gangca-Tianjun animal husbandry unit
	IIB2-Northern Ili animal husbandry unit	IIIC7-Eastern Huangshui animal husbandry and industrial unit
	IIB3-Southern Ili animal husbandry unit	IIIC8-Xining urban cluster unit
	IIB4-Ejin Banner industrial service and ecological unit	IIIC9-Southern Lanzhou agricultural and industrial unit
	IIB5-Hexi Corridor agricultural unit	IIIC10-Hezuo animal husbandry unit
	IIB6-Jiuquan-Jiayuguan urban cluster unit	IIIC11-Western Linxia animal husbandry unit
	IIB7-Zhangye-Wuwei urban unit	IIIC12-Maqin industrial and animal husbandry unit
	IIB8-Delingha urban unit	IIIC13-Northern Maqin animal husbandry and ecological unit
	IIB9-Western Dulan agricultural and industrial unit	
	IIC-Low supply sub-region	
	IIC1-Western Gangca-Tianjun animal husbandry unit	
	IIC2-Western Huangshui river basin animal husbandry and industrial unit	

northern middle reaches of the Tarim River agricultural and industrial unit, and the lower reaches of the Tarim River agricultural and industrial unit via the Tarim River basin. Glacial runoff (the replenishment effect) gradually decreases while the influence of snow cover on water resources increases heading north to the Junggar basin. It serves the eastern Turpan-Hami basin agricultural, industrial and urban unit, the Emin basin animal husbandry unit, the northeastern Tianshan mountain industrial unit, and the northeastern slope of Tianshan mountain urban agglomeration unit. The Tianshan glaciers have been affected by climate change and have retreated significantly since 1959 and the reserve loss rate reached 12.16% according to Jin et al. [42]. Increased melting of glaciers and snow cover has resulted in increased river runoff, which is extremely important to long-term sustainable water resource utilization in agriculture, animal husbandry, industry, mining, and urban settlements in the areas around middle and lower reaches of rivers [43–52].

- The Altay mountain front animal husbandry unit is categorized both as a moderately affected and a high supply region. The main source of water replenishment is the snow cover in the Altay mountains, but water replenishment is also affected by snow cover in the southern foot of the Altay mountains. Water distribution is via the Irtysh River and the Ulungur River, which support oasis agriculture, mountain forestry, and animal husbandry and are also features highlighted for ice and snow tourism and lake scenery tourism.
- The northern Ili animal husbandry unit and southern Ili animal husbandry unit are each categorized as both moderately affected and medium supply regions. They are affected by water collection due to terrain and precipitation. Various cryosphere elements are abundant in the Ili valley. Glacial runoff regulates peak flow and replenishment and supports the local grassland and animal husbandry.
- The northeastern Tianshan mountains industrial unit and northeastern slope of Tianshan mountain urban agglomeration unit are each categorized as both weakly affected and high supply regions. The main source of water replenishment, distributed via the Tarim River, is the Tianshan glacier. Here, the cryosphere supports

a growing oasis agriculture, animal husbandry, the Kashgar urban cluster, and the urban belt along the Tarim River (e.g., Hailar, Korla, and Kuqa).

- The northwest foot of the Kunlun Mountain animal husbandry and ecological unit is categorized as both strongly affected and a high supply region. The northeast foot of the Kunlun Mountain ecological unit, the northeast foot of the Kunlun Mountain animal husbandry and ecological unit, and the northeast foot of Kunlun Mountain animal husbandry unit are each categorized as both moderately affected and high supply regions. These units are replenished by meltwater from the glacier at the northern foot of the Kunlun Mountains. The water resources are distributed via the Hotan River and many other small rivers which support oasis agriculture and the growing urban belt along the northern edge of the Kunlun Mountains.
- The Taklimakan desert agricultural and ecological unit is categorized as a strongly affected and medium supply region, and the Taklimakan desert ecological unit is categorized as a weakly affected and medium supply region. Water is distributed through the Hotan River and through groundwater and supports agriculture and ecological maintenance in a sensitive area.
- The western Turpan-Hami basin agricultural, industrial, and urban unit and the northern Turpan-Hami basin ecological unit are each categorized as weakly affected and high supply regions. The eastern Turpan-Hami basin agricultural, industrial, and urban unit is categorized as a moderately affected and high supply region. The main source of replenishment water is the Tianshan mountains glacier, which is distributed via the Karez, a subterranean water distribution system, and small watersheds. As a consequence, the cryosphere services oasis agriculture, tourism, industry, and mining and makes possible the creation of important urbanization axes such as the Turpan-Hami urban cluster.

4. Conclusion and discussion

4.1. Conclusion

Using the framework of base–supply–demand, we constructed a quantitative regionalization system for natural and human-driven use of CSs based on natural geographic features and human-constructed land boundaries. The system considers the types, quantities, and spatial distribution of different cryosphere resources, the differences in water reserves, regulation capacity, run off from glacial and snow cover meltwater, and spatial differences in water resource usage and socio-economic development.

Within a framework of top-down and bottom-up inferential processes, we used cluster analysis of spatial and attribute constraints, developed an importance index of cryosphere resources, used a location entropy model, and devised a uniform scale for grid, watershed, and administrative divisions to create a regionalization schema for CSs in a study area in Northwest China. Regionalization enabled us to divide the study area spatially into relatively independent and complete units at different hierarchical levels. First tier (base) regionalization consists of three regions, according to the degree of CS consumption. Second-level (supply) regionalization divides each first level region into three sub-regions, depending on the use of available cryosphere resources. Third-level (demand) regionalization consists of 63 units, determined by natural and human-determined use of different CSs, which emphasize the intra-regional similarities and inter-regional differences.

The regionalization of CSs is an important part of cryospheric science. It is also an interdisciplinary activity that combines physical geography, human geography, ecology and other disciplines to meet the practical needs of the Belt and Road Initiative, preparation for the Winter Olympics, and sustainable ecological development. Regionalization also benefits the country in helping to meet China's major strategic needs. It meets the scientific goal of increasing our knowledge of the cryosphere by filling the gaps in research related to regionalization and strengthening our scientific understanding of the spatial differentiation, complex diversity and characteristics of CSs, which are becoming increasingly important. Overall, regionalization is the best way to rationally use CSs without risk.

4.2. Discussion

4.2.1. About scenarios

Regionalization of CSs must be flexible enough to adapt to various kinds of changes because of the growing fluidity of socio-economic factors and the increasingly severe impacts of climate changes. These factors make it more difficult to characterize the dynamic changes in CSs by giving an average over a specific time period. Combining the steady state and the dynamic change to reflect the varying characteristics of the many factors in a region over time by incorporating leading factors or weighting the factors in regionalization will dynamically adjust the overall effect of factors according to the objective requirements. This would combine the effects of human activity and natural events in multi-scenario and dynamic regionalization.

A climate change scenario can be created by using five sets of representative concentration pathways that are spatially downscaled and offset-corrected which can be obtained from the Inter-Sectoral Impact Model Intercomparison Project. These five global climate models are all derived from the Coupled Model Inter-comparison Project Phase 5. Combined with quantitative data for items such as population, GDP, technology productivity, income growth rate, and other socio-economic indicators, such as income distribution, under the Shared Socioeconomic Pathways, changes in CSs and the response of the climate system to different temperature thresholds of 1.5°C or 2°C can be investigated. Thus the construction of a dynamic monitoring system for the comprehensive regionalization of CSs with bidirectional spatio-temporal dimensions and goal-oriented functions, and the development of software to permit dynamic identification and simulation for regionalization, are urgent tasks. By graphically displaying regional characteristics and status under different scenarios, it is possible to provide decision support for economic adjustments, industrial development pathways, and environmental sustainability measures.

4.2.2. About applicability

Comprehensive analysis and adaptive countermeasures based on the scenario of maximum cryosphere service utilization can achieve the goal of trans-regional water drainage on a watershed scale and guide the optimization of water utilization in an administrative division. These goals are beneficial to a rational distribution of urban population in cold and arid regions, as they improve the transition of water utilization patterns and improve water-use efficiency. This would make regionalization transcend mere lines on a map to become closely integrated with China's regional strategies and result in better predictions and guidance for future decisions and actions

Close attention should be paid to the impacts on local socio-economic conditions resulting from changes in the use of CSs. Scarcity and efficiency demand that the problem areas are delineated on the bases of regionalization. The study area can equally well be divided into resource-scarce zones, equilibrium zones and resource-abundant zones, or enhancement zones, declining zones and relatively stable zones. Thus the targeted recommendations and countermeasures for structuring efficient water resource utilization for different problem orientations are an important policy export for regionalization. As the theory and practice of regionalization mature, the practice will spawn more derivative applications and play more of a guiding role in predicting potential regional development, adjusting the layout of industries, selecting public services, and allocating regional materials and resources.

4.2.3. About interlinkage

Regionalization of CWRS is a preliminary attempt at the comprehensive regionalization of CSs. The ultimate goal is to reveal the causal relationships between cryosphere activity and provisioning services, regulation services, social and cultural services, and habitat services determined by the characteristics of the various cryosphere components. If systematic means of evaluating the values attached to CSs can be established, it would benefit decision-makers and the public by raising their awareness of the importance of environmental protection. The major CSs have been identified as provisioning services, regulation services, social and cultural services, and habitat and engineering services. A comprehensive regionalization of CSs ultimately serves national and local development strategy decision-makers and can have profound practical significance as well as avoiding environmental degradation by the pursuit of short-term economic profits and rapid economic development.

Acknowledgement

This research is supported by National Natural Science Foundation of China (41690145); and, the GDAS' Project of Science and Technology Development (2016GDASRC-0101, 2017GDASCX-0101).

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