



Distribution of carbonate rocks and variation analysis of karst water resources in China

Wenjie Sun^{1,2,3} · Jianxin Song^{4,5} · Wenkai Yang¹ · Yuejun Zheng⁵ · Chunyan Li⁵ · Da Kuang¹

Accepted: 12 October 2020 / Published online: 27 October 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract

Carbonate strata are widely distributed in China, which can be found in more than 30 provinces and cities, covering about 1/3 of the country's territorial area. Affected by different geological and climatic conditions, carbonate strata in China geographically present different karst landscapes and groundwater resources. Specifically, northern China is dominated by large karst springs, while southern China is characterized by underground rivers. By determining the distribution range of carbonate strata in China, this paper pointed out the locations of large karst springs in the north and underground rivers in the south, analyzed the distribution characteristics of carbonate rocks in the north and south, the degree of karst development as well as their geological and climate genesis, and discussed the differences between karsts in northern and southern China in terms of occurrence forms of karst water and groundwater systems.

Keywords Carbonate rocks · Karst water resources · Karst water system · Large karst springs · Underground rivers

Introduction

China has a wide distribution of carbonate strata and is one of the countries with the most karst development types in the world. In recent years, many scholars have carried out a lot of research on karst problems in China, and have achieved

fruitful research results. Lu et al. expounded some hydrogeological and engineering geological conditions of karst development in China, as well as karst water resources and their eco-hydrological characteristics in typical areas, and studied the exploitation, utilization and protection of karst groundwater resources in southwestern China (Lu et al. 1973, 2006; Lu 2011). Liang et al. studied the division and characteristics of karst water systems in Northern China, and summarized environmental problems of karst water in the north (Liang and Wang 2010; Liang et al. 2013). He et al. comparatively analyzed the differences in the types, development characteristics, scale, intensity and formation mechanisms of karst collapse in the south and north of China (He et al. 2017). Karst is widely distributed in China, which is closely related to the safe mining of mineral resources, exploitation, utilization and protection of groundwater resources and people's daily life (Guo 2011; Wu et al. 2014; Zhu et al. 2019; Sun et al. 2015). On the basis of previous studies, we once again investigated and researched distribution characteristics of karst and karst water resources in China. Through the long-term field research, the article determined the distribution range of carbonate strata in China, pointed out the locations of large karst springs in the north and underground rivers in the south, and elaborated the degree of karst development in China, in order to provide data support and theoretical

Wenjie Sun and Jianxin Song contributed equally to this work.

✉ Wenjie Sun
swj@cumb.edu.cn

✉ Jianxin Song
songjx@mail.cigem.gov.cn

- ¹ National Engineering Research Center of Coal Mine Water Hazard Controlling, China University of Mining and Technology (Beijing), Beijing 100083, China
- ² State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330013, Jiangxi, China
- ³ Fundamental Science on Radioactive Geology and Exploration Technology Laboratory, East China Institute of Technology, Nanchang 330013, Jiangxi, China
- ⁴ College of Water Sciences, Beijing Normal University, Beijing 100875, China
- ⁵ Groundwater Investigation and Monitoring Laboratory, China Institute of Geo-Environment Monitoring, Beijing 100081, China

guidance for the safe mining of mineral resources and the exploitation and utilization of karst water resources.

The distribution of carbonate rocks in China

The distribution characteristics of carbonate rocks in China

Carbonate rocks in China, according to their development patterns and characteristics, are divided into two parts, the south and the north, along the Qinling Mountain-Huaihe River line. The south is dominated by exposed and shallow-covered type, and underground rivers are mainly developed. The north, however, mostly belong to buried and covered type, and large karst springs are primarily developed. Carbonate rocks in the south are centered around the Yunnan-Guizhou Plateau, which is the karst area with the largest continuous distribution area of carbonate rocks in the world, with an area of about $78 \times 10^4 \text{ km}^2$. The distribution of carbonate rocks in the main provinces in Southern China is shown in Fig. 1 (Institute of Karst Geology, Chinese Academy of Geoscience 2016a Phased results report of Comprehensive study and information system construction of hydrogeology environment geology in southwest karst area; Xia 2018). As one of the occurrence forms of groundwater, karst underground rivers in the south are important water supplies, particularly because of their abundant resources, clean water quality and steady water flow. According to the latest statistics, there are more than 3000 underground rivers in the southern karst regions, with a total flow of more than $473.04 \times 10^8 \text{ m}^3/\text{a}$ (Yuan et al. 2007). Moreover, the storage space there is huge and the underground river resources are rich, which means they can also be used as natural reservoirs. The carbonate rocks in Northern China stretch over an area of about $68.5 \times 10^4 \text{ km}^2$, with 218 large karst springs

(Liang et al. 2013). Figure 2 shows the distribution of carbonate rocks of major provinces in Northern China (Institute of Karst Geology, Chinese Academy of Geoscience 2014; Liang 2013; Liang et al. 2013). Those highly concentrated and dynamically stable large karst springs with good water quality are the significant water supplies for Northern China, sustaining the local socio-economic development, people's livelihood security and energy base construction.

Geological and climatic factors of carbonate rocks in China

Taking the Qinling Mountain-Huaihe River line as the boundary, geological and climatic conditions in the south are different from those in the north, and thus leading to the differences in the distribution and characteristics of carbonate rocks in the south and north of China.

The southern karsts are mainly located in Yangtze platform, and locally distributed in South China Para-platform. Since the Mesozoic Era, the two tectonic units have been evidently reactivated—the crustal activity is large and the compressional folds and fractures are strongly developed, among which the deformation folds are the most common. Finally, many anticlines, synclines, arches and bundle fold structures have been formed (Yuan et al. 1994; Professional Committee of Karst Geology of Geological Society of China 1982; Li et al. 2013; Han et al. 2016; Peng et al. 2018). Carbonate rocks were mainly born in the two sedimentary periods of Late Sinian-Ordovician and Middle Devonian-Middle Triassic. The sedimentary strata are characterized by interbedding of limestones and clastic rocks and large deposition thickness. Generally, the thickness is above 1500 m and most often is between 2000 and 3000 m. Karsts in Northern China are located mainly in North China Platform, and the block-faulting tectonics and synclines are developed. Furthermore, the strata are gentle, but with large fractures. The landscapes

Fig. 1 Distribution of carbonate rocks of major southern provinces in China

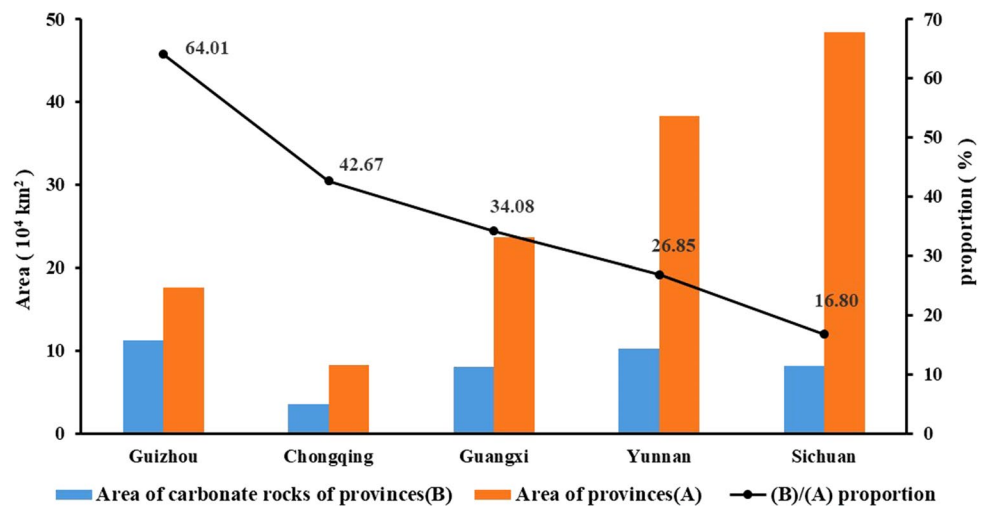
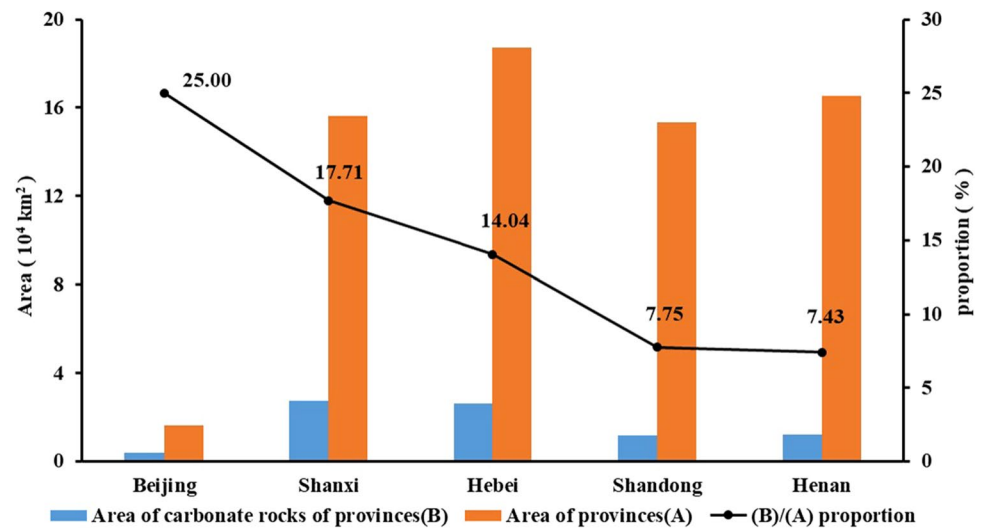


Fig. 2 Distribution of carbonate rocks of major northern provinces in China



assume a unitary appearance of overall uplift of parcels or settling basins (Lu et al. 1973; He and Zou 1996; Chen et al. 2010, 2011; Yang et al. 2017a, b; van Loon et al. 2013; Ni et al. 2011). The relatively stable sedimentary environment has particularly led to thick marine argillaceous limestones, dolomitic limestones and pure limestones deposited continuously in Cambrian–Ordovician. Among all the soluble rocks, those from the Meso-Neoproterozoic and the Paleozoic are the majority.

The south enjoys a subtropical climate, with hot weather and an annual rainfall of more than 1000 mm. Therefore, karsts in Southern China show a large development degree and scale. They also have diverse forms, including hoodoo plains, sword-shaped stone forests, sinkholes, dolines, series of peaks, karst canyons, stony sprouts and stalagmites, curtains and stalagmites, and karst windows and stalactites. Meanwhile, the underground river systems are particularly well developed, mainly pipelines or channel systems, closely connected with surface water, with great flood and low flow variations. While Northern China lies in temperate zones with an annual rainfall of less than 800 mm. Therefore, karsts in the north are relatively low in development degree and scale. The dominant development forms are normal karst mountains, normal karst hills, karst microtopography (such as solution fissures, karst caves, pores, and solution pores), and karst dry valleys, and karst springs are the most common. Besides, there are basically no typical karst landforms in Southern China karst regions such as peak clusters, hoodoos, and stone forests. Underground rivers are rare in the north, but the karstic collapse columns are unique in this region. Surface karst is confluent with underground solution fissures or vein systems, finally merges into a water-rich karst region. In addition, the discharge areas are mostly confined springs. Their catchment areas are large while the flood and low flow vary slightly.

The differences between the karsts in northern and southern China

Occurrence differences of karst water resources

The total amount of karst water resources in Northern China is 128×10^8 m³/a, which only accounts for about 6.3% of the national karst water resources, and currently about 70–80% of them have been exploited and utilized (Yuan et al. 1994; Professional Committee of Karst Geology of Geological Society of China 1982; Lu et al. 2006). The resources are mainly distributed in North-China Platform, particularly in the region to the east of Helan-Liupan Mountain, south of Yinshan Mountain and Shenyang province, north of Huaihe River, and west of Yellow sea-Tanlu fault, covering the administrative provinces such as Shanxi, Henan, Hebei, Shandong, Tianjin and Beijing. As shown in Fig. 3, the average annual precipitation of these areas ranges between 200 and 600 mm/a, and in the southern part of Xinjiang Province, it is less than 100 mm/a—the typical rainfall amount in arid and semi-arid climate. However, hundreds of karst water systems still remain in the north (see Table 1) (Institute of Karst Geology, Chinese Academy of Geoscience 2013, 2014). According to statistics, there are 6 karst water systems with an area larger than 5000 km², 44 with an area ranging from 1000 to 5000 km², and 69 with an area of less than 1000 km² (Liang and Wang 2010). The annual flow rate is 1–13 m³/s (Lu et al. 2006). According to the field investigation of 67 karst springs in North China (see Fig. 4), there are 35 karst springs whose spring flow (Q) is below 0.5 m³/s, which are mainly distributed in the areas such as Inner Mongolia, Beijing, Shanxi, Shandong and Henan. And Yikeer Shuangquan has the smallest flow whose spring flow is only 0.014 m³/s. There are 23 karst springs with spring flow (Q) between 0.5 and 5 m³/s, mainly distributed

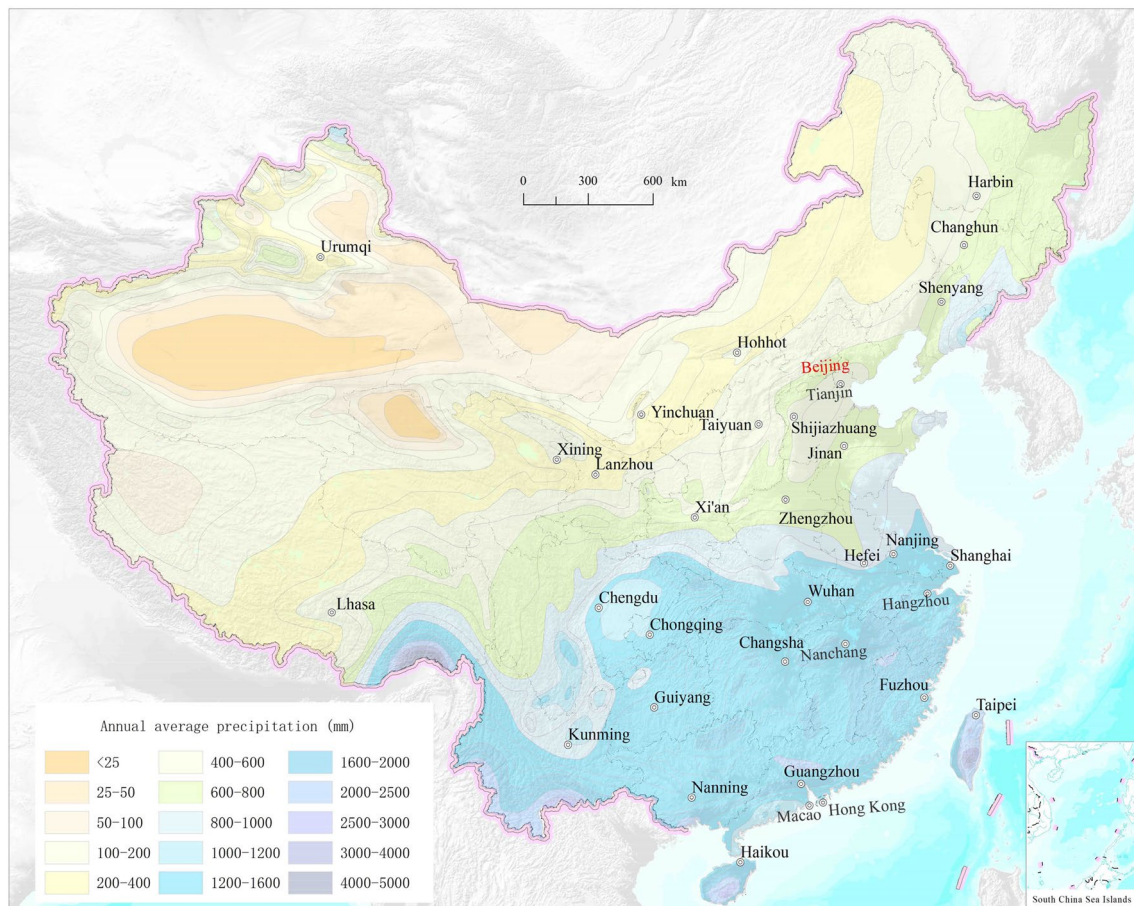


Fig. 3 The annual average precipitation of China (1981–2017)

Table 1 Statistics of large karst springs in northern Chinese provinces

Regions	Large karst springs number	Flowing quantity in dry season ($\times 10^8 \text{ m}^3/\text{a}$)
Shanxi	89	33.87
Shandong	41	3.37
Henan	20	8.62
Beijing	11	0.69
Hebei	13	11.55

in Shanxi, Shandong and Shaanxi. For the spring flow (Q) is greater than or equal to $5 \text{ m}^3/\text{s}$, there are 9 karst springs, mainly distributed in Shanxi, Henan and Hebei. The spring flow of Niangziguan spring in Shanxi is up to $12.6 \text{ m}^3/\text{s}$.

The total amount of karst water resources in southern China is as high as $1847 \times 10^8 \text{ m}^3/\text{a}$, about 91% of the nation's total volume. However, only 8–15% are exploited at present, which shows great mining potential (Yuan et al. 1994; Professional Committee of Karst Geology of Geological Society of China 1982; Lu et al. 2006). The carbonate

rocks are mainly distributed in provinces of Guangxi, Yunnan, Guizhou, Sichuan, Chongqing, Hunan and Hubei, taking up 41.31% of the whole karst area in Southern China. The climate there, with an average temperature of $16\text{--}22 \text{ }^\circ\text{C}$ and an annual rainfall of about $1200\text{--}2000 \text{ mm}$ (see Fig. 3), is conducive to the development of karst. Compared with the north, the southern karst water system is smaller in size, mostly between tens and hundreds of square kilometers and only a few more than 1000 km^2 . Among the mainstreams of the underground rivers, up to 92.88% are less than 10 km long, while only 0.44% are longer than 40 km (Yuan et al. 1994). According to statistics, as of 2016, there are about 106–711 underground rivers in major southern provinces, whose flowing quantity in dry seasons reaches 22.42×10^8 to $91.69 \times 10^8 \text{ m}^3/\text{a}$ (see Table 2 and Fig. 5) (Institute of Karst Geology, Chinese Academy of Geoscience 2016b Phased results report of Comprehensive study and information system construction of hydrogeology environment geology in southwest karst area; 2016 Report on the compilation of karst geological Series Map in China and Southeast Asia; Pu 2013). After the field survey of 94 southern underground rivers (see Fig. 5), there are 46 underground rivers whose

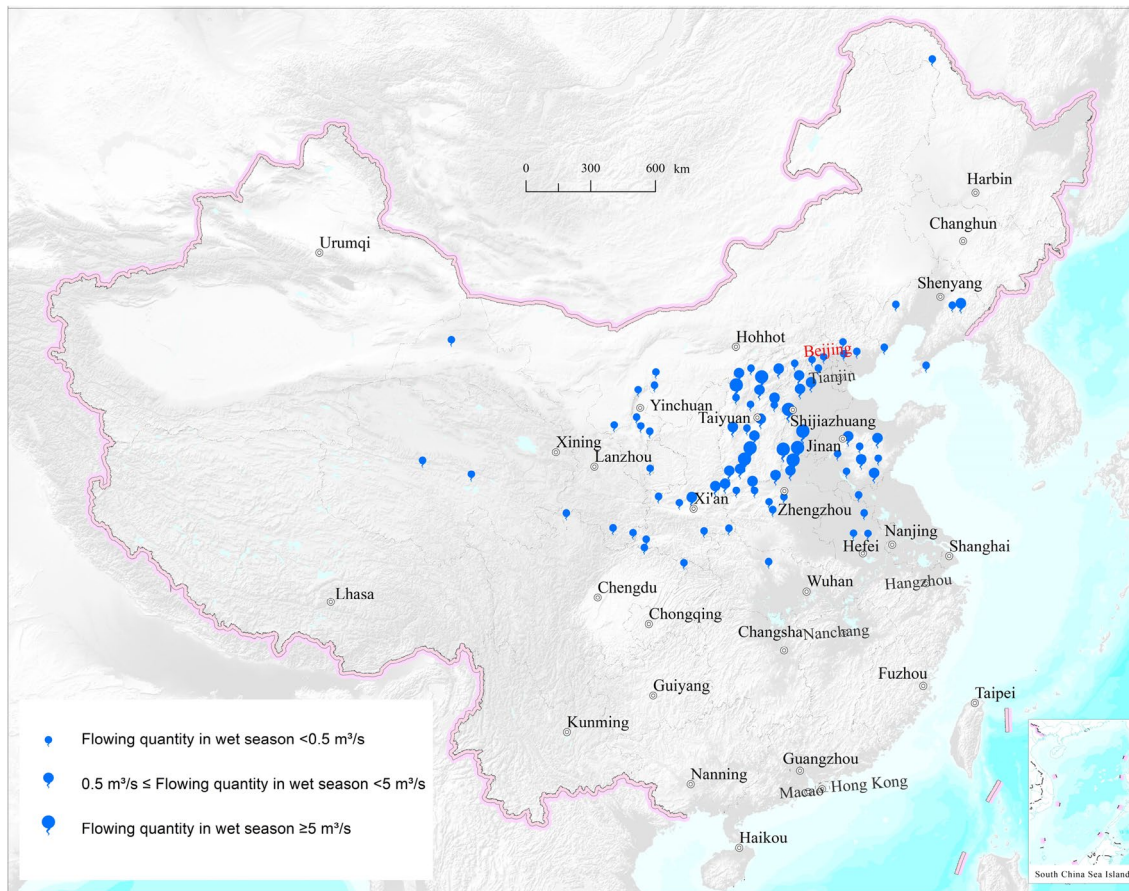


Fig. 4 The map of large karst springs in Northern China

spring flow (Q) is below $0.5 \text{ m}^3/\text{s}$, which are mainly distributed in Guangxi, Guizhou, Yunnan, Chongqing and Sichuan. Fuda underground river in Guangxi has the smallest flow with $0.13 \text{ m}^3/\text{s}$. There are 37 underground rivers with spring flow (Q) between 0.5 and $5 \text{ m}^3/\text{s}$, mainly distributed in the areas such as Guangxi, Guizhou, Sichuan, Yunnan. For the spring flow (Q) greater than or equal to $5 \text{ m}^3/\text{s}$, there are 11 underground rivers, mainly distributed in Yunnan, Guangxi and Guizhou. Baishiyan underground river in Yunnan has the largest spring flow, up to $34.52 \text{ m}^3/\text{s}$.

Differences in groundwater systems

Influenced by geological conditions and climate, China's karst groundwater system can be divided into the north part and the south part, with Qinling Mountain–Huaihe River line as the boundary. The northern system is the humid and sub-humid, subtropical-temperate, arid and semi-arid temperate karst groundwater system, and the southern one is a wet tropical and subtropical karst groundwater system. The two karst water systems have obvious differences in hydrogeological conditions, which are mainly manifested

in hydrogeological units and structures, buried types, water-bearing medium, types of karst underground water, the way of recharge, runoff and discharge and hydrochemical characteristics (Liang et al. 2013; Liang and Wang 2010; Lu et al. 2018; Xie et al. 1983).

Controlled by regional block-faulting tectonic, the scale and area of karst hydrogeological units in northern China are relatively large, ranging from tens to hundreds or even thousands of square kilometers. The karst areas have the structural characteristics of “the coexistence of water and coal with the former lying under the later”. The carbonate rocks in this structure are mainly buried and covered, and the aquifer is thick with a unified water-bearing medium, which can be classified as a large karst fissure network medium system. Karst groundwater is mainly water-bearing type of solution crack, which is mainly controlled by bedding fissure. Therefore, most of the northern karst areas are developed into solution crack, and some are karst conduit, and the zone where karst strata are strongly developed lies in Northern Xinjiang, Beijing, Tianjin, Shanxi and Hebei (see Fig. 6) (Institute of Karst Geology, Chinese Academy of Geoscience 2014; Liang et al. 2013; Xia 2018). Primarily

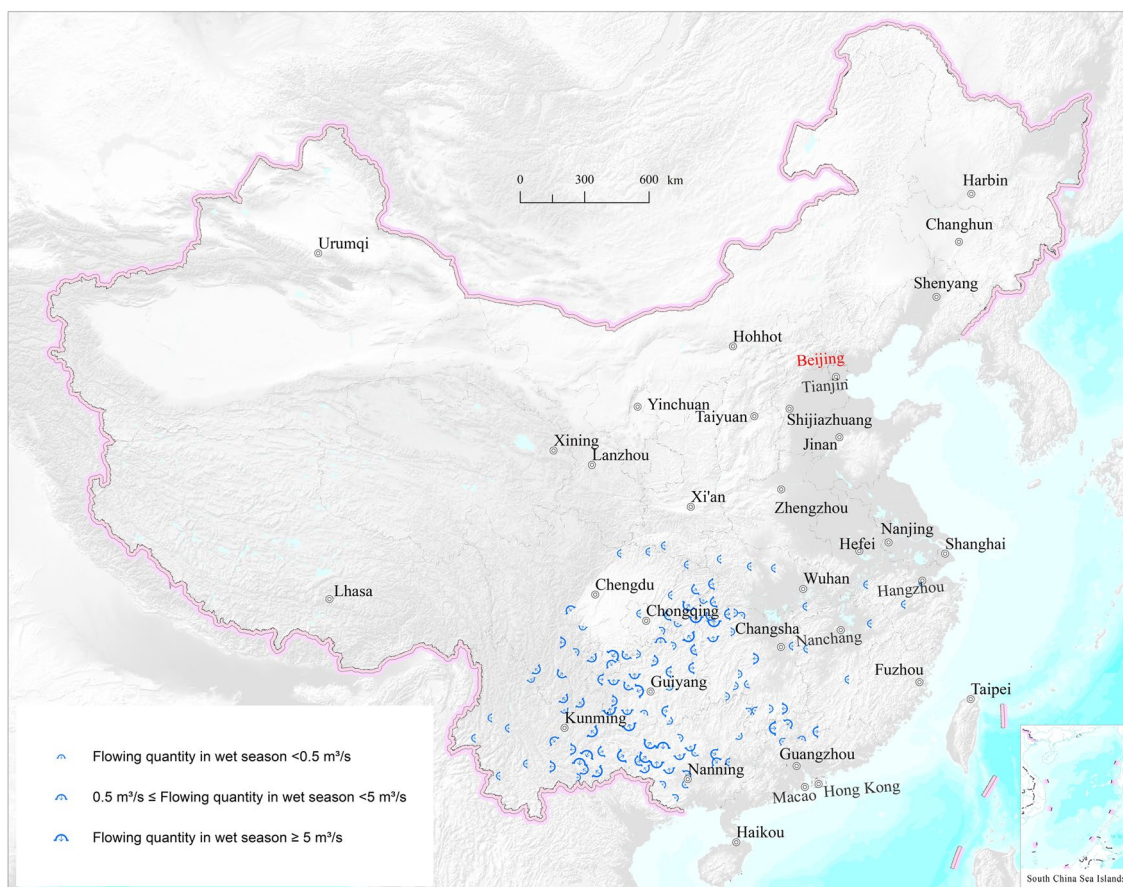


Fig. 5 Map of underground rivers in Southern China

Table 2 Statistics of underground rivers in southern China major provinces

Regions	Ground river number	Flowing quantity in dry season ($\times 10^8 \text{ m}^3/\text{a}$)
Yunnan	258	64.82
Guizhou	482	81.25
Guangxi	711	91.69
Sichuan	106	30.35
Chongqing	121	22.42

recharged by lateral runoff and supplemented with leakage recharge, the buried and covered karst water in the north barely receives water from atmospheric precipitation. Atmospheric rainfall needs to flow through hundred- or even thousand-meter-thick overburdens, which is a piston recharge that runs from top to bottom. The distance from the recharge area to the discharge area is generally long and the depths and hydraulic gradients of the groundwater often gradually decline, reducing the corrosion and carrying capacity of groundwater. Therefore, the dynamic effect of

groundwater is relatively weak. However, in the discharge area, the water is rich, excreting in the form of large karst springs or cluster of springs. The karst water in northern China belongs to fresh water of $\text{HCO}_3\text{-SO}_4\text{-Ca}$ type with a salinity of less than 1 g/L, high hardness and alkaline pH.

Determined by stratum folds, the karst hydrogeological units in southern China are relatively small in scale and area, varying from a few to hundreds of square kilometers. The commonly seen structure is “water locating under soil”, suggesting that the karst is not developed deep in the strata, and the carbonate rocks are most often exposed and shallowly covered. The aquifer with various water-bearing mediums is relatively thin, compared with that of the north, which makes the water dynamics strong. The groundwater, composed of the gap-pipe type and the fracture-dissolution type, forms a complex karst aqueous medium system. Therefore, the karst area mainly developed karst conduit and underground rivers and in Guangxi, Guizhou, Yunnan, Sichuan, Chongqing and Xizang, karst has developed the strongest (see Fig. 6). The southern exposed karst water is primarily recharged by atmospheric precipitation and replenished rapidly through channels such as dolines, sinkholes and funnels. The water

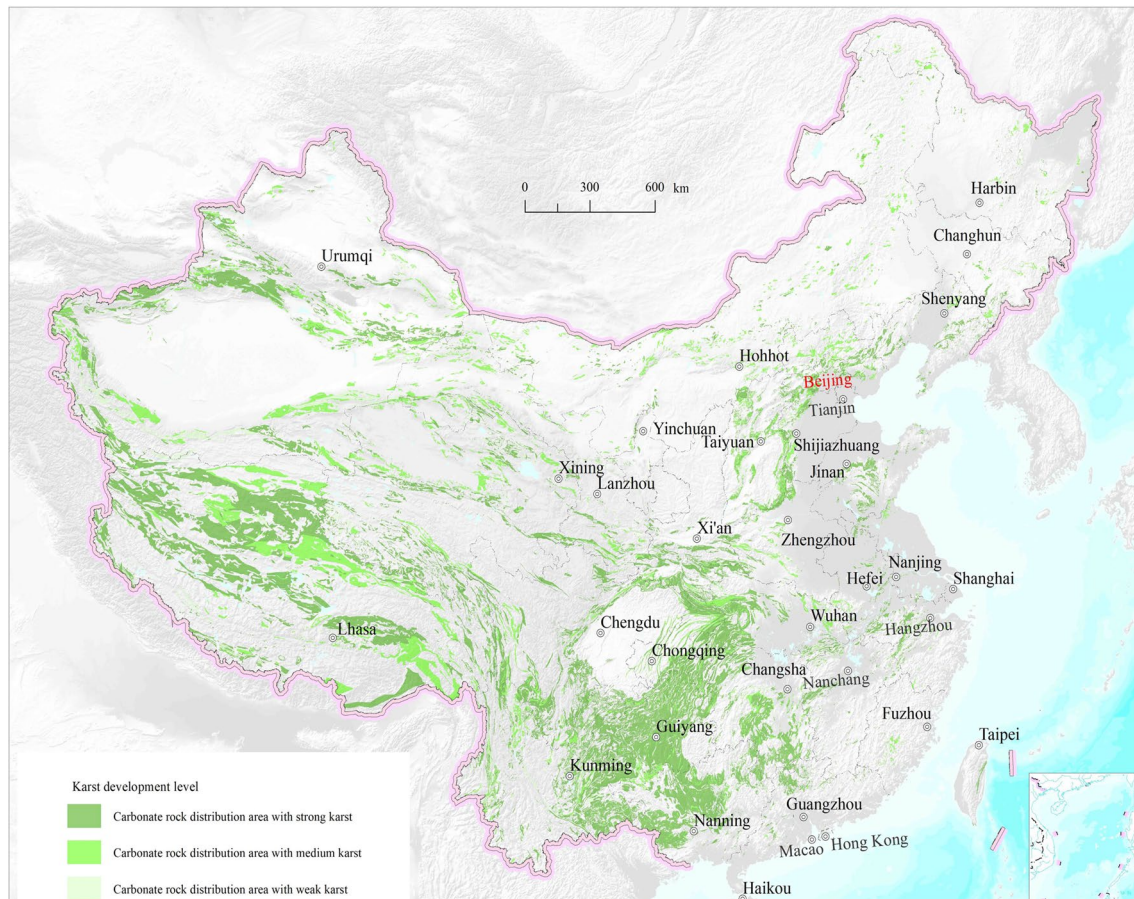


Fig. 6 Map of karst development level in China

travels a short distance from the recharge zone to the discharge zone with large hydraulic gradient, contributing to great flow rate and fast velocity. The water has the characteristics of rapid dynamic change and smooth flow with little blocks in the runoff. Compared with that of the north, the southern karst water has relatively stronger dissolution and handling capacity. It is often discharged by underground rivers and generally belongs to fresh water of $\text{HCO}_3\text{-Ca}$ and $\text{HCO}_3\text{-Ca}\cdot\text{Mg}$ types. The water temperature and dissolved total solids vary significantly with the shifts of seasons, but the average salinity is lower than that in the north, generally under 0.2 g/L to be exact, and its pH is neutral.

Conclusions

- (1) By the boundary of Qinling Mountains and Huaihe River, carbonate strata in China are divided into the northern and southern karst. Affected by different geological and climatic conditions they are distinct in terms of occurrence forms of karst water and systems of groundwater.
- (2) In the south, extrusion folds and fractures are strongly developed, especially deformation folds. Limestones contain some clastic rocks. Besides, karst development forms are complex and various, and underground rivers are particularly well developed. The northern strata and folds are gentle, and block-faulting tectonics are primary. Pure limestones take up most of the sedimentary strata and the forms of karst are relatively few. At the same time, large karst springs in the north appears most often, and karstic collapse columns are unique in this region.
- (3) The north and south karst groundwater systems differ in their hydrogeological units and structures, buried types, bearing mediums, groundwater types, recharge runoff and discharge methods and hydrochemical characteristics. The karst hydrogeological units in southern China are relatively smaller in scale and area, and the carbonate rocks are most often exposed and shallowly covered, forming a karst structure of “water locating beneath the soil”. The water-bearing medium system is complex. Groundwater is mainly fissure-conduit type and fracture-dissolution type, recharged by atmos-

pheric precipitation, with strong water dynamic. The karst water's quality is generally the $\text{HCO}_3\text{-Ca}$ and $\text{HCO}_3\text{-Ca-Mg}$ types. The scale and area of karst hydrogeological units in north China are relatively large. The carbonate rocks are mainly buried and covered with a structure of "the coexistence of water and coal with the former lying under the later". The water-bearing medium system is unified. Karst groundwater is primarily water-bearing type of solution crack, and mainly recharged by lateral runoff. Its dynamic effect is weaker and water quality can be classified into $\text{HCO}_3\text{-SO}_4\text{-Ca}$ types.

- (4) China is rich in karst water resources, $128 \times 10^8 \text{ m}^3/\text{a}$ in total in the north and $1847 \times 10^8 \text{ m}^3/\text{a}$ in the south. However, the exploitation rate in the two regions is contradictory to their amount—only 8–15% karst water in the south is utilized while 70–80% of that in the north has been exploited. For this reason, more underground water reservoirs should be constructed in the south, and the exploitation of the large karst systems in the north should be restricted.

Acknowledgements We gratefully acknowledge financial support provided by the: National Key R&D Program of China (2017YFC0804104), Fundamental Science of State Key Laboratory of Nuclear Resources and Environment, East China University of Technology (NRE1906), Fundamental Science on Radioactive Geology and Exploration Technology Laboratory, East China Institute of Technology (RGET1902), Program of the Geological Survey of China (DD 20160299).

References

- Chen J, Han HZ, Zhang F, Fan H, Fan A, Yang R (2010) Early diagenetic deformation structures of the Furongian ribbon rocks in Shandong Province of China—a new perspective of the genesis of limestone conglomerates. *Sci China Earth Sci* 53:241–252
- Chen J, Chough SH, Lee J (2011) An extensive erosion surface of a strongly deformed limestone bed in the Gushan and Chaomidian formations (late Middle Cambrian to Furongian), Shandong Province, China: sequence-stratigraphic implications. *Sediment Geol* 233:129–149
- Guo F (2011) Carbonate sedimentology. Petroleum Industry Press, Beijing ((in Chinese))
- Han C, Li B, Zai C, Wu M, Lin W (2016) The lithofacies and reservoir characteristics of the Upper Ordovician and Lower Silurian black shale in the Southern Sichuan Basin and its periphery, China. *Mar Pet Geol* 75:181–191
- He YB, Zou CJ (1996) Comparison between Southern and Northern karst water characteristics in China. *Carsol Sin* 03:54–63 ((in Chinese))
- He KQ, Wang B, Guo L, Du RL (2017) Comparative study on karst collapse in Northern and Southern China. *J Hebei GEO Univ* 40(01):57–64 ((in Chinese))
- Institute of Karst Geology, Chinese Academy of Geosciences (2013) Survey results report of karst carbon sink in typical areas of China ((in Chinese))
- Institute of Karst Geology, Chinese Academy of Geosciences (2014) The demonstration report of hydrogeological environmental geology investigation in the karst area of North China ((in Chinese))
- Institute of Karst Geology, Chinese Academy of Geosciences (2016a) Phased results report of comprehensive study and information system construction of hydrogeology environment geology in southwest karst area ((in Chinese))
- Institute of Karst Geology, Chinese Academy of Geosciences (2016b) Report on the compilation of karst geological series map in China and Southeast Asia ((in Chinese))
- Li W, Dong Y, Guo A, Liu X, Zhou D (2013) Chronology and tectonic significance of Cenozoic faults in the Liupanshan Arcuate Tectonic Belt at the northeastern margin of the Qinghai–Tibet Plateau. *J Asian Earth Sci* 73:103–113
- Liang YP (2013) The problems of karst groundwater environment and its protection in North China. Geological Publishing House, Beijing ((in Chinese))
- Liang YP, Wang WT (2010) The division and characteristics of karst water systems in northern China. *Acta Geosci Sin* 31(06):860–868 ((in Chinese))
- Liang YP, Wang WT, Zhao CH, Wang W, Tang CL (2013) Variation of karst water and environmental problems in North China. *Carsol Sin* 32(01):34–42 ((in Chinese))
- Lu YR (2011) Exploitation and protection of karst groundwater resources in Southwest China. In: Karst and environmental geoscience—selected papers of Academician Lu Yaoru's 80th Birthday, pp 236–241 ((in Chinese))
- Lu YR, Jie XY, Zhang SL, Zhao CL, Liu FC (1973) The law of karst development and some hydrogeological and geological conditions in China. *Acta Geol Sin* 1:121–136 ((in Chinese))
- Lu YR, Zhang FE, Liu CL, Tong GB, Zhang Y (2006) Karst water resources in typical areas of China and their eco-hydrological characteristics. *Acta Geosci Sin* 27(5):393–402 ((in Chinese))
- Lu HP, Zhang FW, Zhao CH, Xia RY, Liang YP, Chen HF (2018) Differences between southern karst and northern karst besides scientific issues that need attention. *China Min Mag* 27(S2):317–319 ((in Chinese))
- Ni J, Guo Y, Wang L, Liu J, Liu Y (2011) Tectonics and mechanisms of uplift in the central uplift belt of the Huimin depression. *J Earth Sci* 22:299–315
- Peng B, Li Z, Li G, Liu C, Zhu S (2018) Multiple dolomitization and fluid flow events in the Precambrian Dengying formation of Sichuan Basin, Southwestern China. *Acta Geol Sin English Ed* 92:311–332
- Professional Committee of Karst Geology of Geological Society of China (1982) Karst and karst water in North China. Geological Publishing House, Beijing ((in Chinese))
- Pu JB (2013) The basic characteristics of the development and distribution of karst underground rivers in Chongqing area. *China Karst* 32(03):266–279 ((in Chinese))
- Sun W, Wu Q, Liu H, Jiao J (2015) Prediction and assessment of the disturbances of the coal mining in Kailuan to karst groundwater system. *Phys Chem Earth* 89:136–144
- van Loon AJ, Han Z, Han Y (2013) Origin of the vertically orientated clasts in brecciated shallow-marine limestones of the Chaomidian Formation (Furongian, Shandong Province, China). *Sedimentology* 60:1059–1070
- Wu Q, Jia X, Cao D, Liang YP (2014) Impermeability evaluation method and its application on the ancient weathering crust of carbonate in Middle Ordovician system in North China coalfield. *J China Coal Soc* 39(8):1735–1741 ((in Chinese))
- Xia RY (2018) Investigation and evaluation of groundwater resources in karst mountainous areas of Southwest China. Science Press, Beijing ((in Chinese))
- Xie YH, Li GF (1983) A few problems of karst and karst water in the North of China. *J Jilin Univ* 02:141–156 ((in Chinese))

- Yang RS, Fan A, Han Z, Han Z, van Loon AJT (2017) Lithofacies and origin of the Late Triassic muddy gravity-flow deposits in the Ordos Basin, central China. *Mar Pet Geol* 85:194–219
- Yang Y, Qiu L, Cao Y, Chen C, Lei D (2017) Reservoir quality and diagenesis of the Permian Lucaogou Formation tight carbonates in Jimsar Sag, Junggar Basin, West China. *J Earth Sci* 28:1032–1046
- Yuan BH (2007) Study on groundwater resources and ecological environment geology in karst rock mountain area of southwest China. University of Electronic Science and Technology Press, Beijing ((in Chinese))
- Yuan DX, Zhu DH, Weng JT (1994) Chinese karstology. Geological Publishing House, Beijing ((in Chinese))
- Zhu CQ, Cui DG, Zhou Z, Li QF, Huang YJ (2019) Similar simulation of mining-induced fissure development law and cave destruction character when mining in karst area. *Chin J Undergr Space Eng* 15(1):93–100 ((in Chinese))

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.