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ORIGINAL ARTICLE

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Karst water resources and geo-ecology in typical regions of China

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Abstract The aim of this work is to compare the different karst water features and related water resources in South and North China. In Southern China there are over 3,358 karst ground river systems with a total discharge of about 420×10^8 m^3 in the dry season. In North China, there are about 100 larger karst spring systems, each with a catchment area from 500 km^2 to over 4,000 km^2, and an average discharge from 1 to 13 m^3/s. The basic geo-ecological features of water, soil and air quality are described for typical karst regions of China. The total quality of geo-ecology is evaluated by five important factors.

Keywords Karst · Water resources · Geo-ecology · China

Comparison of karst water resources in South and North China

The karst is widely developed in China (Lu et al. 1973; Lu 1986), but its basic features are different in the main karstified areas of South and North China (Lu 1999, 2003).

South China

In China, the provinces, autonomous regions and municipalities under the central Government distribute karst water resources (Lu 1988). The Yunnan, Guizhou, Sichuan, Chongqing, Guangxi, Hunan and Hubei regions have a total area of 1.76×10^6 km^2. The distribution of thick carbonate rocks in these seven regions is about 540.8×10^3 km^2, or about 30.9% of the total area. The thin carbonate rock interbeds in these regions are about 189.8×10^3 km^2, about 10.73% of the total area. Taken together, carbonate rocks occupy 41.31% of the total area. Rainfall in these regions is 1,000–2,200 mm/a; annual average temperatures are mostly ~16–22°C. Climatic conditions are favorable for karst development.

The bare karst types in South China are mainly broad corrosion karst, limited corrosion karst and corrosion-erosion karst (Lu 1986). Karst water resources are listed in Table 1. The annual average groundwater resource used per person is estimated at 514–1,784 m^3/a, of which karst waters are 157–1,053 m^3/a per person.

In South China, there are 3,358 developed karst river systems, which have been investigated with total flowing quantity about 420×10^8 m^3 in dry season Lu et al. 2002a (Table 2).

Sub-surface karst river stream

Many surface rivers sink into the ground, then after a certain distance, the sub-streams flow out to form a surface river again. The related formula is expressed as

$$Q_{Oi} = Q_{I,i-t} \pm \sum_{p-1}^{n} q_{p,i-tp} \pm \sum_{f=1}^{m} q_{f,t-tf} + \sum\nolimits_{Qa}, \qquad (1)$$

where Q_{oi}—exit flowing quantity of the sub-surface karst river stream in i time, m^3/s; $Q_{I,i-\mathrm{t}}$ entrance flowing quantity of the sub-surface karst river stream in i–t time, m^3/s; $q_{p,i-\mathrm{tp}}$—the flowing quantity of p branch of the

Table 1 Karst water resources in main regions of South China

Content regions	Ground water resources (A) 10^8 m^3/a	Karst water resources (B) 10^8 m^3/a	(B)/(A)%
Yunnan	742	345	46
Guizhou	479	386	80
Sichuan	551	135	24
Chongqing	160	118	73
Guangxi	699	374	53
Hunan	456	263	57
Hubei	416	185	44
Total	3,503	1,806	51

sub-surface karst river stream in i–tp time, m^3/s; $q_{f,i-\mathrm{tf}}$—the of flow quantity corroded fissure into the sub-surface stream in i–tf time, m^3/s; ΣQ_d—the condensation water between i–t and i time into the sub-surface stream, m^3/s.

Karst ground river systems

The karst ground river systems mainly collect the percolating ground water from sinkholes or corroded fissures. The related formula is:

$$Q_{Oi} = \sum_{s=1}^{n} q_{s.i-ts} \pm \sum_{p-1}^{n} q_{p,i-tp} \pm \sum_{f=1}^{m} q_{f,i-tf} + Q_{Oi} \sum_{Qd}, \tag{2}$$

where $q_{s,i-ts}$—the flow before i–ts time, the flowing quantity directly sinking into the ground (m^3/s), other marks are as in formula 1.

Ground water reservoirs in many forms have been constructed in the karst ground river systems and subsurface karst river systems of South China (Lu et al. 1973; Lu 1986; Milanović 1981, 2000). At present, the karst water resources only exploit about 8–15% of the total karst water resources in South China. More subsurface reservoirs are planned.

Table 2 Karst groundwater systems in different regions

Content regions	Ground river number	Flowing quantity in dry season 10^8 m^3/a
Yunnan	148	39.02
Guizhou	1,130	71.35
Sichuan	895	63.96
Chongqing	201	28.68
Guangxi	435	191.00
Hunan	338	17.65
Hubei	211	14.85
Total	3,358	426.69

North China

In North China are the Beijing, Tianjin, Hebei, Shangdong, Henan and Shanxi regions. Average annual precipitation is 400–600 mm/a, and average temperature is 4–12°C. The main karst types are limited corrosion type and corrosion-erosion type. There is less of the broad corrosion type. Although the northern regions mostly have semi-dry climatic conditions, there are over 100 larger karst spring systems (Lu 2003), each with a discharge from 1 to 13 m^3/s and a catchment area from 500 km^2 to over 4,000 km^2 (Table 2).

Of the rich karst water resources of 125×10^8 m^3/a in North China, about 70–80% of the total resources have been exploited. At present, only 29.71×10^8 m^3/a karst water resources remain. Considering stream ecological needs, it is better to reserve about 1/2–1/3 for discharge, i.e., to allow about 40–60 $\times 10^8$ m^3/a flow down stream. The over-exploitation of karst water resources is one of the most negative factors for deterioration to the local geo-ecology (Table 3).

Basic features of karst geo-ecology in typical regions of China

Karst water quality

A series of scholars have researched the ecosystems controlled by water. Study subjects relate to the river, reservoir and lake under different climatic conditions, such as dry-semi-dry condition, tropical rain forest, subtropical, etc. (Bayer 1982; Fernandzez et al. 2001; Golluscio et al. 1998; Porporato et al. 2002). The QWASI (quantitative water, air, sediment interaction) have been studied (Mackay and Diamond 1989).

Besides the normal chemical elements, the persistent organic pollutants (pops) are very important contents for analysis. The polluted sources of karst water in three Gorges region of Yangtze River in China have been tested for isotope nitrogen (Fig. 1) by the formula (Penchen 1993; Lu 1999):

$$\delta_N^{15} = \frac{{}^{15}N/{}^{14}N(\mathrm{sample})\,{}^{15}N/{}^{14}N(\mathrm{standard})}{{}^{15}N/{}^{14}N(\mathrm{standard})} \times 1,000. \tag{3}$$

The soil contents must also be studied. Jenny (1941) (after Soil Institute, CAS 1994) pointed out that oil features are influenced by climate (cl), organic mass of living things (O), relief (r), parent material (p) and time (t). Lu et al. (2002c) stated that the geological process (g), including water-soil processes and interactions of mankind (M) must also be considered. Therefore, the formula related to soil features (s) is:

Table 3 Karst water resources in typical regions of North China (data from Chen Honghan)

Karst water resources (10^8 m^3/a)				
Conclition regions	Nature	Possible exploitation	Already exploiting	Remaining quantity
Shangxi Plateau	35.50	32.87	20.86	11.98
East Taihan Shan Mt	31.69	24.10	18.67	5.42
Middle-south Shandong	35.74	28.29	20.53	7.67
Yan shan Mt	11.75	3.46	1.69	1.77
South Shandong	5.13	4.13	3.38	0.75
West Henan	4.32	3.99	1.87	2.12
Total	125.13	96.74	67.00	29.71

$$S = f(p, g, \mathrm{cl}, r, O, M). \quad (4)$$

Water-soil (or rock) process

The geo-ecological features of coordination and relation between water-soil are presented in Fig. 2.

Biogenetic-geochemical processes

The microbiological process in formation of mineral deposits has been studied in many ways (Yan and Zhang 2000). The biological process in the compound karst is also interesting. Gypsum and anhydrite under anaerobic (*D. seulfovibria*) conditions will product H_2S (Lu et al. 2002b, 2002c):

$$CaSO_4 + \text{organic} \xrightarrow{\text{bacteria}} CaCO_3 + H_2S + H_2O.$$

When the water containing dissolved oxygen percolates into the ground, another chemical process is possible. Under oxidation (by *T. thioporus*), the pH value decreases into the range of 5–4.5 and promotes dissolution of $CaSO_4$:

$$2H_2O + O_2 \xrightarrow{T.Thioporus} 2S + 2H_2O$$
$$2s + 3O_2 + 2H_2O \xrightarrow{\text{Oxidation}} 2H_2SO_4.$$

The new production of H_2SO_4 will strongly dissolve carbonate rock, while gypsum may be deposited. The reactions are:

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$$
$$CaMg(CO_3)_2 + H_2SO_4 \rightarrow CaSO_4 + MgCO_3 + 2CO_2 + 2H_2O$$
$$CaSO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O$$
$$CaCO_3 + MgSO_4 + 2H_2O \rightarrow CaMg(CO_3)_2 + CaSO_4 + 2H_2O$$

Therefore, the microbiological process is very important for carbonate-sulphate compound karstification. The biogenetic-chemical processes are also the main factors controlling eco-hydrology or eco-hydrogeology.

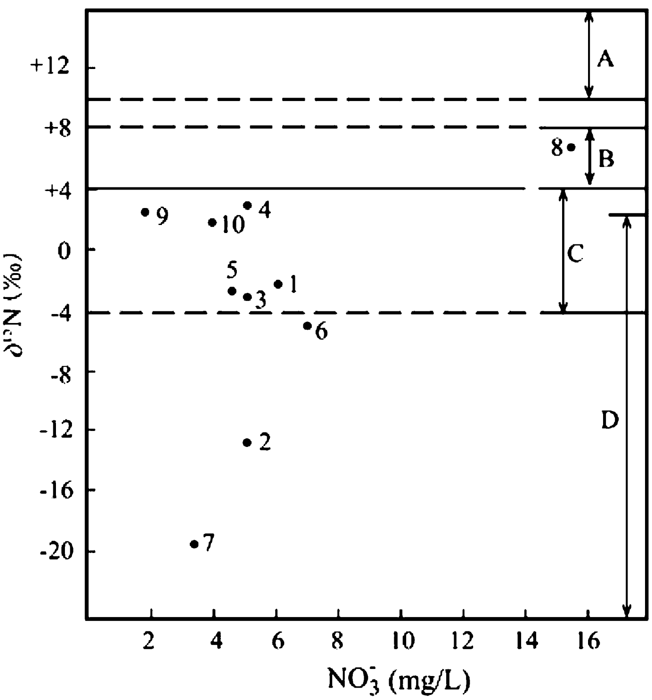

Fig. 1 Relation of $\delta^{15}N$ and of NO_3^- surface and karst water in three Gorges Region of Yangtze River in China. *A*—influenced zone by animal excrement; *B*—influenced zone by soil organics; *C*—influenced zone by fertilizer and industrial waste water; *D*—influenced zone by rainfall l

Evaluation of the geo-ecological quality in karst regions of China

The eco-hydrology and eco-hydrogeology include water quantity, quality and dynamic condition and quantitative water-soil-air alternation, as well as the mechanisms of biogenetic-chemical-physical-geological processes. Overexploitation of karst water resources will directly influence the geo-ecological quality by the lowering the karst water level.

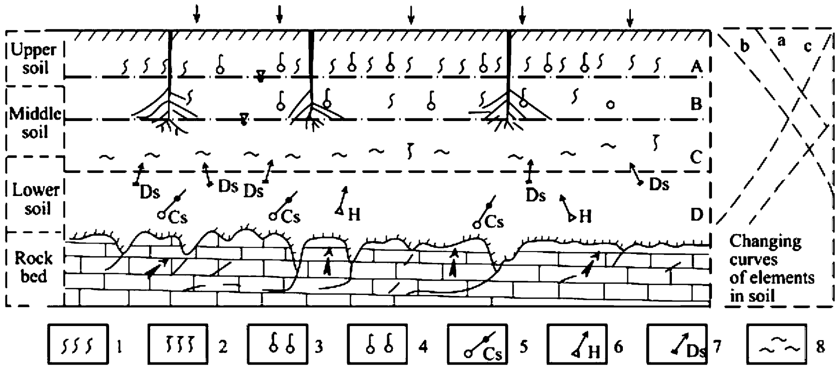

Fig. 2 Analysis of water-soil geo-ecological feature related to soil nutrients, diffusion and absorption of plant. 1—first eluviation; 2—second eluviation; 3—first evaporation; 4—second evaporation; 5—consistency diffusion in soil; 6—heat diffusion in soil; 7—dynamic diffusion; 8—absorption of roots of plants; *A*—upper percolation-eluviation zone; *B*—eluviation-evaporation zone (fluctuation zone of ground water level); *C*—accumulation zone of soil nutrients; *D*—activity zone of bedrock-soil; curves related to some element changes: a: Ti, Ni, Zn, Ca, Pb, Hg, As; b: Cu, Mn; C: Cr

The geo-ecological quality will be influenced by the following important factors: vegetative covering rate; soil erosion rate; decreasing ability to resist natural hazards; rocky desertification rate (Lu 1990, 1993); and water-soil pollution rates. Decreasing ability to resist natural hazards is based on the mechanisms of natural hazards' chains reflecting the interrelationships between climatic, geological and biogenetic processes.

Rocky desertification is usually caused by improper land use and over-development; such as over-exploitation of karst water resources, over-cutting forest and destroying the grassland to increase soil erosion. In the karst regions where bare carbonate rocks with little or no surface vegetation are found, the rocky desertification coefficients are expressed by the formulas:

$$R_i = \frac{\sum_{i=I}^{n} F_{ei}}{\sum_{i=I}^{n} P_{ei}}, \tag{5}$$

$$P_{ei} = \frac{Cm}{m} \sum_{j=1}^{m} K_j R_j \rho R. \tag{6}$$

Ri-rocky desertization coefficient; F_{ei}—the soil erosion rate in *j* karstified zone, t/km^2 a; P_{ei}—the annual average soil production rate in *j* karstified zone, t/km^2 a; R_j—the un-dissolved material content in carbonate rock in *j* zone, 100%; K_j—the dissoluted rate of carbonate rock in *j* zone, mm/a; P_{kj}—the special weight of un-un-dissolved material, t/m^3; *Cm*—calculated coefficient, 1,000; *m*—calculated number.

The rocky desertification rates are ~6.94–156.25 in some regions. It may be only a few decades to several 100 years before erosion is common in the karstified mountain regions.

The total quality of geo-ecology in karst regions may be expressed by the following formula:

$$E_{GC} = \sum_{i=1}^{n} A_{wi}, \tag{7}$$

where E_{GC}—coefficient of comprehensive evaluation related to geo-ecology; A_{wi}—evaluation of *i* factor. The four classes of geo-ecology in karst regions of China will be separated, which are: E_{GC} = 81–100 (best class); E_{GC} = 61–75 (good class) E_{GC} = 31–60 (common class); E_{GC}—lower than 30 × bad class.

Conclusion

Karst water resources in South China are richer than those in North China. The exploitation rates in South China are about ~80–15% of the total karst water resources, while in North China rates are already near 70–80%.

Both kinds of karst ground river systems enable more ground reservoirs to be constructed in different forms in South China. The larger karst spring systems control exploitation in North China.

Karst water quantity and quality are closely reflected in geo-ecological features. The karst water dynamic, water-soil processes and bio-chemical processes, as well as other factors, together make up the total karst eco-hydrogeological condition. The total quality of karst geo-ecology is usually evaluated based on comprehensive studies of all these systems.

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