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A NEW TYPE OF UNDERGROUND RESERVOIR IN KARST AREA —A Case Study in Xiaopingyang, Laibin County, Guangxi, China

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1 INTRODUCTION

There is a severe drought problem in the south China karst area that has restricted for long the agricultural production in the region. The causes for this are as follows. (1) The ability of the environment to regulate natural runoff is very poor in the naked karst areas, and most part of the water resources run away rapidly through surface and subterranean hydrographic network in the rainy season, and stream flow declines sharply once drought weather occurs. In most cases the low water flow can not meet the water needs for irrigation even all of it is exploited. (2) The geological conditions of construction of surface reservoirs are rather poor because of serious karst leakage problem, which makes the stream flow unregulated artificially. For these reasons, looking for effective tools for regulating stream flow in naked karst areas is a prominent challenge faced by Chinese karstologists. Recently, engaged in a drought management project in Laibin County, we find out that the epikarst zone in the peak forest-plain area possesses a great potential of regulation capability and the epikarst aquifers may serve as good reservoir storage rooms. Thus a proposal of a pumping type underground reservoir is put forward[1]. The technological practicability and economical feasibility of constructing such a reservoir in the Xiaopingyang Experimental area are discussed in details.

2 THE PRINCIPLES

Reticulated network conduits often develop in the epikarst zone in karst plain areas and few successful examples of regulating runoff by construction of common surface and underground (dam-type) reservoir are known. On the other hand, the permeability and storage capacity of the epikarst aquifers is large enough for a large-roomed drawdown cone to form and makes them feasible for construction of pumping type underground reservoir. The principle of such reservoir is to overpump groundwater in the dry season to form an artificial

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drawdown cone (underground reservoir storage) in order to obtain necessary water for irrigation, which can be filled again by natural recharge in the next wet season. This type of reservoir fits in with the natural conditions in the karst plain areas with depth of water table less than 30 m. The technique is not too sophisticated to master and may become an effective tool for runoff regulation.

3 THE TECHNICAL PRACTICABILITY

The major technical problems in constructing pumping type underground reservoir are: (1) estimation of reservoir storage; (2) formation of drawdown cone; (3) recharge of water.

3.1 Reservoir Storage and Regulation Capacity

3.1.1 The water needs for irrigation

Xiaopingyang Township covers an area of 215 km^2, in its eastern and northern parts there are peak cluster recharge areas with a total area of 65 km^2; the rest are plains (Fig. 1). There is a total of 4180 ha cultivated land, including 1900 ha of rice field. Assume that the irrigation quota is 1.4×10^4 m^3/ha for rice and 0.36×10^4 m^3/ha for sugercane, the total needs for irrigation water come to 3.48×10^7 m^3 in the dry year (probability 90%).

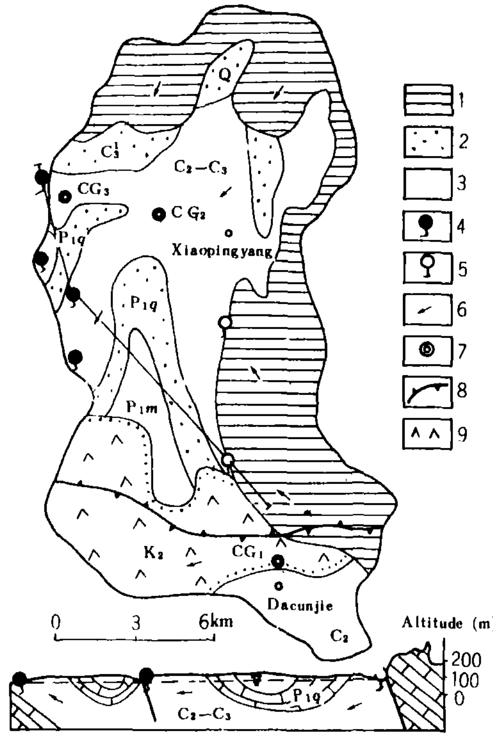

Fig. 1 Schematic hydrogeological map of Xiaopingyang Township

1. Peak cluster recharge area; 2. Poorly karstified aquifer in plain area; 3. Intensely karstified aquifer in plain area; 4. Perennial spring; 5. Seasonal spring on the border of peak cluster; 6. Groundwater flow direction 7. Point for water level monitoring; 8. Underground watershed; 9. Red bed

3.1.2 Water resources exploited at present

(1) The surface water resources According to the hydrometric data, the mean annual rainfall is 1316 mm and runoff coefficient is 0.45. It gives a total natural runoff in the area of 1.27×10^8 m^3/a. However, only 0.50×10^7 m^3/a of it is regulated (by more than 10 reservoirs), thus the artificial regulation capacity is very important.

(2) Groundwater runoff in the dry season There are four perennial karst springs that drain the area. Their maximum outflow sums up to 3.2 m^3/s, with a minimum of 0.5 m^3/s. According to a detailed study[2], the runoff modulus for the low water season in Laibin

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County averages 3.32 l/s • km^2 and 6.92 l/s • km^2 for peak cluster and plain areas respectively. This results in an average groundwater flow of 1.25 m^3/s for the whole area. By statistics, about 0.50×10^7 m^3/a of the stream flow is utilized directly by pumping or diversion works.

3.1.3 The reservoir storage

As noted above, there is only 1.00×10^7 m^3 water has been exploited annually, thus irrigation water needed comes to a shortage of 2.48×10^7 m^3 in the dry year. Therefore, the contradiction between supply and demand is very sharp and to regulate runoff by means of underground reservoirs with a total storage room of 2.48×10^7 m^3 is needed.

3.1.4 The regulating capacity of underground reservoir

The main intensely karstified aquifers in the plain area are carbonate formations of C_2, C_3, P_{1m} and K_2 (calcibreccia) ages, with a total outcrop area of 120 km^2 and thickness of more than 2000 m. Their regulating capacity was estimated using the following mathematic model. Assuming that the storage space of epikarst aquifers serves as the storage room of the underground reservoir (Fig. 2), the storage coefficient (ψ) designates the replenishing capacity and the re-storage index (λ) is an indicator of the regulating capacity, the following formulas may be derived

$$\psi=V_f/(V_s+V_t)$$
$$\lambda=V_f/V_t$$

where V_f is the re-storage room which equals the total recharge resources of the reservoir in an integral hydrological year; V_s is the minimum storage room in the lowest water season; V_c is the maximum storage room; V_t is the maximum regulative room which equals V_c minus V_s.

If μ represents specific yield of aquifer; F is horizontal area; $\triangle H$ is average amplitude of water level fluctuations; $\Sigma\triangle H$ is accumulative hight of level uplift; H_{max}, H_{min} are average thickness of aquifer at highest and lowest water level respectively, we have

$$V_f=\mu\cdot\Sigma\triangle H\cdot F$$
$$V_s=\mu\cdot H_{min}\cdot F$$
$$V_t=\mu\cdot(H_{max}-H_{min})\cdot F$$

and the ψ and λ are given by:

$$\psi=\Sigma\triangle H/H_{max} \quad (1)$$
$$\lambda=\Sigma\triangle H/(H_{max}-H_{min}) \quad (2)$$

Given the $H_{max}=30$ m, $\Sigma\triangle H=12.13$ m, $\triangle H=6.42$ m (according to the results of groundwater monitoring), and $H_{min}=23.58$ m, solving Eqs. (1) and (2), we have $\psi=0.404$ and $\lambda=1.889$. This means that 40.4% of groundwater in the epikarst zone is being renewed yearly under present extraction rate, and the annual regulation volume is 1.9 times

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the storage space. Finally we come to the conclusion that the regulating capacity of the shallow karst zone is great enough to cover the deficit of irrigation water in the dry season.

3.2 The Formation of Drawdown Cone

3.2.1 Effective porosity (specific yield of aquifer)

(1) The results derived from groundwater monitoring The drainage area of the monitored four springs totals 175 km^2. Given the attenuation coefficient $\alpha = 0.0114$, $t=120$ d, $Q_0 = 2.73\times 10^5$ m^3/d, $V=1.79\times 10^7$ m^3, solving Eqs. (3), (4) and (5), describing attenuation of springs with the monitoring data results in an average drawdown of water level $\Delta H_t = 3.28$ m in the attenuation period and average specific yield for the karst plain area $\mu = 0.031$.

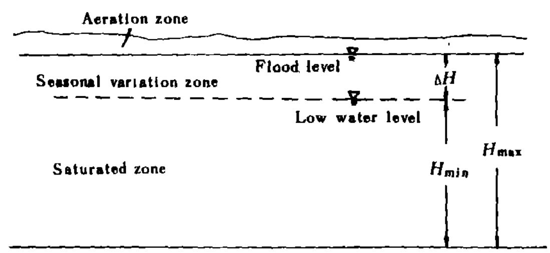

Fig. 2 Conceptural model for calculating regulative capacity of underground reservoir

$$Q_t = Q_0 e^{-\alpha t} \tag{3}$$

$$V = \int_0^t Q_0 e^{-\alpha t} \mathrm{d}t \tag{4}$$

$$V = F \cdot \Delta H_t \cdot \mu \tag{5}$$

(2) Statistics from boreholes Thirty tube wells were analysed statistically in Xiaopingyang Township and Laibin County for effective porosity at an 5 m interval. The results range from 0.11% to 10.7% varing with depth which yields an average effective porosity $\mu = 0.023$ for the upper 30 m zone.

So the results calculated above using different methods are 0.031 to 0.023, and agree to each other rather well. We adopt 0.025 and 0.022 as the average effective porosity for karst plain and red bed area respectively in the following discussion.

3.2.2 Drawdown

Assume that a drawdown cone is formed, which affects just the intensely karstified aquifers and covers an area of 120 km^2 (80 km^2 in the plain and 40 km^2 in the red bed area). By calculation the regulated room will be 2.88×10^6 m^3 for 1 m drawdown in average. Therefore, an average drawdown of 8.61 m is needed to meet the water demand for irrigation (shortage of 2.48×10^7 m^3) in the drought year.

3.2.3 The techniques for aquifer drainage (disposition of pumping well)

There are two key problems with drainage techniques. The first is how to raise the success ratio of drilling boreholes; the second is how to dispose pumping wells so as to get the best drainage effect in general. The former is called the borehole location techniques; the lat-

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ter is a multi-well drainage problem.

(1) The borehole location techniques One of the key technical problems involved in exploitation of a fissure or karst aquifer is how to locate a borehole in right place so that it can pierce water-bearing fissures or caves. In general, Chinese hydrogeologists are possessed of the techniques of exploitation of karst water with tube wells at quite high level. In particular case of rural country the success ratio of borehole location is too low (about 30% in average) for the karst water to be exploited efficiently and economically. At present, Chinese scientists and engineers have summed up previous practical experiences in this field and succeeded in increasing the success ratio in many cases up to 80% and more. Recently in the Institute of Karst Geology a rapid borehole location techniques has developed, well applicable to the rural conditions of karst plain areas. This will make borehole location more independent of those constraints imposed by the aquifer heterogeneity.

(2) The multi-well drainage There is strong evidence indicative of possibility of forming rather uniform cone of influence with large radius in the epikarst aquifer by means of the multi-well irrigation system.

① In one of the experimental areas of Xiaopingyang Township, six dugging wells tapped the epikarst aquifer for continuous sixty days irrigation in 1991. The water tapped totaled 8.1×10^{5} m^{3} and drained an area of about 8 km^{2}. This would have caused, according to calculation, a water level lowering 4.05 m. Actually, the observed lowering in dugging wells was 4~5 m, suggesting thus formation of a quite uniform drawdown cone in the area.

② The results of a karst water monitoring network with thirty observation wells in the Xiaopingyang experimental area showed a quite uniform pattern of the water level fluctuation. The reason for this was believed that well communicated hydraulically and reticulate karst network was developed in the epikarst aquifer.

3.3 Replenishment of the Drawdown Cone

3.3.1 The intensity of precipitation infiltration

Fluctuation of groundwater level is close correlated to precipitation in the area, which indicates that the atmospheric precipitation is the main source of groundwater recharge. Processing of the monitoring data gives a rainfall infiltration coefficient α equal to 0.227 and 0.233 for the diffuse flow in the karst plain and groundwater flow in the red bed area respectively (Tab. 1).

Tab. 1 Rainfall infiltration coefficient calculated

Research area	$\Sigma\Delta H$(m)	μ	P(mm)	α(diffuse)	α(total)
Karst plain	12.13	0.025	1336	0.227	0.411
Red bed calcibreccia	14.13	0.022	1336	0.233	0.422

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According to the data obtained for the whole Laibin County[1], the conduit flow accounts to 81.3% of diffuse one. Adding up the two terms gives annual infiltration coefficient of precipitation of 0.411～0.422.

For example, during the first heavy rain in April, 1993 with a rainfall $P=58.5$ mm, the water level rised 0.39～3.38 m (1.29 m in average) within 1～4 days after the rainfall event, which results in an infiltration coefficient $\alpha=0.551$, a value 34.4% more than the calculated mean for the region. This means that the infiltration coefficient increases as the regional water level lowers, because the infiltration conditions are further improved by forming a regional drawdown funnel and thus promotes recharge effects.

3.3.2 Natural recharge data of water

According to the data of water level monitoring in the area, the time lag between groundwater level rising and rainfall ranges from 1 day to 3 days and the ascending part of the water level versus time curve is very steep, but the attenuation part appears fairly gentle (Fig. 3), which implies a high recharge rate and significant regulating capacity of epikarst aquifer. Thus natural replenishment process can be completed within 3～5 days after a heavy rain event with some 100 mm rainfall.

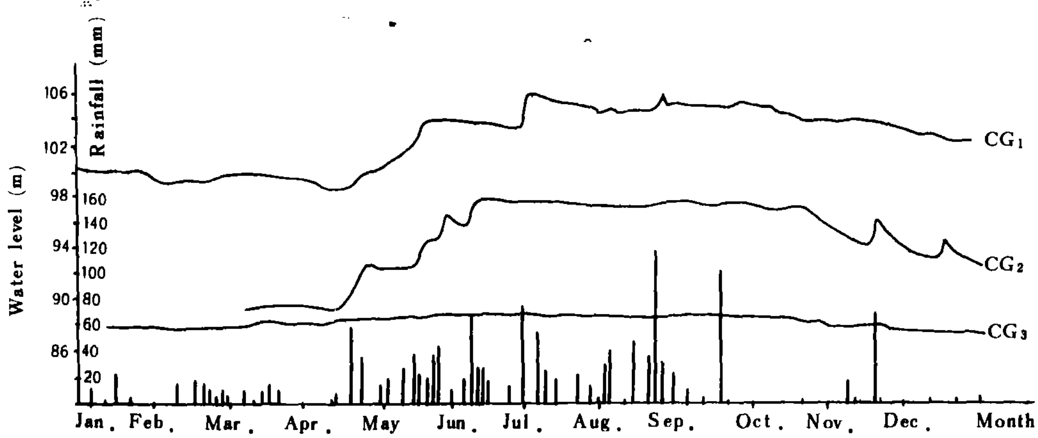

Fig. 3 1993 time versus groundwater level curves for Xiaopingyang

3.3.3 The recharge by precipitation infiltration in the dry year

As Xiaopingyang has a drainage area of 215 km^2 and minimun rainfall of 820 mm (in 1989) for the last fifteen years, the total recharge by precipitation infiltration would be 7.28×10^7 m^3 in the most dry year.

3.3.4 The recharge with recovered irrigation water

The water retention ability of irrigated fields is quite poor, for the soil here is thin and contains much coarse material such as sand and gravel and thus highly permeable. Investigation[3] has showed that about 50% of irrigation water percolates into the ground feeding the aquifer, and the recovered irrigation water in the Xiaopingyang area amounts to 1.74×10^7 m^3 annually.

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Therefore the total volume of water recharged by both precipitation infiltration and recovery of irrigation water sums up to 9.02×10^7 m^3 in the most dry year, a value approximately four times larger than the needed reservoir storage capacity (2.48×10^7 m^3).

4 THE ECONOMICAL REASONABLENESS

The development and use of surface water in Xiaopingyang suffer from shortage of resources in the dry season, and drawing water from outside is believed unreasonable economically. For instance, in case of pumping river water from the Hongshuihe River (40 km north of Xiaopingyang), a series of problems such as high-lift (50 m), long irrigation canal (40 km), taking up much farmland, long construction period and difficulties of management will arise, and the construction investment would be two times more expensive compared to that for groundwater utilization.

In addition, the running costs (including energy consumption, administration, upkeep of equipment, etc.) also double those of groundwater irrigation systems. There are also other advantages of use of local groundwater over drawing surface water from outside. Construction of underground reservoir does not take up farmlands, they are safe in running and do not require emigration. Besides, they help to reuse irrigation water, thus increasing the utilization coefficient of water resources and reducing waste of fertilizer.

5 THE ENVIRONMENTAL PROBLEMS

The main environmental problems caused by construction of the pumping type underground reservoir are collapse and depletion of spring outflow, which are thought to be much earlier manageable in comparison with these by construction of surface reservoir.

5.1 The Karst Collapse

Exploitation of groundwater in large-scale may cause karst collapse, a problem which should be treated carefully. The development of collapse is controlled by many factors, such as karstification degree, characteristics of soil cover, depth to water level and its regime, and follows certain regularities. In the research area, the thickness of soil cover is less than 10 m in common. Therefore, large-sized collapse occurs rarely. Even if a patch of farmland is affected by collapses, the problem is still less serious in comparison with the farmland inundation and inhabitant emigration by construction of surface reservoirs. However, when groundwater extraction is planned, the disposition of pumping wells should be considered carefully, and the wells should be keeped away from residential areas and railway as far as one can get, especially where subterranean conduit flow may come across. Moreover, the evaluation, monitoring and forecast of collapse should be undertaken.

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5.2 The Depletion of Spring Outflow

Experience in the Xiaopingyang experimental area shows, that in case of extracting less than 20% of the regional groundwater resources, depletion of outflow of the regional emergence, the Sanzhou Spring, will behave mainly as retardation of flood peak and shifts of attenuation phase ahead and the reduction of outflow is not greater than 50%, even if the water withdraw is several times larger than the natural flow for more than one month. The reason for this is that the epikarst aquifer is thin and the underground catchment area is usually composed of a number of relatively isolated smaller catchments of lower orders.

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抽水型岩溶地下水库的设想
——以广西来宾县小平阳乡为例*

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摘 要

抽水型岩溶地下水库的基本原理是在枯水季节抽取超过天然径流量的地下水，形成人工疏干漏斗(即地下水库调节库容)，以获得需要的水资源量；雨季通过天然回灌，把调节库容重新充满。岩溶平原区水资源天然调节能力差，地下水丰、枯流量变化大，即使开发利用全部的枯季径流也难以满足灌溉需要。而平原区浅层岩溶带管道多呈网络状发育，岩溶发育强烈且相对均匀，岩溶渗漏问题严重，通过修建地表水库或堵洞成库调节径流，成功率极低。利用地下水库调蓄是解决干旱缺水问题的主要手段之一，技术上可行，经济上合理。

小平阳岩溶平原区强富水含水层出露面积 120 km^2，浅层岩溶含水层(0~30 m)平均给水度为 0.025；实行全乡耕地 90%水利化，需地下水库库容 2480 万 m^3，疏干漏斗平均深度 8.61 m。枯水年地下水入渗补给量约为水库库容的 5 倍，雨季回灌时间 3~5 天。抽水引起的疏干漏斗在丰水期都能得到回灌恢复，不致于造成区域地下水位持续下降。开发抽水型岩溶地下水库可能引发的主要环境问题是岩溶塌陷和泉流量减少；但如果开发利用流域水资源的 20%，则上述问题不严重且相对易于处理。

关键词 岩溶平原区 抽水型地下水库 人工调蓄 疏干与回灌 来宾县小平阳

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