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THE GROUNDWATER RESOURCES AND ITS SUSTAINABLE DEVELOPMENT IN THE SOUTH EDGE OF TARIM BASIN

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ABSTRACT: There is a potential to certain extend for groundwater development in the piedmont plain in south edge of Tarim Basin. If the surface water use keeps the scale as present, the maximum safe yield of groundwater is about $2.05 \times 10^9 m^3/a$ that is 55.8% of the recharge. Thus the evapotranspiration discharge will reduce 60.4%, while spring water reducing 35.6%. If the surface water use rate is up to 80% and coefficient of canal water use increase to 0.55 in the future, the maximum safe yield of groundwater will reduce to $1.85 \times 10^9 m^3/a$ with the recharge reducing to $3.1 \times 10^9 m^3$. However, the sustainable groundwater development is depended on the protection of the quality aspect linked with the quantity aspect. In particular, protection of the glacier and water conservation forestry in the Kunlun Mountains and coordinating development of surface water and groundwater should be taken seriously. Besides, the legislation, administrative management and the technology construction, and ability construction are also critical important and necessary.

KEY WORDS: groundwater resources; sustainable development; safe yield; Tarim Basin

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1 INTRODUCTION

Sustainability as present understand comes from word protection strategy commission, which firstly put forward some wide excepted environmental sustainability principles and three important identifications for life support system: soil, air and water. Then, in the report of Our Common Future (WCED, 1987), the concept of sustainable development is put to an outstanding level. Sustainable groundwater resources development is then a great issue in the recent years and the future (DAS *et al.*, 1997). Groundwater is usually considered an available and valuable resources for domestic, agriculture and industry, and undoubtedly, provides the cheapest and safest water supplies throughout the word. But its, hitherto, excellent reputation has become tarnished. A number of factors have all combined to knock groundwater from its pedestal as a panacea for all problems. Then unacceptable results of aquifer system exhausted and related serious environmental problems such as land subsidence, desertification and water quality deterioration has been produced through blindly over exploitation of groundwater combined with drought condition (DANIELOPO *et al.*,

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1994; WEI *et al.*, 1997). Tarim Basin, the largest inland basin in China and with the second world largest desert i. e. Taklimakan Desert in it, lies in the hinterland of Eurasia and is surrounded by high mountains. Both groundwater and ecosystem are extremely vulnerable to climate change or human activities. Especially, the south edge of Tarim Basin belongs to the typical ecological vulnerable zones and groundwater vulnerable zones. On the other hand, it is becoming increasingly important to meet the demand for water resources in pace with expansion of the oil exploitation scale in Tarim Basin. But there is no surface runoff, and the groundwater is very poor both in quantity and quality in the vicinity of the oil field in the hinterland of Taklimakan desert. Then the focus of people' s attention is concentrated to the south of Tarim Basin, which is nearer than the north part for one thing, and where several rivers go through the desert and maybe storing up rich and fresh groundwater for another thing. However, the hydrogeological condition and groundwater status still keeps an insoluble mystery to people. Challenge for the new millennium is gargantuan, but work has begun with involved in the solution to these issues across several continents: understanding of basic hydrogeology, assessing the recharge of groundwater, assessment of maximum safe yield and discussing the principles of sustainable groundwater development.

2 HYDROGEOLOGY & GROUNDWATER RESOURCES

2. 1 Hydrogeology

The south edge of Tarim Basin cut across two structural geology units—the southwest depression and the southeast depression. In the later Tertiary, with the violently fold uplift of Tianshan geosyncline and Kunlun geosyncline, Tarim basin began to subside down quickly and developed an integrated vast inland Basin. At the same time, the basin extensively accepted continental clastic sediments which is the impermeable bed of the Quaternary aquifers. Since the end of Pliocene epoch, with continuing rising up of the surrounding mountains and subsiding of the piedmont depression, the basin accepted deep loose diluvial and alluvial deposits, and some eolian deposits and lacustrine deposits, which formed the good water storing aquifers of 200 – 900m thick. The piedmont slope plain is single cobble gravel aquifers, in which the specific capacity is 20 – 500 $m^3/(d \cdot m)$, and coefficient of permeability is 1 – 6m/d. At the front edge of slope plain, the Quaternary aquifers are interbedded loose diluvial and alluvial cobble gravel, sand gravel, fine sand and clay, in which the specific capacity amounts to 200 – 1000 $m^3/(d \cdot m)$ and coefficient of permeability is up to 50 – 212 m/d. Then with the grain turning to finer, the permeability and capacity become smaller and smaller. The confined aquifers are not widespread and just between the Keriya River and the Niya River extends 70. 5km from south to north and covers approximately 9517km^2, and there are two layers of impermeable clay in the 150m depth. the depth of groundwater table varies from 50 – 100m in piedmont slope plain to 1 – 3m in the fine soil plain, and the TDS is 1 – 3g/L in the former, and 3 – 10g/L in the later. The groundwater chemistry corresponding become from $Cl \cdot HCO_3 - Ca \cdot Mg$ or $HCO_3 \cdot Cl - Mg \cdot Ca$ to $Cl \cdot SO_4 - Na \cdot Mg$ or $Cl - Na$. The water quality in the ancient channels is better than that in other region in general.

2. 2 Groundwater Resources

Groundwater resources in the inland river basin can be classified into two parts (CHEN, 1992): repeated and irrepeated groundwater. The former, transformed by surface runoff, is recharged by seepage of natural channel, canal system and field irrigation. The latter is recharged by side ground runoff and rainfall penetration. Then it can be written as:

$$G = R_g + R_i + R_f + G_l + X \qquad (1)$$

where G is natural groundwater resources; R_g is recharge of channel seepage, there are 36 rivers with total surface runoff of 7. 26 × $10^9 m^3$ flowing out the Kunlun Mts. in the Hotan Region of south edge of Tarim Basin. The seepage rate differs from different water season and different rivers (MA *et al.*, 2000a). Then the recharge of channel seepage is 1. 24 × $10^9 m^3$, which counts for about 17. 1% of the surface runoff. R_i is recharge of canal system seepage, about 58. 4% of the surface runoff is drawn to artificial conduit, of which the utilization coefficient is from 0. 4 to 0. 49 with pebble lining, concrete lining and plastic film lining. R_f is recharge of field seepage through irrigation, excepting for consumption as evapotranspiration for gropes growing, there is still some water seepaging to recharge groundwater where groundwater level is no more than 5m deep because of backward irrigating technique. Field water coefficient of utilization is about 0. 8 to 0. 84. G_l is recharge of side ground runoff, because there is a large fault-hills zone of 10 to 35km width between bedrock fracture aquifers in Kunlun Mts. and the quaternary aquifers in the plain of Tarim Basin, the side ground runoff from fracture aquifers is very limit. X is recharge of rainwater penetration, due to the drought climate and scarce rain, rainwater penetration only occurs in the irrigation area where groundwater table depth is no more than 5m and rainfall intensities much than 10mm(QU *et al.*, 1995). The coefficient of penetration is 0. 04 – 0. 18.

Table 1 The groundwater resources of the piedmont plain in the south edge of Tarim Basin(10^9m^3)

River basins	Surface runoff	Channel seepage(R_g)	Canal seepage(R_i)	Field seepage(R_f)	Side-base flow(G_l)	Rainwater penetration(X)	Groundwater resources(G)
Pishan R.	0. 705	0. 150	0. 255	0. 009	0. 032	0. 009	0. 455
Hotan R.	4. 391	0. 113	1. 244	0. 041	0. 058	0. 016	1. 472
Qira R.	0. 581	0. 191	0. 191	0. 005	0. 017	0. 009	0. 413
Keriya R.	1. 007	0. 367	1. 344	0. 012	0. 038	0. 015	0. 776
Niya R.	0. 576	0. 421	0. 084	0. 020	0. 025	0. 015	0. 565
Hotan Region	7. 260	1. 242	2. 118	0. 087	0. 170	0. 064	3. 681

According to the equation (1), the total groundwater recharge resources is 3. 681 × 10^9m^3 (Table 1). The majority of groundwater resources is seepage transformation of surface water including runoff and irrigation water in the canal system and field, which is accounting for more than 94% of total groundwater recharge. The precipitation infiltration and side-base flow, only accounts for no more than 6%. The extensive evapotranspiration is the mainly discharge of groundwater in the fine soil plain, while enormously spring groups discharge groundwater in the slope plain. At the front edge of slop plain a great part of groundwater overflows aquifers and transforms to surface water again which is the main source of the river runoff and groundwater in the lower reach of river basin in the desert.

2. 3 The Utilization of Groundwater Resources

There are four groundwater resource sites had been set up for drinking and irrigation, and 108 wells were drilled with total 0. 037 × 10^9m^3 groundwater developed, which is less than 1. 3% of the groundwater recharge (Table 2). The area irrigated with groundwater is only 4. 2 × 10^3 ha. On the other hand, groundwater used directly in the terms of spring account for a large ratio with a value of 0. 802 × 10^9m^3. Together with spring water, the groundwater net usage ratio is up to 9. 4% with the value of 0. 344 × 10^9m^3. It is evident that there are great potential for groundwater development according to the ratio between recharge and discharge.

Table 2 The groundwater development status in the south of Tarim Basin(10^9m^3)

River basins	Groundwater recharge	Spring water use	Groundwater drilled	Net groundwater use	Total groundwater use rate(%)	Net groundwater use rate(%)
Pishan R.	0. 455	0. 087	0. 056	0. 067	14. 8	6. 0
Hotan R.	1. 472	0. 466	0. 014	0. 176	12. 0	0. 8
Qira R.	0. 413	0. 093	0. 004	0. 036	8. 8	0. 5
Keriya R.	0. 776	0. 138	0. 007	0. 057	7. 4	1. 0
Niya R.	0. 565	0. 018	0. 006	0. 007	1. 3	0. 1
Hotan Region	3. 681	0. 802	0. 037	0. 343	9. 4	1. 3

3 THE ASSESSMENT OF MAXIMUM SAFE YIELD

According to the hydrogeological condition and possibility of groundwater resources development the whole region can be divided into 7 parts (Fig. 1).

The aquifer with fresh water suitable for drinking and irrigation is distributed at the middle to front of piedmont alluvial plain between the Niya River and the Karakax River. The groundwater level varies from 100m to 10m with aegree of mineralization less than 1g/L or 1 - 3 g/L, and the thickness of the aquifer is about 300 - 900m correspondingly. Especially, the aquifer with the depth of 200 - 300m has large water capacity of well with a value of 3000 - 5000m³/d, which is rational pumping for drinking and irrigation with well group.

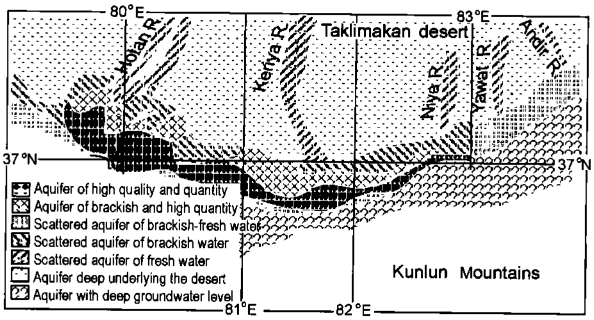

Fig. 1 The groundwater development condition in the southern piedmont plain of Tarim Basin

The hydrological cycle in subersurface can simply concluded as recharge - storage - discharge. The storage capacity increases and water level goes up when recharge is larger than discharge, whilst the storage capacity decreases and water level goes down when discharge exceed the recharge. In a cycle period without human disturbance, the discharge will keep balance with the recharge in an aquifer, so that the storage and water level will keep stable in a long time averagely. But when pumps, another supplement discharge will break the balance and a new balance would be formed. The groundwater balance equation under pumping can be written as follow:

$$(Q_r + \Delta Q_r) - (Q_f - \Delta Q_f) - Q_k = \mu F(\Delta h / \Delta t) \quad (2)$$

where Q_r is natural recharge, Q_f is natural discharge, Q_k is pumping capacity, ΔQ_r, ΔQ_f are the add recharge and discharge respectively under pumping, μ is aquifer yield capacity, F is aquifer area, Δh is water level change in the time Δt. $\mu F(\Delta h/\Delta t)$ is water come from storage, which is zero when pumping is stable. Because the region suitable for well drilling is situated in the spring discharge zone and its around area with shallow water, whilst the recharge mainly occurs at middle to up area of piedmont plain, it is impossible to get supplemental recharge and ΔQ_r keeps zero. If rearranging to give Q_k, Equation (2) reduces to

$$Q_k = Q_r - Q_f + \Delta Q_f \quad (3)$$

In a balance period natural recharge is equal to discharge, so that the pumping water actually deride from reduction of discharge ΔQ_f with the maximum value of natural discharge or recharge. However, the spring water has been used as the separate resources in the arid land of Northwest China, hence to reduce spring discharge for adding pumping is not rational nor scientific development. Thus reduction of evapo-transpiration is the main way for groundwater developing but cannot do that absolutly due to extreme aridity in Hotan Region. Then the maximum safe yield of groundwater can be calculated as:

$$\max Q_k = Q_r - E_g' - Q_{sp}' - Q_z' \quad (4)$$

where E_g', Q_{sp}', Q_z' are groundwater discharge under pumping via evapo - transpiration, spring and base out flow respectively. In the arid inland basin such as Hotan region of southern Tarim Basin, recharge is affected dramatically by runoff utilization, and is reduced seriously with increasing of runoff use (MA *et al.*, 2000a). Then the groundwater yield must be changed accordingly with the extent to that the runoff is or will be used. There are two programs to be taken account here according to the present water use status and future development condition.

Program I: Assuming runoff and spring water use keep stable as former, which is $5.04 \times 10^9 m^3$ out of the total runoff $7.26 \times 10^9 m^3$ averagely long time. On the other hand, the ecology water in the low reach and desert with the value of $2.18 \times 10^9 m^3$ according to present use must be drainaged from river to satisfy the reduction of spring water. Compared to the other inland river basins such as Malase river basin at the north edge of Tianshan Mountains and Hexi corridor in the north part of Qilian Mountains, the modulus of pumping is around $180 \times 10^9 m^3/a.km^2$ and the maximum water level dropdown is less than 5m. The maximum safe yield of groundwater is about $2.05 \times 10^9 m^3/a$ that is 55.8% of the recharge. Thus the evapo-transpiration will reduce about 60.4%, while spring water reducing 35.6% (Table 3).

Program II: According to economy and water engineering development extend, assuming water use rate is up to 80% except 65.8% in the Hotan River and 50% in the Niya River after WuLwarti Reservoir is finished in 2010, and accordingly, the factor of canal use also arrive to 0.55 from 0.4 – 0.49. As a result, the recharge will decrease 15.6% with the value of $3.1 \times 10^9 m^3$. The maximum safe yield of groundwater will reduce to $1.85 \times 10^9 m^3/a$. In this program the evapotranspiration will decrease 70%, whilst the spring discharge reducing 49.4% compared to present (Table 4).

Table 3 The maximum safe yield of groundwater under program I

River basins	Groundwater recharge				Groundwater discharge					Maximum safe yield
	R_g	R_i	$C_l + X$	Q_r	E_g'	Q_{sp}'	Q_z'	Q_f'	max Q_k	Modulus ($10^3m^3/km^2$)
Pishan R.	0.109	0.301	0.041	0.451	0.109	0.046	0.013	0.168	0.283	120.2
Hotan R.	0.095	1.491	0.073	1.659	0.439	0.285	0.039	0.764	0.895	165.11
Qira R.	0.112	0.255	0.026	0.392	0.049	0.056	0.017	0.122	0.271	66.5
Keriya R.	0.244	0.426	0.053	0.723	0.138	0.182	0.019	0.339	0.384	116.28
Niya R.	0.375	0.113	0.040	0.528	0.215	0.067	0.026	0.308	0.219	5.7
Hotan Region	0.935	2.586	0.233	3.753	0.940	0.646	0.114	1.701	2.052	134.4

Table 4 The maximum safe yield of groundwater under program II

River basins	Groundwater recharge				Groundwater discharge					Maximum safe yield
	R_g	R_i	$G_l + X$	Q_r	E_g'	Q_{sp}'	Q_z'	Q_f'	max Q_k	Modulus ($10^3m^3/km^2$)
Pishan R.	0.100	0.240	0.041	0.381	0.099	0.037	0.013	0.149	0.232	98.3
Hotan R.	0.083	1.249	0.073	1.406	0.281	0.234	0.039	0.554	0.852	157.3
Qira R.	0.100	0.202	0.026	0.328	0.038	0.045	0.017	0.100	0.228	140.5
Keriya R.	0.201	0.370	0.053	0.624	0.136	0.139	0.019	0.294	0.330	99.9
Niya R.	0.274	0.134	0.040	0.448	0.156	0.054	0.026	0.236	0.212	92.8
Hotan Region	0.758	2.195	0.233	3.187	0.710	0.509	0.114	1.333	1.854	121.5

4 PRINCIPLES OF SUSTAINABLE GROUNDWATER DEVELOPMENT

Sustainable groundwater resources development implies long-term benefit of efficient and rational groundwater use as a kind of water supply. The following key principles reflect the several aspects of sustainable development of groundwater resources.

(1) The Quantitative Protection of Groundwater Resources. It is obviously, first of all, critically important and necessary to take action for protecting water conservation forest and glacier in the Kunlun Mountains (QU, 1982), due to where the groundwater in the aquifer of piedmont plain mainly derive from. Secondly, groundwater should be developed together with surface water in a river basin as a unit, which constitutes an integrated ecology system. Groundwater resources must be allotted quantitatively for industry, agriculture, forestry and animal husbandry as well as ecology environment in proportion to surface water. Surface water cannot be used recklessly, so that it is rational way to extend water engineering and advanced water-saving irrigation technical for efficient use and reduce waste via evaporation and leakage of surface water. Wells are drilled both for pumping and drainage where the groundwater level is shallow to avoid water logging or salinity.

(2) The protection of groundwater quality. The quantitative aspect of resources availability for sustainable use is a basic concern for the evolution of water management. However, the quality aspect is also critical importance and is closely linked with the quantity

aspect(MA, 1997). The protection of groundwater quality must be taken seriously. Because of the complexity of various contaminate source diffusion and dispersion in complex hydrogeological environment, it is very difficult to make a simple direct relationship of cause and effect. Further more, once aquifer is contaminated, the affection will spread quickly and thus difficult to be controlled and treated. Therefore, the occurrence of contamination should be prevented and potential source is controlled as soon as possible in order to avoid reaction with groundwater system. On the other hand, when the aquifer is contaminated, it should be taken active measures to find and eliminate the contaminate source and keep the zone not to be spread or try to renew the water quality. Assessing and mapping of groundwater vulnerability, and setting up groundwater quality controlling program are key measurers and plans.

(3) Prevent possible negative environmental effect of groundwater development. Groundwater is an organic part of hydrological cycle and ecology system. The regulating and controlling role of ecology of groundwater is very outstanding in the fragile ecology of south of Tarim Basin (MA *et al.*, 2000a). The most indispensable factor in sustainable groundwater development is taking ecology sustainable seriously. The whole hydrology cycle and its close environment will change via disturbing the groundwater system, especially where the groundwater is closely hydraulic connections with river, lakes and spring(WEI *et al.*, 1997). The continue drawdown of water level will indisputable lead to groundwater exhausted and quality deteriorated, which in turn cause the environmental problems such as plant degradation, land aridity and desertification. So that in terms of environment sustainable, groundwater development is under the principle of no causing plant degradation.

(4) The technology and ability construction. Besides, the legislation, administrative management and the technology construction, and ability construction are also critical important and necessary. The ability construction is to explore the extend to which members of the general public are receptive to calls to change aspects of their everyday behaviors for the sake of the water resources. In particular, the focus should be put on the calls for whole society to take part in providing information services for decision-making and scientific propaganda of water problems. To do so, it is necessary to provide scientific education for public in particular the farmers of water resources problems, irrigation technology and legal awareness.

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