Study on functions and rational allocation of Shule River Basin groundwater resources

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Abstract: Based on Investigation and Assessment on Rational Exploitation and Utilization of Groundwater Resources in Typical Areas of the Hexi Corridor, the thesis studies on groundwater and environmental problems arising from the large-scale agricultural development projects in Shule River Basin. The thesis analyzes problems in exploiting and utilizing water resources, defines the function zoning of groundwater resources in key areas and evaluates them. Finally, the thesis uses three-dimensional unsteady flow simulation and regional social and economic development plan to study on the allocation of groundwater in Shule River Basin. A proposal for rational allocation of Shule River Basin water resources has been put forward.

Keywords: Shule River Basin; The function zoning; Assessment of groundwater resources; Rational allocation of water resources

Introduction

The work area mainly includes Shule River Basin located in western Hexi Corridor. Yumen-Tashi Basin, Anxi-Dunhuang Basin and Huahai Basin are in the middle and lower reaches of Shule River Basin. Shule River Basin is about 19 300 m^2 with Qilian-Altun Mountains in the south, Beishan Mountains in the north, Kumtag desert in the west and Jinta Basin in the east. Shule River Basin has large irrigation areas, including Changma, Shuangta, Huahai and Danghe River areas (Fig. 1).

Shule River Basin is an area with the lowest utility rate of water and land resources, and greatest development potential of groundwater resources in the Hexi corridor. In 1996, a large agricultural development project “Integrated Development Project of Agricultural Irrigation and Migration Settlement in Shule River Basin” was implemented. Since then, the local people have adopted a series of engineering measures, including constructing Changma reservoir, renovating local irrigation system and digging wells. The utility rate of surface water has been much improved. The area of arable land has been increased 27 213.33 hm^2 and the population of newly migrants is up to 75 000. The development project has significantly changed the use pattern of surface water and groundwater resources.

To study groundwater and environmental problems arising from the large-scale agricultural development projects in Shule River Basin, from 2003-2005, China Geological Survey Bureau included “Investigation and Assessment on Rational Exploitation and Utilization of Groundwater Resources in Hexi Corridor” as part of “Investigation and Assessment on Rational Exploitation and Utilization of National Groundwater Resources (Phase 1)” project. The investigation and assessment project helps establish simulation models of surface water and groundwater resource allocation in key areas of Shule River Basin. Together with regional social and economic development plan, the project provides rational allocation and protection plan for water resources in Shule River Basin. In this way, a geographic theory has been established to better help rationally allocate water resources and plan how to use national land and resources.

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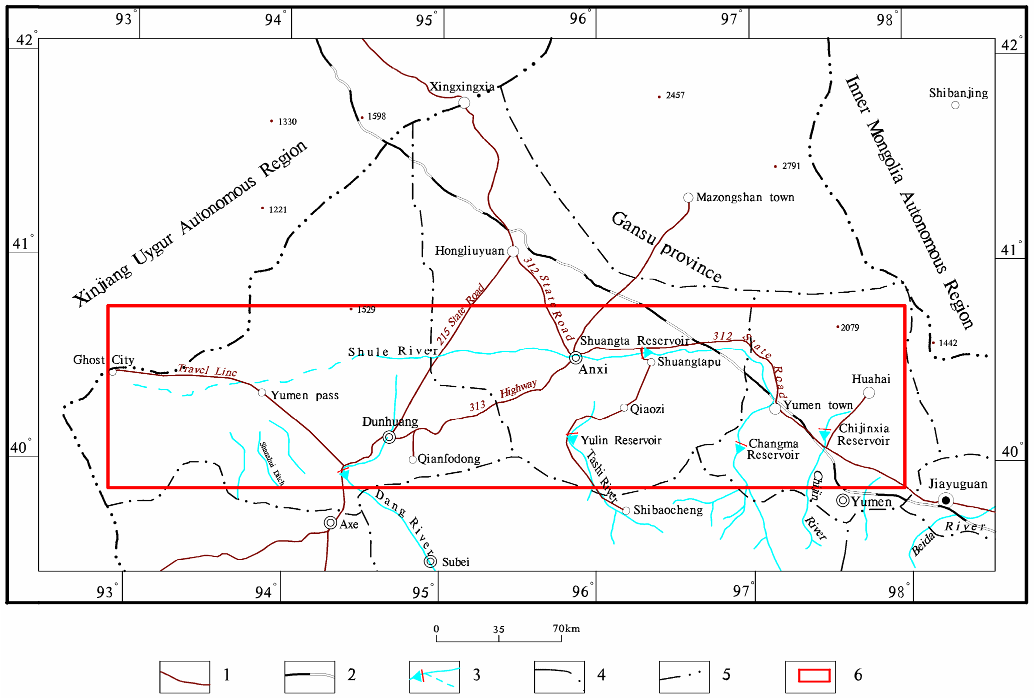


Fig. 1 Location map of the study area

1. Road; 2. Railway; 3. River or reservoir; 4. County boundary; 5. Provincial boundary; 6. Scope of study area

1 Major research contents

1.1 Problems in exploiting and using water resources

Over the past decades, great achievements have been made in exploiting and utilizing surface water and groundwater resources in Shule River Basin. A lot of hydro-projects have been established. Under extremely dry weather conditions, an irrigation area of 83 113 hm^2 has been built and it brings about great social and economic benefits. However, the exploitation and utilization of local groundwater cannot completely meet the economic and social development requirements. Specifically, the problems in exploiting and using water resources are as follows:

(1) Severe waste of water resources and low benefits of exploitation and use

Agriculture is a major user of ground and surface water in Shule River Basin. Over 90% of exploited groundwater has been used for agricultural irrigation. Due to backward irrigation technologies in Shule River Basin, most irrigation areas still use extensive and inefficient wild flooding irrigation. The water of duty is 9 750-12 000 m^3/hm^2 on average. The water of duty for some areas even reaches 15 000 m^3/hm^2. The utility rate of irrigation areas is 0.45-0.55 on average with that of some areas being 0.35-0.45. Every cubic meter water on irrigation land produces 0.15-0.30 kg grain and water consumption is 3.2-6.8 m^3/kg. Every cubic meter water on irrigation land produces 0.030 kg cotton and water consumption is 8-26.5 m^3/kg. The comprehensive output value is only 2.46 yuan/m^2, ranking the last one in the Hexi Corridor.

(2) Irrational well spacing and insufficient overall planning

Now, most water exploitation wells in the Basin have been built based on the location of arable lands and water demands, that is to say, there is no overall planning for well spacing. Too many wells are located in one place, so during the peak period of irrigating, inter-well interference is serious. Pumps may fall, which can even lead to premature well failure. Therefore, the local industrial and agricultural production has been greatly restricted.

(3) Overexploitation in some areas leading to environmental and geological problems

In Shule River Basin, Danghe River irrigation area has been exploited most with an average well density of 8 m^3/a, the amount of exploited groundwater of 72 860 000 m^3/a and exploitation modulus of 333 800 $m^3/km^2 \cdot a$. Most of Danghe River irrigation area has been overexploited. Therefore, the groundwater level in the southern of Danghe River irrigation area is declining continuously and, thus, the famous Crescent Lake is shrinking greatly. In Wudun county, some trees withered. If appropriate measures cannot be adopted in time, hundreds of millions hectare cropland will become desert.

(4) Irrational water usage structure

In Shule River Basin, rather than animal husbandry and forestry, most water has been used in agriculture. The imbalanced water usage structure reduces the benefits of water usage. Shule River Basin has a long history of animal husbandry. Developing animal husbandry can help effectively use grassland resources within the basin. As forage grass widely adapts to water and soils and can use the groundwater unsuitable for developing agriculture, it improves the use benefits of water resources. Also, planting forage grass can improve the quality of soil and curb desertification. At present, with surging population, reclaiming land and planting monocrops cannot bring economic benefits. Specifically, it brings no good to local production and livelihood, hinders the development of other business activities and harms the vulnerable ecological and environment system. Irrigation areas of forestry and animal husbandry should be developed. Overexploitation of groundwater should be avoided so that the groundwater level will stop declining. Also, the abundant groundwater resources should be exploited and used.

(5) Unified management of Shule River Basin and lack of optimal dispatch of water resources

There are still a lot of problems in allocating upstream and downstream water, exploiting surface water and groundwater and protecting ecological environment. The transformation relationship between surface water and groundwater is complex. The water usage in the middle reaches of Shule River Basin is relatively large. In the lower reaches, the spring water transformed from groundwater is quite important. Due to the water usage increase in the upper and middle reaches, since the beginning of 1970s, water in the lower reaches has continued to decline. In the lower reaches below the Double-tower Reservoir in Shule River Basin, the groundwater almost dries up. In the past, the local people irrigated land by using water from river and spring. Now, they can only irrigate land by using water from rivers and wells. To realize the sustainable development within water resources carrying capacity, we must have an overall picture. We must rationally integrate, allocate and dispatch water resources so that Shule River Basin develops in a balanced manner and local people no longer need to abandon land in the lower reaches.

1.2 Assessment on the functions of groundwater resources

1.2.1 Assessment indicator system

According to Technical Requirements of Investigation and Assessment on National Groundwater Resources and Environment Issues II and Applied Teaching Materials of Assessment and Method Generalization, together with the hydrogeology and environmental conditions of Shule River Basin, an assessment indicator system of groundwater resources function has been established for Shule River Basin (Table 1). The indictor system focuses on the functions of groundwater resources, ecologic environment and geologic environment. The indicator system is a “driving force-status-reaction” (DSR) system. The system consists of driving factor group, status factor group and reaction factor group. The indicator system has a four hierarchical structure, that is to say, 1 systematic objective layer, 3 functional baseline layers, 9 property indicator layers and 25 elementary indicator layers (Table 1).

1.2.2 Assessment methods

According to the systematic distribution of basin groundwater and the scope of project work area, the functional assessment focuses on Yumen-Tashi Basin, Anxi-Dunhuang Basin and Huahai Basin in Shule River Basin. According to the water supplementations, runoff and discharge in the middle and lower reaches, and deep groundwater storage situation, all basins were divided into infiltration supplementary zone, runoff storage zone and evaporation discharge zone. Shule River Basin could be divided into 9 assessment zones (Fig. 2). Further, basic assessment units were partitioned as $1.5 \times 1.5\ km^2$ in MAPGIS and 10 621 effective units.

Table 1 Assessment indicator system and indicator grade division of groundwater function in Shule River Basin

System layer (A)	Function layer (B)	Property layer	Indicator layer	
Name and code of the systems	**Name and code of functions**	**Name and code of the property**	**Indicator name**	**Property and code**
System (A_1)	Resource function (B_1)	Resource occupancy (B_1C_1)	Supplementary occupancy of external resources	S, $B_1C_1D_1$
			Supplementary occupancy of internal resources	S, $B_1C_1D_2$
			Available resource occupancy	S, $B_1C_1D_3$
		Resource reproducibility (B_1C_2)	Supplementary availability	D, $B_1C_2D_1$
			Supplementary balancing rate	D, $B_1C_2D_2$
			Supplementary rate of rainfalls	D, $B_1C_2D_3$
		Resource adjustability (B_1C_3)	Variation difference supplementary ratio in water level	S, $B_1C_3D_1$
			Variation difference exploited ratio in water level	S, $B_1C_3D_2$
			Variation difference rainfall ratio in water level	R, $B_1C_3D_3$
		Resource usability (B_1C_4)	Exploitation modulus	S, $B_1C_4D_1$
			Quantity indicator of resources	S, $B_1C_4D_2$
			Degree of resource exploitation	S, $B_1C_4D_3$
	Ecologic function (B_2)	Sustainability of landscape environment (B_2C_5)	Correlation between limnological environment and groundwater	R, $B_2C_5D_1$
			Correlation between landscape indicator and groundwater	R, $B_2C_5D_2$
		Correlation between water environment (B_2C_6)	Correlation between water environment mineralization and groundwater	R, $B_2C_6D_1$
			Correlation between nitrogen and phosphorus, and groundwater	R, $B_2C_6D_2$
		Plant environment sustainability (B_2C_7)	Correlation between meadow changes and groundwater	R, $B_2C_7D_1$
			Correlation between natural planting and groundwater	R, $B_2C_7D_2$
			Correlation between oasis and groundwater	R, $B_2C_7D_3$
		Correlation between soil and water (B_2C_8)	Correlation between land desertification and groundwater	R, $B_2C_8D_1$
			Correlation between land salinization and groundwater	R, $B_2C_8D_2$
			Correlation between land quality and groundwater	D, $B_2C_8D_3$
	Geological environment function (B_3)	Groundwater system degradation (B_3C_9)	Correlation between groundwater quality and water level	R, $B_3C_9D_1$
			Correlation between spring and groundwater	S, $B_3C_9D_2$
			Groundwater supplementary change ratio and difference ratio in water level	S, $B_3C_9D_3$

Note: D represents driving force indicator, S, status indicator and E, reaction indicator

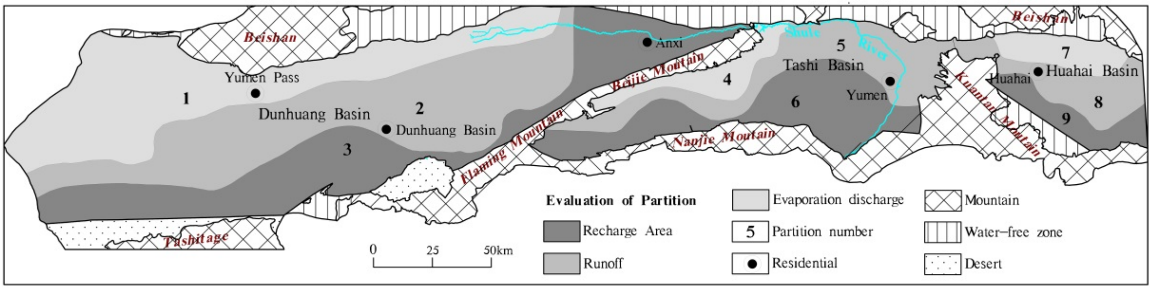


Fig. 2 The assessment zone map of groundwater function of the basins in Shule River Basin

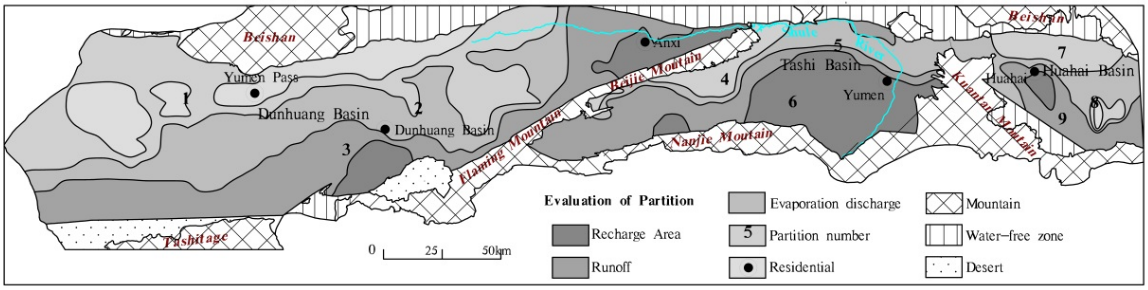


Fig. 3 The system multiple grade index map of the groundwater function

According to the above dividing and unit partitioning results, all center point coordinates and zone codes were caught by the techniques of MAPGIS space analysis. Zones were set up and information data documents were partitioned based on the requirement of GFS software.

Then, engineers operated GFS software and input data files into programs. After complex computation of software, composite index of all assessment indicators come out. Then, in accordance with the grading principle of all indicators in Technical Requirements, assessment result map of groundwater function has been drawn by Kring interpolation in MAPGIS.

1.2.3 Assessment results

With data calculation at indicator level, specialized assessment at property level and comprehensive assessment at functional level, the assessment results of groundwater function in the Shule River Basin were made. The system multiple grade index map of the groundwater function has been drawn (Fig. 3). Changma diluvial fan area of Yumen-Tashi Basin in the middle reaches, the middle and upper Yulin diluvial fan area, the middle and southern Shuangta irrigation area of Anxi-Dunhuang Basin in the lower reaches, the southeastern Danghe River diluvial fan area and the middle Huahai irrigation area had strong sustainability. The joint belt between the front area and the irrigation area of Changma diluvial fan in the middle reaches, the middle and lower reaches of Yulin diluvial fan area and the western desert zone, the north and west of Shule River dry delta in Anxi-Dunhuang Basin of the lower reaches, the diluvial slope in front of Beijie Mountain, the middle diluvial fan area of the Danghe River and the diluvial slope in front of western Karatashitag Mountain, the peripheral part of Huahai irrigation area and diluvial fan in front of Kuantan Mountain had relatively strong sustainability. Most of Changma irrigation area in the middle Yumen-Tashi Basin, the front fine-grained soil zone of Yulin dilvial fan area, the western desert zone of Shuangta irrigation area in Andun Basin of the lower reaches, Danghe River irrigation area, the middle and lower Danghe River diluvial fan area, the lower part of the diluvial slope in front of Karatashitag Mountain, Petroleum River diluvial fan area of Huahai Basin, Qingshan Farmland and the middle and eastern basin had general sustainability. Tuhulu-Qiaozi Nature Reserve of the middle Yumen-Tashi Basin, the lower Lucaogou, West Lake irrigation area of the lower Anxi-Dunhuang Basin, Yitang Lake, the peripheral and northern area from Houkeng west of Yumen Pass to Wanyao Nature Reserve, the northern nature reserve of Huahai Basin and the middle and eastern well irrigation area had relatively weak sustainability. The ancient riverway of the basin in lower Shule River, Houkeng in the west of Yumen Pass to Wanyao Nature Reserve, the eastern part of well irrigation area in Huahai Basin had weak sustainability.

1.3 Assessment on groundwater resources potential

1.3.1 Groundwater resources potential

The groundwater resources potential of Shule River Basin mainly comprises of the usage potential and exploitation potential. Usage potential refers to the groundwater which is saved in the use process and can be reused to release the exploitation pressure. The exploited groundwater is mainly used for irrigation in Shule River Basin, which can save much water. However, since industrial and living consumption of water are relatively small, saving water from industry and daily living is limited. Agricultural groundwater-saving potential can represent the present usage potential. It is calculated that the usage potential of Shule River groundwater is 27.49×10^6 m^3, among which Huahai Basin occupies 5.64×10^6 m^3, Yumen-Tashi Basin, 7.98×10^6 m^3 and Anxi-Dunhuang Basin, 13.87×10^6 m^3 (Table 2, Table 3).

Table 2 Saving water quantity in combined irrigation area of wells and channels

Basin	Irrigation area	Area (hm^2)	Current duty of water (m^3/hm^2)	Reasonable duty of water (m^3/hm^2)	Saving water quantity in reasonable irrigation (100×10^6 m^3/a)	Saving groundwater quantity in reasonable irrigation (100×10^6 m^3/a)
Huahai	Huahai	8 707	8 250	6 750	0.1306	0.0094
Yumen-Tashi	Changma	42 613	8 250	6 750	0.6392	0.0722
	Yulin	2 513	8 250	6 750	0.0377	0.0068
	Qiaozi	480	8 250	6 750	0.0072	0.0008
Anxi-Dunhuang	Shuangta	1 949	8 250	6 750	0.2924	0.0465
	Danghe River	21 826	9 000	7 500	0.3274	0.0922
Total					1.4345	

Table 3 Saving water quantity in well irrigation areas

Irrigation area	Area (hm^2)	Current duty of water (m^3/hm^2)	Reasonable duty of water (m^3/hm^2)	Saving water quantity in reasonable irrigation (100×10^6 m^3/a)
Huahai	3 133	7 500	6 000	0.047

Table 4 Calculation of exploitation surplus

Basin	Exploited resources (100×10^6 m^3/a)	Current exploited quantity (100×10^6 m^3/a)	Exploitation surplus (100×10^6 m^3/a)
Yumen-Tashi	1.2935	0.4990	0.7945
Anxi-Dunhuang	1.4010	1.0761	0.3249
Huahai	0.3112	0.1120	0.1992

The formula for exploitation potential is exploited resource minus current exploitation quantity, namely exploitation surplus. It is calculated that groundwater exploitation surplus of Yumen-Tashi, Anxi-Dunhuang and Huahai Basin in Shule River are 79.45×10^6 m^3, 32.49×10^6 m^3 and 19.92×10^6 m^3, respectively. All basins had their own exploitation potential (Table 4).

As the confined aquifer roof was not steady in most irrigation areas of Shule River and the exploitation well cut through aquifer, the boundary between confined groundwater and phreatic water was unclear, and phreatic water and confined groundwater were exploited together. In the exploitation area, the phreatic groundwater mainly had the degree of low salinity from 1 g/L to 3 g/L and had been used as exploited resources. Therefore, the exploitation surplus of the groundwater can be used as exploitation potential.

1.3.2 Groundwater potential coefficients

The formulas below have been used to calculate groundwater potential coefficients.

$$\alpha=(Q_{\text{exploited resources}}+Q_{\text{enlarged quantity}})/(Q_{\text{exploitation resources}}-Q_{\text{usage potential}}) \qquad (1)$$

Among which, α-groundwater potential coefficient; $Q_{\text{exploited resources}}$- the quantity of exploited resources in the exploitation layer; $Q_{\text{exploitation quantity}}$- the exploited quantity in the exploitation layer; $Q_{\text{enlarged quantity}}$- the quantity of enlarged exploitation resources; $Q_{\text{usage potential}}$- groundwater usage potential; This area is calculated by taking basin as one unit and there are no enlarged exploitation resources from external water sources. Therefore, the formulas above can be simplified as:

$$\alpha=Q_{\text{exploitation resources}}/(Q_{\text{exploited quantity}}-Q_{\text{usage potential}}) \qquad (2)$$

Groundwater potential multiple grade can be seen in Table 5.

The simplified formula can be used to calculate the corresponding groundwater potential coefficients of Yumen-Tashi Basin, Anxi-Dunhuang Basin and Huahai Basin. The coefficients are 3.16, 1.51 and 5.66, respectively in Shule River. The groundwater potential is very huge, though Anxi-Dunhuang Basin has the relatively small coefficient (Table 6).

Table 5 Multiple grade of groundwater potential coefficient

Potential coefficient (α)	Assessed grade
$\alpha<1$	No groundwater potential
$1\leqslant\alpha<1.2$	General groundwater potential
$1.2\leqslant\alpha<1.4$	Relatively huge groundwater potential
$\alpha\geqslant1.4$	Huge groundwater potential

Table 6 Groundwater potential coefficient of Shule River Basin

Basin	Exploitable resources (100×10^6 m^3/a)	Exploited quantity (100×10^6 m^3/a)	Usage potential (100×10^6 m^3/a)	Groundwater potential coefficient	Potential grade
Yumen-Tashi	1.2935	0.4990	0.0798	3.16	Area with huge potential
Anxi-Dunhuang	1.4010	1.0761	0.1387	1.51	Area with huge potential
Huahai	0.3112	0.1120	0.0564	5.66	Area with huge potential
Total	3.0057	1.6871	0.2749	2.13	Area with huge potential

1.4 Water resources allocation in the basin

1.4.1 Water resources allocation plans

Three plans were chosen for analysis, calculation, and simulation.

(1) Plan 1: Drawing mainly from surface water, made in the Shule River Relocation Project

This plan was made in the Shule River Agricultural Irrigation and Relocated People Development Project. The plan was proposed when the Changma Reservoir was put into service, thus enabling water transfer among three different reservoirs. In this plan, agricultural irrigation will draw only from surface water, while industrial consumption (except for Factory 404 which uses surface water) and drinking water for people and livestock all come from groundwater. The water demand of every irrigation area is regulated strictly following the planned quotas in the Project. More specifically, rural and urban drinking water for people and livestock stands at 11×10^6 m^3/a (supply from groundwater), water demand of rural companies stands at 8×10^6 m^3/a (supply from groundwater), industrial water demand of Factory 404 stands at 82.75×10^6 m^3/a (supply from surface water), agricultural irrigation demand stands at 632.33×10^6 m^3/a (supply from surface water), and water demand of irrigation for surrounding woods and protection forests stands at 11.16×10^6 m^3/a (supply from surface water).

(2) Plan 2: Drawing mainly from surface water with supplements from groundwater

Plan 1 mostly draws water from surface water sources and gives relatively less consideration to the exploitation of groundwater and the water demand of ecological environment in the downstream. Therefore, in Plan 2, groundwater is used as a supplementary source for irrigation. The extraction of groundwater is increased, while the use of surface water is relieved. The surface water saved in this plan will be transferred to the natural watercourses via reservoirs, which will help alleviate the deterioration of ecological environment in the downstream areas.

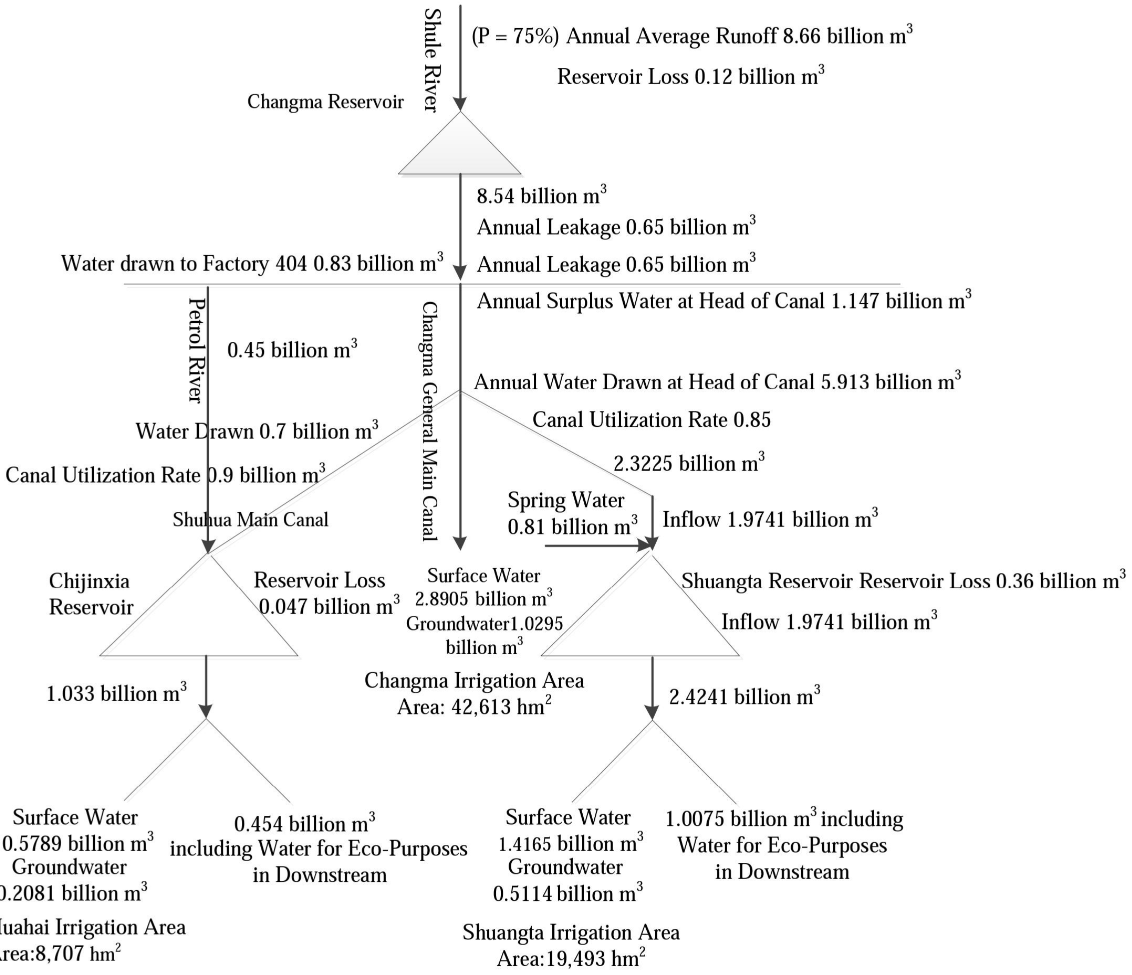
To be more specific, rural and urban drinking water for people and livestock stands at 11×10^6 m^3/a (supply from groundwater), water demand of rural companies stands at 8×10^6 m^3/a (supply from groundwater), industrial water demand of Factory 404 stands at 82.75×10^6 m^3/a (supply from surface water), agricultural irrigation demand stands at 632.33×10^6 m^3/a (550.86 million from surface water and 81.47 million from groundwater), and water demand of irrigation for surrounding woods and protection forests stands at 11.16×10^6 m^3/a (supply from surface water).

(3) Plan 3: Emphasis on soil improvement and ecological balance based on proper usage of surface water and groundwater

If water is allocated according to Plan 2, the newly-reclaimed land in Changma irrigation area, Shuangta irrigation area and huahai irrigation area will all rely on surface water for irrigation. This will inevitably lead a rise in water tables in some oases and newly-reclaimed wasteland, where water tables are already less than 5 m deep, to the salinization critical point (2 m-2.5 m) of the basin, resulting in secondary salinization. In the newly-reclaimed land where water table depth is less than 2 m all year round, measures have to be taken to drain salt out of the soil to ensure that the soil remains eligible for long-term use. Although efforts have been made by using horizontal canal systems for salt drainage, according to past experience in soil improvement, this measure alone will not yield the expected results. Thus, shafts need to be employed to help with salt drainage efforts. With vertical shafts, water tables can be lowered to a point deeper than the salinization critical point of the basin, thus avoiding secondary salinization. An added benefit of using shafts is that well irrigation can also be integrated to make full use of water resources and save more water for the fragile ecological environment in this area.

Based on the assessment of the function and potential of this basin’s groundwater, combined with analysis of water demand and supply relationships, the following analysis was rendered: Given that the total water demand in Shuangta irrigation area, Changma irrigation area, and Huahai irrigation area remains unchanged, if well irrigation is used and shafts are employed for salt drainage in some newly-reclaimed land where water tables are less than 5 m deep, soil salinization can be relieved and more groundwater can be extracted for agricultural irrigation. Compared to the original water extraction amount in these three irrigation areas, another 6.15×10^6 m^3/a, 5.346×10^6 m^3/a and 13.82×10^6 m^3/a of water can be extracted from underground in Huahai Irrigation Area, Changma Irrigation Area and Shuangta irrigation area respectively. Consequently, less water is needed for irrigation from surface sources.

Specifically, total water demand of three irrigation areas stands at 745.24×10^6 m^3/a, rural and urban drinking water for people and livestock stands at 11×10^6 m^3/a (supply from groundwater), water demand of rural companies stands at 8×10^6 m^3/a (supply from groundwater), industrial water demand of Factory 404 stands at 82.75×10^6 m^3/a (supply from surface water), agricultural irrigation demand stands at 632.33×10^6 m^3/a (477.43 million from surface water and 154.9 million from groundwater), and water demand of irrigation for surrounding woods and protection forests stands at 11.16×10^6 m^3/a (supply from surface water). Please refer to Fig. 4 for water utilization details when P=75%.



Note: All the water quantity in this diagram takes the unit of 100 million m^3/a.

Fig. 4 Water utilization at Changma, Shuangta, and Huahai irrigation areas in Plan 3

1.4.2 Model prediction results

A corrected 3D groundwater unsteady flow model is applied to produce balance analysis and predictions on the above mentioned three plans. The results were as follow: When P=50%, the water supply in all three plans could meet the demand of agricultural, industrial and drinking consumptions. In addition, the surplus water from each irrigation area and the water for ecological environment both exceeded 0.25×10^6 m^3/a, an amount sufficient to satisfy ecological water demand (According to the report Proper Use of Water Resources and Protection of Ecological Environment in the Hexi Corridor, 0.25×10^9 m^3/a of water is needed to maintain the current ecological environment in the basin of the Shule River.) When P=75%, the water supply in all three plans could still meet the demand of agricultural, industrial and drinking consumptions. Yet, in terms of water saved for the environment, the surplus water and water for ecological purposes in Plan 1 and Plan 2 stood at 109.3×10^6 m^3/a and 185.3×10^6 m^3/a respectively, an amount unable to meet the water demand of environment. Only in Plan 3, the surplus water and water for ecological purposes reached 261×10^6 m^3/a, which would be able to maintain the current ecological environment.

For Danghe irrigation area, both Plan 1 and Plan 2 make use of water currently available, while in Plan 3, allocation is made based on the results of water conservation efforts. For every 1 500 m^3/hm^2 of irrigation quota reduction, 30×10^6 m^3/a of groundwater was spared from extraction. Thus the drafting of ground water remained within the upper limit of 45.56×10^6 m^3/a in this area, reaching a balance between water supply and demand.

According to our simulation, after Plan 1 had been implemented for 30 years, around 18 560 hm^2 of land in the irrigation areas would have a water table less than 2.5 m deep, which failed to avoid salinization. Of the said land, Huahai irrigation area accounted for 1 193 hm^2, Changma irrigation area accounted for 14 613 hm^2, and Shuangta irrigation area 2 753 hm^2.

Compared to Plan 1, with an investment of 382×10^6 yuan, another 153.74×10^6 m^3/a of groundwater could be exploited in Plan 2. The extra groundwater could irrigate 86 720 hm^2 of land and the equivalent amount of spared surface water could then be saved for the environment. Yet in Plan 2, there remained 16 673 hm^2 of land with a water table depth of less than 2.5 m, which could not guard against salinization. Among the said land, Huahai irrigation area accounted for 1 086 hm^2, Changma irrigation area accounted for 13 073 hm^2, and Shuangta Irrigation Area accounted for 2 513 hm^2.

With an investment of 62×10^6 yuan, another 73.43×10^6 m^3/a of groundwater could be extracted. Consequently, 15 673 hm^2 of land could be improved and enough water was saved for ecological protection. This plan could basically guard all the land where water table depth is less than 2.5 m against salinization.

3 Conclusions and discussions

After comprehensive calculation, analysis and comparison, the following conclusions are reached:

Plan 1 is simple in which agricultural irrigation relies solely on surface water and little consideration is given to the utilization of groundwater. As agricultural consumption depending solely on surface water, the recharge source for groundwater in Changma irrigation area will change from current river water to irrigation water, while the recharging area will move downward from the diluvial areas in the south to the fine earth plain areas in the north. Meanwhile, the water tables in artificial oases, especially newly-reclaimed areas, will rise, as a result of over dependency on surface water for irrigation, to the salinization critical point of 2 m to 2.5 m in the Shule River Basin, resulting in secondary salinization in areas with shallower water tables. For newly-reclaimed areas where water table depth is already less than 2 m, currently only horizontal canal systems are used for salt drainage. However, according to past experience, this measure alone will not yield the expected results. Thus, shafts and well irrigation need to be employed to help with salt drainage efforts. Otherwise, the reclaimed land will once again be abandoned. This plan fails to give sufficient consideration to the water demand of ecological environment. When P=75%, only 109.3×10^6 m^3/a is saved for ecological purposes, yet the required amount is 250 million m^3/a. Suppose water for ecological purposes continues to stand at 47×10^6 m^3/a in Danghe irrigation area, another 203×10^6 m^3/a of water is needed for ecological purposes, leaving a gap of 93.7×10^6 m^3/a. In such a scenario, current ecological environment cannot be maintained, let alone improved. Even when P=50%, water for ecological purposes stands at 299×10^6 m^3/a. This may seem sufficient for the environment but upon careful examination, there is a huge disparity in water supply geographically: Water for ecological purposes in Changma stands at 210×10^6 m^3/a, in Huahai 33×10^6 m^3/a, and in Shuangta 56×10^6 m^3/a. However, Shuangta irrigation area and most of the natural oases to its west demand a large amount of water to maintain its current ecological environment. Insufficient ecological water supply will further deteriorate the local environment. Therefore, it can be concluded that Plan 1 is not feasible on many accounts.

Both Plan 2 and Plan 3 use a mix of surface water (main supply) and groundwater (supplementary supply) for agricultural irrigation. The main flaws in Plan 2 are as follow: Plan 2 is lacking in its consideration to soil improvement. As the newly-reclaimed areas depend solely on surface water for irrigation, in areas with a water table depth of less than 5 m, the infiltration of irrigation water will lead to a rise in water tables. Especially in areas with a water table depth of less than 2 m, no shaft salt drainage is planned which will lead to secondary salinization. In terms of water for ecological purposes, when P=50%, water for ecological purposes stands at 395.8×10^6 m^3/a (including 47×10^6 m^3/a of water in Danghe irrigation area), which not only exceeds the 250×10^6 m^3/a of water required to maintain the current status, but also basically meets the 403×10^6 m^3/a of water required to keep the ecological environment in a good shape. Therefore, the situation will be conducive to the improvement of degraded vegetation and the ecology of the whole area.

When P=75%, water for ecological purposes stands at 236×10^6 m^3/a (including 47×10^6 m^3/a of water in Danghe irrigation area). This may seem able to meet the environmental water demand of 250×10^6 m^3/a, but upon careful examination one can find that in Changma irrigation area, water for ecological purposes stands merely at 45×10^6 m^3/a. This insufficient water supply for the environment will lead to a considerable decline in the recharge of groundwater. As a possible result, spring water ranging from Qiaozi to Maquan areas could suffer a sharp drop and the environment will also be negatively affected. Although Plan 2 fares better than Plan 1, it is still lacking in its consideration to soil improvement, environment protection, and vegetation recovery.

Plan 3 is an improvement based on Plan 1 and Plan 2. While it takes agricultural, industrial and drinking consumptions as a priority, it also gives full consideration to environment protection and soil improvement. In terms of agricultural, industrial and drinking consumptions, all is provided by groundwater with the exception of Factory 404 which draws its 83×10^6 m^3/a of water from surface sources. Agricultural irrigation mainly replies on surface water and is supplemented by groundwater. In terms of environment protection, to maintain the current status, 250×10^6 m^3/a of water is needed. If water for ecological purposes remains at 47 million m^3/a in Danghe irrigation area, the other three irrigation areas altogether need 203×10^6 m^3/a of water. In Plan 3, when P=50% and P=75%, water for ecological purposes of these three irrigation areas stands at 444×10^6 m^3/a, and 259.2×10^6 m^3/a respectively. It can be observed that the water is sufficient for these three irrigation areas to maintain their environment, and there is even a surplus of 241×10^6 m^3/a and 56.2×10^6 m^3/a respectively. In this scenario, the environment can be further improved, some degraded vegetation and wetland can be restored, and it is also conducive to the protection of endangered animals and plants and their habitats. In terms of soil improvement, some of the newly-reclaimed areas have a water table depth of less than 5 m. As the salinization critical point of this basin stands at 2 m to 2.5 m, for areas with a water table depth of less than 2 m, a combination of well irrigation, shaft and horizontal canal salt drainage should be used. In addition, all the irrigation water should come from underground, which will push water tables to deeper than 3 m. For areas with a water table depth between 2 m and 5 m, as its annual change is subject to infiltration from irrigation water, and some areas may rise above the critical point, irrigation should be supplemented by groundwater and a combination of well irrigation and shaft salt drainage should be partially used to avoid secondary salinization. It can be observed that in this plan, soil can be improved, surface and underground water is effectively used with well irrigation and shaft salt drainage, and the environment is protected and restored with sufficient water. Yet, it is not a perfect plan. It is noteworthy that in soil improvement with well irrigation and shaft salt drainage, in order to avoid decline in water tables in surrounding areas, measures are taken which may lead to vegetation degradation and desertification. To avoid such problems, shaft number, spacing and extraction have to be carefully regulated in the implementation of this plan. In addition, a monitoring network should be set up in the soil improvement areas and their surrounding areas to keep the changes in water table depth in check. It is noted that Plan 3 is an improvement from Plan 1 and Plan 2. Being more reasonable and sound, this plan allocates surface water and groundwater properly via water conservancy facilities. It facilitates sustainable economic development of the whole basin area, protects and improves local ecological environment, raises the efficiency of water utilization in the whole basin, and promotes balanced regional economic, social and environmental development.

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