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Research on the mechanism of water resource loss in east karst mountain area of Sichuan

Xiaobing Kang, Sheng Luo, Mo Xu*

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China
Tel. +86 028 84078874; Fax: +86 028 84073193; email: xm@cdut.edu.cn

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ABSTRACT

On the eve of the twenty-first century, the world is facing a water crisis of unprecedented magnitude and water crisis is more serious in the karst mountain area. Water loss, contradiction between provision and demand, water environmental ever increasingly exacerbation are serious in middle regions of Huaying mountain in Sichuan province, which belongs to the karst mountain area and influences people's normal life and work. Furthermore, they had severe impacts on the construction and development of regional economy. With combination of field survey and indoor data analysis and calculation, the mechanism of water resource loss in this area has initially been identified; four main factors: climate change, topography, social economic growth, and human engineering activity are involved, decrease of rainfall and steep topography in the mountain region resulted in the shrink of water replenishment. In addition, social economic growth, expansion of human engineering activities led to great water consumption. Both loss of water yield and degradation of water quality had occurred in the area. The volume of losing water in the west wing of Huaying mountain is larger than that of the east wing; the north part of the west wing is the most serious region which suffered the biggest water loss.

Keywords: Karst mountain area; Water resource; Loss mechanism; Human activities

Water is so crucial to life that human beings and any other organisms are unable to live without it. It is a natural resource of great value and unlikely to be substituted, which supports industrial and agricultural production, economical and social development, and environmental esthetics [1]. Water crisis in the past usually meant scarcity of drinking or irrigation water due to drought in a regional or time-constrained way. However, the frequency and amount of the areas that are affected by water problems have increased significantly over several decades [2]. At present time, water loss in the middle region of Huaying mountain is striking and water quantity cannot satisfy the demands of field irrigation and domestic use.

Water resources include surface water and groundwater, mainly from the water cycle. The water cycle manifests itself through many processes and phenomena, such as clouds and precipitation; ocean—atmosphere, cryosphere—atmosphere, and land—atmosphere interactions; mountain snow packs; groundwater; and extreme events such as droughts and floods. On land, the water cycle is considerably more complex,

*Corresponding author.

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and includes the deposition of rain and snow on land; water flow in run-off; infiltration of water into the soil and groundwater; storage of water in soil, lakes and streams, and groundwater; polar and glacial ice; and use of water in vegetation and human activities.

Huaying mountain is located in southern China, which receives abundant precipitation and belongs to the karst mountain area. Groundwater in this area is critical to both humans and ecosystems. Karst groundwater in Huaying mountain is predominantly of the karst cavern–conduit type and the karst crack–karst interstice type, which usually intertwine to form a complex system. Karst water often feeds into a submerged stream [3], the infiltration coefficient up to 60–80%, surface water and groundwater is often one of each other. Hydrological tests performed at Huaying mountain showed the movement of groundwater through the karst system in connection with caves, springs, and streams. The distribution and structure of the underground drainage systems are unusually heterogeneous and, as a result, the groundwater shows anisotropy in its hydraulic connection.

Karst water is one of important potable water sources, especially in arid and semi-arid zones. Due to its vulnerability and high sensitivity to pollution, water resources protection is one of important measures to be observed in karst resources management [4]. Various types of water resource developments have been carried out in many karst regions of the world. The cost of success was in many cases expensive failure [5]. While, many people study the management of water resources in karst regions [6–10], there are few studies of the mechanism on water loss in the karst area. Therefore, it is imperative to investigate the conditions and the cause of water loss and water environment present situations, assessing the degree of water loss and taking effective measures accordingly to protect and improve the existing water environment.

1. Physical geography of the study area

1.1. Location of the study area

Huaying mountain is the main body of mountain range which parallels, extending hundreds of kilometers. The middle part of the mountain is located in the area where the north boundary is Juantong town, Qu county, Dazhou City, the south reaches Gaotan town, Linshui County, covering Guangxin, Daishi towns, and Linshui county, and geographic coordinates east longitude 106°20′–106°50′, north altitude 30°00′–30°40′, length up to 115 km, width about 15 km; covering the east and west wings of Huaying mountain anticline, a scope of 1,330 km^2. It presents a northeast sliver shape (Fig. 1).

1.2. Social economic survey

Most of the study areas are located in Guangan City, Huaying country and Linshui county consisting of 82 towns and 91 villages. The area of the study is 6,344 km^2 with a population of 4,350,720, of which the urban population is 500,000. The region's GDP reached to 75.655 billion yuan in 2007, with an average annual growth rate of 13.7% from 2003. Predominant industries include coal, electricity, and building materials, which are growing fast to provide for the industrial economy [11].

1.3. Climate

The study area is located in the eastern Sichuan province, which belongs to a subtropical monsoon climate. Based on the data from the weather bureau in Guangan, the annual precipitation is 848.7–1474.1 mm, with the average annual precipitation of 1109.4 mm, and the rainy season is from May to October, with frequent torrential rains between June and August. The maximum daily precipitation is 132 mm, with the largest rainfall duration of 19 days and a rainfall rate of 172.5 mm. The dry period without rainfall reaches up to 24 days. The area belongs to an adequately humid region.

The average annual temperature of the region is 17–18 ℃. June, July, and August is the hot season in which the maximum temperature can reach 38 ℃; December, January, and February is the cold season with the minimum temperature of −2 ℃.

2. Geological environment survey

2.1. Topography and landform

Mid-Huaying mountain is strip-like shape alternating with dale, paralleling with Tongluo and Mingyue mountains, which forms a "川" shape (Fig. 2). The mountain ridge trend closely accords to the direction of regional tectonic lines, extending toward the bearing of N25–30°E. The features of the landform are controlled by geological formation, roughly high in the south, low in the north, and high on the ridge, low on both flanks. The highest point of the region is in the southern region with an elevation of 1,704 m. The lowest point, about 320 m, is located near the Wushan Village, Zhujiaqiao Town. A general elevation in the region is between 500 and 800 m. The area has steep and undulating hills. Thus, the area is classified

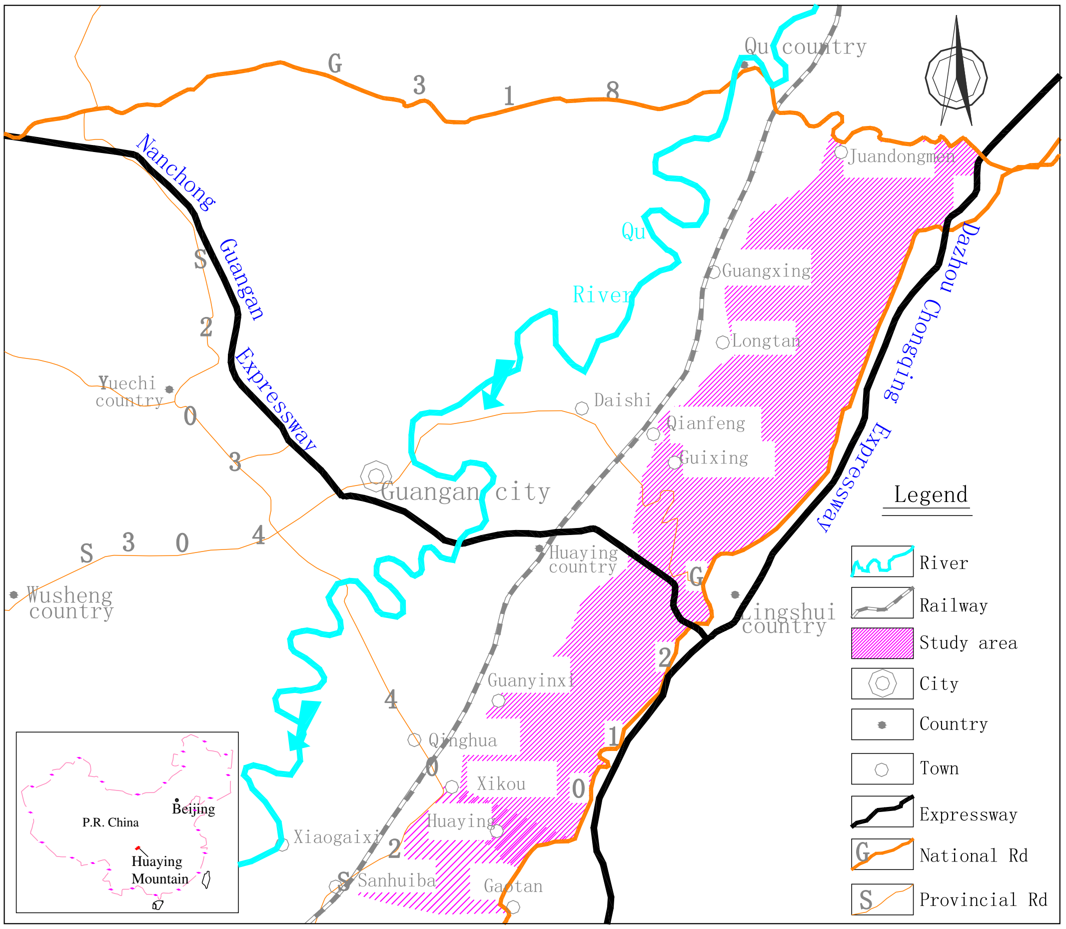


Fig. 1. Study area and transportation.

as low to medium landform with typical tectonic denudation and erosion.

2.2. Strata lithology

The oldest strata outcrop in the study area is lower and middle series of XiXiangChi group in the Cambrian of Paleozoic with the absence of Paleozoic Devonian and lower series of Carboniferous. The major strata outcrops are the Permian and Mesozoic Triassic to Jurassic strata in the area. Quaternary consists of modern river terrace diluvium, alluvium, and eluvium with nonuniform thickness. Paleozoic strata exposed in the core of Huayingshan compound anticline, two wings of which largely extend the Mesozoic strata with the total thickness of 5,000 m approximately. Lithological composition is dominated by clastic rocks, followed by shallow marine carbonate rocks and volcanic eruption rock outcrops scattered.

2.3. Karst features

The studied area has a rainy, torrid, and moist Central Asia tropical climate, which contributes to the development of karst. The main surface karst forms are karren, solution groove, clint, funnel, sink hole, karst depression, trough valley, etc. These include the Madakong underground water in Zhujia Village, Guixin Town, Guangan City; the underground water karst window in No. 1, Qingping group, Chengbei Town, Linshui County; the karst funnel in Bajiaowan, Lejie Village and No. 8 group, Kuaile Village, Guanyin Town; the karst depression and sink hole and the dry karst in Chuanshi Village, Juantong Town, Qu County, and dry caves distributed in Rui Courtyard, Juantong Town, etc. Due to the development of surface karst, occurs collapse doline depression and other forms, a rapid infiltration happens through the surface to underground karst aquifer during precipitation.

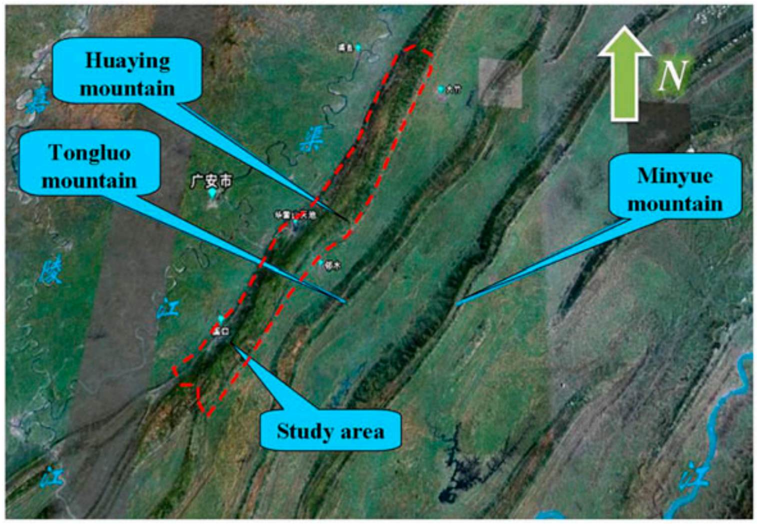


Fig. 2. Topography and landform satellite photo.

2.4. Geologic structure

2.4.1. Fold

The middle Huaying mountain is located in the third subsidence zone in the neocathaysian structure system, the western edge of the eastern Sichuan ejective fold belt in Sichuan Basin, a series of parallel asymmetric fold which is typical ejective feature. Anticline becomes into a hill, as a result of tight squeeze, while the syncline forms dale which is relatively flat. It is a typical ejective fold structure. Anticline is characterized by a steep west wing and a relieved east wing. Its hinges often undulate presenting features of paralleled compound folds combination or asymmetrical, case-like folds, while a synclinal form is relatively simple. From west to east the main fold structures are: Huaying mountain compound anticline, Linshui syncline, etc. Axes of trend are almost the same among different land folds, extending toward N25–30° E with east-dipping axial plane. In the region, secondary folds and faults are fully developed (Fig. 3).

2.4.2. Faults

Fractions and folds in the area studied are in most cases mutually accompanied, mainly developed in Huaying mountain compound anticline. They are dominated by compressive and compresso-shear ones matched by compressive and compresso-shear faults in the trending direction. But extension faults are weakly developed, so are the extension joins. In addition, in adjacent places of the eastern Sichuan subsided fold bundle and the arch platform in the Middle Sichuan area, there is still Huaying mountain major fracture existing, which is after the Jinning movement had become the dividing line between the two abutting parts, mainly buried in the ground belly,

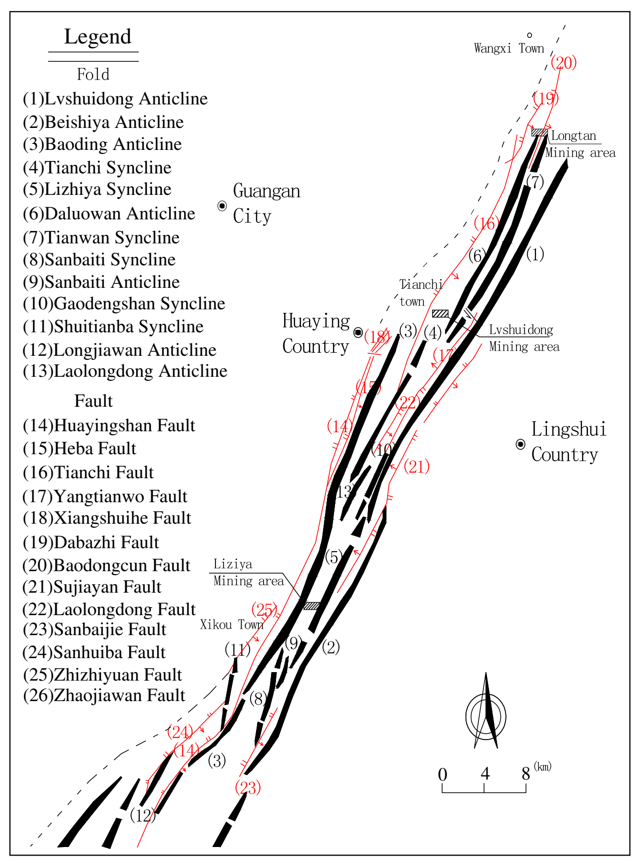


Fig. 3. Huaying mountain geologic structure schematic diagram.

with the nature of deep fault. In the geohistory it had several succession activities of different sizes and intensities controlling the geohistory, evolution, structure emergence, and development of both west and east sides.

2.5. Hydro-geological conditions

According to water-bearing characteristics, rich aqueous and hydraulic conductivity differences of the exposure stratum in the region, rock groups divided into four types, strong water-bearing rock groups/semi-strong water-bearing rock group/semi-weak water-bearing rock group/relatively impermeable water-bearing rock group (Table 1). Strong water-bearing formation of the aquifer system in the region is mainly distributed in five layers: Triassic Leikoupo group (T_2l)/Jialing Group (T_1j) and Feixianguan group 3+4 paragraph (T_1f^{3+4}) and Permian Department Maokou/Qixia Formation (P_1m+q), the water content of the water-bearing formation is relatively weak or relatively impermeable.

3. Current water conditions

3.1. Distribution of the surface water system

The study area is the middle region of Huaying mountain compound anticline. The west boundary of the area is the Qu River and the east boundary is the Yulin River. The north and south boundaries are Juantong Town, Qu Country and Sanba Town, Chongqin, respectively. The main rivers are Qujiang and Yulin which flow aside two wings of the anticline, towards northeast and southwest. The lateral Level 1 rivers or streams of which are fairly developed, with a common space of 5–10 km. As a result, the mountain ridge is divided into strip, elliptical shaped mountain fragments with various sizes. A hydrologic net is formed, where the mountain ridges are regarded as watersheds and the valleys are regarded as water catchment. Water conflux together finally flow eastward into the Changjang River through the Yulin River and westward into the Qu River. Within the region, the river discharge is 0–8,080 l/s, the surface run-off ranges from 3 to 10 km (Fig. 4).

3.2. Dynamic variation of discharge

Currently, water in the study area shows a sharp decline compared to that in 1980s. Surface water and groundwater both experienced a run-off, to different

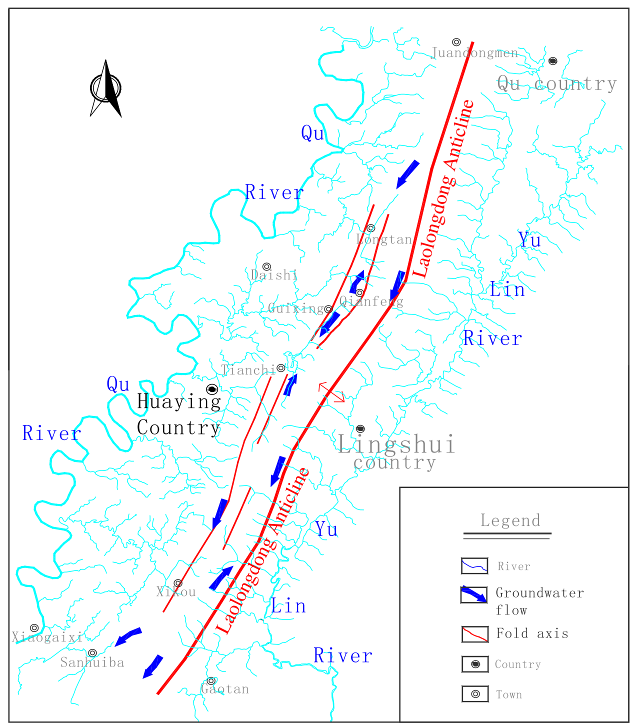


Fig. 4. Distribution of rivers in Huaying mountain.

Table 1
The dividing table of the exposure water-bearing rock groups in the region

Stratum water-bearing characteristics	Groundwater type	Corresponding strata code
Relatively impermeable water-bearing rock group	Clastic rock pore fissure water	J_1z, J_2s
Semi-weak water-bearing rock group	Clastic rock fracture confined water between the layers	T_3xj
Strong water-bearing rock groups	Carbonate fissure karst water	T_2l, T_1j, T_1f^{3+4}, P_1m, P_1q
Semi-strong water-bearing rock group	Clastic rock fissure cavern water carbonate rocks	T_1f^{1+2}, P_2c, P_2l
Relatively impermeable water-bearing rock group	Clastic rock pore fissure water	P_1l, C_2h, S_1, S_2
Semi-strong water-bearing rock group	Clastic rock fissure cavern water carbonate rocks	O_{2+3}, O_1, $\mathrm{Є}_3$

extents (Fig. 5). The main evidences shown are as follows:

Surface water gets discontinuous. For instance, a fragment of the rivers and streams has dried up in Guixing Town, Guangan City and No. 1 Group, Luojie Village, Linshui County. Groundwater and old wells were totally drained off in Guihua Group, Longjiawan, Guixing Town, Guangan City and Linshui County; No. 7 Group, Lejie Village, Chengbei Town, Linshui County; Shiziwan, Chengbei Town, Linshui County; Group 3, Tianjia Village, Linshui County. So far, the region has a heavy water shortage, common use of water for drinking and irrigation cannot be guaranteed. Paddy field becomes dry land. Furthermore, impounding water level of the natural lake and reservoir in the study area was gradually decreasing year by year, even dried up. The water level of the Heiwodang karst lake has decreased by 2 m in the past five years. Some power stations cannot generate electricity due to the great shrink of the river and stream discharge.

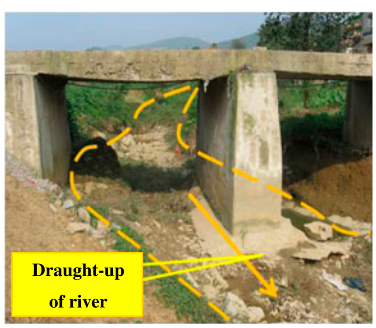
3.3. Water quality deterioration

The field survey showed that water quality in the most parts of the area has deteriorated. Many rivers and streams are contaminated to different extents. The deterioration of water quality is indicated by nontransparent or semi-translucent water with muddy yellow, black, or off-white color (Fig. 6). Groundwater in the study area has mainly HCO_3–Ca, the salinity is 0.2–0.3 g/l. As groundwater polluted by mining has high salinity, generally for 2 g/l, sulfide in wastewater exceeds 2–54 times, COD exceeds 4–30 times, as compared with the surface water quality standard (GB3838–2002) public class V water (generally applicable to industrial water). According to the villagers, living has become worse in the region where the Lengshui River flows through, in recent 5 years, the river water quality has markedly deteriorated, fish and some aquatic organisms have sharply decreased, in some areas, fish has even decimated.

4. Factors of water lose

4.1. Climate factor

Weather is the main factor in the cycle of water. Temperature variations have effects on cross-ventilation, latent heat, sensible heat, and heat conduction near the globe surface. These lead to an adaptation in the evapotranspiration process. Evapotranspiration



Guihua Group, Longjiawan, Guixing Town

No.7 Group, Lejie Village, Chengbei Town

Fig. 5. Current conditions of water reduction.

Nontransparent black water（Xikou town）

Simi-translucent muddy yellow water（Heliu town）

Fig. 6. Serious contamination of river water.

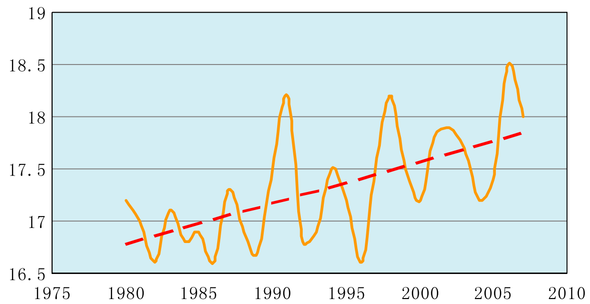


Fig. 7. Variation curves of annual average temperature (℃).

adaptation, in turn, results in an alternation in the water loss during the hydrologic process by run-off, infiltration etc., bringing about changes in water circulation and water resource [12].

The analysis of meteorological data in the past 30 years is shown in Fig. 7. It indicates that the average temperature in 2000 is 1℃ higher than that in 1980s with 6.6% increase. This causes the variation of hydrology circulation in this area. Increase in temperature directly enhanced evaporation. It is seen from Table 2 that evaporation rate in 1980s was the lowest with the lowest average monthly temperature. The temperature has become higher after 2000. The evaporation rate increased gradually as a result of the rise in temperature, achieving the highest in three stages.

Precipitation, as the only recharge into the source of water in this area, plays a significant role in water circulation of the river basin. The precipitation rate in the region is 20 mm, nearly 1.75% less than that in 1980s. The study area of 6,344 km^2, which can calculate the total rainfall recharge less than in the 1980s $1.2688 \times 10^8\ m^3$. Obviously, the decrease in annual precipitation and rise in temperature have a direct impact on the circulation of water resource. Less run-off depth, run-off coefficient and run-off rate lead to the reduction in water resources.

Table 2
Summary of monthly evaporation rates for each stage in the study area

Time (year)	Average monthly rainfall (mm)	Average monthly temperature (℃)	Average monthly evaporation rate (mm)
1980–1989	95.18	16.90	75.60
1990–1999	88.85	17.40	79.80
After 2000	93.53	17.80	80.96

4.2. Social economic growth

Social economic growth also exacerbates water shortage by increase in both population and industrial economy aspects [13].

4.2.1. Impact of the increase in population

Pressure of water resources is related to the population size. It is the most fundamental coefficient for estimating the intensity of human action. In the study, the analysis of the dynamic variation in population was based on the data from the Guangan City. As shown in Fig. 8, the total population of Guangan City has increased apparently in a decade (1994–2004) with the average annual growth rates of 35,900 people per year. The increase in population leads to a rise in water consumption. With an assumption of fixed individual water consumption rate, the gross amount of water consumption would grow continually due to the increase in population. Actually, with the improvement of people's living standard, individual use of water would increase simultaneously. According to the standard of water quantity for city's residential use, daily water consumption in the study area is 100–140 l/d, with the minimum water consumption of 100 l/d. In the past

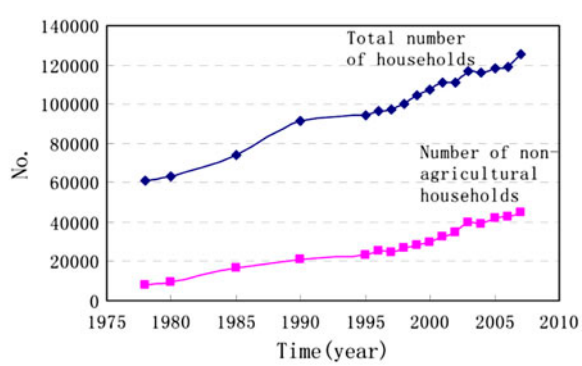


Fig. 8. Population dynamic fluctuation in Guangan City.

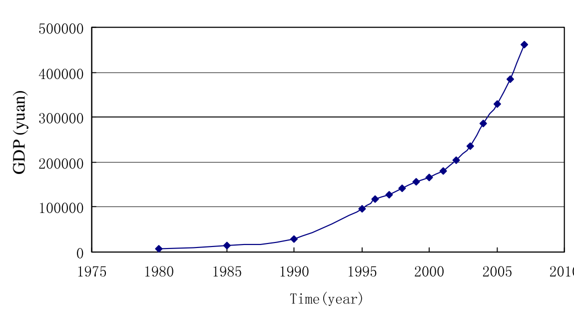


Fig. 9. Annual gross industrial output value of Guangan.

10 years, water consumption increase in the study area has been $1.31 \times 10^6\,m^3$ per year.

4.2.2. Impact of industrial water consumption

Fig. 9 shows annual variation of gross industrial output value of Guangan City. It is indicated that the gross industrial output value has increased from 4.243 billion yuan in 1994 to 11.794 billion yuan in 2004. The rate of increase is 178%. Such enormous growth in industry has a great stress on water resources. This would put forward a higher demand for water supply. However, if water consumption overloads the water resources transport, the natural moving path would be destroyed inevitably in the region.

4.3. Landform factor

Terrain slope affects the cross-flow velocity and duration, in an uniform soil nature and rainfall condition, the bigger the slope is, the higher the speed of cross river will be, leading to a short duration and a smaller amount of infiltration [14]. Through this research, villages that suffered the most serious water loss within the field are located in a relatively high elevation mountain area of Mount Huaying, which, with high mountain and steep slope, makes the precipitation form into slope run-off promptly after it reaches the ground and then converge into streams or grooves to drain off, at the same time the replenishment of infiltration becomes rather slight leading the groundwater to a long run dearth of precipitation supply. The other way round, rainfall in karst area immediately penetrates into the earth after falling down and then converging into underground river to let off. Hence, the water circulation in this place goes so fast that it becomes one factor for inducing the water loss. An evidence is that for Huaying mountain fold, its west wing water loss is higher than the east and the north part of the west wing is the most drastic area which is attributed to the unsymmetrical terrain with a steep west wing and a flat east wing.

4.4. Human activities factor

Human activity in the field has a significant impact on the local water resources. Particularly, the coal mine and the vehicular tunnel excavation result in an irremediable impair of water circulation path in the field (Fig. 10). As a consequence of human activities, the environmental impacts were: groundwater quality deterioration, water resource loss, and induced sinkholes. The crucial question in karst is how to keep the balance between the necessity for development and preservation of nature.

4.4.1. Coal mining

Coal mine in Huaying mountain went back in history of more than 200 years. Along the outcrops of coal layers, old coal pits or caves densely discrete. Before 1949, there were more than 10 small coal mine pits of the Permian period. So far, there have been four pairs of productive mines possessed by Huaying mountain Guangneng Group Corporation. In addition,

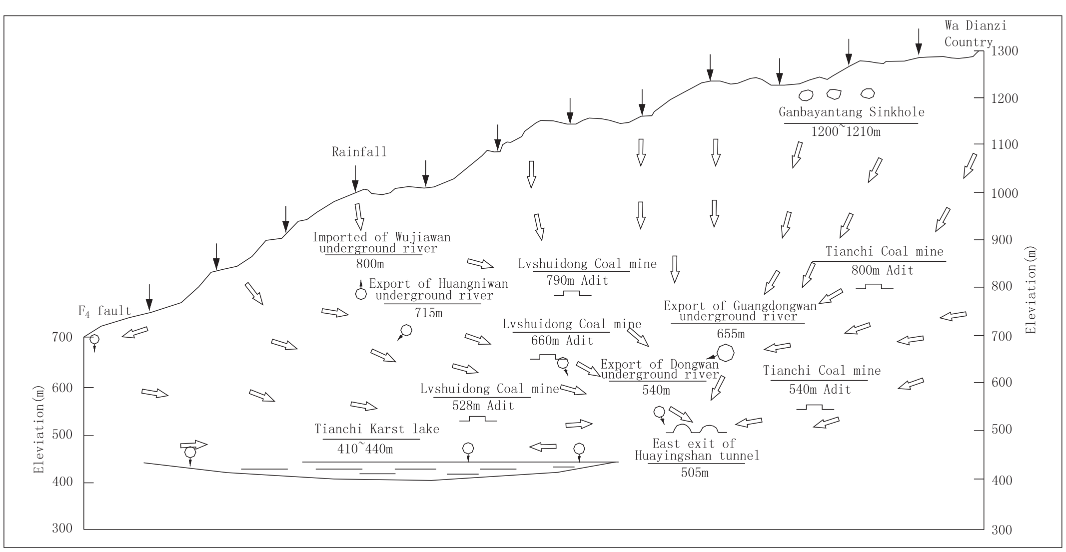


Fig. 10. Change in groundwater flow due to coal mining and tunnel construction in Huaying mountain.

there are multitudes of local small and medium size mines, not less than 10.

Coal mine induced the alteration of the underground water flow and discharge conditions. The original pathway of the underground water flow was exposed to coal mines [15]. This water was drained off directly through the mine roadway. Preceding springs naturally outcropped on earth detracted its flux for the deprivation effect of the pathway begot by mining coal during run-off process, some more serious even experienced dry-up phenomenon.

Based on the major regional mine discharge data, the average discharge water of Guangan coal mine is 3,1578 m^3/d; the total water inflow in Caishandong coal mine is generally 4,870 m^3/d; Longtan coal mine normal water inflow 53,066 m^3/d; Lvshuidong coal mines for many years the average discharge water 7,078 m^3/d. The large number of coal mining leads to groundwater drainage, and loss of groundwater in the area.

4.4.2. Underground construction

With the social and economic development, construction of roads and other infrastructures increase. As a result, the region inevitably suffers from artificial rock excavation, which has adverse effects on groundwater run-off conditions and water balance [16].

One of the underground projects having the large impact on water in the study area is the Huaying mountain tunnel in the Guanglin highway. It is located in the Huaying mountain region, and also on the border of Huaying County and Linshui County in Guangan City, the Guangan–Linshui highway, a feeder highway of the main trunk of HuRong National Highway. As the tunnel was excavated, groundwater was drained. Karst groundwater flows to the tunnel and forms a new central exchange. Movement of groundwater undertakes a significant shift. To the south of the tunnel, the direction of groundwater flow remains from the southwest to northeast; while to the north of the tunnel, within a certain range, groundwater flow from northeast to the southwest, draining at the center of the tunnel [17].

In the long-time drainage conditions, the whole underground water system in the tunnel area (including the aquifer and the relative aquiclude in a limited part from the rift zone) suffered a straight decrease in the groundwater level, which equaled the elevation of the tunnel trunk. According to the field survey, the buried depth of underground water level reached over 200–300 m, the water loss of the place higher than the tunnel is estimated at about $3 \times 10^8\ m^3$.

5. Amount of water resources loss calculation

Mountains and highlands are typical areas that provide considerable quantities of water, the latter being an important resource for the lowlands. This loss of quantities remains discernible in the superior scale river systems and contributes significantly to the global water resources. Therefore, the rainfall infiltration factor method was used to calculate the amount of loss of water resources.

5.1. Dividing water resources calculating units and basic data

In order to figure out the accurate amount of water resources loss, the estimated units are divided based on the run-off area of streams and rivers, namely considering the karst distribution region of catchment area of every stream and river. First, the study area is divided into two regional surface water systems by ridge of regression of the main anticline, the watershed area of surface water. To system I, surface water flows from east to west converging into the Qu River, to system II, it flows from west to east eventually into the Yu Ling River. Since in each of the two systems, there exist several smaller independent sub-region surface water systems, system I is divided into nine water source estimation units, system II—into 22 units, the total amount of units is 31.

The basic data for calculation was obtained from collecting and utilizing relevant documents, field investigation, and flow measuring observation of the surface water system, the measuring place is located in the junction of karst strata (T_2l) and non-karst strata (T_3x). The main parameters obtained are: flux, run-off modulus, area. Fig. 11 shows the process of calculation.

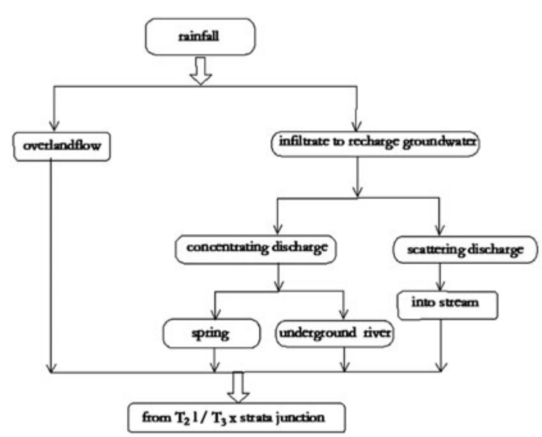


Fig. 11. Water resource calculation process.

5.2. Calculation results

By calculating the concentrating discharged amount of groundwater resources in the groundwater system, it is indicated that compared to the 1980s, the concentrating discharge amount of groundwater appears to decline obviously, annual conservative amount of loss is approximately 91.12 million m^3.

6. Conclusion

The study has carried out field survey, indoor comprehensive data analysis and calculation on current water resources situation and space distribution of water loss. It is concluded that current condition is not desirable, regular living, and working conditions of the residents are extremely affected. For example, precipitation is the only water source available for few villages in the study area. In addition, due to a limitation in precipitation in this area, there is no sufficient water for irrigation in drought years. People have to cultivate dry land to sustain life. Water loss in the west wing of Huaying mountain fold is greater than that in the east; the northern part of the west wing faces the most serious water loss problem. Annual conservative amount of loss in this area is approximately 91.12 million m^3. Water loss in the middle region of Huaying mountain is mainly associated with the climate change, terrain, social economic growth, and increased intensity of human activities. Inter alia human activities were the most significant factor that puts pressure on the water resources adaptation ability.

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