Zonation of a karstic water system by quantitative hydrogeological structural analysis using GIS

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Abstract: Veritable recognization and clear description of the structural features and the path of groundwater flow for a karst-water system is a base for establishing the hydrogeological conceptual model, mathematical model and evaluation of groundwater resources in a basin. It is really necessary to regionalize the karst-water system to realise, objectively, the actuality of water utilization.

The purpose of this paper is to realize the quantitative zonation of karst-water system in the frontier mountain area of Xinding Basin. On the basis of groundwater system theory and geographical information system (GIS), we analysed the lithofacies paleogeography, geology, tectonics and hydrogeologic condition for extracting quantitative structural information, including the contours of the base of regional karst-water aquifers and the map of the karst-water system. The map can reveal the distribution range of karst-water aquifers, the permeability of the stratum, the boundary characteristics and the relationship between the inner system and exterior system.

The results show that karst-water system in the frontier mountain area of Xinding Basin can be divided into three subsystems: (I) Xiamajuan spring karst-water system, (II) Nanwang karst-water system, (III) Pingshang spring karst-water system. However, only karst-water system I and II are close related to the groundwater in the basin. We have regionalized a regional zone of saturation (including the unconfined-saturated zone and the confined saturated zone) and the carbonate unsaturated zone in the two systems. Some questions had been met in the processes of groundwater exploitation in past can be cleared explained with this method. According to the karst-water system analysis, we also propose some new suggestions about exploitation, protection and management of karst-water resources of the study area. This kind of integrated method can be applied to mountain areas without enough investigated data in north China, where carbonate formation is the most important aquifer.

Résumé: Une véritable reconnaissance et une claire description des caractéristiques structurales et du flux de l'écoulement des eaux souterraines pour un système des eaux karstiques constituent la base de l'établissement d'un modèle conceptuel hydrologique, d'un modèle mathématique et l'évaluation des ressources d'eaux souterraines dans un bassin. Il est important de régionaliser le système des eaux karstiques afin de réaliser objectivement l'utilisation réelle de l'eau. Le but de cette publication est de mettre en œuvre une répartition quantitative en zone du système des eaux karstiques en sites frontaliers montagneux du bassin de Xinding .Sur la base de la théorie du système des eaux souterraines et du système d'information géographique (SIG) nous avons analysé l' information quantitative structurale sur la condition tectonique hydrogéologique de lithofaciès paléogéographique et géologique ,y compris les contours de la base régionale des aquifères des eaux karstiques et les cartes du système des eaux karstiques .Une carte peut réveler le domaine de distributions des eaux karstiques des aquifères , la permiabilité des couches , les caractéristiques de la limite et la relation entre des systèmes intérieurs et extérieurs.

Les résultats démontrent que le système des eaux karstiques dans les ères limitrophes montagneuses du bassin de Xinding peut etre diviser en quatre sous-systèmes: (I)système Xiamajuan des eaux karstiques printanières. (II) Système Nanwang des eaux karstiques. (III)Système Pinshang des eaux karstiques printanières Cependant seuls les systèmes (I) et(II)présentent des affinités avec les eaux souterraines du bassin.Nous avons régionalisé une zone locale de saturation(comprenant une zone non confinée-saturée et une zone confinée-saturée), et une zone insaturée d'hydrocarbures dans les deux systèmes Quelques problèmes rencontrés dans le passé dans le processus de l'exploitation des eaux souterraines peuvent trouver une explication claire par cette méthode. Selon le système d'analyse des eaux karstiques ,nous émettons des suggestions concernant l'exploitation,la protection,et la gestion des sites de ressources en eau karstique étudiés.Cette méthode intégrée peut etre appliquée aux sites montagneux manquant d'études suffisamment chiffrées de la Chine du nord où le plus important aquifère est la formation d'hydrocarbures .

Keywords: Karst-water system, Basin, Hydrogeology, Geographical information system (GIS), Saturated zone

INTRODUCTION

Numerous groundwater studies show that regionalizing different groundwater system is very important procedure used to test or refine different conceptual models, most importantly for water-resource management, predict how the aquifer might respond to changes in pumping and climate. In some cities of north China, such as Taiyuan, Yuanping, Linfen in Shanxi province, the prevailing water supply source for agricultural and industrial use, as well as for daily life, is karst-water. With the development of the groundwater exploitation, the existent pattern of the regional groundwater system has been changed. It is necessary to resolve the increasingly conflict on water supply. We should consider the relationship between karst-water system and pore water system or among the inner part of karst-water system for regionalizing groundwater system to investigate regulation of groundwater recharge, runoff and discharge.

The regionalizing process of the karst-water system is the process of extracting, processing and organizing information to establish a model for reflecting the hydrogeologic characteristics in the study area (Zhang et al., 1990). However, past research paid much attention to qualitative information rather than quantitative information from geologic and hydrogeologic data. Stratigraphy, lithology, and structure determine the type of aquifer, and the location of recharges and discharge areas (Hess et al., 1989). Numerous measurements and an accumulated stock of experience in organizing them are necessary in karst terrains to obtain accurate and reliable data indispensable for defining parameters for accurate hydrological regionalization (Bonacci, 1990). Information about lithologic units, faults, joints, and karst features (sinkholes, caves, and springs) contributes to an understanding of the hydrology of the area. Geologic studies that identify karst, stratigraphic, and structural features contribute to the understanding of how aquifers interact and how groundwater is transported (Orndorff et al., 1999). Some hydrogeologists consider that observation wells and pumping tests are very important information sites and that the functioning of the whole aquifer can be inferred from well observations (Bonacci 1982, 1995).

A karst system is similar to a river catchment area, with comparable properties, defined by an extension, contours and boundary conditions (Bakalowicz, 2005). This paper, using groundwater system theory, and taking as an example zonation of the karst-water system of the frontier mount area around Xinding Basin, regards the contours of the top of the regional aquiclude as the main clue to an analysis of the internal structure of the karst-water system. The important method is based on extracting quantitative or semiquantitative geologic and hydrogeological information by GIS technique by analysizing areal lithofacies paleogeography, sequence stratigraphy, lithostratigraphy, stratic aquosity and drawing the maping of karst-water system to confirm the hydraulic permeability of the boundary. The research results put forward the basic pattern of Xiamajuan spring and Nanwang karst-water system through the analysis of the condition of the spring outlet and the riverbed elevation. These information sources establish a base for regionalizing the karst-system and analysing the spatial distribution and embedding regulation of the karst water-bearing medium and the recharge, runoff and drainage characteristics of karst-water. It is significant to delineate the spatial distribution of the aquifers and exactly evaluate karst-water sources.

METHODOLOGY

Based on the theory of groundwater system analysis and regionalized technique, we carried out the research by analysing the geologic and hydrogeologic condition around Xinding basin.

Generalized workflow is as follows:

- Confirming the position of the relative aquicludes by analysing stratum permeability in different geological age according to the data of fissure statistics and investigation in the field.
- Mapping the spatial distribution and layer thickness of regional lithofacies paleogeography in the mount area with karst aquifers, which are mainly the limestone of Cambrian and Ordovician, to reflect the distribution range and regulation.
- Establishing database by collecting control points, which are the intersection between topographic contour and line of geological limitation on the geologic map with a scale of 1:200,000 and the topographic map with a scale of 1:250,000.The information includes the stratum thickness and dip for the interrelated calculation and spatial analysis.
- Drawing the contours map of the top of the regional aquiclude by the location and elevation of the discharge points, such as spring outlet, river bed, groundwater table and so on, to deduce the groundwater hydraulic gradient and regionalize the carbonate unsaturated zone, the unconfined-saturated zone and the confined saturated zone.
- Drawing the hydrogeologic cross section perpendicular to the boundary of karst-water system for exactly explaining hydraulic permeability of the boundary.
- Delineating the recharge relationship between karst-water system and groundwater system in basin, and putting forward the corresponding flow pattern.

Currently GIS is used to pre-process data or to make maps of input data or model results by providing the necessary spatial database for hydrogeologic models. GIS offers an effective support for hydrological modeling. Such a tool is capable of archiving, analysing and handling the large amounts of data required describing hydrological processes on different scales (Fuhrmann, 2000; Asadi and Hale, 2001). GIS can represent the geo-referenced characteristics and spatial relationships of systems, however predictive and related analytical capacities are more useful and necessary for solving complex water resource planning and management problems (Walsh, 1992). The development of a GIS-based model allows for the integration of thematic maps specifically to demarcate artificial recharge zones for groundwater development (Krishnamurthy et al., 2000). Using GIS, a groundwater vulnerability assessment (pathway) is derived using a simple index system to assess the potential problems through the unsaturated zone of the Permian-Triassic Sandstone aquifer to the water table, by taking into account the intrinsic characteristics of the aquifer and the overlying strata (Tait et al., 2004). This study has extracted the quantitative information of the geologic and hydrogeology data by using GIS technology.

STUDY AREA

The study area is located in the eastern part of Shanxi province (Figure.1). The longitude ranges from 112˚33′E to 114˚05′E and the latitude ranges from 38˚15' N to 39°20' N. The area of Quaternary deposition is 3597 km^2 in extent; the corresponding mount area is 5547km^2. The basin around mountains belongs to the upper reaches of Hutuo River. The blind fault is the borderline between basin and mount area. The region is characterized by a continental monsoon climate. Mean annual precipitation is 418mm, with the primary precipitation occurring from June through September. The mean annual temperature is 7~9°C with great evaporation capacity. Hutuo river flows across the whole basin about 260km. The stream network develops well in this region and includes Hutuo river, Yangwu river, Yunzhong river and so on. Yangwu river and Yunzhong river in the Midwest of the basin belong to the first branch. Yangwu river flows across the limestone and the granite gneiss. Yunzhong river divides near its mouth and forms the north Yunzhong river and the south Yunzhong river. There is Muma river in the south of the basin. Two parts of Yunzhong river and Muma river eventually flow in Hutuo river.

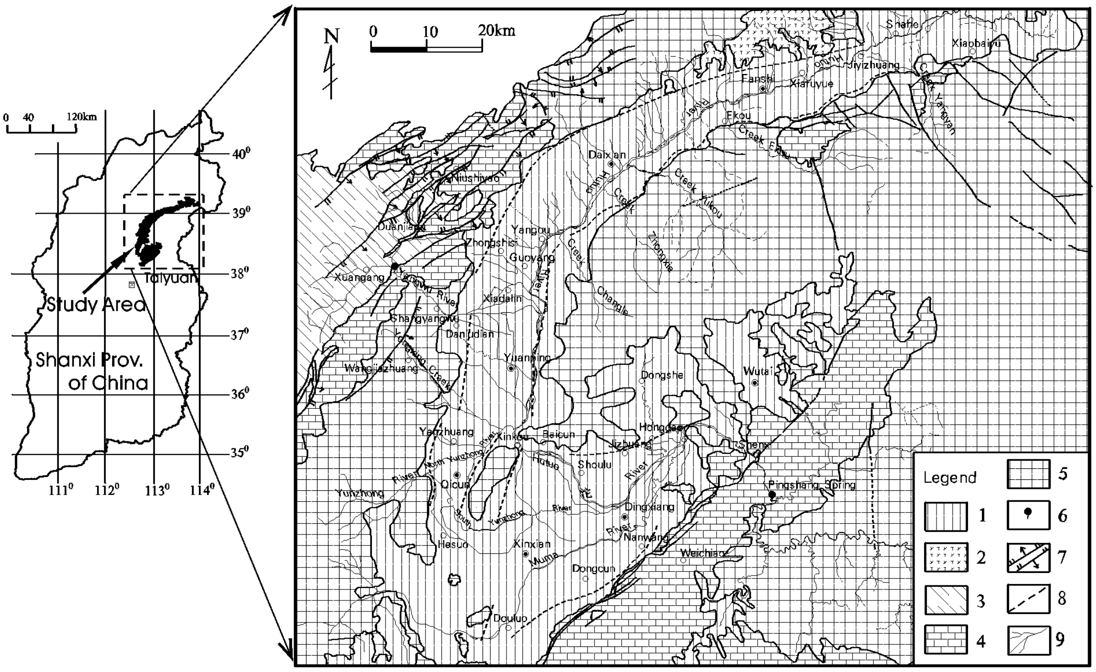

Figure 1. Sketch map of the hydrogeology in the frontier mountain area of Xinding basin
Legend: 1. Pore water in Quaternary deposition; 2. Fissure water in Tertiary deposition; 3. Fissure water in detrital rock of Carboniferous-Jurassic; 4. Karst-water in limestone of middle and upper Cambrian and middle Ordovician; 5. Weathering Fissure water in igneous and metamorphic rocks of the middle and lower Archean; 6. Big karst-water spring; 7. Down and reverse fault; 8.Blind fault; 9.Stream network

Geology

The eastern part of the basin is Wutai anticline, the western part is the north Lvliang anticlinorium, and the middle part is Hutuo river depression. Wutai mountain, Heng mountain, Yunzhong mountain, the upper reaches of Hutuo river and the basin are spread along N65°~70°E. The major fault zones include the fault zone in the north foot of Jizhou mountain, the fault zone of the frontier mount along the south bank of Hutuo river and the fault zone in the south foot of Yunzhong mountain. These fault zones are along N60°~70°E and extends from several kilometres to a few decades, even up to 30km.

The prevailing outcrop strata in the study area is igneous and metamorphite rock of the middle and lower Archean, carbonate rock of the Cambrian and Ordovician, coal measure strata of the Carboniferous and Permian, detritic formation of the Triassic, and Cainozoic sediments (Figure 1). There is structural-fractured zone due to the effect of the tectonic movement. The stratum of the Cambrian and Ordovician, mainly limestone, are distributed aong Niushiyao and Duanjiapu in Jizhou Mountain and the northwestward Yunzhong Mountain. The western part of the basin, along Duanjiapu and Xuangang, is covered with the massive sandshale of the Carboniferous, Permian, Triassic and Jurassic. Basalt of the Tertiary distributed from Fanshi to Shahe along the north bank of Hutuo river trend towards the south gently.

Hydrogeologic setting

The types of groundwater in the study area include weathering-fissure water in series of rocks of the middle and lower Archean, karst-fissure water in carbonate rock of the Cambrian and Ordovician and sandshale-fissure water in the Carboniferous, Permian, Triassic and Jurassic. In this paper, we mainly discuss karst-water system recharged by atmospheric precipitation.

The confined aquifers are covered with the sandshale of the Carboniferous, Permian and Triassic, as well as Jurassic, basically without vertical recharge, and belong to the confined runoff area. Massive carbonate outcropping distributed along Guandi and Niushiyao is the unconfined aquifer with better water abundance. Because the complex geologic and tectonic condition, the karst fissure develops the larger depth and heterogeneous distribution with the great buried depth of groundwater. The dominant drainage points are Xiamajuan spring in the northwest Yuanping and Pingshang spring in the south Duanjiazhuang. In general, the water flows towards the spring from far and near. Xiamajuan spring group lies to 27km away from the northwest of Yuanping and is the headstream of Yangwu river and the water source for irrigation of Yuanping, as well as the water supply source of Xuangang coal mine. The elevation of the spring group ranges from 1120m to 1150m. The average annual flux of the spring is $1.3m^3/s$. The spring group dispersedly appears in the limestone-fissure of the Cambrian and Ordovician along the side banks of Yangwu river.

Massive area of carbonated outcrops, about $860km^2$, is distributed along Weichiao and Shenxi in the south part of Xinding basin. Pingshang spring appears in the unconfined aquifer, which is the limestone of the Cambrian and Ordovician mainly recharged from atmospheric precipitation and discharged into Hutuo river. The elevation of the spring group ranges from 640m to 703m. The study area is a complex geological, tectonic and hydrogeologic environment with typical hydrogeology in northern China: a group of springs are the predominant way of regional groundwater discharge.

RESULTS AND DISCUSSION

Drawing the contours map of the top of the regional aquiclude

According to the analytical procedure mentioned above, the shale of Cambrian Xuzhuang group ($\in_2^x$) can be regarded as the top of the regional aquiclude. First, some subareas can be plotted out from certain scale map by accuracy request. Secondly, it is necessary to integrate multiple layers of information derived from the thickness map. Thirdly, the contours map of the top of the regional aquiclude can be drawn according to interpolating and calculating the related data.

GIS technique are capable of managing large amounts of spatially related information, providing the ability to collect and calculate large numbers of data and to draw the contours of the top of regional aquiclude. In the analysis of the karst-water system, based on the data of strata thickness and lithology mentioned above, it is then necessary to plot the points showing the intersection between topographic contour and line of geological limitation. The elevation of the regional bed of the karst-water aquifers can be attained using the following equation:

$$H=H_0-k\cdot(\cos\alpha)^{-1}$$

where H is the elevation of the top of the regional aquiclude; H_0 is the ground elevation of the collected points; k is the total thickness from the point to the bed of the karst-water aquifer; α is stratum dip.

The interpolation method can be used to plot the contours of the top of regional aquiclude, which is an important basis for the analysis of the karst-water system. The upheaval and depression of the impermeable bed can be reflected regionally from this map, and can include quantitative information such as the extent of fault displacement. In a sense, the contours of the top of the regional aquiclude may also describe the characteristics of the geologic structure, in three-dimensional space.

In the light of the method mentioned above, the strata thickness of the regional lithofacies paleogeography map is very useful information to the study of geologic structure. According to this, the stratum thickness of each geological age can be obtained (Table 1.). The intersecting points refer to the point where the topography contours intersect the geologic boundary, including the boundary of the pervious outcropping, such as C_2^b/O_2^f, O_2^f/O_2^s, O_2^s/O_2^x, O_2^x/O_1, $O_1/\in_3$, $\in_3/\in_2$. The density of the points can be controlled by the variable tendency of the contour lines and boundary geometry. There are about 12500 points collected from the study area. A part of the points attribute can be seen from Table 2. Based on the calculated elevation of the regional aquiclude top, we can draw the contours of the top of regional aquiclude (Figure 2.). For the unconfined aquifer, the top of regional aquiclude dominates the karst-water flow. But for confined aquifer, the piezometric head dominates the karst-water flow. Thus, it is not significant to plot the contours of the top of regional aquiclude in the confined saturated zone.

Table 1. Stratic thickness (m) of different geologic ages in Nanzhuang maparea (1:50,000) in study area

ID	O_2^s	O_2^x	O_1	$\in_3^f$	$\in_3^{ch}+\in_3^g$	$\in_2^z$	$\in_2^x$
1	281	153	170	68	30	100	80
2	289	145	166	62	28	96	78
3	286	140	168	64	22	94	72
4	298	143	162	58	24	92	70

EXPLANATION : ID-the number of the subarea in this maparea; O_2^s,O_2^x,O_1,$\in_3^f$, $\in_3^g$,and $\in_2^z$ are the stratic codes.

Table 2. Parts results of the elevation of the regional aquifer bed in Nanzhuang maparea (1:50,000) in study area

ID	NO	H_0(m)	Intersectant stratum	α (°)	Strata thickness (m) of different geologic ages							k(m)	H (m)
					O_2^s	O_2^x	O_1	$\in_3^f$	$\in_3^{ch}+\in_3^g$	$\in_2^z$	$\in_2^x$		
1	588	1440	$\in_2/\in_1$	45								0	1440
	2040	1550	C_2^b/O_2^s	14	281	153	170	68	30	100	80	882	641
	482	1500	O_2^s/O_2^x	45		153	170	68	30	100	80	601	650
2	1020	1100	$\in_3/\in_2$	14						96	78	174	921
	605	1300	O_2^s/O_2^x	45		145	166	62	28	96	78	575	487
	418	1000	O_2^x/O_1	27			166	62	28	96	78	430	517
3	496	1800	O_2^s/O_2^x	6		140	168	64	22	94	72	560	1237
	870	1480	O_2^x/O_1	6			168	64	22	94	72	420	1058
	2036	1400	C_2^b/O_2^s	14	286	140	168	64	22	94	72	846	528
4	639	1800	$O_1/\in_3$	6				58	24	92	70	244	1555
	779	1400	$\in_3/\in_2$	27						92	70	162	1218

EXPLANATION: ID- the number of the subarea in this maparea; H_0-the ground elevation of the point position; NO-the number of the collected points; α-the outcropping dip; k-the total thickness from the point to the bed of the karst-water aquifer; H-the calculated elevation of the impermeable bed.

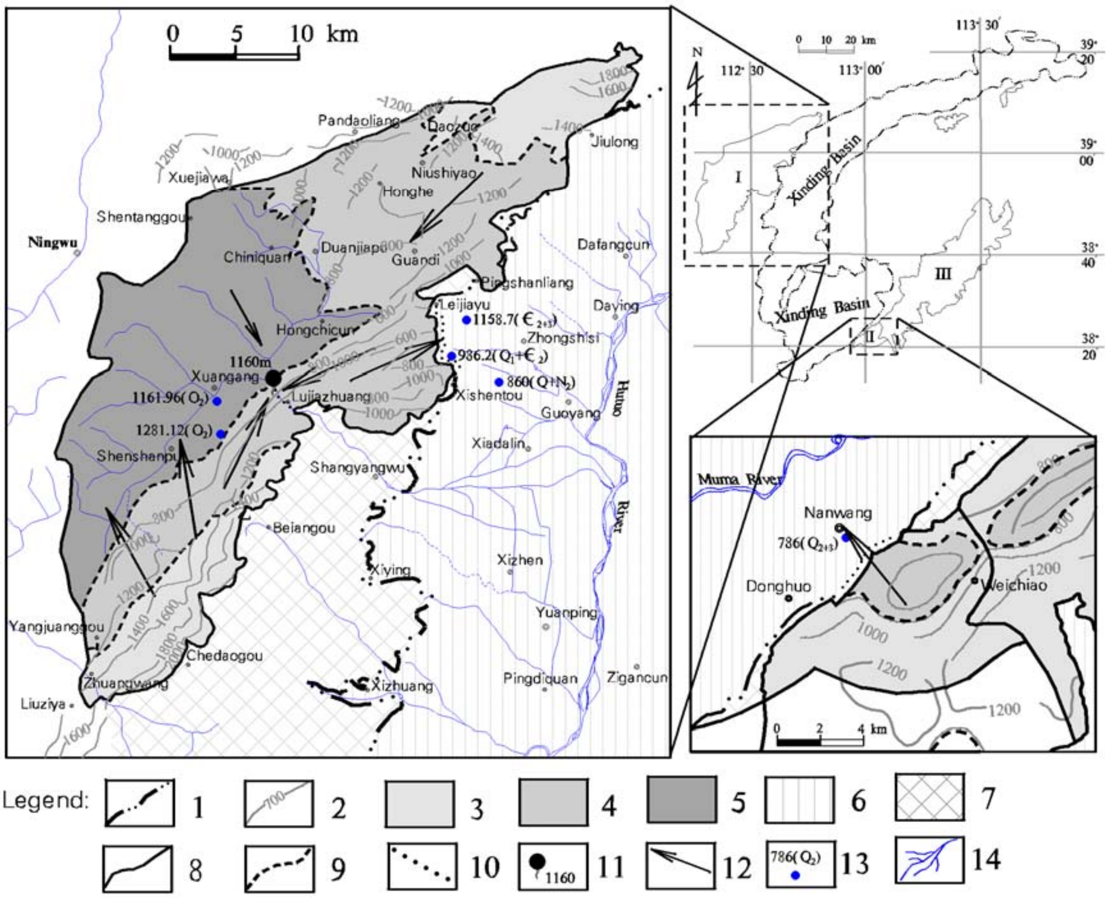

Figure 2. Zonation map of the karst-water system (I) and (II) in the frontier mountain area of Xinding basin. Legend: 1.Basin borderline; 2. Contour of the regional base of karst aquifer; 3. Carbonate unsaturated zone; 4.Unconfined-saturated zone; 5.Confined saturated zone; 6.Xinding basin area; 7.Igneous and metamorphic rock area; 8.Boundary of karst-water system; 9.Inner borderline of karst-water system; 10. Discharge zone of karst-water; 11.Spring and elevation of its head; 12.Karst-water flow direction; 13.Mornitoring wells with water table and water-yielding stratum; 14. Stream network

Zonation of karst-water system

Analysed the contours of the top of regional aquiclude to integrate geologic and hydrogeologic data, the karst-water system around Xinding basin can be separated into Xiamajuan spring karst-water system (I) located in the north Yunzhong mountain, Nanwang karst-water system (II) and Pingshang spring karst-water system (III) located in the north Jizhou mountain. But only the system I and II are related to groundwater in basin. The system III is discharged into Hutuo river along the section of river valley and eventually flows into Hebei province. In this paper, we mainly discuss the system I and II. The karst-water systems in the study area mainly get recharge from the infiltration of the atmospheric precipitation. The coverage area of the system I and II are 754km^2 and 62.21km^2 respectively.

The karst-water tables of the hydrogeologic wells, which lie to the south of Xuangang and can be seen from Figure 2., are 1161.96m and 1281.12m respectively. According to the elevation of the spring vent and the natural hydraulic gradient, we can make out the regional saturated zone linked to the big karst spring. On the contours map of the top of regional aquiclude, the distribution range of unconfined-saturated zone can be described by virtue of the intersecting lines where the water table intersects at the impermeable bed. The karst-water tables of the hydrogeologic wells, which are located in the basin, are 1158.7m and 986.2m respectively. However, groundwater table in the basin is 860m. There is a discharge zone from Leijiayu to Xishentou, and karst-water is discharged into the basin.

The system II is dominated the undulated top of the aquiclude, which inclines to the basin. The karst-water table near Nanwang is 786m. There is a discharge zone, about 5.4km, along the basin boundary in the south of Nanwang.

Boundary characteristics of the karst-water system

The geologic, hydrologic, and hydrogeological borderlines are usually treated as the boundary of the natural groundwater system. And the types of boundary include geologic impermeable boundary (GIB), hydraulic impermeable boundary (HIB) and discharge boundary (DB). GIB mainly refers to the boundary (GIB-1) where the aquiferous system contacts with the impermeable stratum; the impermeable boundary (GIB-2) formed by incision effect of the fault breaking through of water; and the impermeable boundary (GIB-3) formed by the structural upheaval and the lower permeable zone. HIB refers to the variable groundwater divide, which can divide the aquiferous system into subsystems with certain hydraulic connection. DB refers to the boundary where groundwater in the aquiferous system is discharged into the other system through the permeable stratum, including the direct contact zone with loose stratum or the zone incised by the river. DB can be regarded as the discharge zone.

According to the analysis of the contours of the top of regional aquiclude, boundary characteristic and water level, the karst-water system around Xinding basin can be divided into several relatively independent systems (Figure 2.). Delineation about the main karst-water system close related to the basin is as follows:

- Concerning Xiamajuan spring karst-water system (I), the north boundary can be described as GIB-2, due to the complex structure and stratum from Pingshanliang to Jiulong, especially with big fault displacement. For the decrease of permeable capability along with the increase of the buried depth of the aquifer, extending into the axial region of the megasyncline, the west boundary is close to the surface watershed, which can be regarded as GIB-3. The south boundary formed by the upheaval of the top of regional aquiclude and the complex separation fracture along Zhuangwang and Liuziya is attributed to GIB-3. The southeast boundary belongs to GIB-1, contacting with igneous and metamorphic rock along Chedaogou and Beiangou. The east boundary where the limestone directly contacts with the loose stratum along the fault zone from Xishentou to Leijiayu can be defined as DB. There exists HIB along the Lujiazhuang and Xishentou in the internal system.
- As to Nanwang karst-water system (II), the northwest boundary where the metamorphic rock or the sandshale contact with the limestone due to the big fault can be taken for GIB-1. The east boundary can be defined as HIB. The contact zone between the north part and the basin is DB.

SUMMARY AND CONCLUSIONS

This article describes the zonation of karst-water system through extracting the quantitative information of the top of regional aquiclude based on GIS. Some conclusions can be drawn:

- Xiamajuan spring karst-water system (I) and Nanwang karst-water system (II) are close related to groundwater system in basin. And groundwater in Pingshang spring karst-water system (III) is discharged into Hutuo river and flows into Hebei province. The internal structure of karst-water system can be divided into the unconfined-saturated zone, the confined saturated zone and the carbonate unsaturated zone.
- The drainage of system (I) is centralized in Xiamajuan spring and along the Yangwu river valley. So, it is a semi-closed system with undercurrent drainage along the frontier fault. With regard to the system (II), because the carbonate aquifer is subjected to the northwest fault and contacting with the igneous and metamorphic rock, and to the southeast upheaval of the aquiclude top, it is a relatively close system.
- The structure in the mountain region is so complex that the top of the regional aquiclude is undulated to a great extent. But there is a general tendency in the regional scale. Groundwater of Nanwang karst-water system without the confined saturated zone flows into the pore water system in Quanternary sediments in the northwest direction.

This kind of integrated method can be applied to mountain areas without enough investigated data in north China, where carbonate formation is the most important aquifer. The research results can provide significant and practical evidence for the reasonable assessment and utilization of groundwater.

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