Evaluation of groundwater potential and eco-geological environment quality in Sanjiang Plain of Heilongjiang Province

WU Ting-wen[1], WANG Li-huan[2], YANG Xiang-kui[3*]

[1]School of Water Resources and Environment, China University of Geosciences(Beijing), Beijing 100083, China.
[2]Geological environment monitoring station in Heilongjiang Province, Harbin 150000, China.
[3]Heilongjiang Institute of Geological survey, Harbin 150001, China.

Abstract: Sanjiang Plain of Heilongjiang Province has become an important commodity grain base in our country after the construction of more than a century. Groundwater is the main water source for industrial and agricultural production and daily life in the area. With the large-scale development and construction in this area, there are a series of ecological and environmental geological problems, such as the reduction of groundwater resources, which seriously restricts the sustainable development of local agriculture and society as well as economy. Based on the characteristics of three-dimensional flowof groundwater in Sanjiang Plain, this paper adopts the simulation software Visual MODFLOW to evaluate groundwater exploitation potential. The results show that overall there is a certain exploitation potential of Sanjiang Plain groundwater but it is unevenly distributed, and overdraft phenomenon exists in seven farms such as Baoquanling and Chuangye. Based on analytic hierarchy process, the evaluation result of eco-geological environment quality in Sanjiang Plain shows that 94.5% of the region features good geological environment quality, medium stability and medium bearing capacity. The study can provide geological evidence for optimal allocation of water resources, land planning and regulation, and the high and stable yield of the commodity grain base in Sanjiang Plain.

Keywords: Sanjiang Plain; Groundwater resources potential; Eco-geological environment evaluation

Introduction

Eco-geological environment system means the study on the interaction between human life system and natural together with social ecological environment centering around the geological environment where human stays (CHEN Meng-xiong, 1999). It consists of geological environment and ecological environment. These two sub-systems are interrelated, mutual reinforcing, influencing and restraining while independent from each other. Eco-geological environment system is a complex mega-system which is constantly changing due to the interference of human activity system and finally has an impact back on it (ZHI Bing-fa, 2008). With the rapid economic growth of Sanjiang Plain, humans have an increasingly larger impact on eco-geological environment system. Sanjiang Plain's natural eco-geological environment system is gradually replaced by artificial-natural compound system and a series of eco-geological environment issues have arisen, such as wetland degradation, water resources decrease, and water pollution.

Groundwater resources serve as the most important water source for agriculture, industry and daily life in northern China (QIAN Yong, 2014). Quaternary pore water is the main water source of all industries in Sanjiang Plain and underpins the eco-geological environment system in Sanjiang Plain. It exerts a huge influence on

*Corresponding author. E-mail: 172652597@qq.com

agriculture, economy and social development. Based on the result of the project, “Investigation and evaluation of groundwater resources potential and eco-environmental geology in Sanjiang plain”, the paper adopts three-dimensional flow model and the simulation software Visual MODFLOW to evaluate groundwater exploitation potential, which has been widely used in groundwater resources evaluation (SHEN Yuan-yuan *et al*, 2009; WEI Dong-sheng *et al*. 2014; FENG Jie, 2013). Eco-geological environment quality evaluation adopts analytic hierarchy process which features less quantitative information to mathematize the thought process in decision-making so as to provide simple and convenient basis for solving multi-objective, multi-principle and non-structural complex issues. As the mainstream evaluation method in the current industry, it has gradually matured. In the evaluation of agricultural eco-geological environment quality in Qian’an, Jilin Province, research on soil water resources distribution in Shijiazhuang, and evaluation of eco-geological environment quality in the source region of the Yangtze River, TANG Jie, ZHOU Fang-cheng and ZHENG Chang-yuan all adopted this method and achieved good results. Based on Sanjiang Plain’s geological environment conditions and ecological conditions, this study conducts grading evaluation of geological environment quality and ecological bearing capacity through analytic hierarchy process at first. Using GIS software’s spatial analysis function (HUANG Run-qiu and XIANG Xi-qiong, 2002), the paper then analyzed the superposition of geological environment quality and ecological bearing capacity grading maps, and generated data about Sanjiang Plain’s eco-geological environment quality. This research can provide geological basis and better serve for the region’s ecological environment construction and protection, and promote the coordination between economic development and resource as well as the environment (HAN Zai-sheng, 2003).

1 Overview of research area

1.1 Overview of hydrogeological conditions

Covering an area of 45 100 km^2, Sanjiang Plain is located in the northeast of Heilongjiang Province. It is an alluvial formation low plain in the north of Wanda Mountain, which comes into being as a result of the convergence Songhua River, Heilongjiang River and Ussuri River (Changchun Institute of Geography, 1983). The region has rich reserve in groundwater and Quaternary pore water aquifer is the main water supplying layer of the region whose thickness is between 50 and 300 m. It is also the evaluation layer of groundwater potential in this paper. Without a steady aquiclude, water in this layer features pore groundwater. Groundwater circulation is frequent in this region. The coefficient of permeability is 12-30 m/d, and specific yield is 0.08-0.20.

In the heartland of depression zones of Suibin and Qianjin, the extremely strong coefficient of permeability is above 30 m/d and specific yield is 0.1-0.25. In the piedmont’s first terrace region, the aquifer is thin and weak infunction. The coefficient of permeability is 6-12 m/d and specific yield is around 0.11.

1.2 Eco-geological environment conditions and problems

1.2.1 Water environment and problems

Water is the most important factor in eco-geological environment and serves as the carrier for substances and energy in the earth’s spheres. Having abundant water resources, Sanjiang Plain possesses 10.24 billion cubic meters’ surface water and 5.145 billion cubic meters’ groundwater.

The main issuesare water pollution and the decrease of water resources. Surface water near the city is seriously polluted and that away from the city is to a less degree. The main pollutants are permanganate index and ammonia nitrogen. Groundwater’s main pollutants are three forms of nitrogen. Water of IV, V types covers over 20% of the total area (WANG En-bao, 2015). With the reclamation of marsh, surface water has decreased. Two thirds of bogs dry up together with the majority of small and medium-sized rivers. From the early liberation to 2002, the groundwater table has dropped by 2-12 m. In the urban areas of Jiamusi and Jiansanjiang and other places, there exist depression cones caused by groundwater exploitation.

1.2.2 Climate conditions and problems

Sanjiang Plain belongs to continental monsoon climate with the accumulated temperature of 2 238-2 560 ℃, whose annual average temperature is 1.6-3 ℃ and ≥10 ℃ has a possibility of 80%. The precipitation is 500-650 mm. The evaporation (E601) is 580-730 mm. The aridity index is less than 0.6. Throughout the year, the soil is frozen for 210 to 250 days with the depth of 1.5-2.5 m.

The main problem is that the flood disasters' frequency is increasing and the climate tends to be arid.

1.2.3 Vegetation conditions and problems

The main vegetation types are forest vegetation, grassland vegetation and marsh vegetation, among which, grassland vegetation and marsh vegetation are the most extensive types and cover a wide area.

The forest vegetation of Sanjiang Plain has decreased to 3.5% from 15% since the early stage of this century. The grassland area has decreased to 420 km^2 from 8 118 km^2 since the early stage of PRC. In 1950s, marsh and wetland accounted for two thirds of the total area of the plain, namely, 31 212.48 km^2. However, they only cover an area of 3 914.91 km^2 nowadays (WANG En-bao *et al*. 2015).

1.2.4 Landform conditions and problems

Sanjiang Plain features three types of landforms: Piedmont flat and monadnock, low plain and valley plain. Human construction activities such as quarrying, sand digging, soil carrying and coal gangue dumping destroy the landform and trigger geological disasters such as debris flows and collapse, *etc*. Besides, mining subsidence that occurred in the plain area of coalfields in Shuangyashans and Hegang with a depth of 0.4-10 m and an area of 15.67 km^2 endangers people's lives and property in the subsidence area.

1.2.5 Soil conditions and problems

Soil in the region includes albic soil, brown forest soil, bog soil, meadow soil, black soil, peat soil and others. Among these kinds of soil, bog soil, peat soil and black soil are of relatively high fertility while albic soil, paddy soil as well as saline-alkali soil are of relatively low fertility.

The main issues are: Firstly, water and soil erosion with an area of 83×10^4 hm^2 which accounts for 23% of the total farmland in the region; secondly, soil erosion and desertification with an area of 69×10^4 hm^2 (PENG Hui and PENG Xuan, 2002); thirdly, soil salinization with an area of 1 657 km^2 which stands for mild salinization.

1.2.6 Rock distribution features and main problems

Sanjiang Plain is almost covered by Quaternary. Bedrock is only about 600 km^2 and stands in the plain in the form of monadnock. Quaternary base is bedrock and is blended with volcanic rock, granite and other intrusion bodies. The main problems are geological disasters such as earthquakes, active faults, landslides, collapse, talus and debris flows, *etc*. The basic seismic intensity of the study area is Ⅵ and Ⅶ. There is a hidden and creep fault in the piedmont zone in the south of the plain, from Jiamusi in the west, through Youyi, to the north of Dahe Town in the east. Geological disasters such as collapse, landslides and debris flows often occur in mining, cutting, site excavation or reservoir bank, *etc.*, and they are related to human activities.

2 Evaluation method

2.1 Groundwater potential evaluation

Sanjiang Plain's Quaternary aquifer can be regarded as a relatively independent and integrated water balance unit and it fully plays its role of multi-year regulation as a greatly thick aquifer. Its water boundary in the north is Heilong River, while its west, south and east are impervious boundaries except the estuaries are flux boundaries. The upper part is the main substances and energy exchange boundary and Tertiary mudstone forms the lower plane's aquitard boundary. The input system is composed of precipitation infiltration, river infiltration, irrigation back-infiltration and lateral groundwater flow as well as bog water infiltration recharge and precipitation infiltration dominates. The output system is composed of phreatic water evaporation, discharge towards rivers and human exploitation, among which, phreatic water evaporation and human exploitation play the leading role.

In order to exploit groundwater more reasonably and prevent the occurrence and worsening of environmental and geological problems (SHI Jian-sheng *et al*. 2010), it is necessary to evaluate groundwater exploitation potential in Sanjiang Plain. Based on the water balance principle, the quantity of groundwater natural resources is calculated. According to 3D transient flow feature of groundwater, the paper adopts three-dimensional flow model and the simulation software Visual MODFLOW to evaluate groundwater exploitation potential. On the precondition of groundwater balance in calculation area and calculation units (divided by administrative region), the maximum exploitable water in the calculation unitis regarded as the amount that can be exploited in the calculation unit. The simulation lasts from May, 2001 to April, 2002. Groundwater exploitation condition is acquired through survey and data gathering. Effective precipitation is determined from monitoring data in the working area and adjacent meteorological stations as well as precipitation stations during the period. Parameters are based on past prospecting documents, the latest research achievements and monitoring data, and they should be finally determined by model identification and verification.

Modulus of groundwater resources potential is used in the classification evaluation of groundwater exploitation potential. It is determined in the flowing way: the ratio between the difference of the exploitable capacity and current exploitation amount in calculation unit and the calculation unit's area. The groundwater resources potential classification standard is listed in Table 1 (YANG Xiang-kui *et al*. 2008).

2.2 Eco-geological environment quality evaluation

Eco-geological environment quality evaluation consists of geological environment quality evaluation and ecological carrying capacity evaluation, both carried out via the analytic hierarchy process (AHP) as the basic method. AHP, also called multi-level weight analytic process, provides qualitative and quantitative evaluations for related factors which have been broken into objectives, principles and index. The method makes complicated phenomena and decision thinking processes systematic, model-based and data-based through systematic planning and evaluation (LI Song *et al*. 2006). The eco-geological environment of the Sanjiang Plain is a compound system of a big target and multiple layers. The key to build an evaluation index system for the system is to select factors, which can fully reflect environment characteristics of the whole system and highlight eco-geological environmental problems of the area and being available out of existing materials (TANG Jie and LIN Nian-feng, 1999). According to environment characteristics and available data of Sanjiang Plain, development intensity of geological environmental problems is considered when selecting geological environment quality evaluation factors and resource conditions and sustainable supply capacity are considered when selecting ecological carrying capacity evaluation factors.

Table 1 Groundwater resources potential classification standard

Groundwater resources potential classification	Groundwater resources potential modulus ($\times 10^4$ m^3/km^2)
High potential	>10
Relatively high potential	5-10
Medium potential	1-5
Low potential	0-1
Over exploitation	<0

2.2.1 Geological environment quality evaluation

The geological environment consists of rock environment, soil environment and water environment. The intensity of environmental geological problems and their impact on the environment quality are considered in the evaluation. Considering geological environmental conditions, problems and data available of Sanjiang Plain, 9 evaluation factors are selected to build a hierarchical system of geological environment system evaluation (Table 2). The system fully reveals the impact of geological factors in the geological environment of Sanjiang Plain. Using reference of the General Principle of 1/250 000 Regional Environment Geological Investigation (DD2004-2) about environment geological problems intensity classification and according to development characteristics of each evaluation factor in different regions, different impact intensity values of 10, 5, 2, 0 are given for being relatively strong, medium, light and less developed (YANG Xiang-kui *et al.* 2008).

Table 2 Table of evaluation index system of geo-environment system

Target layer	Principle layer (impact factor layer)	Index layer (sensitivefactor layer)
Geological environment quality	Rock environment quality (Ⅰ)	Earthquake ($Ⅰ_1$)
		Collapse, landslides and debris flows($Ⅰ_2$)
		Land deformation ($Ⅰ_3$)
	Soil environment quality (Ⅱ)	Water and soil erosion ($Ⅱ_1$)
		Land desertification ($Ⅱ_2$)
		Soil salinization ($Ⅱ_3$)
	Water environment quality (III)	Uneven distribution of water resources (III_1)
		Drop of groundwater level (III_2)
		Water pollution (III_3)

After the evaluation system is established, the weight value of each factor layer and single factor is given via expert scoring and AHP. When compare the relative importance of each factor of a same layer to each principle of the last layer, the relative importance is scaled from 1 to 9 in order to build a pairwise comparison judgment matrix. The weight is determined by the judgment matrix (YANG Xiang-kui *et al.* 2008) and it's also tested by it. When CR<0.01, it proves that the judgment matrix is satisfactorily consistent.

Finally, the quality index is used as the quantitative index to evaluate the geological environment quality. To this end, the mathematical model of the geological environment system quality index is established as follows:

$$A=\sum_{j=1}^{n} a_j \cdot N_j \quad \text{(of which n=1, 2, …,9)}$$

of which: A–geological environment system quality index

a_j–weight of the jth environment geological problem

N_j–intensity value of the jth environment geological problem

The geological environment quality is divided into 5 levels according to the quality index value (YANG Xiang-kui, 2008). Please refer to Table 3.

Level I refers to good environment quality, level II refers to relatively good environment quality, level III, medium environment quality and level IV-V, relatively poor and poor environment quality.

Table 3 Classification standard of environmental quality

Level	Level Ⅰ	Level Ⅱ	Level Ⅲ	Level Ⅳ	Level Ⅴ
Index	<3	3-4	4-5	5-6	>7

2.2.2 Ecological carrying capacity evaluation

Ecological carrying capacity refers to the ability of self-maintenance and self-regulating of the eco-system, the supply and carrying capacity of resources and environment sub-systems, the intensity of socio-economic activities that can be maintained and the number of people with a certain standard of living. It is also an important indicator for eco-geological environment quality evaluation. The ecological carrying capacity of Sanjiang Plain is evaluated by hierarchical evaluation method: the Level I evaluation uses the ecological elasticity as the evaluation criterion, the Level II evaluation takes the resource carrying capacity as the criterion.

Determinative factors of ecological elasticity include landform, soil, vegetation, climate and hydrology; while determinative factors of the carrying capacity include water resources and land resources. According to natural resource conditions of Sanjiang Plain, evaluation factors are divided into five levels of good, relatively good, medium, relatively poor and poor with the assignment intervals of 100-80, 80-60, 60-40, 40-20 and＜20. Two methods are used in deciding the evaluation value: for factors with specific data, piecewise regression is used; for factors with no specific data, semi-quantitative method is used (YANG Xiang-kui *et al*. 2008). Weight of each factor is decided via AHP. The ecological carrying capacity classification is shown in Table 4.

Table 4 Classification evaluation table of ecological carrying capacity

Level \ Carrying capacity value	<20	20-40	40-60	60-80	>80
Level I evaluation	Instability	Weak stability	Medium stability	Relatively good stability	Good stability
Level II evaluation	Low carrying capacity	Weak carrying capacity	Medium carrying capacity	Relatively high carrying capacity	High carrying capacity

3 Results and analysis

3.1 Groundwater resources potential

According to calculation, the multi-annual average groundwater recharge amount of the area is 514 522.93×10^4 m^3; of which, vertical recharge amount is 33 8142.65×10^4 m^3, the river net recharge amount is 58 314.54×10^4 m^3, marsh and wetland net recharge amount is 72 538.87×10^4 m^3, adjacent run-off net recharge amount is 45 526.86×10^4 m^3. The precipitation infiltration recharge amount out of the vertical recharge amount is 277 768.91×10^4 m^3, canal irrigation and paddy field back-infiltration recharge amount is 60 373.74×10^4 m^3.

The groundwater discharge amount in the whole are aunder multi-year balance conditions: river net discharge amount is 22 402.12×10^4 m^3, marsh and wetland discharge amount is 13 523.07×10^4 m^3, groundwater evaporation discharge amount is 46 369.87×10^4 m^3, adjacent run-off net discharge amount is 60 730.70×10^4 m^3; the total groundwater discharge amount is equal to the total recharge amount. After years of exploitation, groundwater of Sanjiang Plain is still in a balanced status and therefore, Sanjiang Plain groundwater system is a relatively independent and unified balanced water system.

Underbalanced conditions for years, around the whole area, exploitable groundwater resources amount is 371 197.40×10^4 m^3, while the groundwater exploitation amount in Sanjiang Plain in 2001 is 21.33×10^8 m^3/a, leaving a margin of 157 820.00×10^4 m^3/a, however groundwater exploitation in areas like Baoquanling Farm, Chuangye Farm, Erdaohezi Farm, 290 Farm, Qixing Farm and Qindeli Farm, the current exploitation amount is greater than the exploitable resources, which is over exploitation. Groundwater resources in other counties, cities and farms still have potential for further exploitation. Please refer to Table 5, Fig. 1.

According to investigation results, shallow groundwater(less than 50 m deep) is mainly used in Sanjiang Plain. Without considering the circulation and transformation characteristics of shallow groundwater, deep groundwater and surface water, deep groundwater and surface water is naturally discharged and can not be effectively utilized.

3.2 Eco-geological environment quality

3.2.1 Geological environment quality

Areas of good and relatively good geological environment quality accounts for 99.9% in Sanjiang Plain; while areas of medium quality accounts for 0.1% and are only distributed in a small area in the south of Hebei County. The overall geological environment quality in Sanjiang

Plain is good, which is favorable to the economic and social development.

3.2.2 Ecological carrying capacity

Most areas in Sanjiang Plain have medium carrying capacity with medium stability (please refer to Table 6). Only small areas in the south of the Luobei County, the west of Fujin, the north of Jiamusi have relatively high carrying capacity with medium stability. This proves that most areas in Sanjiang Plain do not have high carrying capacity and easily get damaged, which means the intensity of human production and economic activities should be within the carrying capacity.

Table 5 Analysis results table of groundwater resources potential

Potential level	Administrative Region
Low potential	859 Farm, 291 Farm, Shengli Farm, Tangyuan Farm, 597 Farm, Jixian County and suburb area of Jiamusi
Medium potential	852 Farm, Hongqiling Farm, Hong River Farm, Mingshan Farm, Qianfeng Farm, Qianjin Farm, Qianshao Farm, Qinglong Mountain Farm, Suibin Farm, Baoqing County, Fuyuan County, Fujin County, Tangyuan County, Youyi County, urban area of Hegang City
Relatively high potential	853 Farm, Daxing Farm, Hongwei Farm, Jiangbin Farm, Jiangchuan Farm, Junchuan Farm, Puyang Farm, Wutong River Farm, Yalu River Farm and Yanjun Farm, Luobei County, Suibin County, Tongjiang City, natural conservation area
High potential	Huachuan County and Raohe County, Raohe Farm and Xinhua Farm
Over exploitation	Baoquanling Farm, Chuangye Farm, Erdaohezi Farm, 290 Farm, Qindeli Farm, Gongqing Farm and Qixing Farm

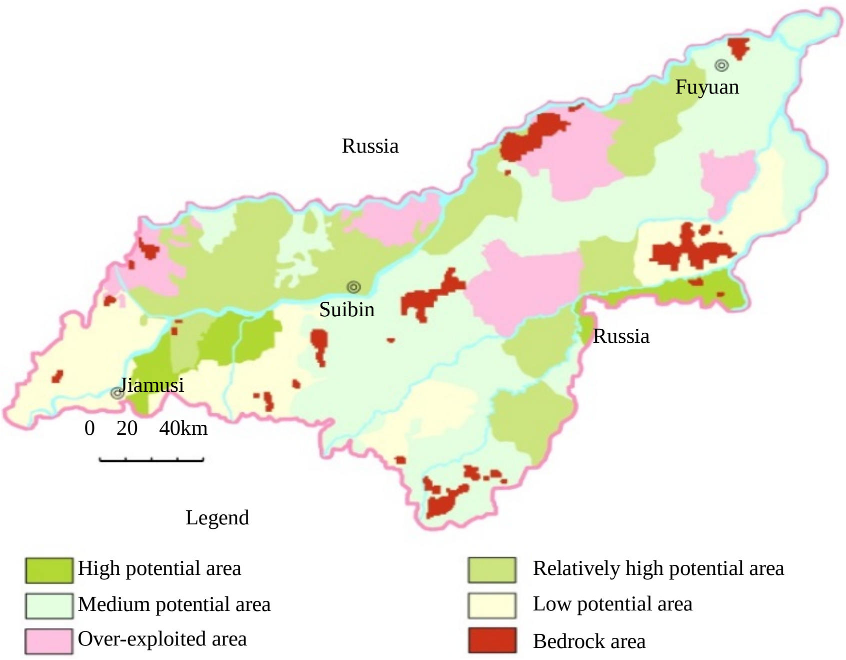

Fig. 1 Quaternary groundwater resources potential subarea chart

Table 6 Ecological carrying capacity partition

	Ecological carrying capacity level	Area (km^2)	% in total areas
I	Medium stability, relatively high carrying capacity	1 743.96	4.1%
II	Medium stability, medium carrying capacity	40 513.80	95.9%

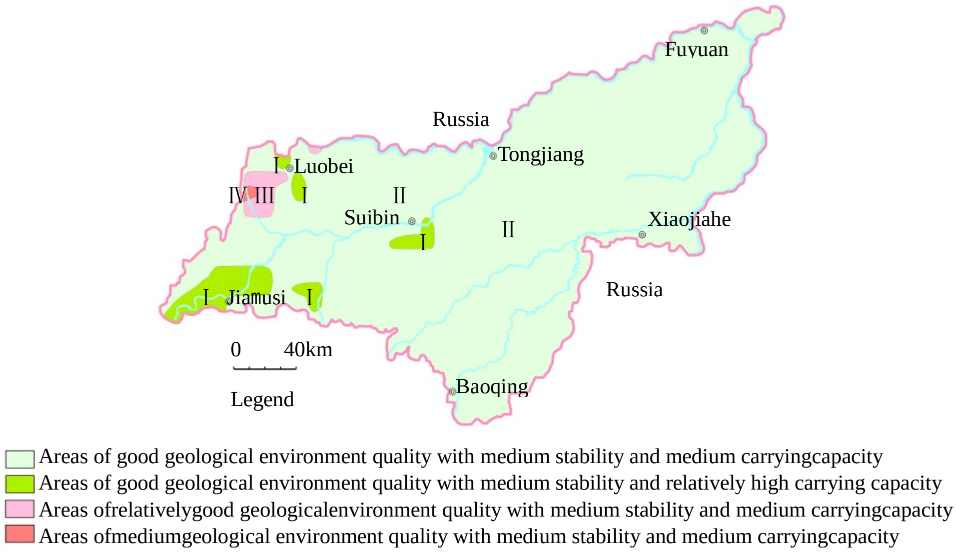

Fig. 2 Eco-geological environment quality partition chart

3.2.3 Eco-geological environment quality

Most areas in Sanjiang Plain are of good geological environment quality with medium stability and medium carrying capacity, which accounts for 94.5% of the total plain area; 4.1% areas are of good geological environment quality with medium stability and relatively high carrying capacity; only 1.3% areas are of relatively good geological environment quality with medium stability and medium carrying capacity; 0.1% areas are of medium geological environment quality with medium stability and medium carrying capacity (please refer to Fig. 2). This shows the geological environment quality in Sanjiang Plain is good but the ecological carrying capacity is relatively weak. This requires that in the process of exploitation and protection of Sanjiang Plain, the overall system effect should be fully considered in order to achieve the sustainable development of economy and society in Sanjiang plain.

4 Conclusions and discussions

(1) The overall groundwater resources in Sanjiang Plain still have a certain exploitation potential, however, the resources are distributed unevenly: Areas with high and relatively high potential are distributed in Tongjiang City, Luobei County, Suibin County, Huachuan County, Raohe County and natural conservation areas and some farms along the Heilongjiang River, Songhua River, Ussuri River and Naoli River; areas with medium potential are distributed in Fuyuan County, Suibin County and Baoqing County in the central of the plain; in areas in the west of the plain, including Jiamusi, Tangyuan County, Jixian County and areas in the southeast of the plain, including 853 Farm, Shengli Farm, the groundwater potential is low; groundwater is over exploited in Baoquanling Farm, Chuangye Farm, Erdaohezi Farm, 290 Farm, Qindeli Farm, Gongqing Farm and Qixing Farm. In areas with over exploitation and low exploitation potential, well irrigation is not suitable in agricultural production, instead, water conservancy facilities should be built for water diversion irrigation in order to utilize local water resources in a scientific and reasonable way.

(2) The overall geological environment quality of Sanjiang Plain is good while the ecological carrying capacity is relatively weak. Most areas have good geological environment quality, medium stability and medium carrying capacity, which are easily damaged without high carrying capacity. A series of environmental geological problems have taken place after unreasonable exploitation of human activities. This requires that ecological effect should be fully considered in the process of exploitation and protection in Sanjiang Plain. Human economic activities should fit eco-geological environment conditions, for example: In piedmont flat areas, it’s suitable to carry out economic activities like afforestation, dryland development, mineral exploitation and

residents living; in plain areas, production activities like paddy field development and protection, dryland comprehensive development, forestry, animal husbandry and fishery development and residents living are recommended; in areas along the river, it's favorable to carry out port development and the development and protection of the combination of tourism and fishery. In the meantime, protection areas for forest, grassland, marsh and wetland should be set up in order to build a sound eco-geological environment system in Sanjiang Plain to ensure grain production safety and the sustainable development of economy and society.

Reference

Changchun Institute of Geography, Chinese Academy of Sciences. 1983. Sanjiang Plain Swamp. Beijing: Science press, 1-195.

CHEN Meng-xiong. 1999. Comments on the eco-environment geological system and the comprehensive survey of it. Hydrogeology & Engineering Geology, (3): 3-12.

FENG Jie. 2013. Application of Visual MODFLOW in groundwater numeric simulation model. Ground water, 35(4): 34-36.

HAN Zai-sheng. 2003. Eco-environmental geological survey: Progress and prospects. Geological Bulletin of China, 22(11-12): 977-983.

HUANG Run-qiu, XIANG Xi-qiong. 2002. Application of the GIS technique in the assessment of the eco-environment. Geological Bulletin of China, 21(2): 98-101.

LI Song, QIU Wei, *et al*. 2006. Applying analytical hierarchy process to assess eco-environment quality of Heilongjiang Province. Environmental Science, 27(5): 1031-1034.

PENG Hui, PENG Xuan. 2002. Forest of Sanjiang Plain ecological environment change. North Environment, (1): 40.

QIAN Yong, ZHANG Zhao-ji, *et al*. 2014. Sustainable exploitable potential of shallow groundwater in the North China Plain. Chinese Journal of Eco-Agriculture, 22(8): 890-897.

SHI Jian-sheng, WANG Zhao, *et al*. 2010. Assessment of over-exploitation of deep groundwater in the North China Plain. Earth Science Frontiers, 17(6): 215-220.

SHEN Yuan-yuan, JIANG Yun-zhong, *et al*. 2009. Current practice and development trend in numerical modeling of groundwater in China. Journal of China Institute of Water Resources and Hydropower Research, 7(1): 57-61.

TANG Jie, LIN Nian-feng. 1999. Comprehensive evaluation on the agricultural eco-geological environmental quality. World Geology, 18(2): 89-94.

WANG En-bao, *et al*. 2015. Sanjiang plain results groundwater pollution survey and evaluation report. Geological Survey Research Institute in Heilongjiang Province, 38-105.

WEI Dong-sheng, LIU Jie, *et al*. 2014. Application of Visual MODFLOW in China. Energy and Energy Conservation, (6): 96-98.

YANG Xiang-kui, YANG Wen, *et al*. 2008. Groundwater resource potential evaluation and eco-environmental geological survey in Sanjiang Plain. Geological publishing house, 32-220.

ZHI Bing-fa. 2008. Some issues on regional eco-geo-environmental quality evaluation-taking the pearl river delta economic zone as an example. Journal of Catastrophology, 23(2): 59-64.

ZHENG Chang-yuan, ZHANG Qi-xing, *et al*. 2010. The application of Analytic Hierarchy Process (AHP) in source region of the Yangtze River's geological environment quality (vulnerabilities) evaluation. Northwestern Geology, 43(1):137-145.

ZHOU Fang-cheng, SONG Xiao-ning, *et al*. 2013. Research on distribution of soil moisture resources using analytic hierarchy process based on GIS and RS: Taking Shijiazhuang City as study case. Journal of China Hydrology, 33(6):16-20.