Journal of Engg. Research **Vol. 4 No. (3) September 2016** pp. 1-17

تطبيق الاستشعار عن بعد وتحليل نظم المعلومات الجغرافية في إمكانية تقدير المياه الجوفية في مقاطعة غرب لياونينغ، الصين

***فيفان دينج، *ذينجدونج دينج، **دان لف، *داكينغ وانغ، *جواجي دوان و*ذيلي زينج**

*جامعة جيش التحرير الشعبى الصينى للعلوم والتكنولوجيا، هيفوزيانج، ونانجينغ، الصين

**أكاديمية الهندسة التابعة لجيش التحرير الشعبى الصينى، دونج ذيانزي، كزوسهو، الصين

الخلاصة

المياه الجوفية هي واحدة من أهم الموارد الطبيعية للبشر، ومن الضروري مراقبتها مراقبة طويلة الأجل من أجل حماية الموارد المائية. الاستشعار عن بعد ونظم المعلومات الجغرافية قد أصبحوا أدوات فعالة في التحقيق الأرضي وقد أظهروا إمكانيات كبيرة وواعدة في الكشف عن المياه الجوفية. وحيث أن هناك علاقة وثيقة بين المياه الجوفية وسطح الأرض الذي يعلوها، اختارت ورقة البحث الخصائص الصخرية والكثافة الخطية وكثافة التصريف والميل كعوامل تؤثر على تشكيل المياه الجوفية، والخمول الحراري والغطاء النباتي كمؤشرات على وجود المياه الجوفية. المعلومات ذات الصلة بالمياه الجوفية تم الحصول عليها من الخرائط التقليدية ومن بيانات الاستشعار عن بعد باستخدام تقنيات الاستشعار عن بعد ونظم المعلومات الجغرافية. تم بناء نموذج قائم على تقنيات عملية التحليل الهرمي لفهم العلاقة بين المعلومات واحتمالية وجود المياه الجوفية، وتم استخدامها لعمل خريطة لاحتمالية تواجد المياه الجوفية في منطقة الدراسة. وتمت مقارنة مؤشر الاحتمالية المقدرة مع بيانات البئر المقاسة ميدانياً. وأشارت النتائج أن مؤشر الاحتمالية والبيانات المقاسة ميدانياً مرتبطين تصاعديا بمعامل ارتباط بيرسون الذي يبلغ 0.8034، مشيرةً إلى أن هذه الطريقة قادرة على تقدير احتمالات وجود المياه الجوفية.

Application of remote sensing and GIS analysis in groundwater potential estimation in west Liaoning Province, China

Feifan Deng*, Zhengdong Deng*, Dan Lv**, Daqing Wang*, Huajie Duan* and Zheli Xing*

**PLA University of Science and Technology, Haifuxiang 1st, Nanjing, China*

***Engineering Academy of PLA, Dongdianzi, Xuzhou, China*

Corresponding author: dengzdong@sina.com

ABSTRACT

Groundwater is one of the most important natural resources for mankind, it is necessary to launch a long-term monitoring of it, for the water resources protection. Remote sensing (RS) and geographic information systems (GIS) have become efficient tools in ground investigation, and shown great potential for groundwater surveying. As there is a close connection between groundwater and the surface above, this paper selected lithology, lineament density, recharge and slope as factors affecting groundwater formation, and thermal inertia and vegetation canopy as indicators of the groundwater occurrence. The groundwater-related information was obtained from conventional maps and remotely sensed data using RS and GIS techniques. A model based on analytic hierarchy process (AHP) techniques was built to understand the connection between the information and the groundwater potentiality, and was used to map the groundwater potentiality of the study area. The estimated potentiality index was compared with field-measured well yield data, and the results suggested that the potentiality index and the field measured data were exponentially related, with a Pearson correlation coefficient of 0.8034, indicating that this method is capable of groundwater potentiality estimation.

Keywords: AHP; GIS; groundwater potentiality; remote sensing; thematic layers.

INTRODUCTION

Groundwater is one of the most valuable natural resources, and has a substantial influence on human activities. Rapid population growth and social development are leading to a greater demand for water, and groundwater is becoming increasingly important, because it is stable in terms of quantity and quality, when compared with surface water, especially in some arid and semi-arid regions, where it is the only water resource available. However, in many places, the improper planning and over exploitation of groundwater have caused many problems, such as wastage of energy and resources and the destruction of the local ecosystem. Therefore, proper management and planning of groundwater are necessary and important to maintain sustainable development. Conventional groundwater monitoring and detecting methods, such as establishing a weather station or a gauging station and digging a borehole, demand much time and effort (Jha *et al.,* 2010), and can only provide point data that cannot clearly depict the regionally distributed information (Brunner *et al.,* 2007).

Remote sensing is an advanced and efficient technology for surveying the ground. It has good spatial, temporal and spectral coverage of the earth (Prihodko & Goward 1997), and the data carries information regarding spatial patterns that can be related to features on the surface or in the shallow subsurface. This type of information can be used directly or indirectly to deduce the underground features because there is a close connection between the surface and the underground. Geographic information systems enable us to manipulate, store and analyze large volumes of multi-resource geographic data, and is a perfect tool for spatial modeling. With the integration of RS and GIS, we can collect volumes of groundwater-related information that are as large as possible, and draw a general picture of the groundwater resources through modeling.

There are many ways to link the groundwater to the surface, because on one hand the occurrence and movement of groundwater in an area is controlled by many factors such as topography, lithology, slope, drainage pattern, landforms, and land use/land cover. On the other hand, groundwater occurrence affects the ground surface through capillary action or heat effects, and can result in different spatial features on the ground such as plant density, thermal properties and soil moisture.

Some researchers suggested that the water content in the ground is influenced by the groundwater within the capillary edge, and designed methods to estimate groundwater levels using remote sensing (Komarov *et al.,* 1999; Huo *et al.,* 2011). Many others (Yamaguchi *et el.,* 1992; Heilman & Moore, 1982; Chen *et al.,* 2006) also developed their own methods for groundwater surveying using RS by linking the groundwater to vegetation types and surface temperature.

The integration of RS and GIS in groundwater monitoring and detection is developing rapidly. To depict a precise picture of the groundwater, most researchers tend to take as many groundwater-related factors into consideration as possible, and the most common factors include geomorphology, lithology, slope, land use/land cover, geology, drainage density, and lineament density (Rekha *et al.*, 2011; Bagyaraj *et al.,* 2013; Preeja *et al.,* 2011; Narendra *et al.,* 2013; Rao, 2006; Sener *et al.,* 2005). Some others think that soil type, post-monsoon groundwater depth, proximity to surface water bodies and rainfall also play important roles in mapping groundwater potentiality (Machiwal *et al.,* 2011; Elewa & Qaddah, 2011; Gumma & Pavelic, 2013; Singh *et al.,* 2011).

Those chosen factors were usually further analyzed to determine the relationships between them and the groundwater, and this step can be processed by GIS modeling techniques. There are many types of modeling methods, such as weighted linear combination, weighted aggregation, index overlay and multi-criteria analysis of the analytical hierarchy process (AHP) (Manap *et al.,* 2013). Over the past decades, many researchers have found that multi-criteria decision analysis (MCDA) is a very efficient tool for groundwater assessment, and one of the most widely used MCDA types is the AHP method, which has been applied in many environmental management problems (Rahmati *et al.,* 2014).

The main purpose of this study is to discuss the possibility of using RS and GIS techniques for groundwater potential mapping, and the western Liaoning Province of China was chosen as the study area. Groundwater potentiality estimation in an area will help people gain a general understanding of the local water resources, and can provide them with guidance when they are making decisions related to site selection, municipal planning, environmental protection, and so on. The integration of RS and GIS provide a quick and inexpensive approach to groundwater surveying, and play an important role in maintaining sustainable development.

OVERVIEW OF THE STUDY AREA

The study area is located in the Chaoyang District, western Liaoning Province of China, extending between 41°20' and 42°N latitude and 120°and 121°E longitude, and covering an area of 5000 km^2; the overall picture of the study area is shown in Figure 1. This is a semi-arid area with a yearly rainfall of 485 mm, high evaporation of 2202 mm, and a mean annual temperature of 8.3°C. There are four main rivers in the study area, and only a few small lakes scattered on the northern part; thus, the groundwater recharge comes mostly from rainfall and runoff. Concerning the characteristics of the study area, this paper selected lithology, lineament density, recharge and slope as the factors affecting groundwater formation, and thermal inertia and vegetation canopy as indicators of the groundwater occurrence, and prepared the database using RS and GIS.

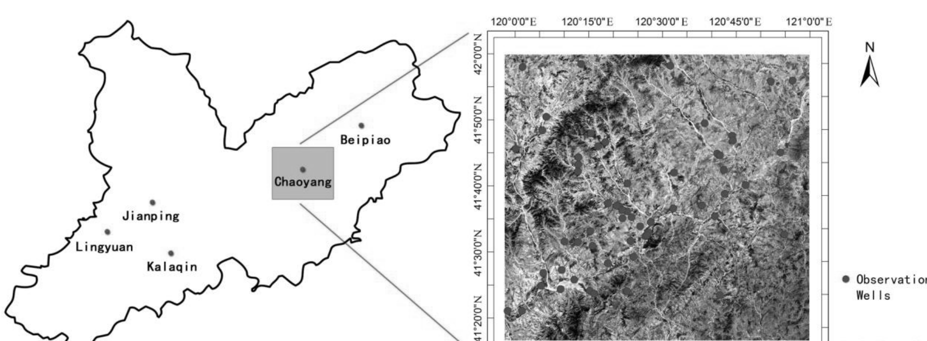

Fig. 1. Location of the study area in Chaoyang, western Liaoning Province of China

MATERIALS AND METHODS

Shuttle radar topography mission (SRTM) DEM data were used to generate the slope map and the recharge map, and a 1:200,000 scale conventional geology map (Map number: K-51-[19], 1980) was used to generate the lineament map and the lithology map. Landsat ETM+ data (Path/Row:121/31, Acquisition Date:19/06/2000) were used to generate the thermal inertia map and the vegetation canopy map. These maps were downloaded from the Geospatial Data Cloud. Geometric registration was applied to the original data to make sure that the coordinate systems of all thematic maps generated agree with each other. Atmospheric correction based on the ENVI FLAASH module was applied to the Landsat ETM+ images to remove the influence of the atmosphere.

The thematic maps were prepared in raster format with spatial resolution of 30m, and because each individual map was defined in different dimensions, it is impractical to use the original maps in the following model calculations. To remove this problem, all of the maps were made dimensionless. Finally, all of the processed maps had a uniform value range of 0-1, which represents poor (0) to good (1) contribution to groundwater enrichment. The normalized thematic layers were further processed using AHP techniques for the weight assignment and modeling, and were calculated in ArcGIS to generate the groundwater potential map. The procedures used to forecast groundwater potential zones in this study are illustrated in Figure 2.

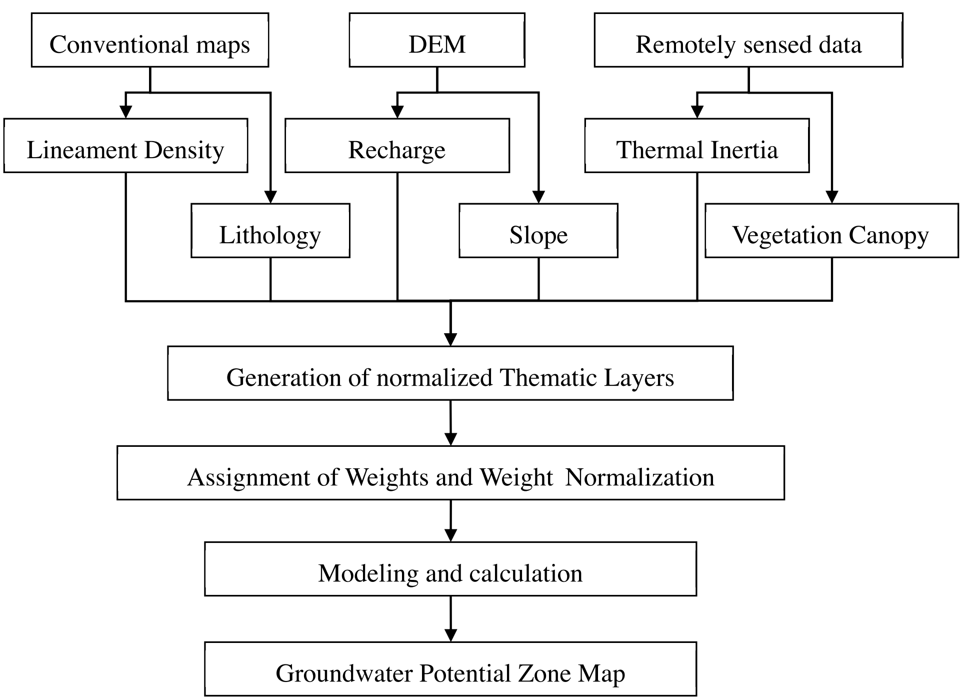

Fig. 2. The procedure for groundwater potentiality estimation

GENERATION OF THEMATIC MAPS

Slope

Shallow groundwater flow is usually driven by surface force, and the boundary of the terrain is mostly the boundary of the shallow aquifer. Slope is important in analyzing the terrain, as it can affect the groundwater in terms of its storage, flow and discharge, especially in mountainous areas. Groundwater is more likely to gather in flat field than a sloping field. The slope map was obtained from the DEM using ArcGIS, and it is shown in Figure 3. It was noticed that groundwater was scarcely found in areas, where slope was larger than 30 degrees. Therefore, the normalization of the slope can be expressed as :

$$L_S = \begin{cases} \frac{30-S}{30}, & 0 \leq S \leq 30 \\ 0, & S > 30 \end{cases} \tag{1}$$

Here, S is the slope measured in degrees.

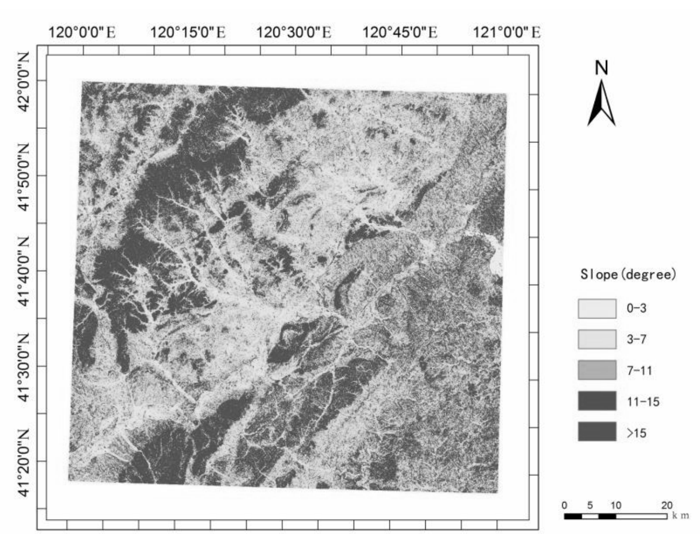

Fig. 3. Slope map in the study area

Recharge

One of the most important reasons for the long term existence of groundwater is constant recharge. Groundwater recharge in the study area comes mainly from the surface water bodies and rainfall. When a groundwater funnel forms due to the natural discharge or over exploitation of groundwater resources, the nearby surface water will provide a steady recharge through infiltration. The river density was introduced to represent the recharge conditions and to quantify the influence caused by surface water, where higher density provides better recharge conditions and vice versa. Flow accumulation was calculated in ArcGIS. It was noticed that river bodies tend to form, where the flow accumulation value is higher than 50000. Thus, pixels with flow accumulation values higher than 50000 were selected to represent river bodies. The river network was then obtained, and was used to generate the river density map as shown in Figure 4. Additionally, the normalization of the river density can be expressed as:

$$L_R = \frac{R_{max}-R}{R_{max}-R_{min}} \tag{2}$$

Here, R is the river density(km/km^2).

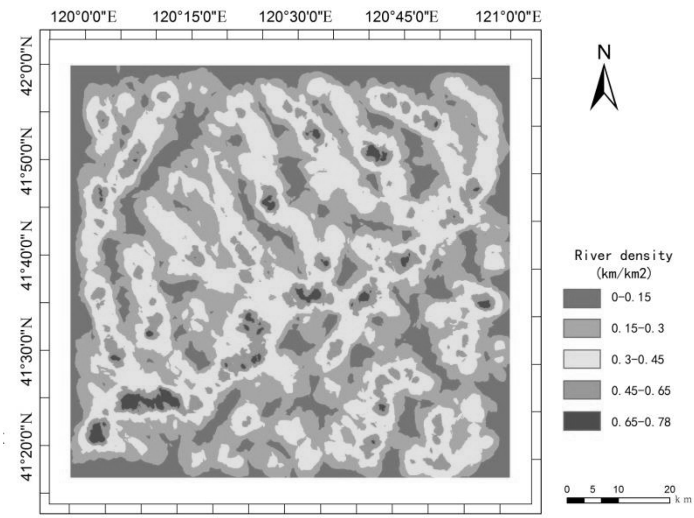

Fig. 4. Recharge map of the study area

Lineament density

Lineaments have often been recognized as conduits of groundwater flow, and were used for the site selection of the wells. Many researchers found that areas with high lineament density are good for groundwater development (Meijerink, 1996; Murugesan *et al.,* 2011; Sander, 2007). A lineament map was prepared using the geology map, and was analyzed in ArcGIS to generate the lineament density map, as shown in Figure 5.

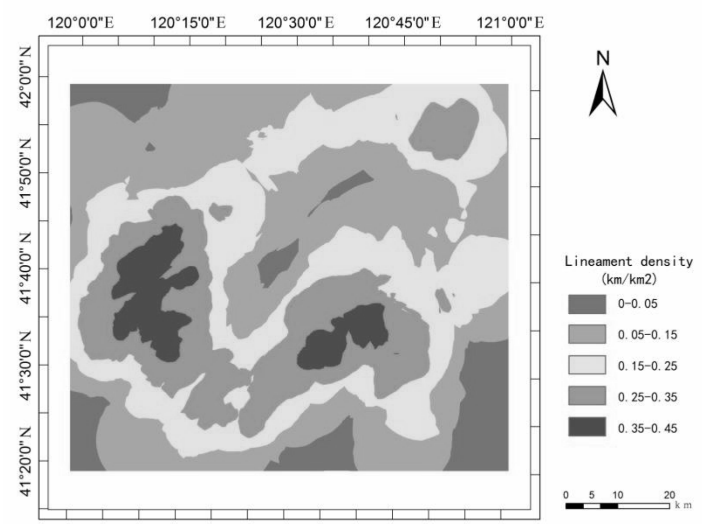

Fig. 5. Lineament density map of the study area

The normalization of river density can be expressed as:

$$L_L = \frac{L_{max} - L}{L_{max} - L_{min}} \tag{3}$$

Here, L is the lineament density(km/km^2).

Lithology

Lithology influences both the porosity and permeability of aquifer, and it has a direct impact on the occurrence and distribution of groundwater. The Quaternary alluvium in the study area consists mainly of sand and gravel, and their good permeability makes these areas a good place for groundwater movement; thus, these areas were assumed to have good groundwater potential. The Sinian system consists mainly of limestone, shale and dolomite. Groundwater yield in this system is mostly poor, except in some places with good joint development, where there may be a good abundance of fissure water. The Jurassic system is moderate in groundwater potential, and mainly consists of basalt and shale with good joint development. The Cretaceous system is relatively poor in terms of its groundwater storage. The lithology layer was prepared by digitizing the 1:250,000 scale geological map, as shown in Figure 6.

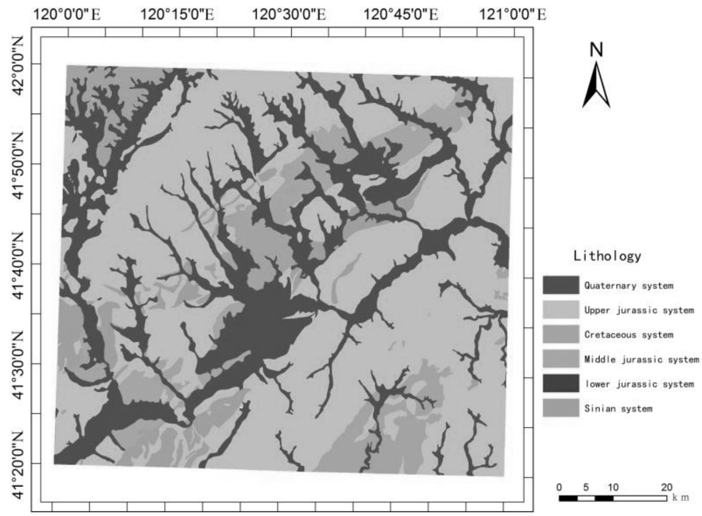

Fig. 6. Lithology map of the study area

The normalization of lithology is shown in Table 1, the score of the lithology was given by experts according to the description in the hydrological and geological report of the study area.

Table 1. Normalization of the lithology

Lithology	Quaternary system	Upper Jurassic system	Middle Jurassic system	Lower Jurassic system	Cretaceous system	Sinian system
Value	0.9	0.5	0.5	0.3	0.1	0.7

Vegetation canopy

One of the earliest applications of remote sensing was to use the species, density and living status of plants to deduce the hydrologic features (Fensholt *et al.,* 2006). Most plants tend to grow in places with abundant groundwater, as they need to continuously absorb water from the soil during their growth process, which makes them indicators for inferring the existence of shallow groundwater. The vegetation canopy in this study was defined as:

$$C = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{4}$$

Here, the normalized vegetation index (NDVI) can be calculated using remotely sensed data, and the NDVI of soil and vegetation can be defined using the NDVI map. The vegetation canopy map is shown in Figure 7, and its normalization can be expressed as:

$$L_C = \frac{C_{max} - C}{C_{max} - C_{min}} \tag{5}$$

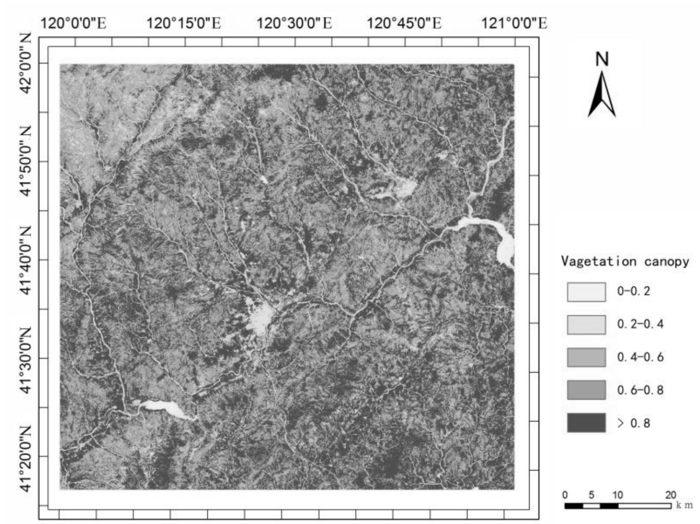

Fig. 7. Vegetation canopy map of the study area

Thermal inertia

Due to the influence of the high heat capacity of groundwater, the areas enriched in groundwater tend to appear as a heat sink in the summer and a heat source in the winter (Becker, 2006). Many researchers found this phenomenon and used it in groundwater resource studies (Chase, 1969; Falconer *et al.*, 1981). The preparation of the thermal inertia map was carried out by the Equation (6) (Carlson,1986):

$$P = \frac{2SV(1-A)}{\Delta T} \tag{6}$$

where the solar amplitude *(S)* and atmospheric transmission *(V)* can be regarded as constant, ΔT represents the temperature variation, and the calculation of the surface albedo was given by the Equation (7) (Liang, 2001):

$$A = 0.356B_1 + 0.130B_3 + 0.373B_4 + 0.085B_5 + 0.072B_7 - 0.0018 \tag{7}$$

The temperature of the study area was retrieved using the Mono-window algorithm (Qin *et al.,* 2001). The thermal inertia map is shown in Figure 8.

$$L_P = \frac{P - P_{min}}{P_{max} - P_{min}} \tag{8}$$

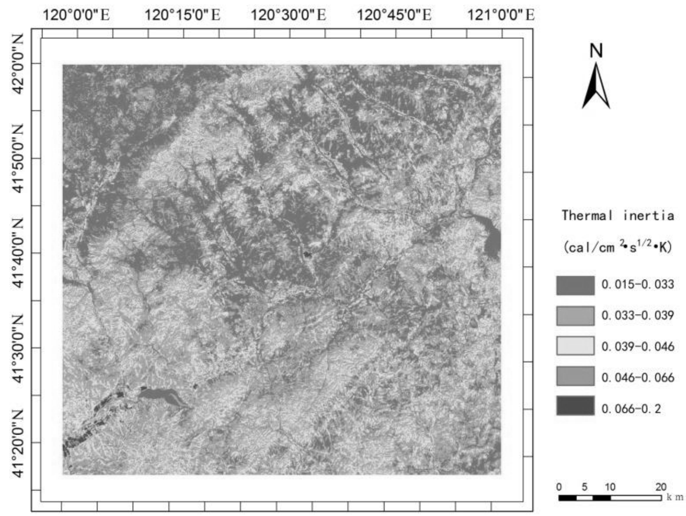

Fig. 8. Thermal inertia map of the study area

ASSIGNMENT OF WEIGHTS AND WEIGHT NORMALIZATION

In this case, six thematic layers, namely slope, lithology, lineament density, recharge, thermal inertia, and vegetation canopy, were selected as the controlling factors or indicators of the groundwater occurrence in Chaoyang District, western Liaoling Province of China. To gain a clear view of the connections between the layers and the groundwater prediction, the analytical hierarchy process (AHP) method was used to determine the weight of each thematic layer. AHP is a systematic analyzing method for decision making and planning, and is widely used in the field of natural resources and environmental management (Saaty,1990).

A total of ten experts in the fields of hydrogeology and geology were invited to a discussion to seek their opinions on the selected thematic layers regarding their ability to predict groundwater potentiality. Those thematic layers were compared in pairs to decide their relative importance. All of the layers were given a score to represent their importance, and the total score of each pair was 10. The normalized weights for each thematic layer were derived by the eigenvector technique, and the pair-wise comparison matrix is shown in Table 2.

Table 2. Pair-wise comparison matrix of layers

Themes	Slope	River density	Lineament density	Lithology	Thermal inertia	Vegetation canopy
Slope	1	6.5/3.5	7/3	5.5/4.5	8/2	7.5/2.5
River density	3.5/6.5	1	6/4	3/7	6.5/3.5	6.5/3.5
Lineament density	3/7	4/6	1	3/7	7/3	6/4
Lithology	4.5/5.5	7/3	7/3	1	7.5/2.5	7/3
Thermal inertia	2/8	3.5/6.5	3/7	2.5/7.5	1	4/6
Vegetation canopy	2.5/7.5	3.5/6.5	4/6	3/7	6/4	1

Before the assignment of normalized weights for the layers, there is a need to examine the consistency of the matrix to avoid unreasonable results. The consistency ratio (CR) was calculated by:

$$CR = \frac{CI}{RI} \tag{9}$$

where the values of the random consistency index (RI) are as shown in Table 3, and the consistency index (CI) was calculated using the following equation:

Table 3. The values of RI used in the calculation

Number of Layers	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{10}$$

where n is the number of layers and λ_{max} was computed by the eigenvector technique.

The value of *CR* should be less than 0.10 to guarantee the reliability of the result. Here, the result showed that:

$$CR=0.0103$$

The consistency ratio of the matrix was found to be less than 10%, thereby suggesting that the assigned weights are consistent. The normalized weights were shown in Table 4.

Table 4. The normalized weights assigned to each layer

Themes	Slope	River density	Lineament density	Lithology	Thermal inertia	Vegetation canopy
Weights	0.291	0.152	0.128	0.262	0.071	0.095

RESULT AND DISCUSSION

The groundwater potential map was prepared by the integration of the individual thematic layers. It was processed in the ArcGIS software using the spatial modeler module, and is shown in Figure 9. Integration of the thematic layers was carried out by the weighted overlay analysis method, as given by the following equation:

$$Y = \sum_{i=1}^{n} W_i \cdot X_i \tag{11}$$

where X_i represents each individual thematic layer, and W_i is the weight assigned to the corresponding layer .

The groundwater potential map is a raster map with spatial resolution of 30m, and it is shown in Figure 9. The pixel value of the map represents the estimated groundwater potentiality. Theoretically, the pixel values range from 0 to 1, representing non-potential to extremely high potential for groundwater.

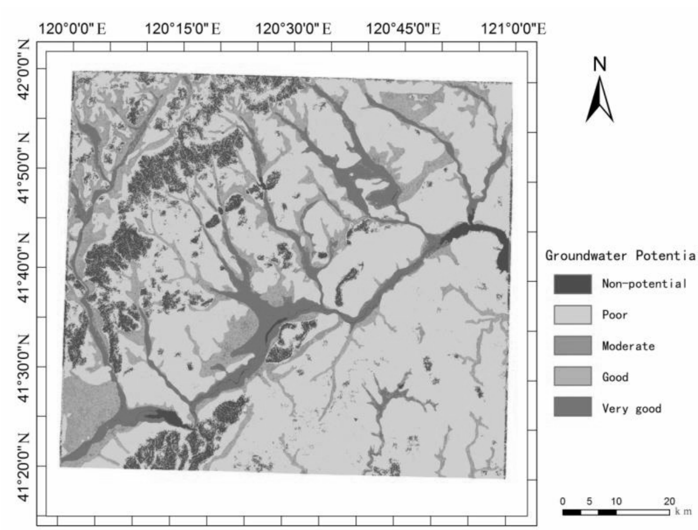

Fig. 9. Groundwater potential map of the study area

To understand the significance of the map in terms of its ability to predict groundwater potentiality, field surveying was made to link the well yield with the groundwater potential index. Groundwater yield data of 47 wells were obtained through field surveying and were compared with the index, as shown in Figure 10. The results show that the predicted groundwater potential index is exponentially related to the measured well yield data, and the correlation coefficient is 0.8034, suggesting that the map is capable of estimating groundwater enrichment.

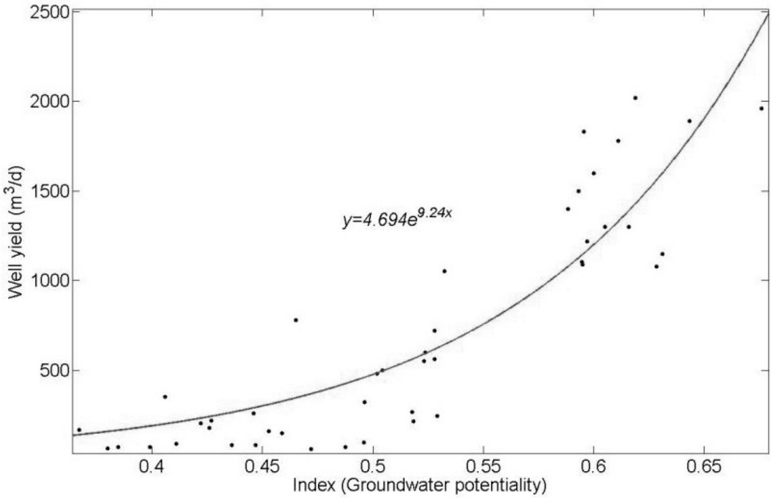

Fig. 10. Comparison between the groundwater potential index and well yield

According to the relationship between well yield and the index, the groundwater potentiality was classified into five zones according to the predicted groundwater yield: very good, good, moderate, poor and non-potential. The groundwater potentiality index (GPI) and the corresponding predicted groundwater yields are shown in Table 5.

Table 5. The GPI and the corresponding predicted groundwater yields

Class	Predicted groundwater yield	GPI
Very Good	1000t/d or more	>0.58
Good	(500-1000t/d)	0.505-0.58
Moderate	(300-500t/d)	0.45-0.505
Poor	100-300t/d	0.331-0.45
Non-potential	100t/d or less	<0.331

The very good groundwater potential zones account for 5.63% of the total area, and are mostly located in the alluvial plain or valley adjacent to the Daling River and the middle and lower reaches of its branches. Those low-lying areas receive good water recharge from the nearby runoff, and are comprised mainly of quaternary alluvium deposits with high permeability, which make it a perfect aquifer for groundwater storage.

The good groundwater potential zones account for 7.01% of the total area, and lie mainly in the upper reaches of the Daling River branches and in the plain at the northern part of the Beipiao City. Those areas are similar to the very good groundwater potential zones. However, the water recharge from surface runoff is relatively poor due to the lower river density.

The moderate groundwater potential zones constitute approximately 11.43% of the whole area, and are found mostly in the vicinity of the alluvial plain and near small creeks, or at the higher parts of the proluvial fan. These areas are short of surface water supply and are mountainous with rugged terrain.

The poor and non-potential zones account for more than 75% of the study area. Most of those places are mountains and hills, where it is hard for water to infiltrate and contribute to groundwater.

CONCLUSIONS

In this study, the Western Liaoning Province was chosen for groundwater potential mapping using RS and GIS. The groundwater formations are affected by lithology, lineament density, recharge conditions and slope, and the enrichment zones are likely to have different features on the surface, such as thermal inertia and vegetation type. Thus, those factors were picked as themes related to groundwater potentiality. The thematic layers were obtained from remotely sensed data and conventional maps using ENVI and ArcGIS. Here, the AHP method was used to analyze the relationship between the layers and groundwater potentiality, and each layer was assigned a weight according to its relative importance. The groundwater potentiality was represented by the index map calculated from the thematic layers, and the index was compared with field measured well yield data from 47 wells. The results showed that they are exponentially related, and the coefficient is 0.8034.

The layers selection and weight assignment depend mainly on the experts' knowledge and experience and their opinions about the whole study area, which means that the groundwater potentiality estimation represents the joint opinion of the experts and it can be both objective and subjective. Therefore, the validation using field measured data is very important as it is the way to link the result to the actual groundwater yield. This result may not be able to provide accurate prediction in pixel level; however, it draws an overall picture of the groundwater distribution.

The integration of remote sensing and GIS can be an applicable method for rapid and large scale groundwater resources assessment. Compared with conventional groundwater surveying, this method is less time consuming and much more cost-efficient, and will give reliable support for researchers by providing detailed hydro-geologic information needed for well site selection and proper management of groundwater resources, as well as play a substantial role in sustainable development.

ACKNOWLEDGMENTS

This work was supported by a grant from Development Program of China (863 Program) NO. 2012AA062601.

REFERENCES

Bagyaraj, M., Ramkumar, T., Venkatramanan, S. & Gurugnanam, B. 2013. Application of remote sensing and GIS analysis for identifying groundwater potential zone in parts of Kodaikanal Taluk, South India. Frontiers of Earth Science, **7**(1):65-75.

Becker, M W. 2006. Potential for satellite remote sensing of ground water. Groundwater 2006, **44**(2):306-318.

Brunner, P., Franssen, H.J.H., Kgotlhang, L., Bauer-Gottwein P. & Kinzelbach, W. 2007. How can remote sensing contribute in groundwater modeling?. Hydrogeology journal, **15**(1):5-18.

Carlson, T. N. 1986. Regional - scale estimates of surface moisture availability and thermal inertia using remote thermal measurements. Remote sensing reviews, **1**(2):197-247.

Chase, M.E. 1969. Airborne remote sensing for groundwater studies in prairie environment. Canadian Journal of Earth Sciences, **6**(4):737-741.

Chen, P., Arnold, J.G., Srinivasan, R., Volk, M., Allen, P.M. 2006. Surveying ground water level using remote sensing: an example over the Seco and Hondo Creek watershed in Texas. Groundwater Monitoring & Remediation, **26**(2):94-102.

Elewa, H.H., Qaddah, A.A. 2011. Groundwater potentiality mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. Hydrogeology Journal, **19**(3):613-628.

Falconer, A., Myers, L., Deutsch, M. 1981. Observations on Lake Ontario Basin hydrogeology from optical enhancements of landsat imagery. Satellite hydrology :427-436.

Fensholt, R., Sandholt, I., Stisen, S., Tucker, C. 2006. Analyzing NDVI for the African continent using the geostationary meteosat second generation SEVIRI sensor. Remote Sensing of Environment, **101**(2):212-229.

Gumma, M.K., Pavelic, P. 2013. Mapping of groundwater potential zones across Ghana using remote sensing, geographic information systems, and spatial modeling. Environmental monitoring and assessment, **185**(4):3561-3579.

Heilman, J.L., Moore, D.G. 1982. Evaluating depth to shallow groundwater using heat capacity mapping mission/HCMM/data. Photogrammetric Engineering and Remote Sensing, **48**(12):1903-1906.

Huo, A., Chen, X., Li, H., Hou, M., Hou, X. 2011. Development and testing of a remote sensing-based model for estimating groundwater levels in Aeolian desert areas of China. Canadian Journal of Soil Science, **91**(1):29-37.

Jha, M.K., Chowdary, V.M., Chowdhury, A. 2010. Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques. Hydrogeology journal, **18**(7):1713-1728.

Komarov, S.A., Mironov, V.L., Romanov, A.N., Yevtyushkin, A.V. 1999. Remote Sensing of the water table: Measurement and a data processing algorithm. Mapping Sciences and Remote Sensing, **36**(1):1-10.

Liang, S. 2001. Narrowband to broadband conversions of land surface albedo I: Algorithms. Remote Sensing of Environment, **76**(2):213-238.

Machiwal, D., Jha, M.K., Mal, B.C. 2011. Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. Water resources management, **25**(5): 1359-1386.

Manap, M.A., Sulaiman, W.N.A., Ramli, M.F., Pradhan, B., Surip, N. 2013. A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat Basin, Malaysia. Arabian Journal of Geosciences, **6**(5):1621-1637.

Meijerink, A.M.J. 1996. Remote sensing applications to hydrology: groundwater. Hydrological sciences journal, **41**(4):549-561.

Murugesan, V., Krishnaraj, S., Kannusamy, V., Selvaraj, G. 2011. Groundwater potential zoning in Thirumanimuttar sub-basin Tamilnadu, India-A GIS and remote sensing approach. Geo-spatial Information Science, **14**(1):17-26.

Narendra, K., Rao, K.N., Latha, P.S. 2013. Integrating remote sensing and GIS for identification of groundwater prospective zones in the Narava basin, Visakhapatnam region, Andhra Pradesh. Journal of the Geological Society of India, **81**(2):248-260.

Preeja, K.R., Joseph, S., Thomas, J., Vijith, H., 2011. Identification of groundwater potential zones of a tropical river basin (Kerala, India) using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, **39**(1):83-94.

Prihodko, L., Goward, S.N. 1997. Estimation of air temperature from remotely sensed surface observations. Remote Sensing of Environment, **60**(3):335-346.

Qin. Z., Karnieli, A., Berliner, P. 2001. A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. International Journal of Remote Sensing, **22**(18):3719-3746.

Rahmati, O., Samani, A.N., Mahdavi, M., Pourghasemi, H.R., Zeinivand, H. 2014. Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. Arabian Journal of Geosciences :1-13.

Rao, N.S. 2006. Groundwater potential index in a crystalline terrain using remote sensing data. Environmental geology, **50**(7):1067-1076.

Rekha, V.B., Thomas, A.P., Suma, M., Vijith, H. 2011. An integration of spatial information technology for groundwater potential and quality investigations in Koduvan ár Sub-Watershed of Meenachil River Basin, Kerala, India. Journal of the Indian Society of Remote Sensing, **39**(1):63-71.

Saaty, T.L. 1990. How to make a decision: the analytic hierarchy process. European journal of operational research, **48**(1):9-26.

Sander, P. 2007. Lineaments in groundwater exploration: a review of applications and limitations. Hydrogeology Journal, **15**(1):71-74.

Sener, E., Davraz, A., Ozcelik, M. 2005. An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. Hydrogeology Journal, **13**(5-6):826-834.

Singh, C.K., Shashtri, S., Singh, A., Mukherjee, S. 2011. Quantitative modeling of groundwater in Satluj River basin of Rupnagar district of Punjab using remote sensing and geographic information system. Environmental Earth Sciences, **62**(4):871-881.

Yamaguchi, Y., Hase, H., Ogawa, K. 1992. Remote sensing for geothermal applications. Episodes **15**(1): 62-67.

Submitted: 15/06/2015
Revised: 05/09/2015
Accepted: 29/09/2015