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Comprehensive Analysis and Artificial Intelligent Simulation of Land Subsidence of Beijing, China

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Abstract: Mechanism and modeling of the land subsidence are complex because of the complicate geological background in Beijing, China. This paper analyzed the spatial relationship between land subsidence and three factors, including the change of groundwater level, the thickness of compressible sediments and the building area by using remote sensing and GIS tools in the upper-middle part of alluvial-proluvial plain fan of the Chaobai River in Beijing. Based on the spatial analysis of the land subsidence and three factors, there exist significant non-linear relationship between the vertical displacement and three factors. The Back Propagation Neural Network (BPN) model combined with Genetic Algorithm (GA) was used to simulate regional distribution of the land subsidence. Results showed that at field scale, the groundwater level and land subsidence showed a significant linear relationship. However, at regional scale, the spatial distribution of groundwater depletion funnel did not overlap with the land subsidence funnel. As to the factor of compressible strata, the places with the biggest compressible strata thickness did not have the largest vertical displacement. The distributions of building area and land subsidence have no obvious spatial relationships. The BPN-GA model simulation results illustrated that the accuracy of the trained model during fifty years is acceptable with an error of 51% of verification data less than 20 mm and the average of the absolute error about 32 mm. The BPN model could be utilized to simulate the general distribution of land subsidence in the study area. Overall, this work contributes to better understand the complex relationship between the land subsidence and three influencing factors. And the distribution of the land subsidence can be simulated by the trained BPN-GA model with the limited available dada and acceptable accuracy.

Keywords: land subsidence; groundwater level change; compressible sediments thickness; building area; Back Propagation Neural Network and Genetic Algorithm (BPN-GA) model

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1 Introduction

Land subsidence is the lowering of the land-surface elevation that takes place underground. The stress, undergone by pore water saturation of the aquitard and aquifer, is transferred to the skeleton of porous media, resulting in the deformation. Common causes of land subsidence from human activity are water, oil, and gas pumping from underground. Generally, long-term and large-scale over-exploitation of groundwater was the main cause for inducing land subsidence. Major subsidence areas are along coastal areas in the world, such as Tokyo in Japan, Anaheim in the USA and Shanghai in China. Attention has been drawn to inland areas, which is the focus of the eighth international symposium on land subsidence (EISOLS). Many studies focused on the models of land

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subsidence (Burbey, 2006; Leake and Galloway, 2010; Ye *et al.*, 2010; Yu *et al.*, 2010; Calderhead *et al.*, 2011), measuring and monitoring technologies of ground displacements (Galloway and Hoffmann, 2007; Gong *et al.*, 2008; Strozzi *et al.*, 2010; Tomas *et al.*, 2011), and land subsidence management (Barends, 2010). The groundwater model and soil mechanics model are the bases of land subsidence management and control. Leake and Galloway (2007) developed the Subsidence and Aquifer-System Compaction Package (SUB-WT) model for Modular Three-dimensional Finite-difference Groundwater Flow Model (MODFLOW), professional software for simulating groundwater flow and aquifer system compaction. The SUB-WT allows geostatic stress to vary as a function of the position of the water table (Leake and Galloway, 2010). In China, some scientists focused on the complicated deformation of sedimentary layers, for example, Shi *et al.* (2008) and Ye *et al.* (2010) studied the elastic, visco-elastic, and elastic-plastic and visco-elastic-plastic deformation. More observation data and field data are needed to build a numerical model of land subsidence.

Beijing is China's political and cultural center, with an area of plain more than 6390 km^2. The population reached 1.58×10^7 in 2006. In Beijing, land subsidence has been one of the geological disasters since the 1960s. In 1999, area of land subsidence with accumulated ground subsidence over 100 mm was 1800 km^2, and that over 200 mm was about 350 km^2. Because of the declining precipitation and increasing demand of water supply, five water sources for emergency purposes have been built since 2001. Groundwater supplied two-thirds of the total water requirement of Beijing Municipality. Over-drafting of aquifers is the major cause of subsidence in Beijing. With groundwater pumping increase, land subsidence becomes much more serious, and five bigger land subsidence regions formed. The biggest accumulative ground subsidence had reached to 1163 mm in 2009 (Yang *et al.*, 2010). Land subsidence had caused many problems, such as the damages of under-ground pipelines, traffic lines and building, and the related environmental-induced geological disasters such as ground fissure. Consequently, to improve the accuracy of the analysis and assessment of aquifer-system compaction, land subsidence has been studied for many years.

In Beijing, land subsidence studies were focused on monitoring (Liu *et al.*, 2007; Gong *et al.*, 2008; Zhang *et al.*, 2009), mechanism (Jia *et al.*, 2007; Zhu *et al.*, 2009; Tian *et al.*, 2012) and numerical simulation modeling (Cui *et al.*, 2003; Gong, 2009). A numerical model of land subsidence constructed with MODFLOW software is good for researchers to understand the relationship between groundwater over-exploitation and the deformation of aquitard and aquifer systems and to make a prediction of the distribution of land subsidence. But simulation results from these types of models only reflected the general tendency of land subsidence (Cui *et al.*, 2003; Gong, 2009). These numerical models of land subsidence include water flow modeling and soil mechanics modeling. To build the numerical models long-time continuous observation data and field data are needed. The sparse available data constrained the accuracy of the numerical model. At the same time, because of the complexity of land subsidence process, the statistical method is not fit for simulating the land subsidence.

Back Propagation Neural Network (BPN) model is nonlinear and has been the most popular form of artificial neural networks. But there are some defects, such as getting the local minimum value not the global value and the slow convergence rate. Genetic algorithms (GA) can resolve these defects of BPN. GA are computational optimization search methods based on several features of biological evolution such as gene structure, and chromosomes (Moghadassi *et al.*, 2010), which are good at exploring a large and complex space in an intelligent way to find values close to the global optimum (Montana and Davis, 1989). Some studies have been carried out to use GA to train the feed-forward networks (Montana and Davis, 1989; Altun and Allahverdi, 2007; Fiszelew *et al.*, 2007; Venkatesan *et al.*, 2009; Moghadassi *et al.*, 2010; Karegowda *et al.*, 2011; Li *et al.*, 2011). In the field of the land subsidence, BPN model has been successfully used to simulate the land subsidence in some coastal cities (Li *et al.*, 2005; Li *et al.*, 2008). Li *et al.* (2009) combined BPN with GA to simulate land subsidence and the model had one input layer, which is the variation of groundwater level.

The purpose of this investigation is to learn the mechanism of land subsidence in Beijing and to give an effective method to simulate and forecast land subsidence with easy-obtained data and acceptable accuracy. The quantitatively spatial relationships between land subsidence and the three factors, i.e. groundwater level change of the pumped aquifer system, the compressible strata thickness and the building area were analyzed. The building area is used to reflect the static loading. A nonlinear artificial neural network, BPN model combined with GA (hereinafter called BPN-GA), was constructed and trained to simulate the land subsidence according to the nonlinear relationship between land subsidence and the three factors. The results could contribute to supporting resource management and hazard mitigation measures.

2 Materials and Method

2.1 Study area

The study area (40°00′–40°30′N, 116°25′–117°00′E) is located at the up-middle part of alluvial-proluvial plain fan of the Chaobai River in Beijing, covering an area of about 1352 km^2 (Fig. 1). It mainly includes plain region of Huairou District, Miyun County and Shunyi District. The study area belongs to the semi-arid and semi-humid monsoon climate zone. The mean annual precipitation from 1959 to 2010 is 615.4 mm. About 80% of the precipitation fell between June and September. From 2000 to 2010, the mean annual precipitation is only 517.1 mm. In 1999, precipitation was about 300 mm. The average temperature is about 11.8℃. In Huairou, Emergency Groundwater Resources Region with an area of about 25 km^2 was built in August 2003, located in the region near Yanxi River and Huai River. There are 21 groups of groundwater-pumping wells for emergency. One group includes two groundwater pumping wells with different depth. These groundwater pumping wells worked as not for emergency, but for daily water supply wells because of the large demand of water resources in Beijing. In the study area, many groundwater-pumping wells belonging to water supply factory were set up along the Chaobai River. There are two land subsidence monitoring stations with borehole extensometer. One is in Tianzhu Town and the other is in Renhe Town both in Shunyi District. Quaternary strata are made up of the pore media and are main water-containing strata. The thickness of quaternary strata is generally thicker in the southern area and western area than those in the northern and eastern areas. There are three aquifer systems (Jia *et al.*, 2007). The first one includes unconfined aquifer (Q_4) and shallow confined aquifer (Q_3) with the depth of aquifer bottom less than 100 m. The second one is deep confined aquifer (Q_2) with the depth of aquifer bottom of about 300 m. The third one is deeper confined aquifer

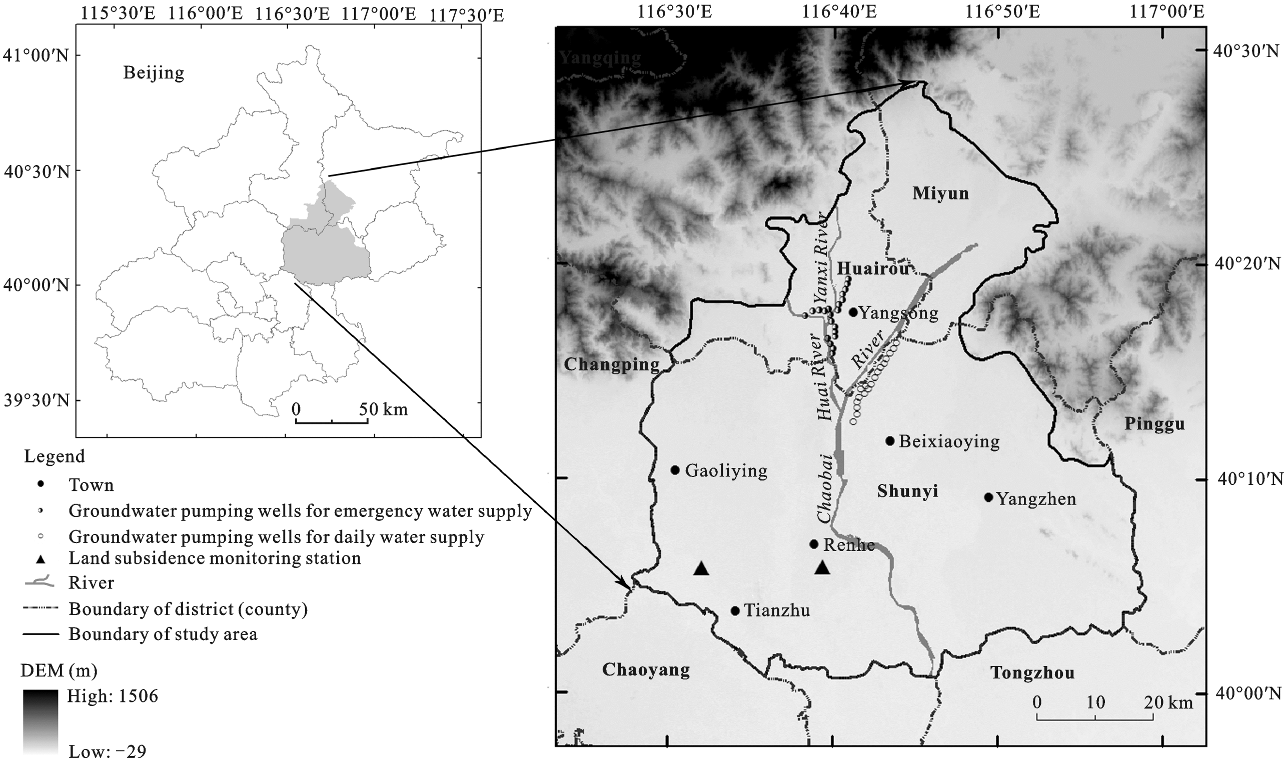

Fig. 1 Location of study area

(Q_1) with the depth of aquifer top of over 300 m. The first aquifer system is mainly for agriculture exploitation. The second confined aquifer system is the main strata for groundwater resource exploitation. The groundwater recharge sources include precipitation, surface water body and irrigation water. Precipitation is main source of groundwater recharge. Exploitation is the main way for groundwater discharge.

2.2 Spatial dataset

To make a quantitative comparison between the cumulative land subsidence and human activity factors, land satellite (Landsat) images were collected to obtain changes in building areas in 1976, 1990, 2000, 2006 in the study area. The image obtained in 1976 was collected by the multispectral scanner (MSS) with a spatial resolution of 79 m. Other images were obtained with thematic mapper or enhanced thematic mapper plus (TM/ETM+) with a spatial resolution of 30 m. The maximum likelihood method of supervised classification was used to extract the building area. To improve the accuracy of the classification, manual interpretation was used to modify the building area with the overall classification accuracy of about 90%.

To quantitatively analyze the relation between land subsidence and three factors, and to build the land subsidence simulation model, land subsidence, groundwater level and strata data were collected. The cumulative land subsidence contour from the period of 1955 to 2005, groundwater level contours in 1965 and in 2005, and the isopach of compressible sediments were obtained. The compressible sediments were made up of fine-grained sediments such as clayey silt in the study area. These contours and isopach were discretized with the cell size of 500 m × 500 m in ArcGIS software.

2.3 BPN-GA model

Neural networks are algorithms for optimizing and learning based on concepts inspired by research into the nature of the brain (Montana and Davis, 1989). It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems (Karegowda *et al*., 2011). During the BPN training process, the error, caused by the difference between the desired output vector and the output layer′s response to an input vector, propagates back through connections between layers and adjusts appropriate connection weights for minimizing the error (Bhise and Pratihar, 2006). It is difficult for BPN model to be used to interpret the relationships between the output layer and the input layers on the basis of the learned weights. Traditional BPN model can asymptotically approach the ideal function and simulate complicated nonlinear system.

In this paper, BPN-GA model was used to simulate the vertical displacement from 1955 to 2005. This BPN model includes three input layers, one hidden layer and one output layer (Fig. 2). The GA was used to optimize the initial weights and thresholds of BPN model, which can contribute to achieving the global optimal parameters rather than the local optimal values. The flow chart of constructing model is shown in Fig. 3. As long as the objective function met the convergence criteria of the minimum mean square deviation or the iteration number

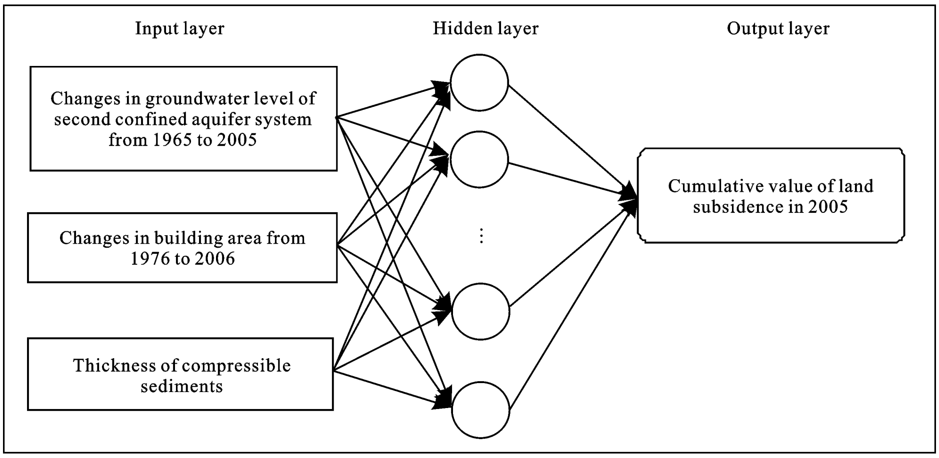

Fig. 2 Structure of Back Propagation Neural Network (BPN) model

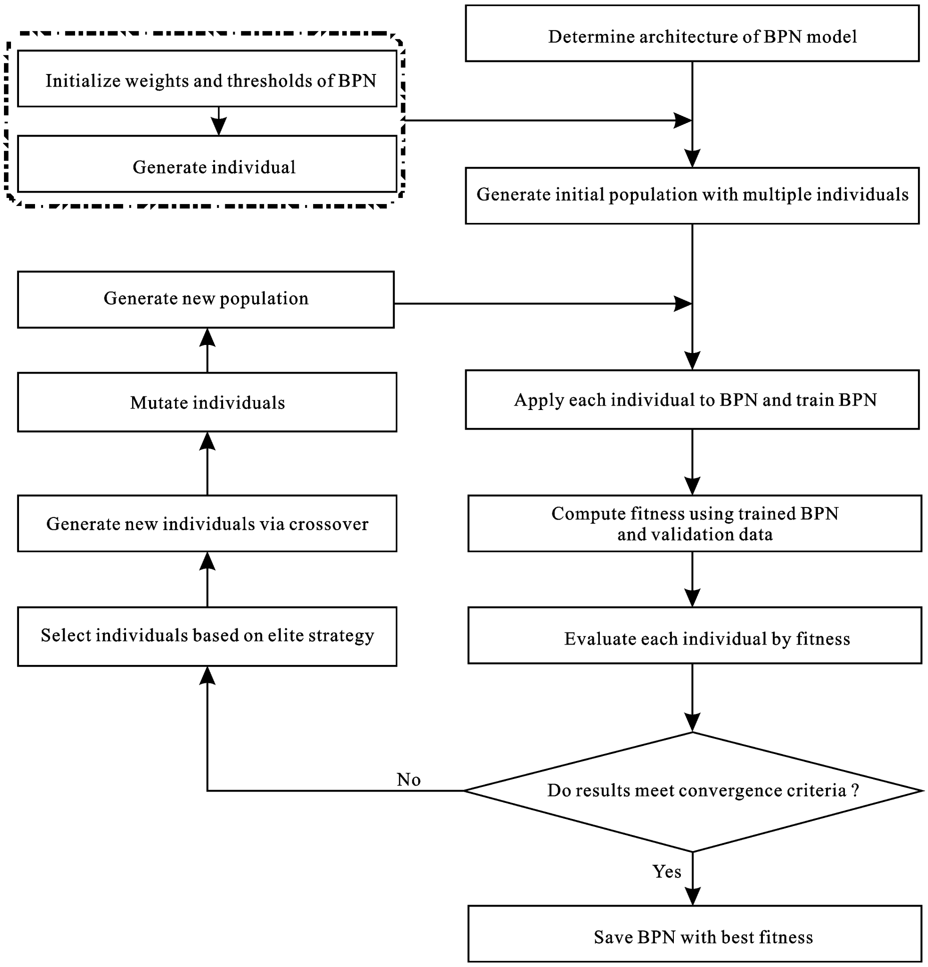

Fig. 3 Flowchart of Back Propagation Neural Network and Genetic Algorithm (BPN-GA) model

of over 100, the BPN model training was terminated.

The weights and thresholds of BPN model were determined by the GA. First, random values were assigned to the population of individuals with initial threshold and weights, which were used to train the BPN model; and the size of the initial population was set as 20. The individuals in the genetic space are called chromosomes. To evaluate the individual's simulation ability of the BPN model, a fitness value was calculated. The simulation accuracy of the trained BPN model increased with the fitness value. The calculation equation of the fitness value (f) is expressed as Equation (1):

$$f = \frac{1}{\sum_{i=1}^{n} \mathrm{abs}(O_i - P_i)} \tag{1}$$

where O_i is the value of land subsidence (mm) at the ith sampling grid with the total discretized grid number of n; P_i is the simulated value with trained BPN model. Second, based on the obtained fitness values, selection, crossover and mutation of the evolution steps of GA were implemented to get the most optimal weights and thresholds, which are treated as the final network weights and thresholds. By using this selection process, the high fitness chromosomes were used to eliminate low fitness chromosomes. The crossover and mutation operations were used to produce new 'fitter' individuals into the population.

3 Results and Discussion

3.1 Relationships between land subsidence and three factors

3.1.1 Effect of groundwater level on land subsidence

In the Huairou Emergency Water Resources region, groundwater level of the shallow confined aquifer system (Q_3) changed significantly since the exploration of the emergency water resources (Fig. 4). The groundwa-

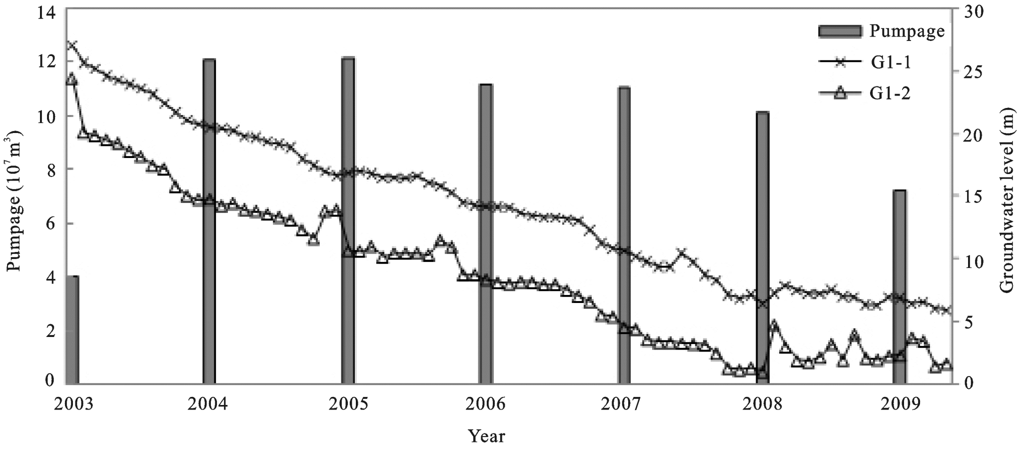

Fig. 4 Dynamic changes of groundwater pumpage and groundwater levels in Huairou Emergency Water Resource region, Beijing (G1-1 and G1-2 are numbers of observation well monitoring groundwater level of stratum with depth of 30 m and 39 m, respectively)

ter level monitoring data showed that the groundwater level declined 7.3 m from August 2003 to the end of 2004, the early stage of the emergency water resource. The groundwater level decreased gradually about 9 m from 2005 to 2007. From 2008 to 2009, with the decrease in groundwater exploitation, the groundwater level declining ratio was down to approximately 0.16 m per month except for July which is a rainy month of the increase in precipitation and surface inflow.

Vertical borehole extensometers are used to measure the continuous change in vertical distance in the interval between the land surface and a reference point at the bottom of a deep borehole (Galloway and Burbey, 2011). Borehole extensometer in Tianzhu Town of Shunyi District with the depth of 308.1 m was established in 2004. The subsidence data monitored by borehole extensometer shows the mean annual groundwater level of aquifers declining from 2005 to 2010. The groundwater levels of strata with different depth showed declining tendency. The values of land subsidence in different strata and depths showed big difference because of the lithology and thickness. Figure 5 shows that the accumulative value of land subsidence increased with the declining groundwater level of the confined aquifer with the depth between 210 m and 218 m. The correlation coefficient between land subsidence and groundwater level reaches to 0.98. Since the borehole extensometer in Tianzhu Town was constructed in April 2004, the start value was set as zero.

In 1965, the groundwater flow field was in natural condition. With the over-exploitation of ground water, there was a great change of flow field of the second confined aquifer system from 1965 to 2005. The area of groundwater funnel and the depth of funnel center in-

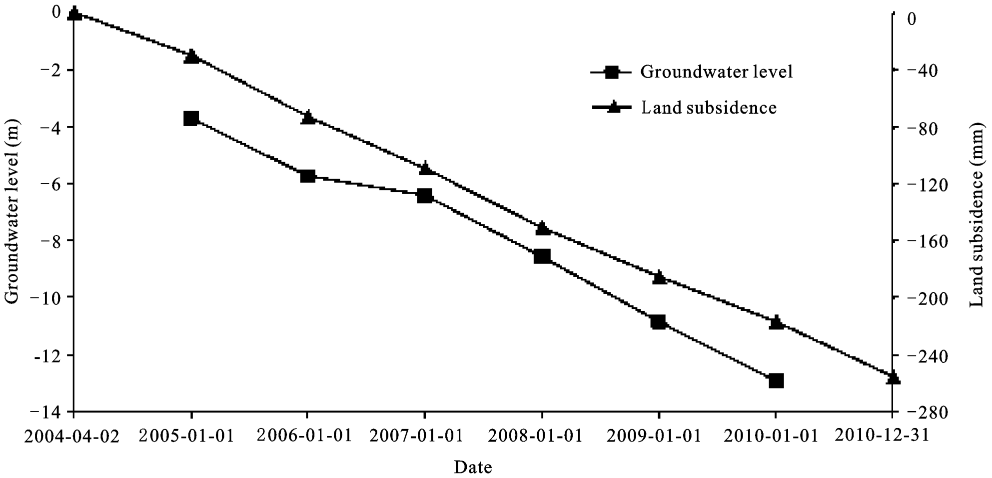

Fig. 5 Groundwater level and land subsidence observed with borehole extensometer in Tianzhu Town of Shunyi District, Beijing

creased continuously. In 1965, the lowest groundwater level was about 20 m above sea level, located in the middle part of alluvial-proluvial plain fan of the Chaobai River. In 2005, the lowest groundwater level was over 10 m below sea level in the western region of Shunyi District in Beijing. To analyze the difference of the groundwater level from 1965 to 2005, the groundwater level in 1965 was subtracted by the level in 2005 by using ArcGIS tools. There were two big groundwater funnels (Fig. 6). One was near the groundwater pumping wells, located in the upper part of alluvial-proluvial plain fan of the Chaobai River, where the deformation was small because of the relatively high groundwater recharge. Another funnel in the western region of Shunyi District with the drawdown of groundwater level was about 40 m, where there were two subsidence funnels with the largest amount of the cumulative land subsidence of about 500 mm during the period from 1955 to 2005.

3.1.2 Effect of compressible sediments thickness on land subsidence

In the study area, the land subsidence is mainly from the deformation of the compressible sediments. Under the same stress situation, the deformation of the compressible sediments such as cohesive soil is much higher than that of sand and sandy pebble (Jia *et al*., 2007). The thicknesses of the compressible sediments and the quaternary strata (Q) in the southwestern region are greater than those in the northeastern region of the study area (Fig. 7). In the western part of Shunyi District, the thicknesses of quaternary and compressible sediments are generally over 400 m and 150 m, respectively. The largest values of the thicknesses reach up to 700 m and 220 m, respectively. In the same region, there are two subsidence funnels. The deformation at the spot of the largest compressible sediments thickness is about 400 mm, which is not the maximum value of the deformation. In the whole study area, the regions of the maxi-

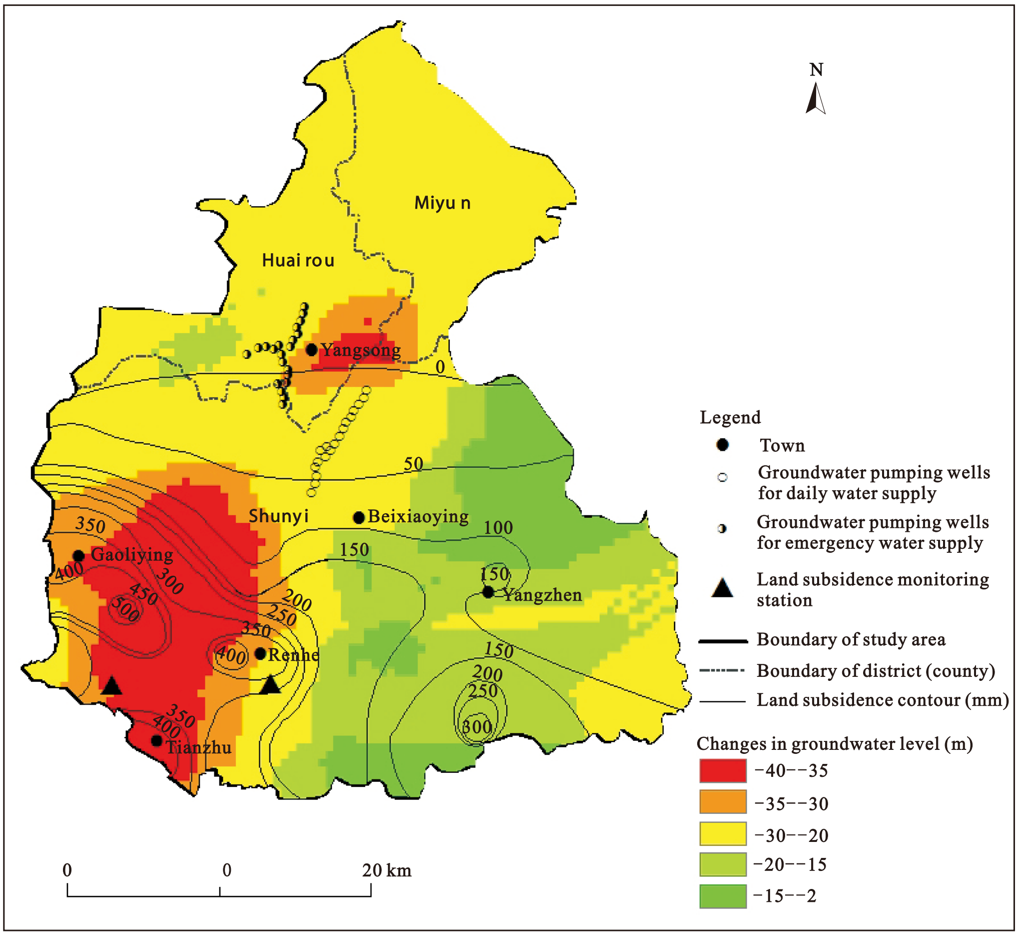

Fig. 6 Land subsidence in 2005 and groundwater level fluctuation from 1965 to 2005 in study area

mum deformation and the largest thickness of the compressible sediments are partially overlapped. From the northern region to the southern region, the value of the land subsidence becomes bigger with the increasing thickness of the compressible sediments. In the northern region, the upper part of alluvial-proluvial plain fan of the Chaobai River, there is no surface deformation. The reason is that there are no compressible sediments in this region (Fig. 7). In the southern region, there is no obvious variation of thickness of the compressible sediments. The distributions of the land subsidence and the compressible sediments show spatial variability.

3.1.3 Effect of building area on land subsidence

Urbanization has greatly increased the urban area. In 1976, the building area was only about 14.28 km^2 and the patch number was ten in the study area (Fig. 8). With the urbanization and increasing population, the building area and the patch number in 1990 had reached up to 162.71 km^2 and 362, respectively. From 1990 to 2006, the increasing ratio of building area was about 6.58 km^2 per year. Generally, the building area was mainly distributed near the district (county) center and the public transport networks. Increasing building area changed the total stress acting on the geological solid. This stress may affect the land subsidence rate. In the southwestern of Shunyi District such as Tianzhu Town, the building area is bigger, and land subsidence is relatively more serious. But the effect of increase in building area on land subsidence is not significant. The possible reason may be the building height and building density not concerned.

3.1.4 Relationships of land subsidence to three factors

The discretized data show that the relationship between the land subsidence and groundwater level change, compressible sediments thickness and the building area are nonlinear. On the whole, the correlation coefficients between land subsidence and three factors are 0.46, 0.64 and 0.25, respectively. In the region with deformation over 50 mm, the correlation coefficients of land subsi-

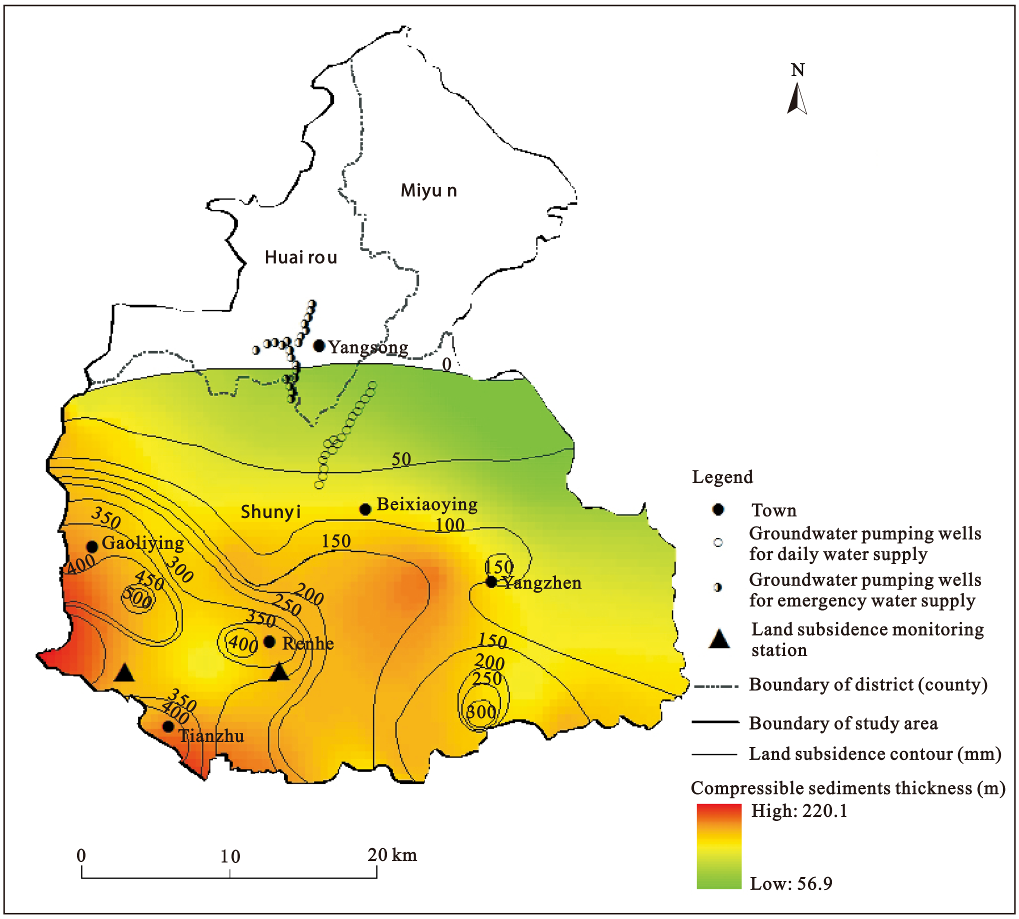

Fig. 7 Land subsidence in 2005 and compressible sediments thickness in study area

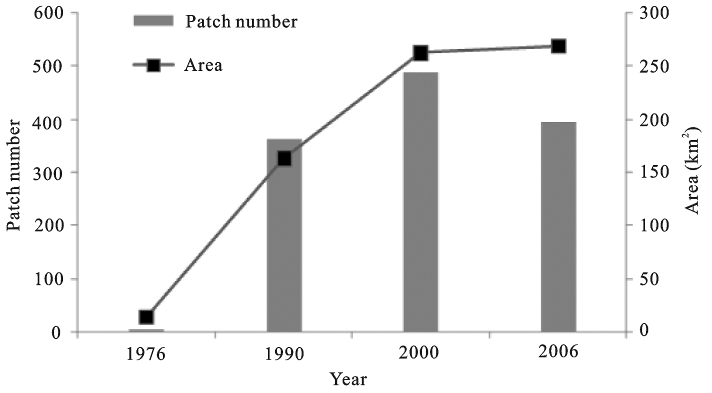

Fig. 8 Building area and patch number from 1976 to 2008 in study area

dence to groundwater change, compressible sediments thickness and building area are 0.63, 0.59 and 0.33, respectively. In the southeastern region of Shunyi District, where the groundwater level change is generally less than 20 m, the correlation of land subsidence to building area is little. That is, the effect of static loading to the land subsidence shows less spatial difference. While the thickness of compressible sediments greatly controls the land subsidence, the correlation coefficient reaches 0.78. In the northwestern region of Shunyi District generally, where the groundwater level change is over 20 m, there are groundwater level funnel and land subsidence funnels.

3.2 Trained BPN-GA model

In the study area, even if the logarithm transformation of land subsidence was adopted, the nonlinear relation between land subsidence and the three factors still remain. The BPN-GA model, including three input layers, one hidden layer including seven neurons, and one output layer with one neuron, was constructed. The hidden layer adopts the hyperbolic tangent sigmoid transfer function, and the output layer adopts linear transfer function. Some parameters of the trained BPN-GA model are showed in Table 1.

This study selected the region with land subsidence over 50 mm as the modeling area. The weights and thresholds of the BPN model are determined by the GA. These weights and thresholds have nothing to do with the effect of the three factors on the occurrence of the land subsidence. About 75% of the discretized data are used to train the improved BPN model. The other 25% of the discretized data are used as verification data to test the accuracy of BPN model.

3.3 Model validation

The comparison of the simulated cumulative value of land subsidence in 2005 with the 25% of the discretized data showed that the average absolute error between the simulated value by using BPN-GA model and the verification data was about 32 mm. During 50 years, 51% of the verification data had an absolute error of less than 20 mm. About 5% of the verification data had an absolute error of more than 100 mm. The average relative error of simulation is about 21.4%. In this study, the larger error points between the simulated value and the verification data were generally distributed in the area of land subsidence or the area with three factors having

Table 1 Parameters of Back Propagation Neural Network (BPN) model and Genetic Algorithm (GA)

BPN model		Genetic Algorithm	
Number of input nodes (I)	3	Population size	30
Number of hidden nodes (H)	7	Individual size	36
Number of output nodes (O)	1	Maximum generations	100
Training function	Trainlm	Probability of crossover	0.7
Learning rate	0.01	Probability of mutation	0.7
Number of epochs	100	Evolution goal	30

Notes: Individual size = (I × H) + H + (H × O) + O; Trainlm is training function adopting Levenberg-Marquardt algorithm abrupt gradient change. The main reason is that BPN-GA model simulated the main pattern of the land subsidence in the study area. This pattern is extracted from the discretized training data. The output layer, the distribution of land subsidence, has significant spatial heterogeneity. These uniformly distributed training data caused the number of points with the land subsidence value of abrupt change less than that of the land subsidence value of spatially slow change. The training aim of the BPN- GA model is to make the error between the simulated value and the actual value having the minimum variance. The pattern of the most training data was learned by the BPN model, which make the features of the small number of the training data un-reflected.

To assess the BPN-GA model, the simulated output of the trained BPN-GA model was compared with the existed studies. Cui *et al.* (2003) used the Interbed Storage package (IBS) package in MODFLOW to simulate the land subsidence from 1995 to 1997 in the part area of Beijing. Only one monitoring point with three years data was used to test the accuracy of the model, which could not reflect the regional situation. The relative error was less than 15%. Gong (2009) employed the SUB package in MODFLOW to simulate the land subsidence from 2000 to 2007 in Huairou Emergency Water Resource Region. The monitoring data of extensometer in Tianzhu Town showed that the simulated results of the numerical model only revealed the general tendency of the land subsidence from 2004 to 2007. About 56% of the time slice of the land subsidence showed the error is more than 50 mm. The largest error is about 60 mm. Overall, the accuracy of the trained BPN-GA model compared with the existing numerical model is improved.

What′s more, based on the discretized training data, the multi-variable function between the vertical displacement and the three factors was constructed. The formula, which is significant at 0.05 level, is shown as follows.

$$Y = -217.69 + 1.63 \times X_1 + 1.77 \times X_2 + 5.15 \times X_3 \qquad (2)$$

where Y is the vertical displacement; X_1, X_2 and X_3 are the building area (10^4 m^2), groundwater level change value and compressible sediments thickness, respectively. The result by using the multi-variable function showed the average absolute error between the simulated value and the verification data was about 54 mm. And 27% of the verification data had an absolute error of less than 20 mm. About 16% of the verification data had an absolute error of more than 100 mm. This result shows that the accuracy of BPN-GA model is better than the multi-variable function for simulating the regional land subsidence.

4 Conclusions

Based on the analyses of the land subsidence and three factors, there is one big groundwater funnel and a small deformation because of the relatively high groundwater recharge and no compressible sediments in the upper part of the study area. In the western region of Shunyi District, Beijing, there is one groundwater funnel and two subsidence funnels, where the compressible sediments thickness has the largest values. The deformation at the spot of the largest compressible sediments thickness is not the maximum value of the deformation. And the regions of the land subsidence funnel and the groundwater funnel center do not overlap completely. The distributions of building area and land subsidence have no obvious spatial relationships.

In the region with deformation over 50 mm, there are the non-linear correlations of land subsidence to three factors. The change of the groundwater level is the most significant influencing factor. The compressible sediments as the media of the occurrence of land subsidence greatly affect the accumulative value of the land subsidence. Serious land subsidence is generally distributed in the region with the thick compressible sediments. The city expansion means the static loading increasing which enlarges the total stress acting on the geological solid and may speed up the land subsidence. But the effect of the increasing building area to the land subsidence is not obvious.

In the study area, there exists a nonlinear relation between land subsidence and the three factors. The trained BPN-GA model can generally simulate the spatial pattern of land subsidence by using the value of the groundwater level change, the compressible sediments thickness and the building area. The trained model can be used by researchers for studying the distribution of land subsidence without exploring the land subsidence mechanism.

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