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Groundwater Overexploitation Causing Land Subsidence: Hazard Risk Assessment Using Field Observation and Spatial Modelling

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Abstract Hazard risk assessment of land subsidence is a complicated issue aiming at identifying areas with potentially high environmental hazard due to land subsidence. The methods of hazard risk assessment of land subsidence were reviewed and a new systematic approach was proposed in this study. Quantitative identification of land subsidence is important to the hazard risk assessment. Field observations using extensometers were used to determine assessment indexes and estimate weights of each index. Spatial modelling was also established in ArcGIS to better visualize the assessment data. These approaches then were applied to the Chengnan region, China as a case study. Three factors, thickness of the second confined aquifer, thickness of the soft clay and the annual recovery rate of groundwater level were incorporated into the hazard risk assessment index system. The weights of each index are 0.33, 0.17 and 0.5 respectively. The zonation map shows that the high, medium and low risk ranked areas for land subsidence account for 9.5 %, 44.7 % and 45.8 % of the total area respectively. The annual recovery rate of groundwater level is the major factor raising land subsidence hazard risk in approximately half of the study area.

Keywords Groundwater overexploitation · Land subsidence · Hazard risk assessment · Extensometers · ArcGIS

1 Introduction

Land subsidence occurs when groundwater has been over-exploited from porous sediments, such as fine-grained materials. Occurrences of land subsidence have been globally reported, such as in Spain (Molina et al. 2009), India (Sahu and Sikdar 2011), Thailand (Phienweij et

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al. 2006), Mexico (Ortiz-Zamora and Ortega-Guerrero 2010), USA (Holzer and Galloway 2005), Ravenna and Italy (Teatini et al. 2005); so is it in China (Li et al. 2006; Yang and Yu 2006; Shi et al. 2007; Wu et al. 2010; Liu et al. 2010). Land subsidence generally results in substantial damage, including loss of ground surface altitude, cracking of buildings, failure of underground pipelines, increase of flood hazards etc. A large number of studies have focused on land subsidence in order to reduce the associated damage and control of land subsidence.

Various methods have also been used to measure spatial variations and temporal rates of the regional and local subsidence. In the early studies, leveling was the main measurement to monitor land subsidence and now it is still commonly used in some studies (Abidin et al. 2001; Odijk et al. 2003). Recently, the satellite-based global positioning system (GPS), remote sensing (RS) and geographical information system (GIS) are gradually used in the regional subsidence studies (Gao et al. 2003; Marfai and King 2007). When more spatial detail is required, LiDAR (light detection and ranging) and InSAR (interferometric synthetic aperture radar) are applied for monitoring land subsidence (Gehlot and Hanssen 2008; Zhao et al. 2009; Hsieh et al. 2011). Extensometers are generally applied in measuring land subsidence (Harmon 2002; Buckley et al. 2003; Wang et al. 2009) which are used to measure continuous change in vertical distance.

To quantify land subsidence, numerous models have been developed (Chen et al. 2003; Ferronato et al. 2003; Kumarci et al. 2008; Zhang et al. 2010; Dong and Liu 2009; Vaezinejad et al. 2011; Ye et al. 2011), which can be categorized into three types, deterministic, stochastic, and artificial intelligence models. Deterministic models analyze the seepage action of groundwater, the soil deformation and the inter-coupling between them based on the mechanism of land subsidence. Plenty of factors cause the consolidation of loose soil, which is accompanied by randomness, so stochastic models are introduced on the basis of the periodical and random characteristics of land subsidence. With the development of computing, artificial intelligence model is gradually used in predicting land subsidence. In some instances, artificial intelligence models are designed to simulate stochastic behaviors. The stochastic data will be transferred into computer signal in artificial model, which is highly efficient and makes the results accurate and reliable.

These models just predict land subsidence in terms of land subsidence, or its maximum/minimum values. They assumed that there will be land subsidence at specific sites and then estimate the value of land subsidence according to the historical, current and prospective conditions. If the probability of the subsidence occurrence at the site is predicted beforehand and some counter measures are taken to reduce the probability, then there would be less hazard of land subsidence, which is more significant than solely modeling the subsidence. Hence it is necessary to introduce hazard risk assessment in this context, aiming at obtaining the probability of occurrence of the land subsidence risk at the spatial scale using modelling tools (e.g. ArcGIS). The distribution of the risk can be better understood as it will show where does not necessarily put us at risk.

Recently, there are a majority of studies on geologic hazards risk assessment, such as hazard risk assessment of landslide, debris flow, collapse etc. (Hürlimann et al. 2006; Bilgot and Parriaux 2009; Kawagoe et al. 2010; Wu et al. 2010; Kappes et al. 2011). But report about hazard risk assessment of land subsidence is rare.

The objective of this study is to present methods of hazard risk assessment of land subsidence caused by groundwater over-exploitation using field observation and ArcGIS spatial modeling. The hazard risk assessment of land subsidence were defined firstly according to geologic hazards risk assessment; then each part of the assessment contents was shown in detail including established methods and data acquisition; and the ArcGIS-based spatial assessment model was introduced, with a case study was presented finally.

2 Methodology

2.1 Hazard Risk Assessment of Land Subsidence

To achieve hazard risk assessment of land subsidence at spatial scale, it is necessary to take the lessons from the approaches of other geologic hazards risk assessment. The index method of hazard assessment includes three steps: choosing indexes, estimating weights of each index and assessing hazard risk using a model; so the hazard risk assessment of land subsidence can be achieved.

However, land subsidence is different from other spasmodic geologic hazards. It possesses some special features: progressivity, irreversibility, regionality and vertical diversity. The hazard risk assessment of land subsidence should concentrate on the physical process of subsidence and its spatial variation. Therefore, understanding the subsidence process is significantly correlated with choosing appropriate indexes and estimating determining weights of each index. The extensometers were thus employed in this study because it is a reliable new technique to measure continuous change in vertical distance, which exactly and effectively represents the subsidence processes. Figure 1 shows a flow chart of hazard risk assessment of land subsidence in this study.

2.2 The Extensometer Rationale

Multiple position borehole extensometers which incorporate magnetic markers anchored to the formation borehole have been used effectively to monitor land subsidence caused by groundwater exploitation, especially in China (Hwang et al. 2008), since the first application in Poland (Lofgren 1969; Riley 1986).

Galloway and Burbey (2011) noted that vertical borehole extensometers are used to measure the continuous change in vertical distance in the interval between land surface and a reference point or ‘subsurface bench mark’ at the bottom of a deep borehole. According to it, the monitoring principle of the multiple position borehole extensometers is achieved. Shi et al. (2007) and Wu et al. (2008) further applied these in the subsidence monitoring and calculations.

2.3 Index Selection: Extensometer-Based Observation

Index selection is a crucial step in assessing hazard risk using index method. The selection should reflect the occurrence and development process of land subsidence. Land subsidence

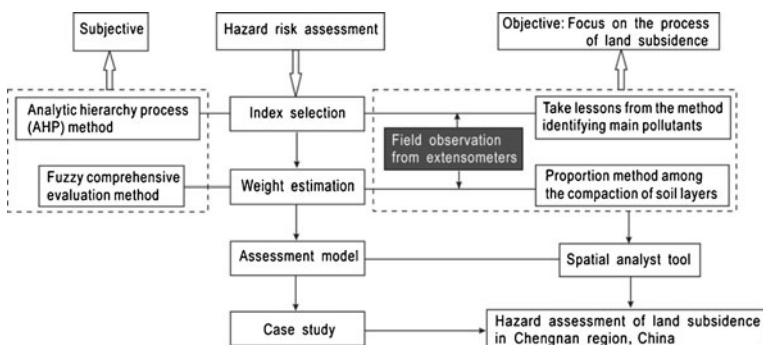


Fig. 1 Methodology of hazard risk assessment of land subsidence caused by groundwater overexploitation

is such a complicated phenomenon that it is hard to consider all the influence factors as evaluating indexes. It is hence significant to pick up the major factors in the hazard risk assessment. In addition, the selected indexes should be quantified and independent on other indexes (Huang et al. 2008).

The influencing factors of land subsidence can be divided into two categories: human activities and geological actions (Xue et al. 2005). In this study, the main focus is on land subsidence caused by groundwater overexploitation as a main human activity. The geological actions always include fracture structure, crust movement, Quaternary geological conditions, etc. In fact, in the areas where land subsidence happened, Quaternary geological conditions are the main geological actions. Therefore we will mainly consider the situation of groundwater overexploitation and Quaternary geological conditions in the selection.

There is a strong correlation between the development of land subsidence and the groundwater level of the main pumping aquifer. So the indexes related groundwater level (e.g. variation rate of groundwater level) can be used to reflect the human activities' effect on land subsidence. In addition, land subsidence is the result of the consolidation of soil layers due to the long-term excessive groundwater pumping of the aquifers. So the indexes related main compressive layers also could be regarded as the evaluating indexes to reflect Quaternary geological conditions' effect on land subsidence.

As analyzed above, the compaction of individual soil layer can be calculated using the observation from extensometers. The soil layers are always with different compactions due to their soil features. The larger the compaction is, the more contribution the soil layer offers to land subsidence. The main compressive soil layer will be obtained by experience from the principle of identifying the main pollutants/pollution sources (Ding 2001). The subsidence of each layer was calculated first (Eq. 1) according to the extensometer's monitoring principle noted by Galloway and Burbey (2011); then the subsidence of each layer is descending ordered by Eqs. 2, 3; after that Eq. 4 is defined. If $\frac{K'}{K} \geq 80\%$, then those layers, whose subsidence of K_1, K_2, \dots, K_m (K_m is the subsidence of the m^{th} layer after being ordered) are corresponding to, would be regarded as the major Quaternary layers suffering land subsidence and the thickness of these layers should be chosen as evaluating indexes of the hazard assessment. The equations are:

$$S_k = D_{E(k-1)} - D_{E(k)} \quad (1 \leq k \leq n) \tag{1}$$

$$K_1 = \max(S_1, \dots, S_k, \dots, S_n) \tag{2}$$

$$K_i = \max[(S_1, \dots, S_k, \dots, S_n) \text{ except for } (K_1, \dots, K_{i-1})] \quad (2 \leq i \leq n) \tag{3}$$

$$K' = \sum_{j=1}^m K_j, \quad K = \sum_{j=1}^n K_j \quad (1 \leq m \leq n) \tag{4}$$

where S_k is the subsidence of the k^{th} of n layers; $E(k)$ is the k^{th} extensometer; $D_{E(k)}$ is the observation data of the extensometer $E(k)$, K_i^1 is the subsidence of the i^{th} layer after being ordered.

2.4 Weight Estimation

Evaluating indexes are chosen from the human activities (groundwater abstraction) and Quaternary geological factors, which can be seen as independent and indispensable with equal significance in inducing land subsidence. Whenever only one factor of these two in

existence, there would be no land subsidence induced. Therefore the Quaternary geological and human factors were assigned the same contribution to land subsidence. The proportional relation is defined as Eq. 5. Then if p ($p > 1$) indexes belong to the Quaternary geological factor, the individual weight was determined according to the proportion among subsidence of corresponding layer, which is defined as Eqs. 6, 7.

$$R_Q : R_H = 1 : 1 \quad (5)$$

$$\frac{R_u}{R_v} = \frac{S_u}{S_v} \quad (6)$$

$$R_Q = R_1 + R_2 + \dots + R_p \quad (7)$$

where R_Q is the weight for Quaternary geological conditions, R_H for human factors, R_u and R_v are the weights for the u^{th} and v^{th} of p indexes; S_u and S_v are the subsidence for the layer which the u^{th} and v^{th} index are corresponding to; p is the total indexes belonging to the Quaternary geological factors.

2.5 Spatial Analysis Tool: ArcGIS

ArcGIS spatial analyst provides powerful tools for comprehensive analysis and spatial modeling of geological hazards risk assessment (Zhou et al. 2003; Rajakumar et al. 2007; Pradhan et al. 2009; Arnous et al. 2011); so was used in this study to assess and zone the hazard of land subsidence. According to the principle of ArcGIS spatial analyst, the computational formula obtaining the hazard index is defined as:

$$I = R_Q \times F_Q + R_H \times F_H \quad (8)$$

$$R_Q \times F_Q = R_1 \times F_Q^1 + \dots + R_p \times F_Q^p \quad (9)$$

where I is the hazard index; and are the raster values for the Quaternary geological and human factors; p is the total number of indexes belonging to the Quaternary geological factors; F_Q^p for the p^{th} the Quaternary geological factor; R_Q and R_H are the same as above.

3 Case Study

The study area (Fig. 2), with an area of 442 km², is located in the middle of Wuxi city, China. It is a developed economy city, with well built inter-city railways.

3.1 Quaternary Geology and Hydrogeology

The Quaternary deposits distribute widely with thickness of 130~170 m increasing from southwest to northeast in this area. The Quaternary sediment is primarily composed of sandy silts, medium-coarse sands and medium-coarse sands with gravels, with clay interlayers.

According to geological logs of nine boreholes, a solid geology map (Fig. 3a) was produced to represent the strata configuration. A geological fence diagram (Fig. 3b) was

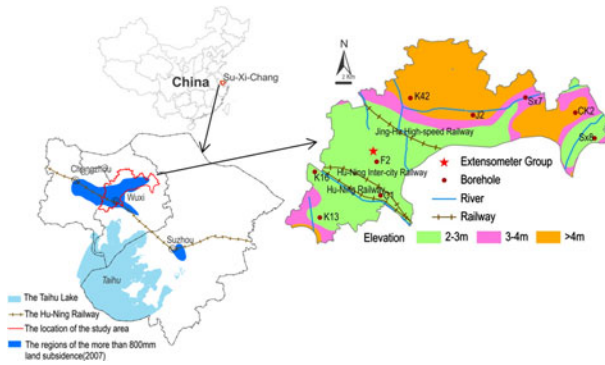


Fig. 2 The location and setting of the study area

further created. The aquifer system is divided into the unconfined aquifer, the first and second confined aquifers. Each aquifer shows mostly homogeneous distribution along entire cross section. The thickness of the second confined aquifer is much larger than that of the unconfined aquifer and the first confined aquifer. Medium-coarse sands, somewhere with gravels, are the major deposits in the second confined aquifer that produces a great amount of groundwater for supply. A less permeable lacustrine formation, about 10–30 m thick, overlays the second confined aquifer, which is consist of soft clay characterized as tight, plastic and highly compressive.

3.2 Land Subsidence and Groundwater Level

With the fast economy development, more and more groundwater has been exploited since 1980s, resulted in regional drawdown of groundwater pressure. In early 1990s, the study area became the centre of the cone of depression in the Su-Xi-Chang area when the groundwater depth fell to 87 m. After 1996, the depth and intensity of exploitation were adjusted and the pumping yields were restricted to control the subsidence in the downtown area. Moreover, government regulated completely prohibiting groundwater exploitation in the Su-Xi-Chang area since 2005. As a result, the rate of subsidence decreased and the groundwater level recovered in some areas.

Figure 4 shows the water level in the second confined aquifer recovered from 2002 to 2008, and the scale of groundwater depression cone reduced. Land subsidence decreased from west to east slowly. Additionally, the subsidence depression cone and the groundwater depression cone coincided spatially, indicating clearly the cause-consequence relationship.

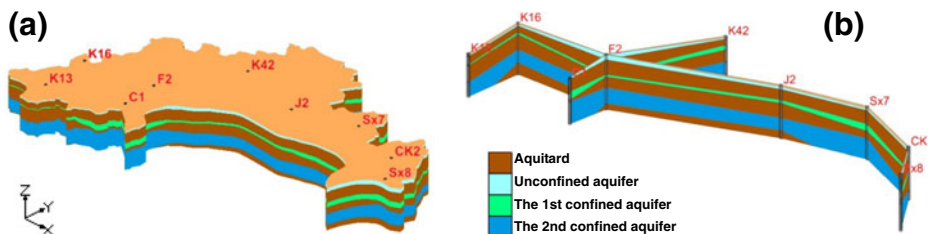


Fig. 3 Geology of the study area: (a) solid stratum configuration and (b) fence cross sections

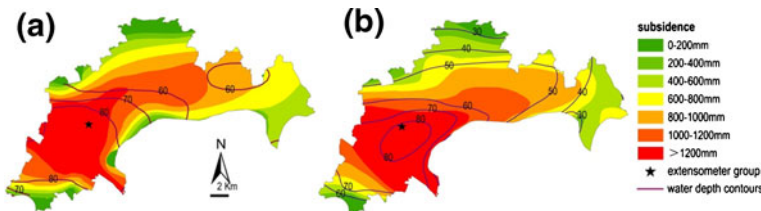


Fig. 4 The distribution of the accumulative subsidence (a: 2000, b: 2007) and the water depth contours in the second confined aquifer (a: 2002, b: 2008)

Where depth to water level of the second confined aquifer was larger, there land subsidence was more serious. And the expanding trend of land subsidence was similar to that of depth to the water level of the second confined aquifer.

3.3 Extensometers Setup

There is an extensometer group in the study area (Fig. 2), set up (Fig. 5) in October, 2002 in the study area. The extensometer group is in the subsidence depression cone shown in Fig. 4, where the process of compaction could represent the characteristics of land subsidence around the study area. The extensometers monitoring for land subsidence from April 2004 (Table 1) indicated those layers that mainly occurred land subsidence. The data after 2005 were particularly used to analyze the land subsidence hazard after completely prohibiting groundwater exploitation in the Chengnan region.

4 Results

4.1 Indexes and Weights

From the data in Table 1 and Eq. 1, the subsidence of each individual layer was calculated. Figure 6 shows the annual mean compression in different layer. From 2006 to 2009, most subsidence was attributed to the second confined aquifer and the soft clay, together they

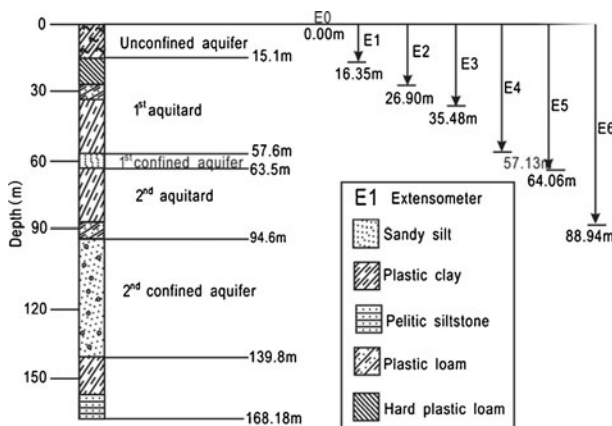


Fig. 5 The setup of extensometers in study area

Table 1 History of the accumulative subsidence of each extensometer (mm)

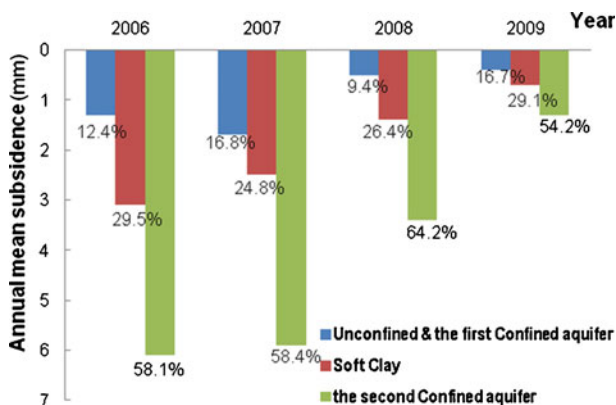
Extensometer	Dec.2004	Dec.2005	Nov.2006	Nov.2007	Dec.2008	Jun.2009	Jan.2010
E0	14.9	33.2	43.7	53.8	59.1	60.3	60.6
E1	13.1	29.2	39.9	49.5	54.4	55.4	56.2
E2	13.7	29.5	40.0	49.8	54.7	55.8	56.6
E3	14.2	30.2	40.1	50.1	55.2	56.0	56.8
E4	13.6	28.6	38.8	47.3	52.1	53.1	54.0
E5	13.2	28.0	37.2	45.6	50.4	50.9	51.5
E6	7.7	17.0	23.1	29.0	32.4	32.8	33.7

accounted for more than 80 % of the total subsidence. So the thickness of the second confined aquifer and the soft clay were selected as the evaluating indexes of the Quaternary geological factor. Figure 7 shows the relationship between annual subsidence rate and annual recovery rate of the groundwater level, indicating an overall negative correlation. When the groundwater level rose quickly, the rate of land subsidence declined slowly. Therefore, the annual recovery rate of the groundwater level was also selected as an evaluating index to reflect the human influence on land subsidence.

Historic subsidence of the second confined aquifer and the soft clay were analyzed based on the results from Eq. 1. Figure 8 shows that the accumulative subsidence of the second confined aquifer was generally larger than that of the soft clay and the ratio is approximately 2. According to Eq. 6, the weight ratio of the two indexes was regarded as 2. Combining Eqs. 6 and 8, the weights of the thickness of the second aquifer, the thickness of the soft clay and the annual recovery rate of the groundwater level were calculated as 0.33, 0.17 and 0.5, respectively.

4.2 Index Processing

Based on the analysis above, three indexes and their weights were determined. The raster maps of these indexes (Fig. 9) were created by ArcGIS Interpolation tool using the data from the boreholes and observation wells. Table 2 lists the criteria to standardize the evaluating indexes. The spatial data of each index were reclassified into three ranks. The ranking

**Fig. 6** The annual mean subsidence in the different layers

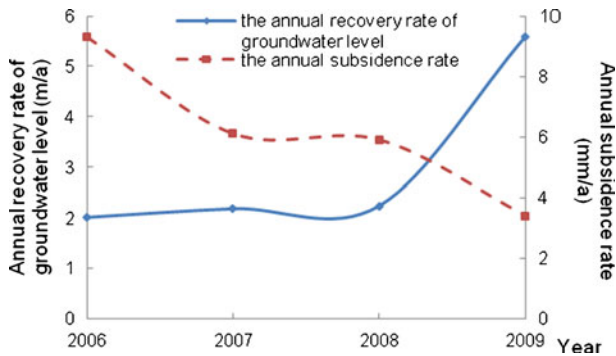


Fig. 7 The relationship between annual subsidence rate and annual recovery rate of the groundwater level

number from 1 to 3 representing low to high hazard risk was assigned to each data on the basis of its relative hazard risk level.

4.3 Hazard Risk Assessment

Land subsidence hazard risk in the Chengnan region was assessed according to Eqs. 8 and 9 and classified into three ranks (Table 3), i.e. high, medium and low, based on the Natural Breaks in ArcGIS. As shown in Table 3 that hazard risk index ranging from 1.7 to 3 can be divided into three hazard levels. The high hazard risk regions account for 9.5 % of the study area, about 42 km², while the medium and low hazard risk regions cover half of other areas respectively. The zonation map is shown in Fig. 10, which demonstrates that the hazard risk level decreases from the centre to the surrounding of the study area.

5 Discussions

The evaluation indexes of the land subsidence hazard risk were selected, following the principle of mutual independence. It is realistic to select the evaluation indexes according to subsidence of the individual layers from the extensometer monitoring data, reflecting the physical process of land subsidence explicitly. It is also objective to estimate weights based on the compaction characteristics of different soil layers.

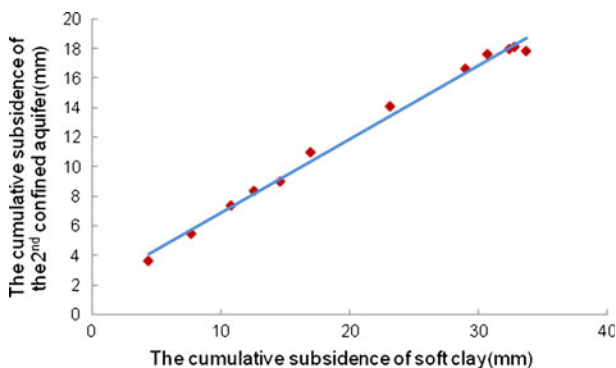


Fig. 8 Accumulative subsidence in the 2nd confined aquifer and soft clay

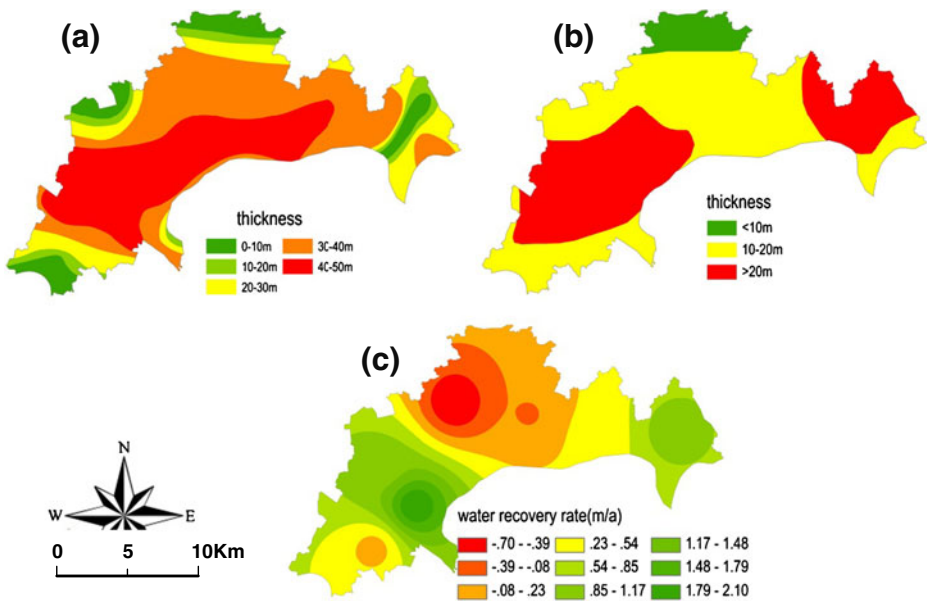


Fig. 9 The raster maps for (a) the thickness of 2nd confined aquifer, (b) the thickness of soft clay and (c) the annual recovery rate of groundwater level

The hazard risk zonation map (Fig. 10) shows the locations where subsidence could happen, even though there is no groundwater exploitation. In the high hazard risk areas, land subsidence will still continue with a larger rate. According to contribution to the hazard risk level of each evaluating index, hazard risk of land subsidence of the study area could be divided into thirteen types (Table 4): three types of high hazard risk areas, four types of medium hazard risk, and six types of low hazard risk areas. Table 4 was established based on Table 2, showing hazard risk level of individual assessment index in different subsidence hazard risk zone.

In Zone I, the hazard risk levels of the three assessment indexes are all high. It could be regarded as the most hazardous area. Not all the hazard risk levels of assessment indexes are high in Zone II and III, but they are high hazard risk areas as well. The hazard risk level of the thickness of the soft clay and the second confined aquifer is medium in Zone II and III, respectively. That is to say the annual recovery rate of the groundwater level has a great effect on hazard risk of land subsidence in Zone II and III.

Table 2 The index system, weight, and grade of land subsidence hazard risk assessment indexes

Factor	Index	Weighed value	Hazard risk level & Value		
			High (3)	Medium (2)	Low (1)
Natural	the thickness of the second confined aquifer	0.33	>40 m	20–40 m	<20 m
	the thickness of the soft clay	0.17	>20 m	10–20 m	<10 m
Human	the annual recovery rate of groundwater lever	0.5	<0 m/a	0–2 m/a	>2 m/a

Table 3 The hazard risk zonation in the Chengnan region

Hazard risk level	Hazard risk index	Area (km ²)	Percentage
High	2.5–3	42	9.5 %
Medium	2.2–2.5	197.7	44.7 %
Low	1.7–2.2	202.3	45.8 %

In Zone IV, both the hazard risk levels of the thickness of the second confined aquifer and the soft clay are high, whilst the hazard risk of the annual recovery rate of groundwater level is medium. It is known that the contribution of the hazard risk level of the later is much larger than that of the two formers. However, in Zone VI and VII, the hazard level of the annual recovery rate of the groundwater level is high, whereas the other two are medium or low. The contribution of the hazard risk level of the annual recovery rate of the groundwater level decreases. The thickness of the second confined aquifer and the soft clay becomes a major contribution factor.

It seems complicated in the zones of low subsidence hazard risk. In Zone VIII, though the hazard risk levels of the thickness of the second confined aquifer and the soft clay are high, the hazard risk level of land subsidence is low. That's because the hazard risk level of the annual recovery rate of the groundwater level is low. On the contrary, in Zone XIII, the hazard risk level of the annual recovery rate of the groundwater level is high, but the hazard risk level of land subsidence is low. That is to say that contribution of the annual recovery rate of the groundwater level is smaller than that of other two assessment indexes in Zone XIII.

The annual recovery rate of the groundwater level is the main factor influencing land subsidence hazard risk in some areas, and in other areas are the other two indexes. These explicit results will help local government effectively and efficiently manage groundwater and control land subsidence. Comparing Zones I, IV and VIII, the hazard risk level of land subsidence is as the same as the hazard risk level of the annual recovery rate of the groundwater level, though the hazard levels of other two indexes are high. In other words, in these areas (Fig. 11) some measures should be taken to control and increase the groundwater level (e.g. artificial recharge), which could mitigate the land subsidence hazard. The same principle is applicable in Zones II, III, IX, V, VI and X. On the contrary, in Zones XI, XII and XIII land subsidence hazard risk is low though the hazard risk level of the annual recovery rate of the groundwater level is high or medium. The thickness of the second confined aquifer is predominant for land subsidence hazard risk. Therefore, governments should pay attention to these areas, by monitoring regularly and taking measures to cope

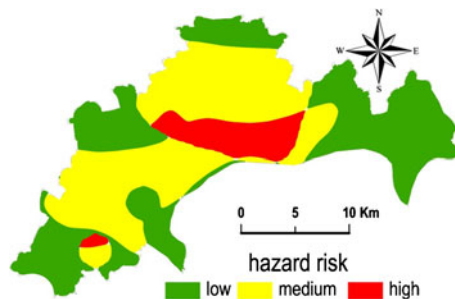
**Fig. 10** Land subsidence hazard risk zonation map in the Chengnan region

Table 4 The hazard risk level of each assessment index in individual land subsidence hazard risk zone

Hazard risk level of land subsidence	Zone	Hazard risk level of each assessment index		
		The thickness of the second confined aquifer	The thickness of the soft clay	The annual recovery rate of the groundwater level
High	I	high	high	high
	II	high	medium	high
	III	medium	high	high
Medium	IV	high	high	medium
	V	high	medium	medium
	VI	medium	medium	high
	VII	medium	low	high
Low	VIII	high	high	low
	IX	medium	high	medium
	X	medium	medium	medium
	XI	low	high	medium
	XII	low	medium	medium
	XIII	low	low	high

with harmful effect caused by land subsidence. In addition, in Zone VII, increasing groundwater level may be a good method to decrease land subsidence hazard on condition that the thickness of the second confined aquifer could not be changed artificially.

6 Conclusions

This study presents a comprehensive approach of hazard risk assessment of land subsidence caused by groundwater overexploitation using field observation of extensometers combining with spatial analyst tool, ArcGIS, which has been applied in a case study in the Chengnan region, China.

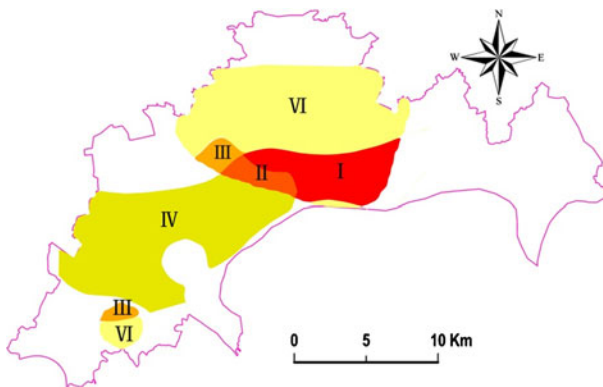


Fig. 11 The distribution of the areas where some measures should be taken to control and increase the groundwater level for mitigating subsidence hazard

In comparison land subsidence caused by groundwater over-exploitation with other geologic hazards, this study addresses the focus upon the process of land subsidence in assessing hazard risk. To support this view, field observation from extensometers has been used in selecting evaluation indexes and estimating their weights for further modeling assessment. ArcGIS spatial modelling then was established for more efficient data handling and better visualization for regional water management.

The hazard risk map of land subsidence has been produced after selecting three factors, thickness of the second confined aquifer and the soft clay and the annual recovery rate of the groundwater level, as evaluating indexes and estimating the weight of each index based on the observation data of extensometers. The results of hazard risk assessment show that the hazard risk level decreases from the centre to the surrounding of the study area and high hazard risk areas account for 9.5 % of study area. The annual recovery rate of the groundwater level plays a main role in land subsidence hazard risk in some areas of 211.3 km². Therefore, to manage and control land subsidence efficiently, local government should pay attention to these areas by taking some measures for groundwater level recovery. For other areas, it would be effective through monitor regularly and cope with harmful effect caused by land subsidence.

To monitor and control the development of land subsidence, the integrated land subsidence monitoring system (Wu et al. 2008), which consists of groundwater level monitoring network and displacement monitoring network, including benchmarks and extensometers, has been established in a number of major cities and areas with severe land subsidence. Therefore, the data needed by these assessment methods are available from existing database infrastructure, which makes the proposed approach more applicable.

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