Environ Earth Sci (2009) 59:269–276
DOI 10.1007/s12665-009-0024-6

ORIGINAL ARTICLE

Risk assessment of land subsidence at Tianjin coastal area in China

Beibei Hu · Jun Zhou · Jun Wang · Zhenlou Chen · Dongqi Wang · Shiyuan Xu

Received: 5 September 2008 / Accepted: 22 January 2009 / Published online: 14 March 2009

Abstract Risk assessment and zoning are very important to risk management. In this study, a land subsidence risk assessment index was proposed based on the Disaster Risk Index. The cumulative subsidence volume, the land subsidence velocity, and the groundwater exploitation intensity were collected, analyzed, and put together to create a land subsidence hazard evaluation map in Tianjin coastal area. The population density, Gross Domestic Product per square kilometer, and construction land proportion were adopted as indexes to create the vulnerability map. In addition, the capability of land subsidence prevention and reduction was also assessed. Finally, the land subsidence risk map was created by combing the hazard, vulnerability, and the capability of land subsidence prevention and reduction map. Specifically, the land subsidence risk was classified into five levels, i.e., very high, high, medium, low, and very low. The result of this research could provide a solid basis for the sustainable development as well as disaster prevention policy-making of Tianjin city.

Keywords Land subsidence · Risk index · Risk assessment · Tianjin coastal area · GIS

B. Hu · J. Wang · Z. Chen · D. Wang · S. Xu (✉)
Key Laboratory of Geographic Information Science of Ministry of Education, East China Normal University, Shanghai, China
e-mail: syxu@geo.ecnu.edu.cn

B. Hu
College of Urban and Environment Science, Tianjin Normal University, Tianjin, China

J. Zhou
Tianjin Land Subsidence Control Office, Tianjin, China

Introduction

Land subsidence is an environmental geological phenomenon that causes the slow lowering of ground-surface elevation. It can induce serious problems such as the damage of building and infrastructures, and in particular the increase of inundation risk and sea water intrusion in coastal zones, which have been documented in many places around the world, including Tokyo, Japan (Yamaguchi 1969), Bangkok, Thailand (Bergado et al. 1987; Phien-wej et al. 2006), Mexico (Adrian et al. 1999), Houston-Galveston Region, TX, USA (Gabrysch and Neighbors 2000), Jakarta, Indonesia (Abidin et al. 2001), Ravenna, Italy (Teatini et al. 2005), Pingtung Plain, Taiwan (Hu et al. 2006), and China (Xu et al. 2008).

Among all factors that can cause land subsidence, human activities and geological actions are probably the two most significant factors. Land subsidence caused by human activities has been extensively investigated. Particularly, it has been found that excessive groundwater exploitation can result in a slow but eventually significant land subsidence (Abidin et al. 2001; Bell et al. 1986; Chen et al. 2003; Ferronato et al. 2003; Finol and Sancevic 1995; Geertsma 1973; Leake 2004; Lee et al. 2006; Lewis and Schrefler 1978; Poland 1984; Poland and Davis 1969; Pratt and Johnson 1926; Shi et al. 2007; Wahyudi 2000; Xue et al. 2005). The occurrence and the development of the land subsidence were closely related to the groundwater pumping both temporally and spatially. In addition, the shape of subsidence cone was basically identical to that of groundwater depression cone.

During the past years, some governments and research institutions have been attempting to assess the hazards and risks of land subsidence as well as their spatial distribution. Specifically, Expert Structural Damage Assessment System

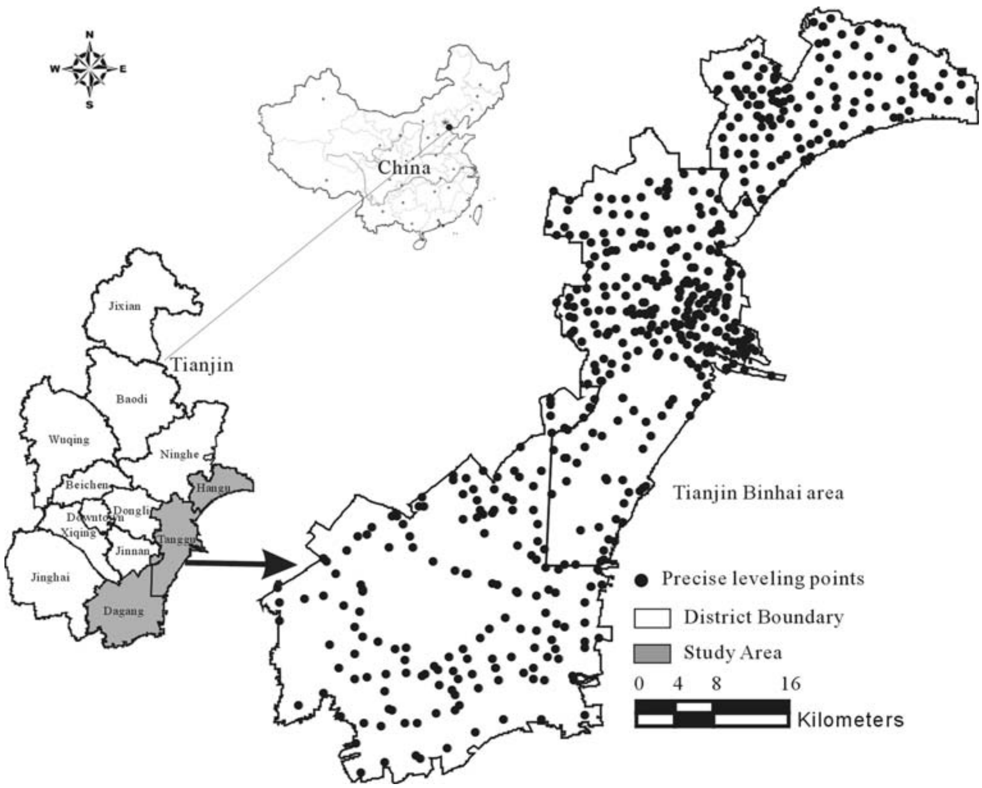


Fig. 1 Schematic map of the study area and the precise leveling points

(ESDAS), has been developed to evaluate the damages due to mining subsidence in the form of risk and in all three vital contributing components, i.e. mining factors, site factors and structural factors (Reddish et al. 1995). In addition, frequency ratio and logistic regression models have been adopted to identify the hazardous areas of subsidence on GIS software platform. The logistic regression model generated a better result than the frequency ratio model (Kim et al. 2006).

Land subsidence caused significant economic losses in China. The economic losses caused by the land subsidence in Shanghai was estimated to be about 294.3 billion Yuan during the period 1921–2000 (Zhang et al. 2003), and will be about 24.57 billion Yuan from 2001 to 2020 (Zhang and Wang 2005) based on the analysis by various methods, including the future value method, the engineering cost method, the shadow engineering method, the replacement cost method, the disaster comparison method, the proportional method of indirect and direct comparison, and so on (Zuo et al. 1993). In addition, in Tianjin, the economic losses from land subsidence during the floodgate operation was 0.345 billion Yuan (Jiang et al. 2008).

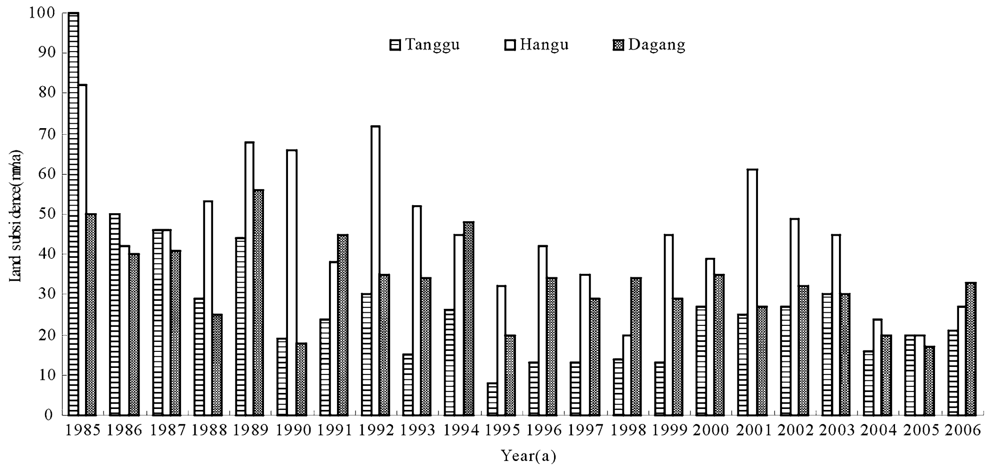
The Tianjin coastal area is located on Bohai Gulf, including Hangu, Tanggu and Dagang districts of Tianjin City. It is one of the most rapidly developing areas in China. However, because it lies within the East Asia monsoon region, it is short of surface and groundwater resources. As a result of rapid economic development and population growth, groundwater in Tianjin coastal area has been intensively exploited during the past decades, and consequently, the rate of land subsidence in Tianjin coastal area is the largest in China. The significant land subsidence together with sea level rise may seriously damage the economy and society.

In this paper, the risk assessment of land subsidence as well as the corresponding zonation in Tianjin coastal area was proposed by means of GIS techniques and disaster risk index and Analytic Hierarchy Process (AHP) method. First, the current situation of land subsidence in Tianjin coastal area was surveyed. Then, the methods to assess the land subsidence risk were presented; three factors as quantitative indices were identified, including the land subsidence hazard, the vulnerability, and the capability of disaster prevention and reduction. Finally, the maps of the hazard, the vulnerability and the risk of land subsidence were created.

The study area

Lying in the northeastern part of the North China Plain (Fig. 1), Tianjin coastal area is located between Latitude 38°40′ and 39°00′ N and Longitude 117°20′ and 118°00′ E, covering an area about 2414.33 km^2 and with a total population of about 1.1 million. It has a continental monsoon climate. Its average annual precipitation varies from 500 to 700 mm, being concentrated in the period from June

Fig. 2 Land subsidence data of Tianjin coastal area during the period from 1985 to 2006



to September, and much less than the average annual evaporation ranging from 1,800 to 2,000 mm.

The study area is a sloped plain oriented northwest–southeast. Its elevation ranges from 1 to 3 m. It belongs to the Neocathaysian tectonic systems. The Huanghua depression, which was divided into two parts by the Haihe River, the Hangu and the Cangdong fault systems, is a key tertiary structure. There have been no major tectonic movements in the subsidence zone of the Neocathaysian systems since the Cenozoic era. As a result of different rates and duration of subsidence, the sediments vary in thickness: the thickness of the Paleozoic, Mesozoic and Tertiary strata ranges from 1,000 to 8,000 m (Hu et al. 2002).

The Haihe River and Jiyun River run through the area before pouring into the Bohai Gulf and form a deposition of Quaternary sediments, which leads to the complex textures and a variety of hydrogeologic conditions in this area. Particularly, there exist aquifers within the interbedded Quaternary strata. Consequently, Tianjin coastal area mainly stands on unconsolidated Quaternary and Upper Neogene deposits. These deposits consist of a layered sequence of marine sands and clays in which ten separate aquifer units have been identified (Shearer 1998). In the south, the deposits are mainly composed of fine silts and sands and are characterized by a moderate permeability, the slow runoff, and the poor recharge. The grain size and deposit thickness decrease from north to south (Hu et al. 2002).

There are three subsidence centers in Tianjin coastal area, specifically, in Tanggu, Hangu, and Dagang, respectively. The land subsidence in Tanggu started in 1959 and its maximum accumulative subsidence was 3.25 m, while in Hangu, the land subsidence started in 1957 and its maximum accumulated subsidence was 3.11 m. In Dagang, the land subsidence started in 1964 and its maximum accumulative subsidence was only 1.01 m. In addition, in the study area, there was about 17 km^2 area below the sea level. The government of Tianjin city has implemented several measures to control land subsidence since 1986. The land subsidence in most parts of the area has been under control (Fig. 2). However, the subsidence area and the accumulative subsidence still keep increasing.

Methods and materials

Based on the principles of disaster risk formation as well as the natural and social characteristics of the study area, three factors have been selected as indices for a quantitative evaluation, including the hazard, the vulnerability, and the capability of disaster prevention and reduction. The disaster Risk Index method, ArcGIS Spatial Analyst, and Analytic Hierarchy Process were adopted to assess the risk of land subsidence in Tianjin coastal area.

Disaster risk index method

Risk is defined as the probability of harmful consequences, or the expected loss (of lives, property, livelihoods, economic activity or environments) resulting from interactions between natural or human induced hazards and vulnerable/capable conditions (ISDR 2002). Risk assessment is a process or application of a methodology for evaluating risk as defined by probability and frequency of occurrence of a hazardous event, exposure of people and property to the hazard, and consequences of that exposure. The quantitative estimation of risk may be determined by using the following relationship (Lirer and Vitelli 1998):

$$D_r = f(H, V, R)$$

where D_r is the disaster risk; H the hazard, i.e., the intensity that disaster will occur in a given area within a given period of time; V the vulnerability, a measure of the fraction that is likely to be lost as a result of a given event; *R* the capability of disaster prevention and reduction.

ArcGIS spatial analyst

ArcGIS spatial analyst provides powerful tools for comprehensive, raster-based spatial modeling and analysis. It has been widely utilized in disaster risk assessment (Chen and Blong 2003; Gambolati and Teatini 2002; He et al. 2003; Kim et al. 2006; Zerger and Wealands 2004; Zhou et al. 2003). In this article, the Spline Interpolation, the Reclassification, and the Raster Calculator tool were used to analyze the data.

The spline interpolation method (SIM) is an interpolation method that estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points. In this study, the Spline Interpolation was used to create the raster surface based on accumulative subsidence volume or land subsidence velocity. Similar criteria were adopted to assign values to raster surfaces when they were reclassified. By this way, several different raster surfaces can be created with the same values at vertices. Reclassification tool was used to deal with the different dimensions of evaluation indices, while Raster Calculator provides a powerful tool for performing multiple tasks. In this article, weighted comprehensive analysis was used.

Analytic hierarchy process

There are several approaches to criteria weighting, one of the most extensively used in the GIS spatial research is the hierarchical analytical process (HAP) (Aceves-Quesada et al. 2007). The AHP is a multi-criteria mathematical evaluation method in the decision making process, in which hierarchical structures are used to quantify relative priorities for a given set of elements on a ratio scale based on the discernment of the user.

Index system

Based on the system approach and the natural disaster risk index theory, a indicator framework for assessing the land subsidence risk was designed, in which there were three first level indicators (the hazard, the vulnerability, and the capability of disaster prevention and reduction) and nine second level indicators. Reclassification tool was used to standardize the evaluating indicator (as Table 1). The data of each indicator were classified into five classes. A ranking number ranging from 1 to 5 was assigned to each data based on its relative risk, in which five indicates the highest risk. Each of these indicators was weighed by its

Table 1 The index system, weight, and grade of land subsidence risk assessment indexes of Tianjin coastal area

Index				Grade and value				
Factor level		Indicator level		Very low	Low	Medium	High	Very high
Factor	Weighted value	Indicator	Weighted value	(1)	(2)	(3)	(4)	(5)
Hazard	0.45	Accumulative subsidence volume (mm)	0.65	0–400	400–600	600–800	800–1,000	>1,000
		Land subsidence velocity (mm/a)	0.18	0–15	15–30	30–40	40–50	>50
		Intensity of groundwater exploitation (10^4 m^3 $km^{-2}a^{-1}$)	0.17	0–4	4–8	8–12	12–16	>16
Vulnerability	0.36	Population density (persons/km^2)	0.42	0–300	300–1,000	1,000–5,000	5,000–1,0000	>1,0000
		GDP per square kilometers (10^4 Yuan)	0.31	0–500	500–1,000	1,000–3,000	3,000–5,000	>5,000
		Construction land proportion (%)	0.27	0–35	35–50	50–65	65–80	>80
Capability of preventing and reducing disaster	0.19	Length of level survey per square kilometers	0.46	>1.25	1.00–1.25	0.75–1.00	0.5–0.75	0–0.5
		Volume of reducing groundwater exploitation/volume of pumped groundwater (%)	0.29	>30	20–30	10–20	5–10	0–5
		Urbanization level (%)	0.25	>70	55–70	40–55	25–40	<25

importance in determining the land subsidence risk as evaluated by AHP.

Different from sudden disasters, land subsidence is a slow-onset geohazard and accumulated over years. Therefore, the accumulative subsidence volume is the key indicator in evaluating the land subsidence hazard (Wang 2006; Wei 2006). In addition, the land subsidence velocity in recent 20 years was adopted as a hazard evaluating indicator to reflect the trend of land subsidence. Specifically, the land subsidence velocity data were divided into four time groups, i.e., from 1985 to 1990, 1991 to 1995, 1996 to 2000 and 2001 to 2005, respectively. The average velocity was calculated for each group. The weight of land subsidence velocity of each group was determined by Delphi technique, that is, 0.1, 0.2, 0.3, and 0.4, respectively. In addition, because the groundwater exploitation is the primary factor for the land subsidence in the study area, the intensity of groundwater exploitation was used as an important indicator in evaluating land subsidence hazard.

Generally, the level of socioeconomic development is an important factor affecting the vulnerability, for the casualty and economic losses from land subsidence could be very seriously in a developed economy as well as densely populated areas. Particularly, buildings, lifeline engineering, surface elevation, etc. can be significantly affected by the land subsidence. Therefore, in this paper, the population density, GDP per square kilometers, and Construction Land proportion were all selected as vulnerability indicators (Zhou et al. 2000).

In order to control the land subsidence, Tianjin Land Subsidence Control Office started a real-time monitoring of land subsidence in 1986 and began to restrict the groundwater exploitation. Since then, the measures as well as managements of disaster prevention and mitigation and the legislative regulation have been improved significantly along with the urbanization, the population quality, and the degree of civil development. Therefore, the length of level survey per square kilometers, the reduction in the volume of groundwater exploitation as well as pumped groundwater, and the Urbanization level were selected to evaluate the capability of disaster prevention and reduction.

Data

An elaborate monitor network has been established in Tianjin coastal area. By the end of 2006, there have been 575 precise leveling points in this area (Fig. 1). The accumulative subsidence volume and land subsidence velocity at every monitor point was calculated using precise leveling data from 1985 to 2006; a surface was then created by the spline interpolation with the output cell size 200 m × 200 m. The population, economic data,

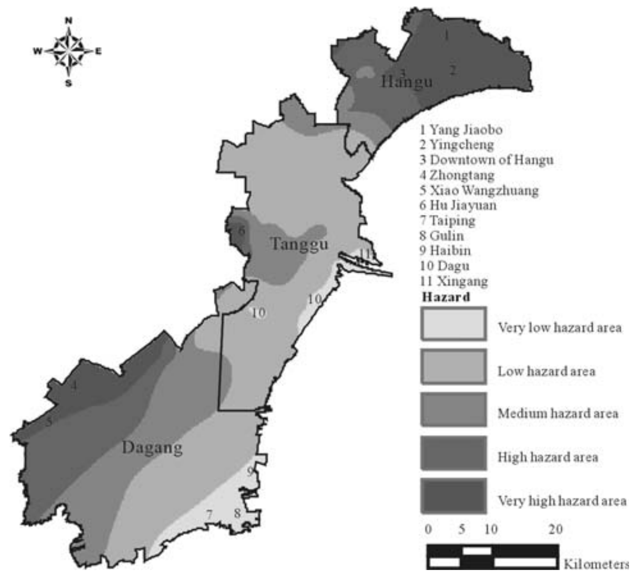


Fig. 3 Land subsidence hazard zonation of Tianjin coastal area

construction land proportion, and urbanization level were obtained from 2007 Tanggu Statistical Yearbook, 2007 Hangu Statistical Yearbook, and 2007 Dagang Statistical Yearbook. The length of level survey per square kilometers and groundwater exploitation data were obtained from Tianjin Water Resource Bureau. In addition, all of these data were plotted in maps that were digitized based on the topographic map to obtain a good spatial coincidence as well as a unified coordinate system and projection system. ArcGIS spatial analyst toolbar was used to convert data from features to raster.

Results and discussion

Land subsidence hazard

As shown in Fig. 3, the High hazard and Very high hazard regions accounted for about 50% of the total study area. Specifically, the Very high hazard regions were mainly in Yang Jiabo Town, Yingcheng Town, part of the Hangu downtown, Zhongtang Town, Xiao Wangzhuang Town, and Hu Jiayuan Sub-district. Particularly, the accumulated subsidence in these regions was above 1,000 mm during the period from 1985 to 2006. On the contrary, the Very low hazard regions were mainly in Taiping Town, Gulin Sub-district, Haibin Sub-district, Dagu and Xingang Sub-district, where the accumulated subsidence was less than 400 mm during the period from 1985 to 2006. Moreover, there was an obvious correlation between the accumulated groundwater extraction and the accumulated subsidence (Hu et al. 2002; Shearer 1998; Shen et al. 2004).

Land subsidence vulnerability

As shown in Fig. 4, the very high vulnerability areas were mainly in Hang Zhoudao Sub-district, Bohai Shiyou Sub-district, and the downtown of Hangu, while the High vulnerability areas were around Hu Jiayuan, Xiangyang and Xingang Sub-district. All of these regions were highly developed economically and had a high population density. Specifically, Hang Zhoudao Sub-district has the highest population density in the study area, with 13,161 people in every square kilometer. In addition, there were many petrochemical companies in Binhai Shiyou Sub-district. Moreover, Tianjin Economic-Technological Development Area (TEDA) located at Xiangyang Sub-district was the most developed area in economy and advanced technology in Tianjin coastal area. The GDP per square kilometers of TEDA in 2006 was as high as 23.65×10^8 Yuan. Finally, Tianjin Port and Tianjin Free Trade Zone are situated at Xingang Sub-district. Therefore, the disaster losses in these areas are expected to be large (Chen and Niu 2002; Zhou et al. 2000). In contrast, the very low vulnerability areas were mainly in Yang Jiabo Town, Yingcheng Town, Gulin Sub-district, Taiping and Xiao Wangzhuang Sub-district, among which Yingcheng Town has the lowest population density, with about 41 people in every square kilometer. It is also the most undeveloped region in the study area with a GDP per square kilometers 431.14×10^4 Yuan.

Capability of land subsidence prevention and reduction

Tianjin Land Subsidence Control Office started a real-time monitoring of land subsidence and groundwater level in 1986. During the period from 2004 to 2006, some effective actions have been taken to close 16 groundwater-

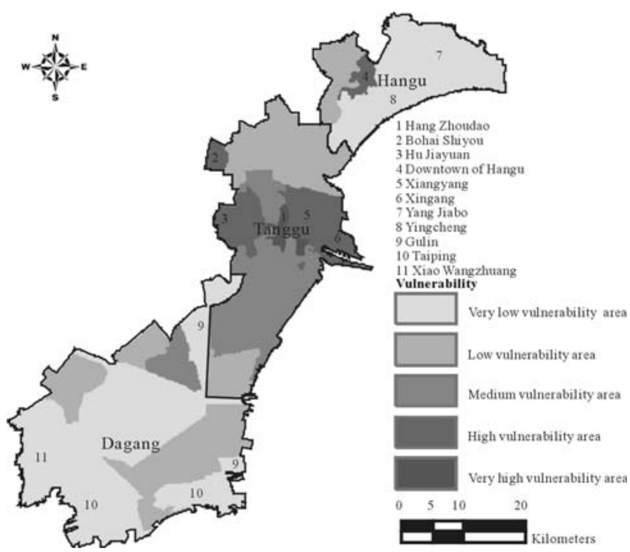


Fig. 4 Land subsidence vulnerability zonation of Tianjin coastal area

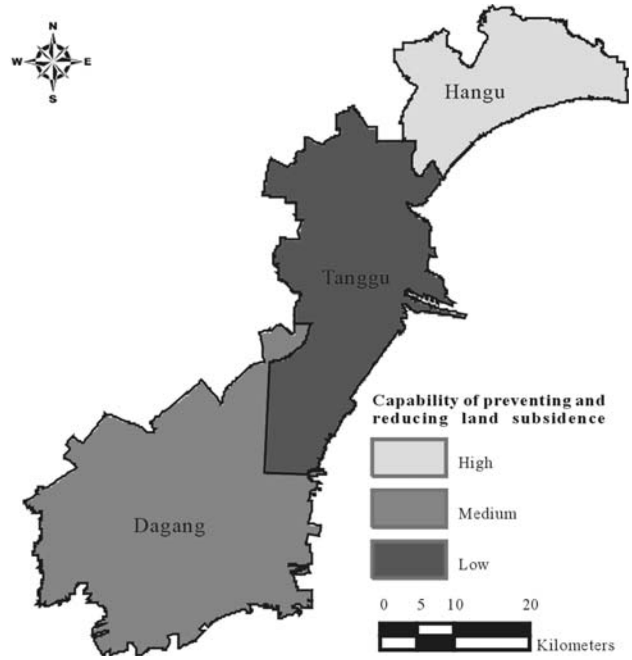


Fig. 5 Effectives of land subsidence reduction measures in Tianjin coastal area

mining wells and reduce the groundwater exploitation by 772.76×10^4 m^3. The capability of land subsidence prevention and reduction has also been improved. Specifically, as shown in Fig. 5, the capability of land subsidence prevention and reduction was high in Hangu, while low and medium in Tanggu and Dagang, respectively. However, there were still many regions undergoing land subsidence, and meanwhile, the subsidence area kept expanding (He et al. 2005; Hu et al. 2004; Xu et al. 2008). Therefore, more work and efforts are needed to improve the capability of land subsidence prevention and reduction in the future.

Land subsidence risk

The land subsidence risk map of Tianjin coastal area was constructed from the Land subsidence hazard map, the vulnerability map, and the capability of disaster prevention and reduction map using GIS (Gambolati and Teatini 2002; Zerger and Wealands 2004). The high risk and very high risk areas were mainly in the part of the Hangu downtown, the northwest of Yang Jiabo Town, the northeast of Yingcheng Town, Hu Jiayuan Sub-district, Hang Zhoudao Sub-district, Zhongtang Town, and Xiao Wangzhuang Town, while Low risk and Very low risk areas were mainly around the south of Chadian Town, the south of Yingcheng Town, Beitang Sub-district, Xinhe Sub-district, Dagu Sub-district, Haibin Sub-district, Gangxi Sub-district, Taiping Sub-district, and Gulin Sub-district (Fig. 6).

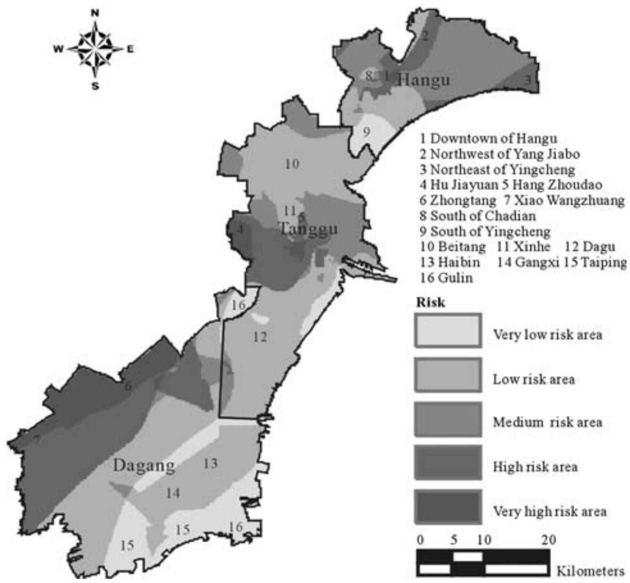


Fig. 6 Land subsidence risk zonation of Tianjin coastal area

Conclusions

Here a method to assess land subsidence risk as well as zoning in Tianjin coastal area was proposed based on GIS and natural disaster risk assessment techniques. The high risk areas were defined as the region with high hazard and vulnerability. The major contribution of this study is the creation of the map of land subsidence hazard/risk of Tianjin coastal area. Specifically, very high hazard regions were mainly located at Yang Jiabo Town, Yingcheng Town, part of the Hangu downtown, Zhongtang Town, Xiao Wangzhuang Town, and Hu Jiayuan Sub-district, while very high vulnerability regions were at Hangzhou Sub-district, Bohai Shiyou Sub-district, and downtown of Hangu. The capability of land subsidence prevention and reduction was found at the high level in Hangu, whereas at the intermediate and low level in Dagang and Tanggu, respectively. In addition, the very high risk regions were mainly in part of the Hanggu downtown, Hu Jiayuan Sub-district, Hang Zhoudao Sub-district, Zhongtang Town, and Xiao Wangzhuang Town.

Acknowledgments This paper was financially supported by the National Natural Science Foundation of China (NSFC) (Project No. 40730526, No. 40571006 and No.70703010). We gratefully acknowledge the thoughtful comments of the editor and reviewers.

References

Abidin HZ, Djaja R, Darmawan D, Hadi S, Akbar A, Rajiyowiryono H, Sudibyo Y, Meilano I, Kasuma MA, Kahar J, Subarya C (2001) Land subsidence of Jakarta (Indonesia) and its geodetic monitoring system. Nat Hazards 23(2–3):365–387

Aceves-Quesada JF, Díaz-Salgado J, López-Blanco J (2007) Vulnerability assessment in a volcanic risk evaluation in Central Mexico through a multi-criteria-GIS approach. Nat Hazards 40:339–356

Adrian OG, Rudolph LD, Cherry AJ (1999) Analysis of long-term land subsidence near Mexico City: field investigations and predictive modelling. Water Resour Res 35(11):3327–3341

Bell FG, Cripps JC, Culshaw MG (1986) A review of the engineering behavior of soils and rocks with respect to groundwater. In: Groundwater in engineering geology. Geol Soc Eng Geol Spec Publ 3:1–23

Bergado DT, Nutalaya P, Balasubramaniam AS, Apaipong W, Chang CC, Khaw LG (1987) Causes, effects and predictions of land subsidence in AIT Campus, Chao Phraya Plain, Bangkok, Thailand. Bull Assoc Eng Geol 25(1):57–81

Chen K, Blong R (2003) Towards an integrated approach to natural hazards risk assessment using GIS: with reference to bushfires. Environ Manage 31:546–560

Chen WJ, Niu XJ (2002) The evaluation of risk degree on land subsidence in Tianjin urban district. In: Proceedings of 11th China symposium land subsidence, pp 155–170 (in Chinese)

Chen CX, Pei SP, Jiao JJ (2003) Land subsidence caused by groundwater exploitation in Suzhou City, China. Hydrogeol J 11:275–287

Ferronato M, Gambolati G, Teatini P, Baù D (2003) Stochastic compressibility in land subsidence modeling. In: 16th ASCE Engineering Mechanics Conference, University of Washington, Seattle, 16–18 July 2003

Finol AS, Sancevic ZA (1995) Subsidence in Venezuela. In: Chilingarian GW, Donaldson EC, Yen TF (eds) Subsidence due to fluid withdrawal: developments in petroleum science. Elsevier, Amsterdam, pp 337–372

Gabrysch RK, Neighbors RJ (2000) Land-surface subsidence and its control in the Houston-Galveston region, TX, 1906–1995. In: Proceedings 6th international symposium. Land Subsidence, Ravenna, Italy, September 2:81–92

Gambolati G, Teatini P (2002) GIS simulations of the inundation risk in the coastal lowlands of the Northern Adriatic Sea. Math Comput Model 35:963–972

Geertsma J (1973) Land subsidence above compacting oil and gas reservoirs. J Petrol Technol 25:734–744

He YP, Xie H, Cui P, Wei FQ, Zhong DL, Gardner JS (2003) GIS-based hazard mapping and zonation of debris flows in Xiaojiang Basin, southwestern China. Environ Geol 45:286–293

He QC, Ye XB, Liu WB, Li ZM, Li C (2005) Land subsidence in the Northern China Plain (NCP). Proc 7th Int Symp Land Subsidence (SISLOS 2005) 1:18–29

Hu RL, Wang SJ, Lee CF, Lee ML (2002) Characteristics and trends of land subsidence in Tanggu, Tianjin, China. Bull Eng Geol 61:213–225

Hu RL, Yue ZQ, Wang LC, Wang SJ (2004) Review on current status and challenging issues of land subsidence in China. Eng Geol 76:65–77

Hu JC, Chu HT, Hou CS, Lai TH, Chen RF, Nien PF (2006) The contribution to tectonic subsidence by groundwater abstraction in the Pingtung area, southwestern Taiwan as determined by GPS measurements. Quatern Int 147:62–69

Jiang YX, Zhu QC, Wang W (2008) A discussion of the economic loss caused by land subsidence during the floodgate operation. Hydrogeol and Eng Geol 1:126–128 (in Chinese)

Kim K-D, Lee S, Oh HJ et al (2006) Assessment of ground subsidence hazard near an abandoned underground coal mine using GIS. Environ Geol 50:1183–1191

Leake SA (2004) Land subsidence from ground-water pumping. http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/. Cited 6 Jan 2005

Lee CJ, Tang XM, Ma TH (2006) Land subsidence caused by groundwater exploitation in the Hangzhou-Jiaxing-Huzhou Plain, China. Hydrogeol J 14:1652–1665

Lewis RW, Schrefler B (1978) Fully coupled consolidation model of subsidence of Venice. Water Resour Res 14(2):223–230

Lirer L, Vitelli L (1998) Volcanic risk assessment and mapping in the Vesuvian area using GIS. Nat Hazards 17:1–15

Phien-wej N, Giao PH, Nutalaya P (2006) Land subsidence in Bangkok, Thailand. Eng Geol 82:187–201

Poland JF (1984) Mechanics of land subsidence due to fluid withdrawal. In: Poland JF (ed) Guidebook to studies of land subsidence due to ground-water withdrawal: studies and reports in Hydrology 40, prepared for the International Hydrological Programme, Working Group 8.4. United Nations Educational. Scientific, and Cultural Organization (UNESCO), Paris, pp 37–54

Poland JF, Davis GH (1969) Land subsidence due to withdrawal of fluids. In: Varnes DJ, Kiersch G (eds) Reviews in engineering geology, vol 2. Geological Society of America, Boulder, pp 187–269

Pratt WE, Johnson DW (1926) Local subsidence of the Goose Creek oil field. J Geol 34:577–590

Reddish DJ, Yao XL, Dunham RK (1995) Risk assessment of surface structural damage due to mining subsidence—an integrated computer-based approach. Trans Inst Min Metall Sect A 104(Sept–Dec):A139–A143

Shearer TR (1998) A numerical model to calculate land subsidence applied at Hangu in China. Eng Geol 49:85–93

Shen SL, Tohno I, Nishigaki M, Miura N (2004) Land subsidence due to withdrawal of deep-groundwater. Lowland Technol Int 6(1):32–43

Shi XQ, Xue YQ, Ye SJ, Wu JC, Zhang Y, Yu J (2007) Characterization of land subsidence induced by groundwater withdrawals in Su-Xi-Chang area, China. Environ Geol 52:27–40

Teatini P, Ferronato M, Gambolati G, Bertoni W, Gonella M (2005) A century of land subsidence in Ravenna, Italy. Environ Geol 47:831–846

United Nations, International Strategy for Disaster Reduction (ISDR) (2002) Living with risk: a global review of disaster reduction initiatives (preliminary version). Geneva: UN ISDR, July

Wahyudi SI (2000) Evaluation and analysis of land subsidence in Tanjung Emas Harbour area in Semarang. In: Proceedings of the sixth AEESEAP triennial conference Kuta, Bali, Indonesia, 23–25 August 2000, pp 509–514

Wang GL (2006) Preliminary studies on dangerous grading standard of land subsidence. Shanghai Geol 4:39–43 (in Chinese)

Wei FH (2006) Researches on geological hazard and risk zonation in Tangshan Hebei. Dsc. Thesis, China Univ Geosci, pp 89–90 (in Chinese)

Xu YS, Shen SL, Cai ZY, Zhou GY (2008) The state of land subsidence and prediction approaches due to groundwater withdrawal in China. Nat Hazards 45:123–135

Xue YQ, Zhang Y, Ye SJ WJC, Lee QF (2005) Land subsidence in China. Environ Geol 48:713–720

Yamaguchi R (1969) Water level change in the deep well of the University of Tokyo. Bull Earthquake Res Inst No.47. http://wwwrcamnl.wr.usgs.gov/rgws/Unesco/PDF-Chapters/Chapter5.pdf

Zerger A, Wealands S (2004) Beyond modelling: linking models with GIS for flood risk management. Nat Hazards 33:191–208

Zhang W, Wang RT (2005) Risk evaluation of the economic losses induced by land subsidence in Shanghai from 2001 to 2020. Adv Water Sci 16(6):870–874 (in Chinese)

Zhang WR, Duan ZL, Zeng ZQ, Shi HP (2003) Evaluation on economic losses resulted from land subsidence in Shanghai: 1921–2000. J Tongji Univ 31(6):743–748 (in Chinese)

Zhou CH, Wan Q, Huang SF et al (2000) A GIS-based approach to flood risk zonation. Acta Geogr Sin 55(1):15–24 (in Chinese)

Zhou GY, Esaki T, Mori J (2003) GIS-based spatial and temporal prediction system development for regional land subsidence hazard mitigation. Environ Geol 44:665–678

Zuo H, Liu TZ, Lin XH (1993) Economic benefit risk assessment of controlling land subsidence in Shanghai. Environ Geol 21:208–211