Engineering Geology 193 (2015) 243–255

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Land subsidence due to groundwater withdrawal in the northern Beijing plain, China

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ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 6 February 2015
Accepted 26 April 2015
Available online 29 April 2015

Keywords:
Land subsidence
Groundwater level
Compressible layer
Building
PSI
GIS

ABSTRACT

Beijing is an international metropolis, where over-exploration of water resource makes land subsidence becoming more and more serious. The related problems cannot be avoided in the coming years because of the giant increase of population. The aims of this study are to quantify land subsidence over the period 2003 to 2010, grasp the evolution of the process, and investigate the relation with the triggering factors in the northern area of the Beijing plain. Various data, including deep compaction from vertical multiple borehole extensometers, land subsidence from Persistent Scatterer Interferometry and leveling surveys, groundwater levels, hydrogeological setting from wellbores, and Landsat TM image were collected and effectively used to detect the spatial and temporal features of land subsidence and its possible relation with groundwater level changes, compressible layer thickness, and urban development. Results show that land subsidence is unevenly distributed and continuously increased from 2003 to 2010. The average loss of elevation over the monitoring period amounted to 92.5 mm, with rates up to 52 mm/y. The distribution of the subsidence bowl is only partially consistent with that of the groundwater depression cone because of the variable thickness of the most compressible fine deposits. In fact, extensometers reveal that silty-clay layers account for the larger contribution to land subsidence, with the 15 m thick silty-clay layer between 102 and 117 m depth accounting for about 25% of the total subsidence. Finally, no clear correlation has been observed between the subsidence rates and the increase of the load on the land surface connected to the impressive urban development. This study represents a first step toward the development of a physically-based model of the subsidence occurrence to be used for planning remediation strategies in the northern Beijing plain.

1. Introduction

Land subsidence is a geological hazard mainly caused by human activities such as over-mining of underground fluids (water or hydrocarbons). More than sixty countries all over the world (Poland, 1984; Gambolati et al., 2005; Galloway and Burbey, 2011) and more than fifty cities in China (Xue et al., 2005) are suffering from land subsidence. An area of about 79,000 km^2 in China has experienced a cumulative subsidence larger than 200 mm (e.g., Wu et al., 2008; Zhang et al., 2014).

Research on land subsidence addresses various aspects, such as monitoring the movements (Amelung et al., 1999; Schmidt and Burgmann, 2003; Galloway and Hoffmann, 2007; Bell et al., 2008; Higgins et al., 2013), characterizing the geomechanical properties of the geologic formations hosting the produced fluids (Poland, 1961; Brutsaert and El-Kadi, 1984; Liu et al., 2004; Ferronato et al., 2013), and simulating the occurrence by appropriate numerical models (Wilson and Gorelick, 1996; Teatini et al., 2006; Shi et al., 2008a,2008b; Ortiz-Zamora and Ortega-Guerrero, 2010). Interferometric processing of satellite-borne synthetic aperture radar (SAR) images is currently used to measure land displacements (Galloway and Burbey, 2011). Permanent Scatterer Interferometry (PSI) has been used to process SAR images taking advantage from the fact that, when the dimension of a reflecting target is smaller than the image resolution cell, the coherence of the reflected radar signal is preserved irrespective of the image pair baseline. Consequently, more observations are available, allowing for a reduction of atmospheric disturbances and the improvement of the processing accuracy, which reaches a few millimeters (Ferretti et al., 2001, 2004). For example, Strozzi et al. (2013) used PSI to monitor the regional land subsidence in the coastal area of Venice, Italy, using natural and artificial reflectors. In-situ deformeters and GPS (Banker and Al-Harthi, 1999), consolidation tests at lab (Shi et al., 2008a, 2008b; Wu et al., 2008; Zhang et al., 2012, 2014) were adopted to investigate the most appropriate geomechanical behavior controlling the compaction of the sedimentary sequence in Shanghai and Beijing. Various numerical models were

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http://dx.doi.org/10.1016/j.enggeo.2015.04.020
0013-7952/

developed to simulated soil deformation, mainly using a 1-D approach (e.g., Leake and Galloway, 2010; Liu and Helm, 2008a, 2008b; Wu et al., 2009; Ye et al., 2004) and, more rarely, a 3-D approach (e.g., Burbey, 2006; Teatini et al., 2006).

Beijing is a metropolis with an acute water shortage and 2/3 of water demand is supplied by groundwater. Along with the increasing urbanization, demands for water resources become larger. To cope with the pressure for water supply, Beijing constructed in the Huairou district the first over-sized emergency groundwater resource region (EGRR) in August 2003. In the following years, the other four EGRRs have been established in different districts around Beijing. The long-time over-exploitation of groundwater resulted in water level fall and land subsidence. By the end of 2010, a region larger than 4200 km^2, which is about 66% of the whole plain area, has been affected by land subsidence larger than 50 mm, with the maximum sinking that reached 1233 mm in Beijing Plain.

The severe land subsidence in Beijing has promoted a deep investigation on the phenomenon over the last few years. Chen et al. (2011) analyzed the relation between groundwater level and land subsidence in Beijing Municipality. Zhu et al. (2013) used an artificial intelligence approach to develop a land subsidence model. Zhang et al. (2014) analyzed the deformation characteristics by using stress–strain records and oedometer tests. Ng et al. (2012) used PSI technology to monitor the movement in the metropolitan area of Beijing. They processed a stack of 41 ENVISAT acquisitions from June 2003 to March 2009, i.e. an image set similar to the one used in this study. However, they focused their analysis mainly in the portion of the Chaobai plain to the east of capital, assuming for the SAR processing a stable reference in Beijing downtown.

This paper is focused on the upper–middle part of alluvial-proluvial fans of Chaobai River, where the Huairou EGRR and the other groundwater well-fields are located, and it is aimed at detecting the spatial and temporal characteristics of land subsidence and its relations with the main triggering factors. PSI is used to quantify land subsidence and GIS spatial analysis is applied to explore the correlations between land movement and the groundwater drawdown, thickness of the more compressible geologic layers, and the evolution and characteristic of the urbanization in the study area.

2. Description of study area

The study area belongs to Chaobai River alluvial-proluvial fan in the north-eastern Beijing plain (northern latitude 40°–40°30′, eastern longitude 116°30′–117°), with a total area of 1350 km^2 divided between the Shunyi, Huairou and Miyun districts (Fig. 1).

The area is characterized by a ground elevation decreasing from 120 m above msl (mean sea level) to the north to 20 m above msl to the south. The mean elevation is about 35 m above msl, with an average slope equal to 2.1%. The mean annual precipitation from 1959 to 2010 amounted to 624 mm, and reduced to 517 mm between 2000 and 2010 (Song et al., 2014). The rainfall concentrates from June to September, which takes up about 80% of the total annual precipitation. Rainfall is the main source of groundwater recharge. The sedimentary sequence is composed of deposits from coarse to fine, with an undifferentiated phreatic sandy-gravel aquifer in the high alluvial-proluvial fans and a multilayer aquifer system in the middle region. Based on the lithology, the area can be divided in four zones from north to south (Fig. 1b):

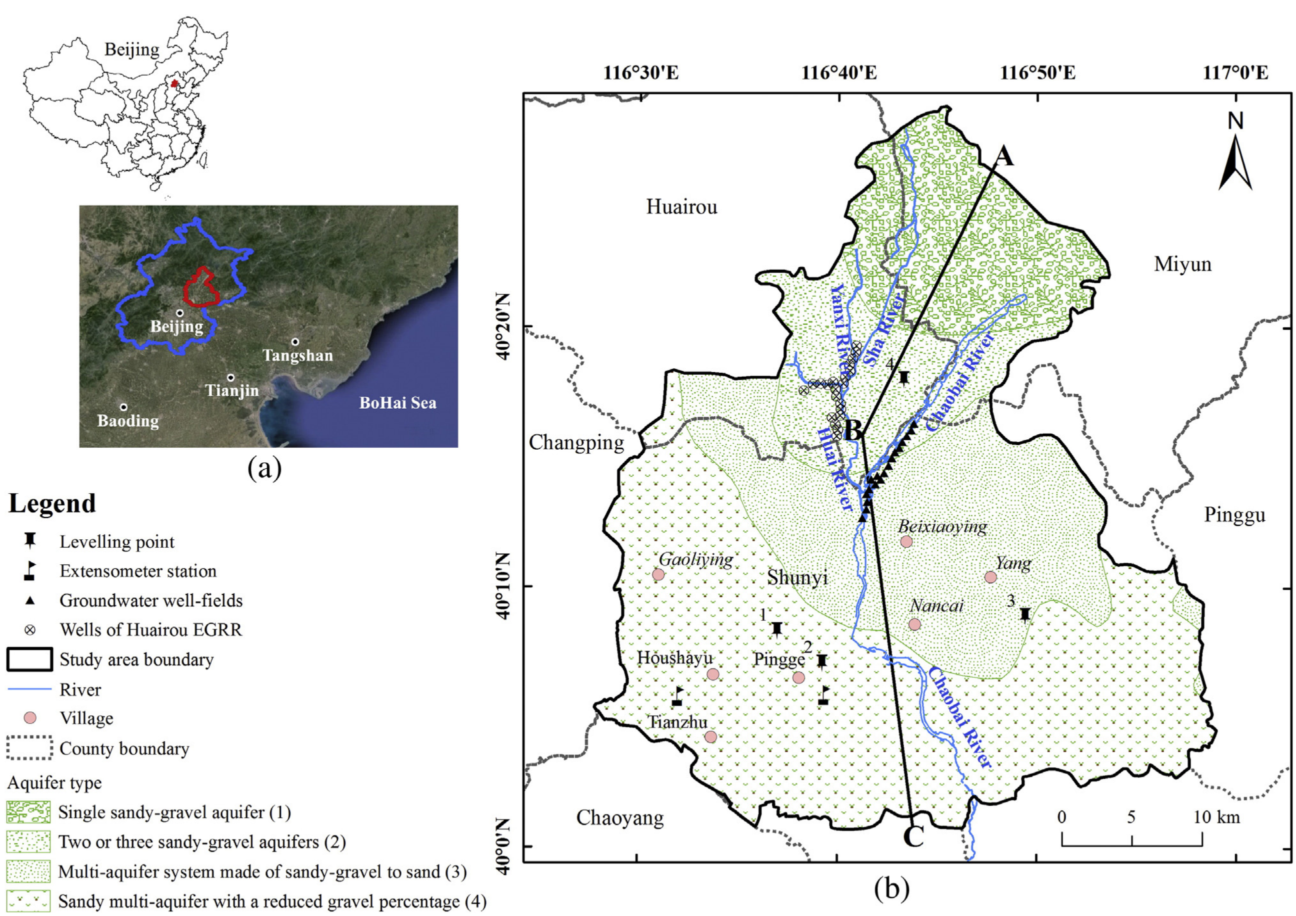

Fig. 1. (a) Position of the study region in central China. (b) Hydrogeological map of the study area with the location of some big well-fields, extensometric stations, and available leveling points. (c) Hydrogeologic vertical section of the Chaobai River alluvial-proluvial fan along the north to south A–B–C profile traced in (b). The bottom of the unconfined aquifer, which extends in the whole study area, is about 20–40 m deep below the land surface. The bottom of the confined aquifer system ranges between 300 m depth in Huairou County and 200–500 in Shunyi District. The confined system is well developed in zones (3) and (4).