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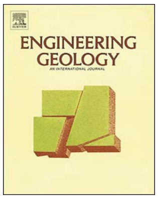

Land rebound after banning deep groundwater extraction in Changzhou, China

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ABSTRACT

More than 30 years groundwater overdraft had resulted in hydraulic head declined from near the ground surface to 85 m deep in the second confined aquifer (CA2) in Changzhou, and lead to regional land subsidence from 1970's to early 2000's. After banning deep groundwater extraction was banned in 2000, the hydraulic head of CA2 had recovered to 37.6 m in Changzhou by the end of 2013. Based on several stages first and second order leveling results and long term monitoring data from the multi-strata borehole extensometer station (BES), it was revealed that the land subsidence is attributed to the compression of both aquifers and aquitards in the porous aquifer system. The spatial characteristics of subsidence are related not only to hydraulic head pattern in the area, but also to the thickness and compressibility of different soil strata, and distance from the aquifer. Since banning deep groundwater extraction, the ground uplifted 37.22 mm (5.4% of the pre subsidence) at BES, Changzhou due to the hydraulic head recovering. Strata compression and rebound was recorded as: the upper most stratum, and the underlying aquitard of CA2, and the upper CA3 are still in the compression process, the lower CA3 layer and the upper most segment of aquitard of CA2 rebounded about 90% of the pre compression recorded since 1984, and the CA2 and its adjacent overlying aquitard rebounded 3.8%–9.7% of the pre compression.

1. Introduction

Excessive groundwater extraction leads to hydraulic head drawdown in aquifers and pore pressure decline in aquitards, or increase of effective stress in aquifers and aquitards, which results in strata compression. If the effective stress remains less than the preconsolidation stress, a further increase in effective stress (or decrease in hydraulic head) causes a small elastic deformation. This deformation is reversible in case the effective stress returns to its initial state. If the effective stress greater than the preconsolidation stress, the deformation is irreversible. The compressibility of soil depends on the composition and previous loading history. Previous loading history is important because compression tends to cause irreversible changes in the soil fabric, grains shift and rearrangement, clay particles deform, cemented bonds break, and even grains crack under loading (Terzaghi et al., 1996). Since these changes are irreversible, the soil displays hysteresis.

Groundwater extractions that vastly exceed the natural recharge, can not only lead to large scale drawdowns of the hydraulic heads, but also cause regional land subsidence (Gambolati and Freeze, 1973; Stiros, 2001; Phien-wej et al., 2006). The subsidence pattern is not solely due to the spatial distribution of drawdowns, but reflects the spatial variability of the skeletal storage coefficients of the interbeds (Hoffmann et al., 2003). Land subsidence induced by groundwater extraction can be either primarily attributed to the irreversible consolidation of fine sediments in aquitards (Bouwer, 1977; Waltham, 2002) or predominantly attributed to the irreversible compaction of the aquifer system (Holzer and Galloway, 2005). One implication of this irreversibility is that the storage coefficients are reduced in the aquifer system. In fact, land subsidence due to long-term excessive groundwater withdrawal can be simultaneously resulted from the consolidation of aquitards and the compaction of aquifers (Wang et al., 2009). In field, significant subsidence might not be observed until hydraulic heads declined > 30 m in many aquifer systems, or until the natural preconsolidation stress was reached (Holzer, 1981). Once the preconsolidation stress is exceeded, the strata are in the process of a virgin consolidation, and will record a new preconsolidation stress at the end of the drawdown. Compression of an aquifer system is not instantaneously settled and may take years and even centuries to complete. The delay is caused by the time required for drainage of fine-grained beds in aquifer systems to reach equilibrium (Holzer and

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Galloway, 2005).

On the other hand, land can rebound or uplift once groundwater starts to recover in an aquifer system. However, the rebound is normally small or insignificant even if the groundwater recovers to the pre-subsidence level (Bouwer, 1977; Wu et al., 2009) and commonly regarded as elastic rebound (Allen and Mayuga, 1970; Waltham, 2002; Chen et al., 2007). Chen et al. (2007) reported an aquifer exhibiting an elastic rebound of 10% of the pumping-induced subsidence in the later stage of groundwater recharge. Motagh et al. (2008) reported an overall rebound of 5 cm in the Santa Clara Valley as water levels restored to the near-artesian levels. Teatini et al. (2011) reported that the land uplift in Venice was a few centimeters, or a fraction of the subsidence occurred after banning water and gas extraction post the 1966 flood.

In previous study, Wang et al. (2009) reported the long term land subsidence and strata compression from 1984 to 2002 in Changzhou based on the monitoring data from the multi-layer borehole extensometers at Changzhou Qingliang Primary School (CQPS). In 2000, the provincial government announced a regulation to comprehensively ban deep groundwater extraction by 2005 to mitigate the widespread subsidence and earth fissures in the Suzhou-Wuxi-Changzhou area. This study extends the study of Wang et al. (2009) to investigate the development of groundwater withdrawal and recovery, and changes of land subsidence and strata deformation from 2002 to 2015 observed in Changzhou, China, in particularly, the land rebound or uplift.

2. Regional settings

2.1. Geological description

Changzhou City is located in the south Yangtze River delta area, with its north adjacent to the Yangtze River and south to Taihu Lake (Fig. 1). The ground elevation is generally < 10 m above sea level in the plain area (Wang et al., 2009), higher in north-west, lower in the middle and south-east, and about 80 to 177.5 m above sea level at several bedrock hills, which are spotted in the far most north and east of the study area.

The subsurface underlying Changzhou City can be divided into bedrocks and porous sediments. The former consists of sedimentary clastic rocks, carbonatites, volcanic clastic rocks and magmatic rocks from Sinian of late proterozoic to Paleogene of Cenozoic, and located from ground surface to about 240 m deep. The porous sediments are deltaic and lacustrine soils formed from Neogene to Quaternary and closely related to tectonic activities and sea level fluctuations. The Quaternary sediments are composed of the Pleistocene and Holocene formations. The thickness of Quaternary sedimentary strata varies, which was determined by sedimentary environment. With the ancient Yangtze River tributary flowing through, and multiple flooding, and cycles of cold and warm climate change occurred during the Quaternary, complex sedimentary facies were formed in most of the area, such as fluvial, alluvial, alluvial lacustrine and transgressive facies.

The lower Pleistocene series consists of lacustrine and alluvial-lacustrine (lower), and fluvial and alluvial-diluvial and alluvial (middle), and diluvial and alluvial-lacustrine (upper) sediments with the thickness varying from 30 m to 80 m. The middle Pleistocene series consists of fluvial and alluvial (lower), and fluvial and alluvial-lacustrine (upper) sediments with the thickness varying from 60 m to 80 m. The upper Pleistocene series consists of lagoon and alluvial-marine and fluvial (lower), and fluvial and lagoon and alluvial-marine and alluvial-lacustrine (upper) sediments with the thickness varying from 30 m to 50 m. The Holocene series consists of alluvial-lacustrine sediments with the thickness varying from 1.10 m to 13.93 m.

2.2. Hydrogeological characterization

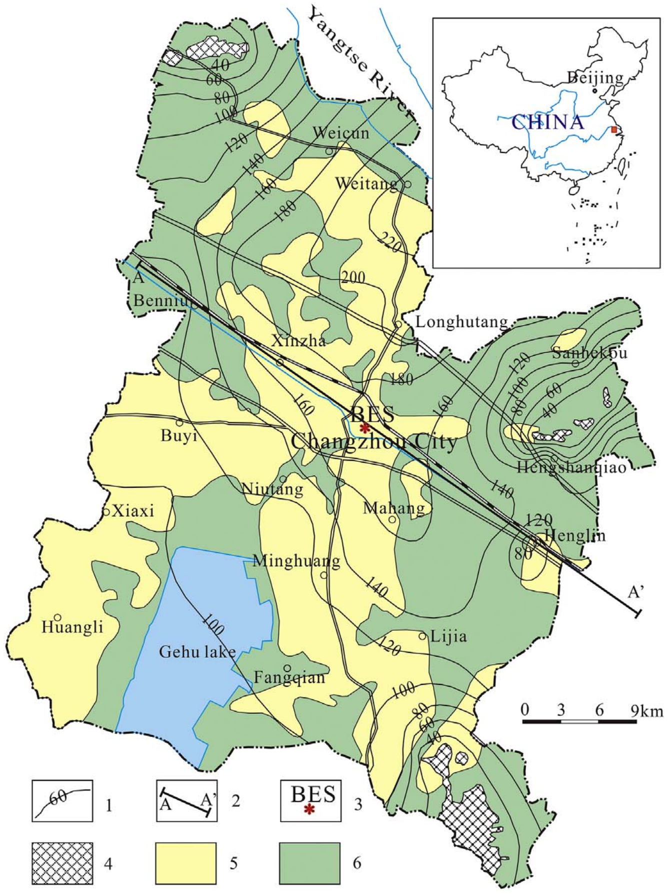

Fig. 1. Location map (1. The buried depth of the bedrock surface; 2. The cross-section line A-A′; 3. The borehole extensometer station (BES); 4. Bedrocks; 5. Upper pleistocene; 6. Holocene).

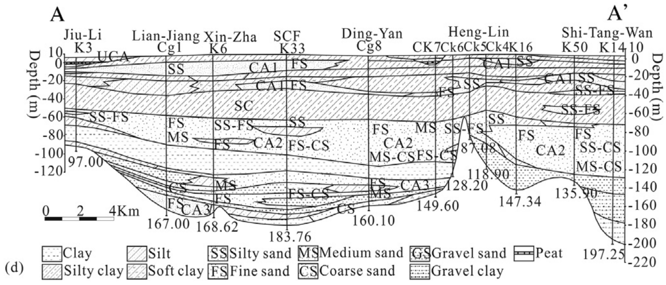

Fig. 2. Cross-section of the aquifer system along profile A-A′ (Wang et al., 2009).

The thickness of the porous sediments is generally 120 m to 240 m (Fig. 1), and there are four aquifers in the porous sediments (Fig. 2), one unconfined and three confined aquifers, and denoted as UCA, CA1, CA2 and CA3, respectively (Wang et al., 2009).

The UCA is widely distributed in the upper Pleistocene-Holocene series, composed of silty clay and silt. The thickness of UCA ranges from 4.0 to 8.0 m. The groundwater level in the aquifer is generally 1-3 m below the ground surface, and changes seasonally. The hydraulic conductivity of UCA is 0.014 m/d, and its storativity is 0.038.

The CA1 is mainly composed of silty sand and fine sand, interbedded with silty clay and silty sand, in the upper Pleistocene series. The buried depth of CA1 is generally from 4.0 m to 58.0 m, and the thickness of CA1 is 18 m to 40 m. The hydraulic conductivity of CA1 is 3.16 m/d, and its storativity is 2.4×10^{-4}.

The CA2 was the primary aquifer pumped in Changzhou (Wang et al., 2009). It is composed of sands of different grades (silty, fine, medium and gravel sands) in the middle Pleistocene series, and the