COPYRIGHT NOTICE

FedUni ResearchOnline

<https://researchonline.federation.edu.au>

This is the peer-reviewed version of the following article:

Wang, G., Zhu, J., You, G., Yu, J., Gong, X., Li, W., & Gou, F. (2017). Land rebound after banning deep groundwater extraction in Changzhou, China. *Engineering Geology*, 229, 13-20.

Which has been published in final form at:
<https://doi.org/10.1016/j.enggeo.2017.09.006>

Copyright © 2014 Elsevier B.V. All rights reserved.

Abstract:

More than 30 years groundwater overdraft had resulted in hydraulic head declined from near the ground surface to 85m 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 37.6m 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 37.22mm (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.

Key words: land subsidence, rebound, land uplift, groundwater extraction, Changzhou

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 & 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 more than 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 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 H., 1977; Wu, 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 less than 10 meters 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 meters above sea level at several bedrock hills, which are spotted in the far most north and east of the study area.

Figure 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)

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 240m 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 60m to 80m. 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 1.10m to 13.93m.

2.2. Hydrogeological characterization

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).

Figure 2 Cross-section of the aquifer system along profile A-A' (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 1-3m 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 18m to 40m. 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 diameter

of gravel is up to 5.0 cm in the north of the area. 2 to 4 rhythm cycles presented in CA2, where the upper sediment is finer and the lower is coarser. The thickness of the aquifer is from 25m to 45m in Changzhou City, and its buried depth is from 60m to 80m. A large groundwater level funnel was formed in late 1970s. The hydraulic conductivity of CA2 is 10-25 m/d, and its storativity is 1.24×10^{-3} .

The CA3 is mainly composed of fine, medium and gravel course sands, containing more argillaceous components, in the lower Pleistocene series, and the diameter of gravel is up to 10mm. The buried depth of CA3 is generally from 95m to 160m, and its thickness is from 25m to 100m in the area. The extent of the groundwater drawdown funnel is smaller in CA3 than in CA2, so the groundwater level is higher in CA3 than in CA2. The thickness of the aquitard between CA2 and CA3 is much thinner in north Changzhou, so it is possible that CA2 and CA3 are connected in this district. CA3 is the second major aquifer pumped in Changzhou. The hydraulic conductivity of CA3 is 2.18 m/d, and its storativity is 1.1×10^{-3} .

2.3 Geotechnical characterization

The Quaternary soil is characterized through a range of soil investigation and tests and reported by Wang et al (2009). The soil column is divided into nine soil layer units at the borehole extensometer station (BES) according to the aquifers and aquitards structure, which are briefly summarized in Table 1.

The BES was constructed in 1983 to monitor land subsidence, strata deformation, and hydraulic head of CA1, CA2 and CA3. Showing in Fig.3a is the soil strata column, including nine borehole extensometers: BH10 was installed into the sound bedrock as reference benchmark, and BM was installed on ground surface, BH1 to BH8 in different interfaces and depths of the porous sediments. The graph of compression index, recompression index and overconsolidation ratio of soils at different depth are presented in Fig.3b.

Figure 3 Soil column and properties at BES at CQPS, a) the soil column and composition;
b) the graph showing the compression, C_c , recompression index, C_s , and the
overconsolidation ratio(OCR) of soils at different depth

Table 1 Strata classification and properties at CQPS BES from Wang et al. (2009)

3. Data and results

The data in the study consists of three components: (1) periodical data from first order and second order leveling since 1979, (2) hydraulic head from systematical monitoring since 1981, and (3) monitoring results at the BES since 1983. The precision of the first and second order leveling was <0.36 mm/km, and it was <0.14 mm for subsidence monitoring at the BES.

3.1 History of deep groundwater withdrawal and land subsidence

Wang et al. (2009) summarized the deep groundwater extraction from 1919 to 1990s in Changzhou, where groundwater exploitation experienced from sustainable prior to 1950s, rapid unsustainable expansion in 1970s and 1980s, peak in 1990s, and comprehensive ban since 2000 (Table 2). Only 18 deep wells was remained in Changzhou by the end of October 2005. Although the overall groundwater extraction was peaked in 1990s in Changzhou, the termination of groundwater level decline depended on location, and varying from 1990s to 2002 (Table 2). For example, at Henglin and Luoyang near the eastern border of Changzhou (Fig. 1), it is observed that the groundwater kept declining till 2002 with the deepest groundwater level >82 m in 2002 (Table 2). Correspondingly, the extraction rate increased from $<1.0 \times 10^4$ m³/day in 1950s to 2.97×10^5 m³/day in 1990s, then down to 8300 m³/day in 2005 (Table 2).

Table 2 Summary of deep groundwater extraction in Changzhou

Shown in Fig. 4 are the hydraulic heads in CA2 and CA3 at CQPS from 1989 to 2014. The hydraulic head kept declining in CA2 until 1994. The rate of drawdown in CA2 slowed down in early 1990s, and started to recover since 1994, which reflects the effects of the restriction on groundwater withdrawal (Table 2). The hydraulic head in CA3 lagged till 2000.

The steadily recovering rate of hydraulic head in both CA2 and CA3 has reached 2-4 m/yr since 2000.

Figure 4 Hydraulic heads in CA2 and CA3 at CQPS, Changzhou

The hydraulic head in CA1 declined steadily at CQPS from 2000 to 2007, reflecting a shift of groundwater extraction from deep to shallow as a result of the ban, and started to recover since 2007 after a new regional water supply infrastructure was constructed. There was little extraction from the UCA, so the phreatic level seasonally fluctuates with precipitation (Fig. 5).

Figure 5 Hydraulic heads in UCA and CA1 at CQPS, Changzhou

As a consequence of the groundwater drawdown, Changzhou experienced land subsidence, which was first observed in 1960s and was severely widespread by 1994 as reported by Wang et al. (2009). From May 1979 to October 1983, the maximum land subsidence was 512.49 mm at the center of the subsidence trough, and the maximum subsidence rate was >100 mm/yr. The subsidence rate remained at 40~50 mm/yr during the next 10 years. The average rate was <40 mm/yr from 1993 to 1998, and at 20 to 30 mm/yr in urban area since 1994, and the subsidence trough expanded towards southeast. From 1998 to 2004, the subsidence rate was clearly slowed down to <10 mm/yr in urban area and 10-20 mm/yr in the southeast. The subsidence was severest in the urban area and some township area. At BES, the subsidence reached 1255.10 mm by 2002, including 696.93 mm monitored by the multi-strata borehole extensometer and 558.17 mm surveyed prior to the construction of the station.

3.2 Land rebound/uplift

Fig.6 presents the monitored data from the BES at CQPS from 2002 to 2015, where the initial data were reset at zero at the start of 2002. The extensometers stopped subsiding in 2004 or 2005, then started to rebound based on the monitoring result. The BH8 extensometer, namely at the top of CA3, exhibited highest uplift, indicating the stratum of CA3 rebounded most. The land subsidence, referred to BM in figure 6, suggested a mix of strata compression and rebound, and a net rebound of 37.22mm for the entire soil strata.

Figure 6 Subsidence and/or uplift at BES at CQPS from 2002 to 2015

Land rebound has also evidenced at the Mahang monitoring station, southeast of Changzhou, which was constructed in 2004. The subsidence bottomed in 2007-2008 (Fig.7), and the ground surface rebounded 1.79mm since 2008.

Figure 7 Subsidence and/or uplift at Mahang, southeast of Changzhou

3.3 Strata deformation

The land subsidence is comprehensive result of strata compression, which reflects groundwater pumping from the aquifer system (Fig.8a), as well as the compressibility of each stratum. The compression characteristics of each stratum were controlled by the soil type, properties, stress history, structure, pumping load, and distance to the pumping layer, etc. Strata compression had accelerated from late 1970s to early 1990s, and slowed down since the late 1990s at CQPS (Fig.8b), demonstrating the effects of law enforcement on groundwater extraction in Changzhou. The land subsidence has been overall suppressed, but the soil strata have experienced a mix of strata compression and rebound (Fig.8b). In the

following session, further investigations are presented on the strata deformation (compression or rebound), refer to Fig.8b, Fig.10 and Table 3.

Figure 8 Strata deformation (compression/rebound) at BES, CQPS: a) versus logarithmic scale of cumulative pumping from 1984 to 2001; b) Versus logarithmic scale of time in day from 1984 to 2015

The 1st stratum, the upper most strata (UCA), exhibited annually compression-rebound cyclic pattern, which is in line with the fluctuation of rainfall (Fig.9). Almost no deformation recorded from 2003 to 2008, and compressed from 2008 to 2013, and had an overall compression from 2002 to 2014 (Fig.8b).

The compression of the 2nd stratum, the CA1 layer, was 10.29mm from 1984 to 2002, and 0.37mm in 2002, and the compressive strain was 0.00079. Since then it rebounded 26.5% of the pre compression from 1984 to 2002, and the rebound was 2.85mm in 2003 (Fig.8b, Table 3).

Figure 9 Rainfall and deformation of UCA (BM to BH1) in Changzhou

The compression of the 3rd stratum, the upper most segment of the aquitard between CA1 and CA2, was 12.73mm from 1984 to 2004, 2.2mm in 2004, and its compressive strain was 0.00063. Since then it rebounded 11.69mm, or 91.8% of the pre compression from 1984 to 2004 (Fig.8b, Table 3).

The compression of the 4th stratum, the middle segment of the aquitard between CA1 and CA2, was 121.79mm from 1984 to 2003, 5.44mm in 2003, and the compressive strain was 0.00373. It rebounded 11.76mm since 2003, or 9.7% of the pre compression from 1984 to

2003 (Fig.8b, Table 3).

The compression of the 5th stratum, the lower segment of the aquitard between CA1 and CA2, was 250.65mm from 1984 to 2002, 0.23mm in 2002, and its compressive strain was 0.012 (Table 3). Since then it rebounded 9.61mm (Fig.8b), or 3.8% of the pre compression from 1984 to 2002.

The compression of the 6th stratum (CA2 layer), was 79.11mm from 1984 to 2002, and its compressive strain was 0.0048 (Table3). Due to groundwater overdraft, the compression increased rapidly with the hydraulic head decline before 1994. Notably, groundwater bottomed in 1994 (Fig.4) near 80m below ground surface when CA2 was compressed 65mm by 1994. Thanks to the restriction of groundwater exploitation, hydraulic head started to gradually recover since 1994, resulting in the compression rate declined from 5.7mm/yr to 1.6mm/yr by 2002. However, the compression of CA2 kept increasing from 65mm to 79.11mm from 1994 to 2002. The rebound of this layer was 6.28mm, or 7.94% of the pre compression from 1984 to 2002.

Figure 10 Hydraulic head of CA2 versus deformation of different layers from 1984 to 2013

The compression of the 7th stratum, the aquitard between CA2 and CA3, was 48.77mm from 1984 to 2007, and its compressive strain was 0.0052. The compression was 2.1mm from 2004 to 2009 and has stopped by 2009. The cessation of compression lagged 4 years due to secondary consolidation, and no rebound has been monitored so far, so this stratum had a net compression from 2002 to 2014 (Fig.8b, Table 3).

The compression of the 8th stratum, the upper CA3, was 150.24mm from 1984 to June 2014, and the compressive strain was 0.00572. However, the compression was 26.08 mm from 2002 to June 2014, and the compressive strain was 0.00099, indicating a significant

slow down since 2002 (Fig.8b, Table 3).

The compression of the 9th stratum, the lower CA3 layer, was 40.96 mm from 1984 to 2005, and the compressive strain was 0.00215. It was the soil stratum of the highest rebound from 2005 to June 2014, rebounding 35.78mm, or 87.4% of the pre compression, and the rate of rebound did not decrease in 2014 (Fig.8b, Table 3).

From above analyses, the compression of different layers showed similar deformation characteristics in Stage 1 before 1994, namely, increasing with the hydraulic head drawdown in CA2, and the compressive strain was in the range of 0.003 to 0.01 (Table 3). The 5th stratum, which is directly overlying CA2, has the highest compressive strain 0.01049; and the 3rd stratum, which is far from CA2, has the lowest compressive strain 0.00028. The hydraulic head in CA2 recovered slowly at Stage 2, e.g. from 1994 to 2002, so the compression rate was slowed down, and the compressive strain was about 0.0008 to 0.0015, or 15%-30% of those in Stage 1. The average groundwater pumping rate decreased by 50% in Stage 2 compared with in Stage 1. The CA2 layer and its overlying and underlying aquitards have started to rebound since 2005 due to ban of deep groundwater pumping. Superimposed by the effect of groundwater pumping from CA3, the 8th and 9th layers showed smaller compression rate in Stage 2 than Stage 1.

The aquifer and its direct overlying and underlying aquitards have quicker response to the fluctuation of hydraulic head (Fig.6, Fig.8b). The large recovery of 4.3m hydraulic head in CA2 in 2003 and the large decline of 3.4m in 2004 had resulted in abnormal deformation almost synchronously (Fig.10). Consequently, the 5th stratum (the aquitard directly overlying CA2) experienced 2.1mm compression and 3.3mm rebound in 2003 and 2004, respectively. So did the 6th stratum (CA2) with 3.0mm compression and 3.6mm rebound and the 7th stratum (the aquitard directly underlying CA2) with 4.65mm compression and 3.4mm rebound (Fig.10).

4. Discussions

The observed delay time between decrease in groundwater head and clay consolidation at CQPS BES is more than 10 years. The consolidation and subsidence process depends on the rate and path of fluid flow of the compressible media and the flow rate is controlled by the hydraulic conductivity. The consequent subsidence is the integrated response of the pressure decrease since pumping began. For aquifer layers, the pore water pressure decrease was considered instantaneously, and imposed on the aquifer layer, but for the overlying and underlying aquitards, the head decrease process is equivalent to a negative pore water pressure exerted on the interface of the aquifer-aquitard over an extended period.

When groundwater is recharged into the starved aquifers to recover the pore pressure, expansion of aquifer sand and gravel layers occurs and contributes to uplift of ground surface as elastic rebound (Waltham, 2002). During groundwater recovery, the recharged sections of the aquifer will release the formerly imposed compressive strain to show dilatation, producing elastic rebound (Chen et al., 2007). Land uplift is primarily due to the release of the effective intergranular stress and secondarily to the shear dilation on the condition that the induced pore pressure is large enough so as the yield surface is intersected by the Mohr-Coulomb circles. Shear dilation accompanies yield and strain weakening with a permanent alteration of the fabric of the water-bearing stratum through irreversible deformation, grain rearrangement, permeability change and porosity increase, thus causing a potential contribution to a measurable rebound of the land surface (Teatini et al., 2011). However, the plastic deformation is irrecoverable in land subsidence (Zhang et al., 2015), and the recoverable deformation is a small portion of the total deformation for both aquitard and aquifer units. In Table 3, the calculated percentage of rebound is large as it is referenced to the strata compression monitored since the establishment of BES (1984) and does not include the deformation before 1984.

The feature of compression and rebound of soil strata in Changzhou are attributed to the heterogeneity in strata compressibility, structure, lithology and stress history, and to the intensity and processing of groundwater exploitation in the area. Most of the strata, both aquifers and aquitards, demonstrated apparent rebound (Fig.8b, Table 3).

Generally, the hydraulic head declined sharply before deep groundwater pumping was banned, and was making lower lows in CA2. Compounding with seasonal fluctuations, CA2 was subjected to the repeated loading (groundwater drawdown) and unloading (groundwater recovery) cycles. When loading surpassed the unloading and made a new low, the effective stress made a new high, and the CA2 was in a virgin compressive process. From 1984 to 2002, it was compressed 79.11 mm, and the compressive strain was 0.00483 (Table 3). Since the ban, the hydraulic head recovered progressively, or the effective stress decreased in CA2, the CA2 layer was in rebound process. However, the rebound is small, 6.28 mm, or 7.94% of the compression from 1984 to 2002. The 5th and 4th strata, the overlying aquitards of CA2, showed similar compression and rebound characteristics, rebounding 3.8% and 9.7% of their pre compression, respectively (Table 3).

On the other hand, no rebound is monitored in the aquitard underlying CA2, and the upper CA3 layer appeared still in the compression phase (Fig.8b), whose compression rate reduced to 1/6 of previous compression rate since 2002. With regard to the aquitard underlying CA2, the hydraulic head recovery in CA2 is actually a loading process, e.g. increased overburden, therefore the compressive process went on. On the other hand, the groundwater recovery from CA2 was coupled by the groundwater drawdown from CA3 from 1994 to 2000 (Fig. 4), so the consolidation of the sediment adjacent to CA2 started to relieve since 1994 as the pore pressure started to increase with the hydraulic head recovery in CA2,

but the sediment adjacent to CA3 experienced further virgin consolidation as the pore water pressure kept declining with the continuous hydraulic drawdown in CA3. Notably, by 2000, the difference of hydraulic head between CA2 and CA3 diminished (Fig. 4), but the stratum would keep consolidating until the groundwater recovery from both CA2 and CA3 balanced previous increase of effective stress in the aquitard. Once the recovery of groundwater captures all the increase of effective stress in the stratum in previous drawdown, the rebound process will occur.

The hydraulic head in the upper most strata, the UCA, seasonally fluctuated within a narrow range (Fig.5). Consequently, this layer exhibited seasonal cyclic compression and rebound (Fig.3b) within the elastic domain. The over consolidation ratio (OCR) of soil in this layer is 5 to 10 (Fig.3b).

The hydraulic head in CA1 declined cyclically by less than 4m from 1999 to 2007, and recovered about 1m since 2007(Fig.5). The annual fluctuation was generally within 1-2m. The total compression was 10.29mm from 1984 to 2002, and the compressive strain was 0.00079. The rebound was 2.85mm, or 26.5% of the pre compression (Table 3). If the recovery continues, most of the pre compression is assumed to rebound(Fig.8b).

The 3rd and 9th stratum had the largest rebound (Fig.8b), accounting for 87.4% and 91.8% of the pre compression, respectively (Table 3). In comparison, the rebounds of other layers were less by one order of the magnitude. This would indicate that these two layers primarily experienced elastic compression during previous groundwater drawdown, or that the increase of effective stress exerted on them is less than the preconsolidation stress, respectively (Fig.3b). In contrast, the strata from the 4th to 8th layers, e.g. aquifers CA2 and CA3, and their adjacent aquitards, might largely experience irreversible plastic compression. However, this need further field observation to verify as the uplift keeps increasing since 2005 (Fig. 8b).

The aquifer and aquitard will continue to compress/consolidate as the result of

time-dependent consolidation caused by hydraulic head drawdown, until hydraulic head has risen to remove deficits of pore pressure (Chen et al., 2007). Land uplift often occurred after the hydraulic head had risen for many years (Schmidt and Bürgmann 2003; Chen et al. 2007). The time lag between the groundwater recovery and the ground uplift is 11 years at BES in Changzhou. At present, the deep groundwater recovered enough in Changzhou to stop further strata compression except for the upper CA3 (Fig.8b).

The net land uplift was 37.22 mm on ground surface over 11 years at CQPS in Changzhou (refer to BM in Fig. 8b), which is 5.4% of the subsidence monitored at BES. It is small in term of percentage, but it trends to rise since 2005 (Fig. 8). The discrepancies may mainly result from the continuous compression of upper CA3, and coupled by the seasonally cyclic compression of the 1st stratum. The change of elevation on ground surface is a summation of all strata deformation, so net land uplift can occur only when the rebound is greater than the compression in all strata. It can be affected by many factors, such as hydraulic head, deformation characteristics, permeability and spatial scale of all layers in the aquifer system. A similar mechanism was invoked to explain the fluctuation of ground surface in Las Vegas affected by seasonal water table variations (Amelung et al., 1999).

5. Conclusions

The land subsidence in Changzhou was due to excessive groundwater extraction from porous sediments. From the long term monitoring of strata deformation and groundwater at CPQS in Changzhou, China, it can be concluded that government regulation and law reinforcement are the most important issue in land subsidence control. Groundwater overdraft occurred from 1970s to 2000 in Changzhou. The pumping intensity decreased progressively from 1991 to 2000, and sharply from 2000 to 2005 with the restriction/ban of deep groundwater exploitation. Groundwater started to recover in CA2 since 1994 and to recover in

CA3 since 2000. Ground surface started to uplift since 2004 or 2005.

The subsidence was the comprehensive compression of both aquifers and aquitards in the porous aquifer system resulted from groundwater overdraft. 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. Different hydraulic head changing mode leads to the variation of loading stages and stress levels in the aquifers and aquitards, resulting in different deformation characteristics of strata (including temporal diversity, e.g. different stage of deformation).

Different soil layers exhibits different compressive strains. The largest compressive strain was 0.012 occurred in the 5th stratum, or the lower segment of the aquitard directly overlying CA2, the soft silty clay layer, whose drainage path to CA2 is the shortest among the three segments of this aquitard. However, the strain was 0.00373 in the middle segment (the 4th stratum), and 0.00063 in the upper segment (3rd stratum). It can be concluded that the drainage distance plays a critical role in the compressive strain in the aquitard overlying CA2.

The ground uplift or stratum rebound occurred after the hydraulic head had recovered for 11 years in Changzhou. At present, most soil strata have rebounded for 10 years, and the total land uplift is 37.22 mm on the ground surface. It is found that the nine soil layers exhibited different strata deformation responding to the groundwater recovery. Seven of them showed rebounds varying from 3.8% to 91.8% of the pre compression monitored at the BES, CPQS, Changzhou. The main pumping aquifer (CA2) and its direct overlying aquitard rebounded 3.8%-9.7% of the pre compression, and the bottom layer and the upper most aquitard layer of the main pumping aquifer

rebounded about 90% of the pre compression. However, the aquitard between CA2 and CA3 and upper CA3 were still in the compression process due to groundwater recovery loading and downward seepage from CA2.

Acknowledgement

This research was funded by the National Natural Science Foundation of China (Grant No. 41772327), and supported by funds from the Special Program for the Public Research of the Ministry of Land and Resources of China (Grant No. 201411096). The authors gratefully acknowledged the constructive comments and suggestions from the editor-in-chief, Prof. Juang, and anonymous reviewers.

References

- Allen, D.R., Mayuga, M.N., 1970. The mechanics of compaction and rebound, Wilmington oil field, Long Beach, California, USA. in: Tjson, L.J. (Eds.), Land Subsidence, Proceedings of the Tokyo Symposium 1969, IAHS Publication No. 89, 410–422.
- Amelung, F., Galloway D.L., Bell J.W., Zebker H.A., Lacznia R.J., 1999. Sensing the ups and downs of Las Vegas-InSAR reveals structural control of land subsidence and aquifer-system deformation. *Geology*. 27, 483–486.
- Bouwer H., 1977. Land subsidence and cracking due to groundwater depletion. *Ground Water* 15(5): 358–364
- Chen C.T., Hu J.C., Lu C.Y., Lee J.C., Chan Y.C., 2007. Thirty-year land elevation change from subsidence to uplift following the termination of groundwater pumping and its geological implications in the Metropolitan Taipei Basin, Northern Taiwan. *Engineering Geology*. 95: 30-47.

- Gambolati G., Freeze R.A. 1973. Mathematical simulation of the subsidence of Venice: 1. theory. *Water Resources Research*, 9(3): 721-733.
- Hoffmann J., Galloway D.L., Zebker H.A., 2003. Inverse modeling of interbed storage parameters using land subsidence observations, Antelope Valley, California, *Water Resources. Res.*, 39(2), 1031.
- Holzer, T.L., 1981. Preconsolidation stress of aquifer systems in areas of induced land subsidence. *Water Resources Research*. 17 (3): 693-703.
- Holzer, T.L., Galloway, D.L., 2005. Impacts of land subsidence caused by withdrawal of underground fluids in the United States, in: Ehlen, J., Haneberg, W.C., and Larson, R.A., (eds.), *Humans as Geologic Agents: Boulder, Colorado*, Geological Society of America, *Reviews in Engineering Geology*, v. XVI, pp. 87–99.
- Motagh M., Walter T.R., Sharifi M.A., Fielding E., Schenk A., Anderssohn J., Zschau J., 2008. Land subsidence in Iran caused by widespread water reservoir overexploitation. *Geophysical Research Letters*. Vol.35, L16403.
- Phien-wej, N., Giao, P.H., Nutalaya, P., 2006. Land subsidence in Bangkok, Thailand. *Engineering Geology*. 82 (4): 187-201.
- Schmidt D.A., and Burgmann R., 2003. Time-dependent land uplift and subsidence in the Santa Clara Valley, California, from Terzaghi a large interferometric synthetic aperture radar data set. *J. Geophys. Res.* 108(B9), 2416.
- Stiros S.C., 2001. Subsidence of the Thessaloniki (northern Greece) coastal plain, 1960-1999. *Engineering Geology*. 61, 243-256.
- Teatini P., Gambolati G., Ferronato M., Settari A.T., Walters D., 2011. Land uplift due to

subsurface fluid injection. *Journal of Geodynamics*. 51, 1–16.

Terzaghi, K., Peck, R. B., Mesri, G., 1996. *Soil Mechanics in Engineering Practice*, Third Ed. John Wiley & Sons, New York.

Waltham, T., 2002. Sinking cities-feature. *Geology Today* 18 (3), 95-100.

Wang G.Y., You G., Shi B., Yu J., Tuck M., 2009. Long-term land subsidence and strata compression in Changzhou China. *Engineering Geology*. 104(1–2):109–118.

Wu J.C., Shi X.Q., Ye S.J., Xue Y.Q., Zhang Y., Yu J., 2009. Numerical simulation of land subsidence induced by groundwater overexploitation in Su-Xi-Chang area, China. *Environ Geol*. 57, 1409–1421.

Zhang Y., Wu J.C., Xue Y.Q., Wang Z.C., Yao Y.G., Yan X.X., Wang H.M., 2015. Land subsidence and uplift due to long-term groundwater extraction and artificial recharge in Shanghai, China. *Hydrogeol J*. 23:1851-1866.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Table 1 Strata classification and properties in CQPS BES from Wang et al. (2009)

Stratum No.: Name	Depth (m)*	Soil composition	w _c (%)	e ₀	G _s	r KN/m ³	I _L	a ₁₋₂ (Mpa ⁻¹)	K, (× 10 ⁻⁵ m/d)
1 st (BM-BH1) UCA	0.00-5.98	Silt clay, clay	23.5 ~25. 0	0.68 0 ~0.7 37	2.72 ~2.7 5	19.2 ~19. 8	0.08 8 ~0.1 32	0.122 ~0.163	3.53-30 3.3
2 nd (BH1-BH2) CA1	5.98-19.0 9	Silty sand, interbedded with silty clay							
3 rd (BH2-BH3) aquitard	19.09-39. 19	Soft silty clay, silty clay, and silty sand	23~4 6	0.66 8 ~1.3 12	2.70 ~2.7 6	17.1 ~19. 6	0 ~0.8 44	0.133 ~0.153	32.2~15 55.2
4 th (BH3-BH4) aquitard	39.19-71. 84	Silty clay, interlayered with silty sand	23.6 ~29. 6	0.68 0 ~0.8 79	2.74 ~2.7 5	18.5 ~19. 3	-0.1 58 ~0.2 80	0.245	0.43~19 00.8
5 th (BH4-BH5) aquitard	71.84- 92.66	Soft silty clay	31 ~31. 7	0.89 2	2.73 -2.7 6	18.5 ~18. 8	0.50 4 ~0.5 70	0.133 ~0.204	11.4~49. 1
6 th (BH5-BH6) CA2	92.66-109. .99	Fine and silty sand							
7 th (BH6-BH7) aquitard	109.99-11 8.50	Silty clay	18	0.51 6	2.71	20.7	-0.0 98	0.122 ~0.133	2.95
8 th (BH7-BH 8) upper CA3	118.50-14 4.78	Silty fine sand, fine sand and medium sand interbedded with clayey silt sand, and sandy silty clay, and stiff silty clay	20.3	0.56 9	2.72	20.3	-0.0 12		4.1
9 th (BH8-bedro ck) lower CA3	144.78-16 3.80	Silty to fine sand, gravel medium sand, interbedded with stiff silty clay, and sandy gravel silt, and clayey silty sand, and gravel clayey fine sand.	20	0.60 4	2.75	20.4	0.02 0	0.122	0.033

* Initial depth of borehole extensometer with reference to ground surface. w_c, water content; e₀, initial void ratio; G_s, specific gravity; r, bulk density; I_L, liquidity index; a₁₋₂, coefficient of compressibility; K, permeability coefficient

Table 2 Summary of deep groundwater extraction in Changzhou

Period	Number of wells	Pumping rate (m ³ /day)	Groundwater level in CA2 (below ground surface)	Cone of depression of groundwater	Status of groundwater extraction
1950s	18	(<1.0×10 ⁴)	initially 0.6m to <10m	No	Slow increase, Sustainable.
1960s		(1.1×10 ⁵)	>20m	a small scale local cone formed	Rapid increase, early indication of unsustainable.
1970s	367	(1.3×10 ⁵)	51.2m in 1975	The entire Changzhou city was encircled	Sharp increase, overdraft.
1980s	376	(2.7×10 ⁵)	64m in 1981	A regional cone formed, and the 35m isoline of groundwater level in CA2 encircled Suzhou, Wuxi and Changzhou of 1500km ² .	Restriction on deep groundwater extraction, but the actual rate was double the limit of 0.8×10 ⁵ – 1.3×10 ⁵ m ³ /day.
1990s	1275	2.97×10 ⁵	82.3m in Changzhou, 85m in Qianzhou and Luoshe, west of Wuxi	The regional cone expanded and deepened, and the 75m isoline of groundwater level in CA2 encircled Mahang.	The groundwater level was lower than CA2, namely CA2 was in dewatering.
2000	933	1.85×10 ⁵	81.7m in Henglin	Recover by 20m in CA2 for an area of 160km ² from 2000 to 2005	Banning deep groundwater extraction in Su-Xi-Chang area. Wells were shut down progressively, only special utilization wells are reserved
2001	646	1.3×10 ⁵	80.91m in Henglin		
2002	386	9.5×10 ⁴	82.70m in Luoyang 82.26m in Henlin		
2003	65	5.20×10 ⁴	80.14m in Henglin		
2004	34	1.74×10 ⁴	77.55m in Henglin		
2005	18	0.83×10 ⁴	75.14m in Henglin		

The data in brackets ( ) in column 3 is cited from Wang et al. (2009)

Table 3 Compression/rebound characteristics of different layers at different stages of groundwater extraction

Layers/Thickness(m)	Compression (compressive strain)				Rebound	Rebound/Pre compression
	Stage1(Before 1994)	Stage 2(1994~2002)	Stage2/stage1	Compressive stage		
Porous strata/163.80	529.27(0.00323)	167.66(0.00102)	31.68%	696.93/2003	37.22	5.40%
2 nd (BH1-BH2)/13.11	8.33(0.00064)	1.96(0.00010)	15.3%	10.29(0.00079)/2002	2.85	26.5%
3 rd (BH2-BH3)/20.10	5.67(0.00028)	1.26(0.00006)	22.2%	12.73(0.00063)/2004	11.69	91.8%
4 th (BH3-BH4)/32.65	90.99(0.00279)	25.4(0.00078)	27.9%	121.79(0.00373)/2003	11.76	9.7%
5 th (BH4-BH5)/20.82	218.42(0.01049)	32.23(0.00155)	14.8%	250.65(0.012)/2002	9.61	3.8%
6 th (BH5-BH6)/17.33	65.40(0.0037)	13.71(0.00079)	21.0%	79.11(0.0048)/2002	6.28	7.9%
7 th (BH6-BH7)/8.51	32.46(0.00381)	9.76(0.00115)	30.0%	48.77(0.0052)/2007	No rebound	
8 th (BH7-BH8)/26.28	90.70(0.00345)	36.68(0.00140)	40.4%	150.24(0.00572)/2014	No rebound	
9 th (BH8-BH10)/19.02	19.06(0.00100)	19.9(0.00105)	104.4%	40.96(0.00215)/2005	35.78	87.4%
(4 th +5 th)(BH4-BH6)/53.47	309.41(0.00579)	57.63(0.00108)	18.6%			

highlights:

- The land subsidence is attributed to the compression of both aquifers and aquitards in the porous aquifer system.
- The compression and rebound is related to compressibility of different soil strata, and distance from the aquifer.
- The monitored ground uplift was 37.22mm, 5.4% of the pre subsidence, and was structural strata compression and rebound result
- The main pumping aquifer and its direct overlying aquitard rebounded 3.8%-9.7% of the pre compression
- The bottom layer and the upper most aquitard layer of the main pumping aquifer rebounded about 90% of the pre compression.
- The direct underlying soil layers of the main pumping aquifer is still in the compression process due to groundwater recovery loading and downward seepage from the aquifer.