

Excessive groundwater withdrawal and resultant land subsidence in the Su-Xi-Chang area, China

Yun Zhang · Yu-Qun Xue · Ji-Chun Wu ·
Xiao-Qing Shi · Jun Yu

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Abstract Excessive groundwater withdrawal has caused severe land subsidence in the Su-Xi-Chang (SXC) area, China. The restriction and prohibition on groundwater pumping have been carried out since the late 1990s. Based on the latest updated field data, the changing pattern of groundwater level and the distribution of land subsidence are analyzed. The distribution of land subsidence in SXC is closely related to that of the cone of depression in the second confined aquifer in time and space. But land subsidence is not in synchronization with the changing groundwater level. Both aquitards and aquifers compacted continuously in the early period of groundwater level rising and behaved as creep materials. A series of laboratory tests were conducted on aquifer sands, which indicated that the creep deformation under virgin compression is much greater than that under recompression and unloading, and that the creep of sands decreases rapidly with the cycles of repeating load. The test results reveal the mechanism of sand creep under the condition of long-term groundwater pumpage. As a consequence of the restriction and prohibition on groundwater pumping, groundwater level has obviously recovered in the vast majority of the SXC area, and land subsidence has slowed down and even a little rebound has occurred in some sites in Suzhou and

Changzhou. If the pumpage is strictly limited continuously, the groundwater level will not decline below the historical lowest value but fluctuate within a certain range. In such a case, land subsidence in SXC will no longer develop obviously.

Keywords Land subsidence · Mechanism of sand creep · Long-term groundwater pumpage · The Su-Xi-Chang area

Introduction

Land subsidence caused by excessive groundwater withdrawal has occurred in many areas in the world, such as Venice (Gambolati and Freeze 1973), San Joaquin Valley, California (Lofgren 1969), Mexico City (Adrian et al. 1999), Shanghai (Zhang and Wei 2005), and Bangkok (Phien-vej et al. 2006). Land subsidence can cause significant damage, including decrease in the clearance under bridges, threats to the safety of high-speed railways, and cracking of buildings and infrastructures, which have resulted in considerable economic loss. Many researchers have been dedicated to constructing mathematical models to predict the development of land subsidence and proposing measures to control land subsidence (Lewis and Schrefler 1978; Gu and Ran 2000). Comprehensively understanding the mechanism of land subsidence is necessary for constructing an appropriate model.

The principle of effective stress, first proposed by Karl Terzaghi in 1925, is often used to explain the occurrence of land subsidence related to groundwater withdrawal (Galloway et al. 1999). By this principle, when the pore water pressure in soils decreases due to excessive groundwater withdrawal, the effective stress increases

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Y. Zhang (✉) · Y.-Q. Xue · J.-C. Wu · X.-Q. Shi
School of Earth Sciences and Engineering,
Nanjing University, Nanjing 210093, China
e-mail: yunzhang.nj@gmail.com

J. Yu
Jiangsu Institute of Geological Survey,
Nanjing 210018, China

correspondingly. Conversely, when the pore water pressure in soils increases due to, for example, artificial or natural recharge, the effective stress decreases. The increasing effective stress causes the soil skeleton to compact and then land subsidence occurs. Thus, the hydrostratigraphic units undergoing the changing effective stress compact is an essential problem to solve in studying land subsidence. It was usually thought that the aquifer units comprising mainly of sands with strong permeability, compact instantaneously when effective stress (pore water pressure) changes, and that the aquitards, consisting primarily of fine-grained silty clays and clays with weak permeability, compact far behind the changing pore water pressure in adjacent aquifers. On the other hand, when the effective stresses in units remain less than the preconsolidation stress, the deformation of the units is elastic and fully recoverable. Otherwise, the deformation is elasto-plastic and largely unrecoverable (Galloway et al. 1999; Chen et al. 2007). However, some cases are more complex because of the complexity of geological and pumping conditions.

As pointed in the previous work of the authors (Zhang et al. 2007), the long-term field data in the Southern Yangtse Delta, China, reveal that the deformation of hydrostratigraphic units is complex and shows very close relationship to the changing patterns of groundwater level. Both aquitard and aquifer units compacted continuously soon after the groundwater level stopped declining. The phenomenon for those deformation characteristics has drawn the attentions of researchers but the mechanism has not been clear yet. Based on the latest updated field and laboratory data, this paper aims to investigate the characteristics of groundwater pumping and land subsidence in the Su-Xi-Chang area, and to discuss the mechanism of land subsidence there.

Basic conditions in study area

The Su-Xi-Chang area, usually abbreviated as the SXC area, is referred to Suzhou, Wuxi, and Changzhou of Jiangsu Province, China. It is located on the lower reach of the Yangtse Delta. It is enclosed by the Yangtse River in the north, Shanghai in the east, Zhejiang and Anhui provinces in the south, and Nanjing and Zhenjiang of Jiangsu Province in the west, as shown in Fig. 1. The SXC area is one of the most affluent areas in China. The developing economics and a rise in population results in rapid increase in demand for domestic and industrial water supply, while the surface water is polluted heavily. A large amount of groundwater is therefore extracted from the aquifer system underlying the SXC area to meet this increasing demand for water, which has resulted in severe land subsidence and great loss to the economy. To investigate the mechanism of

land subsidence and its developing trend, the monitoring network for observing the change in groundwater level was gradually constructed from the beginning of the 1980s in the SXC area. The first extensometer group in this area was built at Qingliang Primary School of Changzhou in 1983, and other five sets of extensometer groups were constructed consecutively after 2000 (Hu et al. 2006). The data obtained from those observation wells and extensometer groups reveal the changing patterns of groundwater level in individual aquifers and the deformation characteristics of the aquifer system during the periods of pumping and post-pumping.

Sedimentary and igneous rocks constitute the basement of the SXC area. Since the middle Pleistocene, SXC has experienced seawater intrusions four times and sedimented a set of Quaternary deposits, in which the clay, silty clay, silt, sand, and gravels are interbedded vertically. The thickness of the deposits is affected by the bedrock. The Quaternary deposits can be considered to be composed of five aquifers: one unconfined and semi-confined aquifer and four confined aquifers denoted from top to bottom as A1–A4, respectively, as indicated in Fig. 2. The first confined aquifer is further divided into two subunits: the upper and the lower. The confining aquitards occurring between aquifers are called aquitards 1–5 from top to bottom, respectively, and are composed of clay and silty clay.

The unconfined aquifer consists mainly of silty clay and clay. Except for a small number of domestic wells, the unconfined aquifer is largely unexploited. A semi-confined aquifer, consisting mainly of silty sand and silty to fine sand, underlies the unconfined aquifer. These two aquifer units have a close hydraulic relation. The water stored in them is called the shallow groundwater (Wang et al. 2004). This combined aquifer is continuous in the study area, with the thickness ranging from 5 to 15 m and probably being greater than 20 m along the bank of the Yangtse River. The groundwater level in the combined aquifer nearly remains steady, only fluctuating within 1–3 m.

The first confined aquifer consists mainly of deposits of the ancient river course. The aquifer becomes thinner from the center to the side of the ancient river course. The deposits are the early Pleistocene silty to fine sand, silty sand, and fine to medium sand. Near the bank of the Yangtse River, the first confined aquifer and the semi-confined aquifer, and the upper and the lower parts of the first confined aquifer are sometimes connected directly. The upper distributes discontinuously and is often lens shaped with the thickness from 2 to 20 m. The lower first confined aquifer distributes continuously with the thickness from 10 to 50 m.

The second confined aquifer consists primarily of the middle Pleistocene deposits of river facies, which are silty to fine sand, medium to coarse sand, and medium to coarse

Fig. 1 Location of the SXC area and the position of cross section A–A

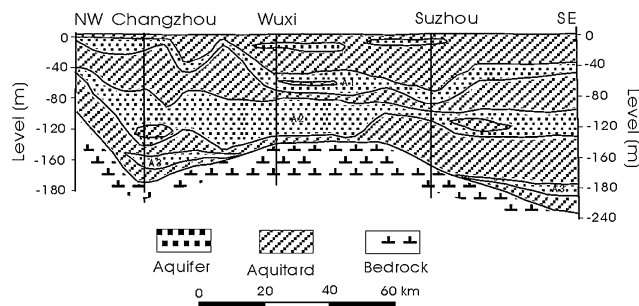
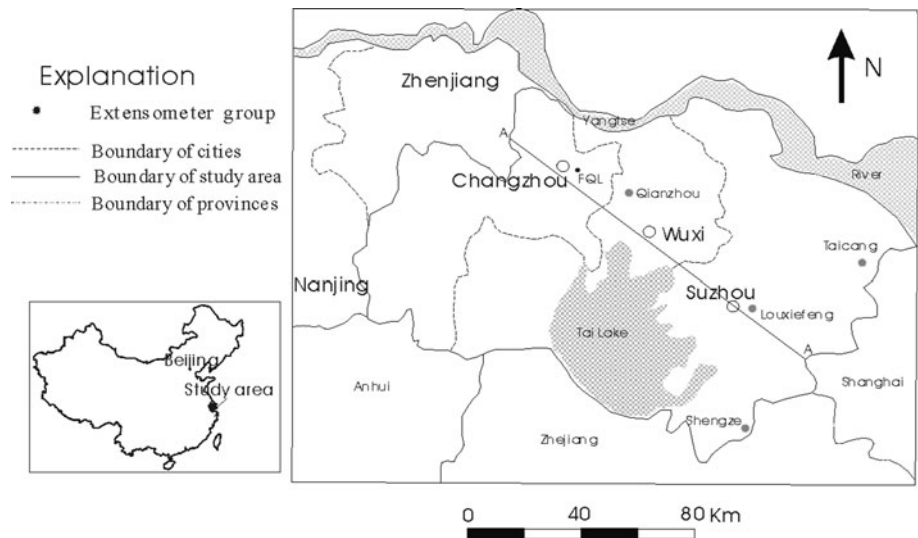


Fig. 2 Hydrogeological cross section of the SXC area

sand with gravel. The second confined aquifer distributes continuously, with the thickness of 10–40 m. The depth of the top increases from 70 m in the west to 150 m in the east. The pumping yield of a single well is 1,000–3,000 m³/day. The third confined aquifer is composed mainly of alluvials that are silty to fine sand, medium to coarse sand, and medium to coarse sand with gravel. The depth of its top is 120–180 m and its thickness is 10–54 m. The pumping yield of a single well is 100–1,000 m³/day. It is sometimes connected directly with the second confined aquifer. The fourth confined aquifer, consisting of fine sand, sand and gravel, only occurs in Taicang and its vicinity, Suzhou; it is unexploited.

Extraction of groundwater and resultant changes in groundwater level

The exploitation of groundwater in SXC began in 1927 and the pumpage was very small in the early period. Extensive extraction of groundwater occurred after 1983 when the town industries developed rapidly. The second confined aquifer is the main exploited aquifer, from which the

groundwater pumped accounted for 61% of the total in the period 1980–2000. In 2000, the groundwater extracted from the first, second, and third confined aquifers was 27, 67, and 6%, respectively. Excessive groundwater withdrawal has caused severe land subsidence and some earth fissures in the SXC area. In 1995, the government of Jiangsu Province issued a resolution to restrict groundwater withdrawal from 1995 and then to prohibit extracting groundwater from 2000 in SXC. During the period 1996–1999, the amount of groundwater withdrawal decreased by 20% each year. The history of groundwater extraction is indicated in Fig. 11 (ESM only). As far as the space concerned, extraction of groundwater largely occurred within the urban areas of Suzhou, Wuxi, and Changzhou during the period 1970–1980, while the pumpage decreased in the urban areas and increased rapidly in the towns nearby the cities within the period 1988–1995.

The changes in the amount of pumpage resulted in changes of groundwater level in aquifers. Amount of field data from observation wells indicate that the groundwater level declined continuously from the initial level before the limitation of pumpage and then recovered gradually. Unlike the complex condition of groundwater withdrawal in Shanghai (Zhang et al. 2007), the history of groundwater exploitation is relatively simple in the SXC area. The changing history of groundwater level in each aquifer can be separated into two periods: declining in the former period and rising in the latter period (Fig. 12, ESM only). The time when the groundwater level in a specific confined aquifer reached its lowest value depended on the location because the amount of groundwater pumpage changed spatially. Most observation wells in Changzhou and Suzhou reached their lowest groundwater levels in 1994 or 1995, while some observation wells in Wuxi reached their lowest levels around the year of 2004. Figure 3 shows the

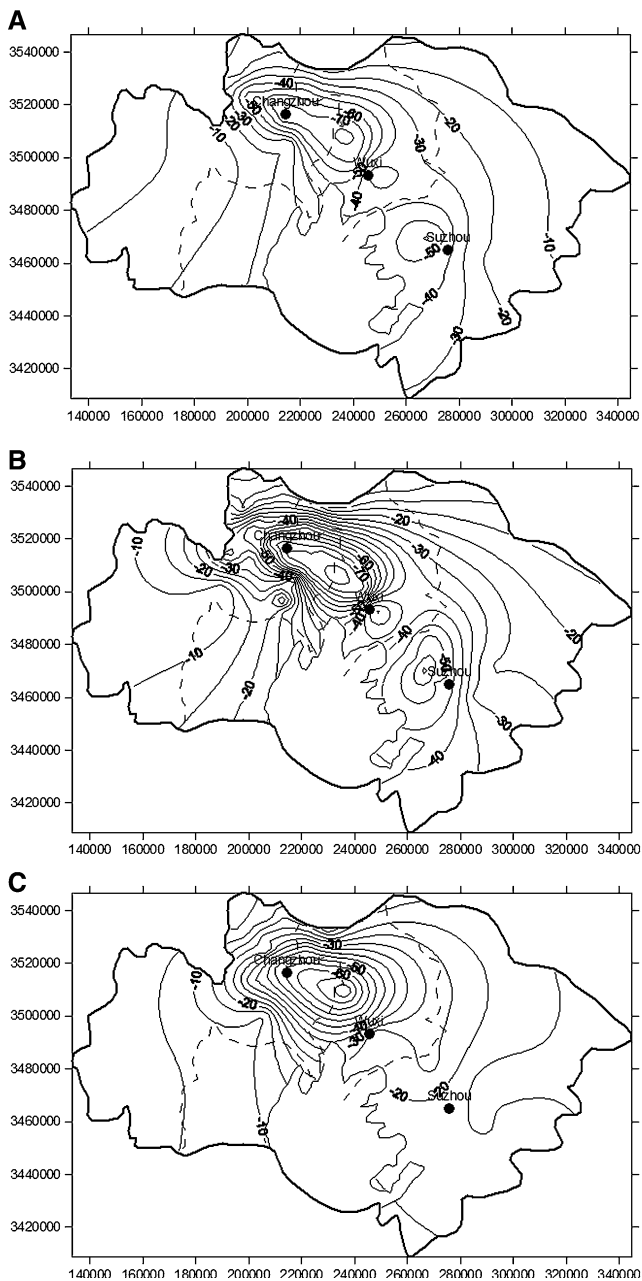


Fig. 3 Contours of groundwater level in the second confined aquifer **a** 1994, **b** 1998, **c** 2007

contours of groundwater level in the second confined aquifer at different times. It reveals that there were two local cones of depression in the study area in 1994: one was near Suzhou with the groundwater level being -61.7 m at the center, the other was located between Wuxi and Changzhou (also called the western Wuxi) with the groundwater level being -82.6 m at the center. The two depression cones then expanded gradually and the groundwater level dropped to -62.4 m at the center of Suzhou depression cone and -83.3 m at the western Wuxi depression cone in 1998. As a result of greatly decreasing

groundwater pumpage, the groundwater level in Suzhou had risen higher than -30 m and the depression cone had disappeared by 2007. The groundwater level for the cone depression at western Wuxi also rose with the level being -74.9 m at the cone center and the hydraulic gradient decreased in this area.

Development and distribution of land subsidence

Land subsidence in SXC was first reported in the late 1950s in Wuxi. The subsidence rate was small at that time and the average subsidence rate was about 7 mm/year during the period 1955–1964. With the increasing scope and intensity of groundwater exploitation both the area affected by land subsidence and the subsidence rate increased. In 1990, the subsidence rate was 91 mm/year in Suzhou, 74 mm/year in Wuxi, and 109 mm/year in Changzhou, respectively. As a consequence of limitation and prohibition of extracting groundwater, the subsidence rate decreased gradually and was 30 mm/year in Suzhou, 52 mm/year in Wuxi, and 20 mm/year in Changzhou in 2000, though the cumulative subsidence still increased (Zhang and Wei 2005). After 2003, recovery occurred at some monitoring locations. Figure 4 indicates the evolution of the land subsidence horizontally. The area affected by land subsidence has a close relation with the developing cone of depression in the mainly exploited aquifer.

The contribution of an individual unit to the total land subsidence depends on its physical and mechanical properties, its thickness, and its distance from the exploited aquifer unit. Figure 5 shows the deformation of individual units measured by the extensometer group at Qingliang Primary School of Changzhou (this extensometer group is denoted as FQL in this paper) from 1984 to the end of 2007. The borehole profile and the layout of the borehole extensometers are shown in Fig. 13 (ESM only). Figure 5 indicates that the compaction of the second aquitard was the greatest and this aquitard was the main subsidence layer, followed by the third confined aquifer and the second confined aquifer. Table 1 presents the percentage of the compaction of individual units in the total subsidence at FQL. During the period 1984–2003, land subsided at Qingliang Primary School. The compaction of the second aquitard (units 3–5, 73.66 m in thickness), which is connected directly with the second confined aquifer, accounted for 54.3% of the total subsidence of 731.99 mm. It is especially noted that the compaction of the mucky silty clay layer (unit 5, 20.82 m in thickness) accounted for 35.1% of the total subsidence. One reason for this is that the second confined aquifer was the main extracted unit and the mucky silty clay layer is just above that aquifer, the other is that the mucky silty clay is of high compressibility.

Fig. 4 Evolution of land subsidence in the SXC area (modified after Yu et al. 2004 and Zhang and Wei 2005)

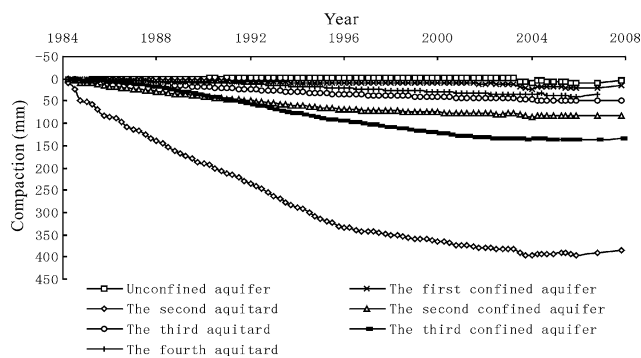
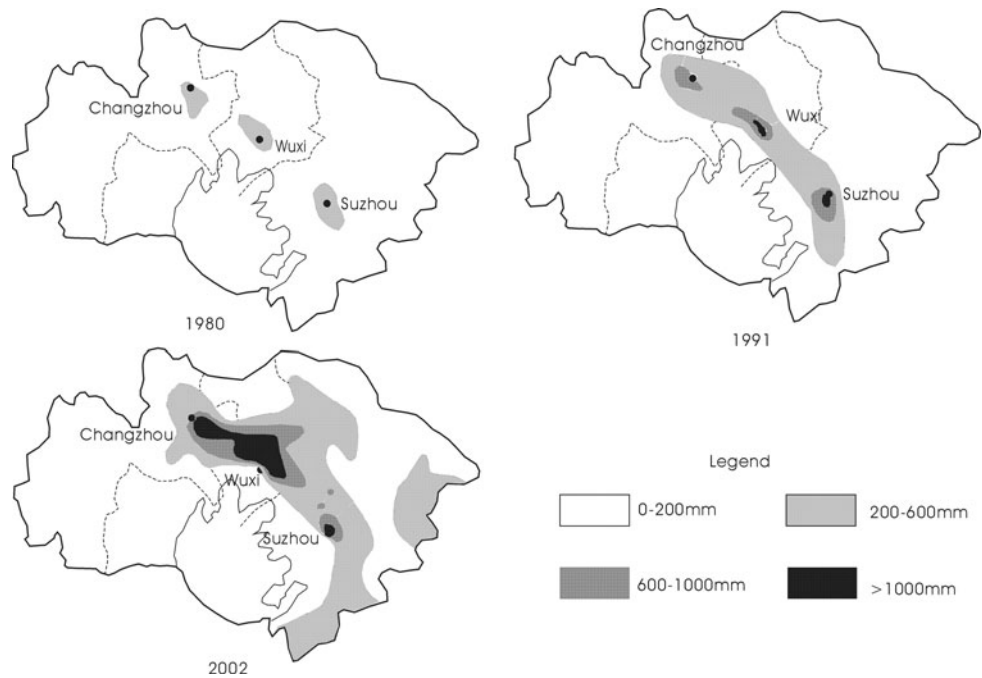


Fig. 5 Compaction of individual hydrostratigraphic units

The field data also reveals that most of units had begun to expand by 2004. During the period 2004–2007, land lifted 26.5 mm at FQL. The expansion occurred primarily within the units 1–4, especially within the units 2 (the first confined aquifer) and 3 (the silt and silty clay underlying the first confined aquifer). Unit 3 is far from the second confined aquifer and its compaction is primarily affected by the change of groundwater level in the first confined aquifer, while the groundwater level in the first confined aquifer at FQL changed a little and ranged from 1 to –2 m during the period 1990–2003.

The contribution of individual units to the total subsidence in Changzhou is different from that in Shanghai where the compaction of the third confined aquifer accounted for more than 50% of the total subsidence and this aquifer was the main subsidence layer when it became the mainly exploited aquifer (Zhang et al. 2007). The reason for this difference lies in that the compaction of a

hydrostratigraphic unit is related to many factors, such as the change of the pore water pressure in the unit, the compressibility of the soil, the stress history the unit has experienced, and the thickness of the unit. The third confined aquifer in Shanghai has a great thickness. For example, the thickness of the third confined aquifer unit accounts for 19.6% of the total Quaternary deposits at the extensometer group of Shuangyang Secondary School. But the thickness of the second confined aquifer unit accounts for 9.6% of the total Quaternary deposits at FQL. Additionally, the third confined aquifer in Shanghai is in the state of low to medium density and has the coefficient of compressibility of 0.25–0.63 MPa⁻¹, and the aquitard unit overlying the aquifer unit is in the state of hard plasticity and has the coefficient of compressibility of 0.07–0.25 MPa⁻¹. However, the second confined aquifer unit in Changzhou is of low to medium compressibility, and the overlying aquitard unit is of high compressibility. Therefore, the main subsidence layer is not always in accordance with the main exploited aquifer unit.

Mechanism and characteristics of deformation of hydrostratigraphic units

FQL is the unique extensometer group that has documented the long-term deformation of individual units in the SXC area. Additionally, there are three observation wells that monitor the groundwater levels in the three confined aquifers near FQL, respectively. These wells and extensometers have provided invaluable field data to analyze the

Table 1 Percentage of contribution of individual units to total subsidence at FQL

Unit	Depth (m)	1984–2003 (%)	2004–2007 (%)
1. Silty clay	0.00–5.98	1.2	–20.8
2. Silty sand (the first confined aquifer)	5.98–19.00	3.2	–31.3
3. Silt and silty clay	19.00–39.19	1.9	–30.6
4. Silty clay	39.19–71.84	17.3	–15.5
5. Mucky silty clay	71.84–92.66	35.1	–2.3
6. Fine sand (the second confined aquifer)	92.66–109.99	11.6	–10.2
7. Clay	109.99–118.5	6.5	3.8
8. Fine sand and medium sand (the third confined aquifer)	118.5–144.78	18.4	–0.8
9. Silty clay	144.78–180.00	4.6	7.5

Positive value stands for compaction, and negative value stands for expansion

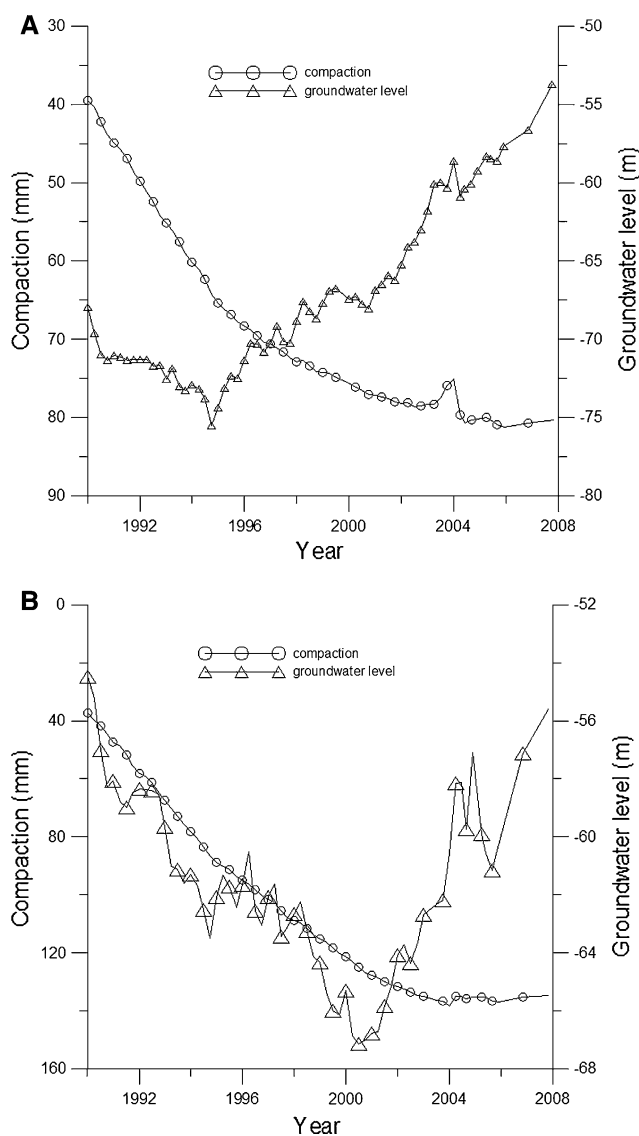


Fig. 6 Changes of groundwater level and compaction of confined aquifer **a** the second confined aquifer, **b** the third confined aquifer

deformation characteristics of individual units. Figure 6 shows the changes in groundwater level and compaction in the second and third confined aquifers. Due to decreasing pumpage, the groundwater level in the second confined aquifer, the mainly exploited aquifer, reached its lowest value of -75.35 m in 1994 and then rose up; it rose to -49.51 m at the end of 2007. But the expansion of the second confined aquifer unit did not occur until 2002. Compared with the recovery of the groundwater level, the expansion lagged behind for 8 years. The groundwater in the third confined aquifer flowed upward to the second confined aquifer and the groundwater level in it is affected by that in the second confined aquifer. Until 2000, the leakage from the third to the second confined aquifer stopped when the groundwater level in the second aquifer was higher than that in the third aquifer. Then the groundwater level in the third aquifer began to recover and rose from the lowest value of -68.01 m in 2000 to the value of -50.90 m in 2007. However, the third aquifer did not begin to expand until 2004; there is a lag in recovery for 4 years. These phenomena indicate that, under the condition of changing groundwater level, the deformation of aquifer units obviously lags behind the changes of groundwater level in themselves. The unit of the mucky silty clay, which is adjacent to the second confined aquifer, had nearly come to a stable state by 2004 and began to rebound a little after 2006 (Fig. 14, ESM only).

The consolidation theory of Terzaghi is often used to explain the lagging of aquitard units behind the changing groundwater level in adjacent aquifer units. But it is difficult to explain the lagging in aquifer units by this theory. In order to study the mechanism of the lagging for aquifers, some laboratory tests have been performed on the sand samples acquired from the confined aquifers. The samples are 61.8 mm in diameter and 20 mm in height. The tests were carried out on high-pressure oedometers. The loading

was applied suddenly, in multiple stages. Each loading increment was maintained until the rate of compression of the samples measured by micrometer dial gauges was no greater than 0.005 mm/day, then the next loading increment was applied. The samples were saturated and kept under water and the surrounding temperature remained within $23 \pm 3^\circ\text{C}$ throughout the tests.

Compression deformation under each loading stage

Figure 15 (ESM only) shows the compression deformation of a saturated sand sample under different loading stages. It indicates that the deformation does not complete immediately after the loading is added, but increases with time. The compression rate decreased with time and gradually came to an end; this process often lasted several days. Sand samples have strong permeability and the time-dependent deformation results from the creep, that is to say, that the sand creeps. The creep deformation can be expressed as Eq. 1 (Zhang et al. 2005)

$$\varepsilon(\sigma, t) = A \left(\frac{t}{t_0}\right)^m \left(\frac{\sigma}{\sigma_0}\right)^n \tag{1}$$

in which, σ_0 is reference stress (it can be chosen as 100 kPa); t_0 is reference time (it can be chosen as 1 min); A ($= \varepsilon(\sigma_0, t_0)$) is the vertical strain of samples under stress σ_0 at time t_0 ; $\varepsilon(\sigma, t)$ is the strain under stress σ at time t ; m is the slope of creep curves in the double logarithmic strain and elapsed time space; and n is the slope of isochronal curves in the double logarithmic strain and stress space. In fact, the value of m changes a little for different loading stages, the average value is therefore adopted. The greater the value of m , the stronger the creep of sand is.

Effect of stress history on sand creep

In order to investigate the effect of preloading on the creep of sand, different preloading p_c , for example, 200, 400, and 800 kPa, is applied. The test results reveal that the value of m around $p/p_c = 1$ changes rapidly and that the value of m for $p/p_c < 1$ is much smaller than that for $p/p_c > 1$ (p is the current loading), as shown in Fig. 7 (Zhang et al. 2009).

Effect of loading increment on sand creep

For the samples with the same initial state, different loading increments were applied. The value of m decreases with the increasing loading increment (Fig. 8). Lesser the loading increment, lesser is the deformation that occurs immediately after the loading is applied, and greater the creep deformation that develops with time. Compared with the loading of usual constructive projects such as buildings and highways, the groundwater level often changes much

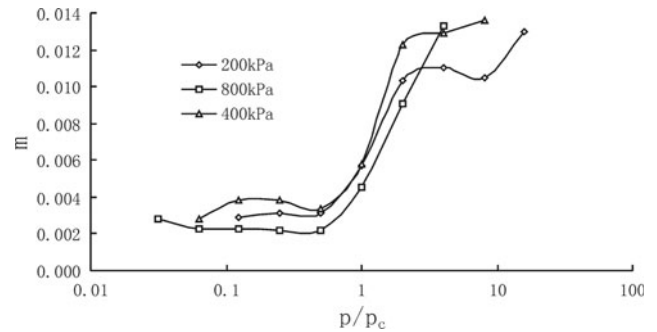


Fig. 7 Relationship between m and load for different preloading

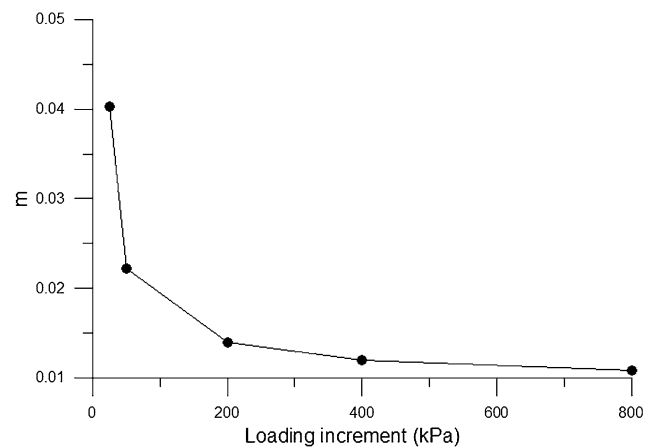


Fig. 8 Relationship of m and loading increment

slowly. This can explain why the aquifer sand behaves obviously as a creep material under the long-term groundwater withdrawal.

Effect of loading–reloading on sand creep

Figure 9a indicates the value of m changes with the number of cycles when loading from 1,600 to 3,200 kPa. It shows that the value of m decreases rapidly with the cycling number. After four cycles, the creep of sand samples was very weak. Figure 9b shows the compression deformation during loading stage and the rebounding deformation during unloading stage. The difference between compression and rebounding deformation become smaller with the increasing number of cycles. The ratio of rebounding to compression is 9, 35, 49 and 60% for the first to fourth cycles, respectively. Therefore, sand will behave elastically after several loading–reloading cycles.

Both field and laboratory data have proved that the deformation of aquifer and aquitard units lag behind the change of groundwater level in aquifers, but the mechanism is not the same. For aquifer units, the lagging is related to the creep, while it is related to the creep and consolidation for aquitard units.

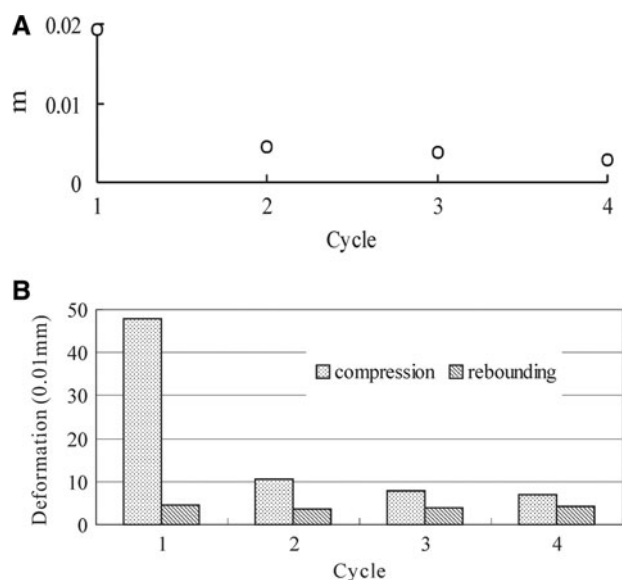


Fig. 9 Effect of loading–reloading on sand creep **a** value of m , **b** compression and rebounding

Current situation and developing trend of land subsidence in SXC

Due to difference in hydrostratigraphic units and in the change of groundwater level, land subsidence changes spatially and temporally. Figure 10a shows the land subsidence in the town of Qianzhou, Wuxi, during the period 2004–2007. There the Quaternary deposit is about 155.9 m thick, in which the first confined aquifer is less than 10 m, the second confined aquifer is 58.87 m, and the aquitard unit consisting of clay and silty clay between the two aquifers is about 80 m. At this site, the groundwater level was higher than -6.1 m in the 1960s, and declined continuously afterwards due to pumping. The town of Qianzhou has become the center of the regional depression of cone in the second confined aquifer since 1992 and the groundwater level declined to -81.5 m in 2004. Then the groundwater level recovered slowly and rose to -74.86 m in 2007. During the period of groundwater level rising, land subsidence still continued but the rate of subsidence had a decreasing trend. The subsidence in 2005 and 2006 is 18.3 and 10.5 mm, respectively.

The groundwater level of the second confined aquifer in Suzhou reached its lowest values of -67.08 m around 1995. Then the groundwater level recovered continuously and rose higher than -20 m in most of the area. Land subsidence during the period 2004–2007 is only 1.4 mm at Louxiewei, indicating that land subsidence has nearly stopped. But at Shengze, Suzhou, land subsidence still developed rapidly, and the subsidence was 40.1 mm in 2005 and 44.8 mm in 2006, as shown in Fig. 10b. The main reason is that more than four-fifths of the Quaternary

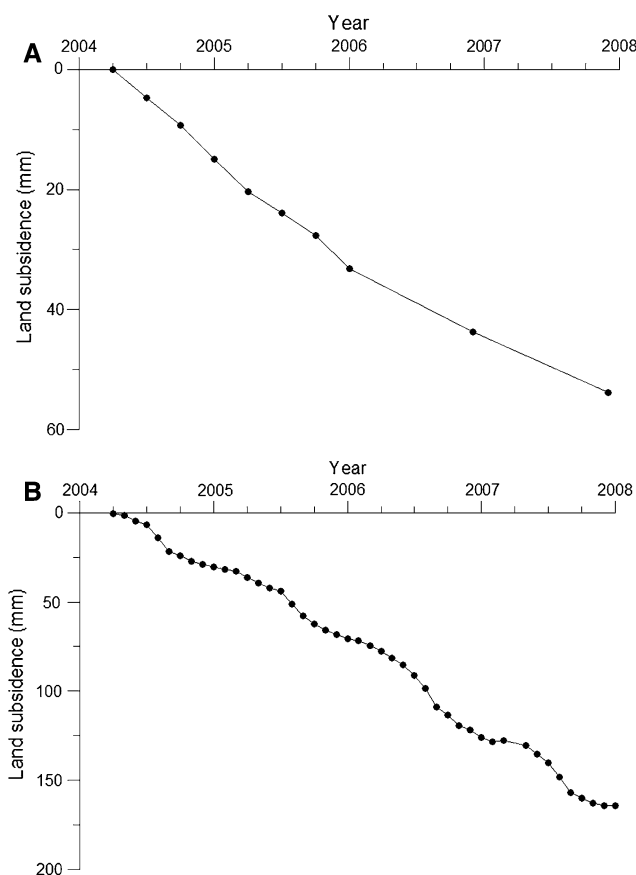


Fig. 10 Development of land subsidence **a** Qianzhou, Wuxi; **b** Shengzhe, Suzhou

deposit in thickness is soft soil with high compressibility and, moreover, the groundwater level still declined by 2005 at this site (Hu et al. 2006).

Horizontally, land subsidence has stopped and a little of rebound has occurred in the city of Changzhou and Suzhou, while land subsidence in western Wuxi will continue due to its late recovery of groundwater level.

Conclusions

Excessive groundwater withdrawal has caused severe land subsidence in the SXC area. After restriction and prohibition on the groundwater pumping, groundwater level has obviously recovered and land subsidence has slowed down. Based on the latest field data from observation wells, it is found that the groundwater level in SXC has undergone a simple changing pattern. It declined continuously and reached its lowest value at a certain time, and then rose continuously though the time when the groundwater level reached its lowest value changes with the sites.

The distribution of land subsidence in SXC is closely related to that of the cone of depression in the second

confined aquifer. It is also affected by the structure of the hydrostratigraphic units. Vertically, the contribution of a specific unit to land subsidence is determined by many factors, including the properties of soils consisting of the unit, the groundwater level changing the unit has experienced. Temporally, land subsidence always lags behind the groundwater level changes in aquifers. This lagging results not only from the consolidation of the clay or silty clay unit, but also from the creep of the sand unit and clay unit. The creep of sand has been testified by laboratory and field data.

The behavior of creep of sand is affected by the stress rate and stress history the sand has experienced. The creep deformation increases as the changing rate of stress decreases. That is the reason why the sand unit behaves as an obvious creep material under the condition of long-term groundwater pumpage. The creep deformation under virgin compression is much greater than that under recompression and unloading. Under repeated loading, the creep of sands decreases rapidly with the cycles.

Now the restriction and prohibition on the groundwater pumping has taken effect. Groundwater level has obviously recovered in the vast majority of the SXC area. Land subsidence has slowed down, and even a little of rebound has occurred in some sites in Suzhou and Changzhou. In the future, if the pumpage is strictly limited, the groundwater level will not decline below the historical lowest value and will fluctuate within a certain range. In such a case, land subsidence will no longer develop obviously.

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References

Adrian OG, Rudolph DL, Cherry JA (1999) The analysis of long term land subsidence near Mexico City: field investigations and predictive modeling. *Water Resour Res* 35:3327–3341

- Chen CT, Hu JC, Lu CY, Lee JC, Chan YC (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. *Eng Geol* 95:30–47. doi:10.1016/j.enggeo.2007.09.001
- Galloway D, Jones DR, Ingebritsen SE (1999) Land subsidence in the United States. US Geological Survey Circular 1182, p 117
- Gambolati G, Freeze RA (1973) Mathematical simulation of the subsidence of Venice: theory. *Water Resour Res* 9:721–733
- Gu XY, Ran QQ (2000) A 3-d coupled model with consideration of rheological properties. In: Carbognin L, Gambolati G, Johnson AI (eds) Proceedings of the sixth international symposium on land subsidence, 24–29 September, vol 2. CNR, Ravenna, Italy, pp 355–365
- Hu JP, Sui ZX, Chen J (2006) Study on geological environmental effect after banning groundwater pumping in Su-Xi-Chang area. *Jiangsu Geol* 30(4):261–264 (in Chinese)
- Lewis RW, Schrefler B (1978) A fully coupled consolidation model of the subsidence of Venice. *Water Resour Res* 14(2):223–230
- Lofgren BL (1969) Field measurements of aquifer-system compaction, the San Joaquin Valley, California. In: Tison LJ (ed) Land subsidence, vol 1. International Association of Scientific Hydrology Publication 88, pp 272–284
- Phien-wej N, Giao PH, Nutalaya P (2006) Land subsidence in Bangkok, Thailand. *Eng Geol* 82:187–201
- Wang CH, Zhu JQ, Chen J (2004) Study on the shallow groundwater mining technique and its environmental effect in Su-Xi-Chang area. *J Geol Hazards Environ Preserv* 15(1):42–45 (in Chinese)
- Yu J, Wu JQ, Wang XM, Yu Q (2004) Research on the correlative prediction model with a regional decomposition base of the land subsidence in the Suzhou-Wuxi-Changzhou area. *Hydrogeol Eng Geol* 31(4):92–95 (in Chinese)
- Zhang AG, Wei ZX (2005) Land subsidence in China. Shanghai Science and Technology Press, Shanghai (in Chinese)
- Zhang Y, Xue YQ, Shi XQ, Song Z (2005) Study on nonlinear creep model for saturated sand. *Rock Soil Mech* 26(12):1869–1873 (in Chinese)
- Zhang Y, Xue YQ, Wu JC, Ye SJ, Li QF (2007) Stress–strain measurements of deforming aquifer systems that underlie Shanghai, China. *Environ Eng Geosci* 8(3):217–228
- Zhang Y, Xue YQ, Wu JC, Liu YT, Pu XF (2009) Experimental research on creep of Shanghai sands. *Rock Soil Mech* 30(5):1226–1230 (in Chinese)