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The effect of stratigraphic heterogeneity on areal distribution of land subsidence at Taiyuan, northern China

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Abstract Taiyuan city has experienced serious land subsidence since the 1950s, with the maximum accumulated subsidence of 2,960 mm and a total affected area of 585 km^2 by 2003. Tectonic settlement was found to contribute about 1% and the major cause is over-exploitation of groundwater. The spatial–temporal relationship between the areal distribution of land subsidence and that of groundwater drawdown from 1956 to 2000 indicates that although land subsidence centers overall match groundwater depression cones, there are local deviations, and that although the time series curves are similar, land subsidence always lags behind groundwater level decline, with different lag time at different sites. The major findings of this work on the control of stratigraphic heterogeneity on the spatial pattern of land subsidence at Taiyuan include: (1) land subsidence centers shift from the corresponding groundwater depression cones to the sides with thicker accumulated clay layers; (2) under the same pumping rate, land subsidence at places with more clay interlayers and thinner individual interlayers is greater and the lag time shorter; and (3) land subsidence is closely related to the physical properties of clay soils. The Interbed Storage Package-1, a modular subroutine of MODFLOW was employed to simulate the areal distribution of individual layer compression. The modeling results show that compression of different clay layers has different contribution to land subsidence. Pumping groundwater from water-bearing zones close to the most compressible clay layers should therefore be carefully controlled.

Keywords Land subsidence · Groundwater · Compaction · Heterogeneity · Clay · Simulation · Northern China

Introduction

In Taiyuan city, capital of Shanxi province, northern China, land subsidence has been observed since the 1950s. By 2003, the maximum accumulated subsidence reached 2,960 mm and the area affected by land subsidence is 585 km^2. The land subsidence has induced very serious economic and social problems at Taiyuan.

As one kind of widespread geohazards, land subsidence caused by excessive pumping of groundwater has been widely reported in many countries and areas (Inaba et al. 1970; Miyabe 1970; Holzer 1977; Nunez and Escojido 1977; Yamamoto 1977; Bergado et al. 1986; Carbignin and Gatto 1986; Guangxiao and Yiaoqi 1986; Prokopovich 1986; Rietveld 1986; Andronopoulos et al. 1991; Balestri and Villani 1991; Holdahl et al. 1991; Liao et al. 1991; Haryono 1995; Lebbe 1995; Nguyen and Helm 1995; Hasanuddin et al. 2001; Xue et al. 2003). Much work has been done on the mechanism of land subsidence due to groundwater withdrawal in the last century. As a result, knowledge about the causes and mechanism of land subsidence and capability of numerical modeling, predicting, monitoring, prevention, control, and risk assessment of land subsidence has been greatly improved (Dimova 1996; Phien-wej et al. 1998; Hu et al. 2004; Don et al. 2005; Teatini et al. 2005). It is well known that water extraction from an unconsolidated aquifer system decreases hydrostatic pressure and causes the compaction of clay interlayers within the system to result in land subsidence (Terzaghi 1925; Longfield 1932; Poland and Davis 1969). Compaction was correlated with clay content in sediments (Meinzer 1928; Jacob 1940; Prokopovich 1991; Liu et al. 2001; Hu et al. 2002; Sato et al. 2003). When groundwater level declines due to extraction, the low permeability of the clay layers would result in slower drainage than in the coarser layers of the aquifer and therefore there will be a time-delay between the extraction and the occurrence of subsidence. The time required for clay layer dewatering depends mainly on the spatial configuration of clay layers, such as the amount, thickness, and sequence of clay layers. Water will be drained quickly if there are a lot of thin clay interlayers. In this case, the lag time between drainage and soil compaction will be comparatively short and the subsidence large, accordingly. In contrast, if there are few but very thick clay layers, water drainage will be slower, the lag time longer, and compaction smaller.

Land subsidence is a gradual settlement process of the ground surface owing to the accumulated compressibility of individual soil layers subjected to increasing effective stress. Under natural conditions, there is hardly any soil layer that extends invariably over a vast territory. Its spatial–temporal pattern is therefore affected greatly by the stratigraphic heterogeneity of subsurface sediments. Most of it occurs in alluvial plains or large inland basins with unconsolidated sediments, which are generally heterogeneous. The feature of subsidence can be quite different because of the high variability of soil matrix in different regions (Sneed et al. 2000; Liu et al. 2001; 2004; Hu et al. 2002; Sato et al. 2003). Therefore, understanding the effect of stratigraphic heterogeneity on land subsidence is necessary for simulating and predicting the land subsidence in these regions.

Although some recent studies have proved the relationship between pattern of subsidence and strata heterogeneity (e.g., Rojstaczer and Deverel 1995; Kooi 2000; Gabrysch 2000; Sneed et al. 2000), more detailed quantitative work is needed to characterize the heterogeneity and evaluate its effect on land subsidence.

The objectives of this study are: (1) to analyze the relationship between groundwater withdrawal and land subsidence in Taiyuan city; (2) to characterize the effect of stratigraphic heterogeneity on land subsidence; (3) to determine the contribution of compression of individual layers and characterize the spatial pattern of sediment compaction; and (4) to propose a better pumping scheme for land subsidence control.

Regional hydrogeology

Taiyuan City is in the northern part of Taiyuan basin, central Shanxi (Fig. 1). The city is bounded by the Lvliang Mountains to the west, and the Taihang Mountains to the east. To determine the boundary conditions, the simulation area was extended to the mountains in the east, west, and north. The study area of 620 km^2 is between 37°40′N–38°00′N latitude and 112°25′E–112°45′E longitude. Physiographically, the altitude lowers from the north to the south and from the east and the west to the central part of the basin.

Groundwater at Taiyuan is recharged by atmospheric precipitation, river and lake leakages, irrigation losses, and lateral seepage from surrounding mountains. Discharge is mainly via pumping and evapotranspiration. Precipitation changes seasonally, with 62% of annual total rainfall from July to September 13–15% (50–65 mm) of the annual rainfall in spring, 58–65% (200–400 mm) in summer, 24% in autumn, and the rest (2–3%) in winter. Accordingly, groundwater level fluctuates seasonally under natural conditions. However, it has been declining continuously in the past 40 years under the impact of long-term excessive pumping.

The unconsolidated sediments in the basin consist of interlayered sands and clays, as a result of alternating deposition of alluvial and lacustrine sediments. The sediments are coarse around the margin of the city and at the heads of pluvial fans, and become fine towards the central part of the basin (Fig. 2).

The subsurface water-bearing system is divided into upper (Unit 1 in Fig. 2), middle (Unit 2 in Fig. 2) and lower water-bearing zones (Unit 3 in Fig. 2). Groundwater is extracted mainly from the middle and lower water-bearing zones in this area.

The unconfined to semi-confined water-bearing zone in the uppermost section of the basin has a burial depth of 5–25 m, consisting of medium sand and medium coarse sand with gravel in the northern part, and of fine-medium coarse sand with interlayers of clay in the southern part. Hydrochemical type of groundwater in the zone changes from HCO_3 type in the north (with an average TDS of 0.5 g/l) to the HCO_3–SO_4 type in the south (with an average TDS of 1.0 g/l).

The middle confined water-bearing zone is thicker than the upper, ranging from 20 to 40 m. It is composed of silt, fine sand and medium sand with interlayers of silty clay from top to bottom in Wujiabao area. The hydrochemical type of groundwater from pluvial fans is dominated by HCO_3–Ca–Mg water, with an average TDS of less than 1.0 g/l, and that

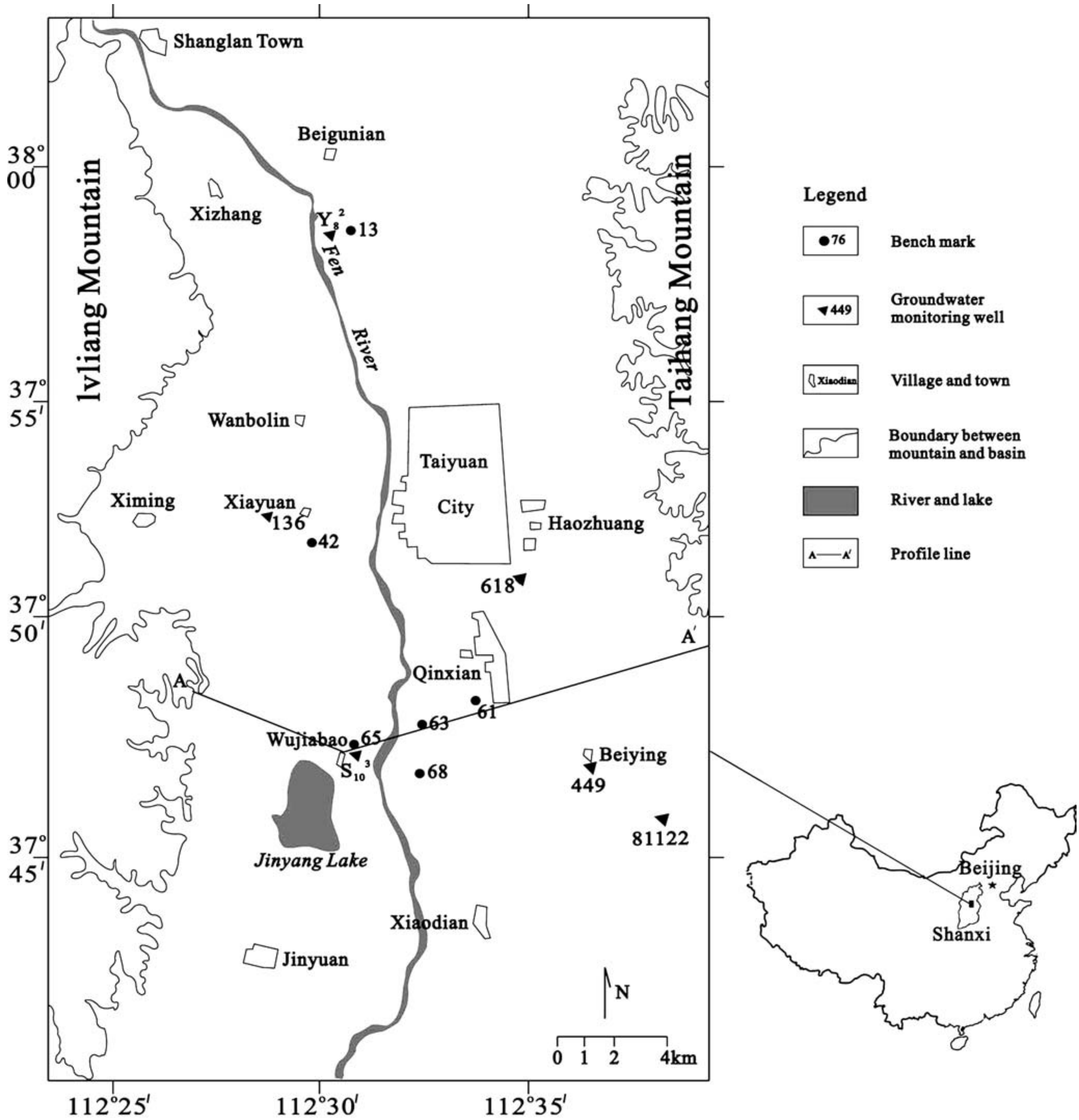

Fig. 1 A simplified geographic map of the study area and locations of groundwater monitoring wells and bench marks used in this study

from the transitional part between alluvium and diluvium is HCO_3–SO_4–Ca–Mg water, with an average TDS of more than 1.0 g/l.

The thickness of the lower confined water-bearing zone ranges from 90 to 105 m. From the north to the south, the sediment becomes finer, and groundwater head declines. The hydrochemical type of groundwater is HCO_3–Ca–Mg water in the north (with an average TDS of less than 1.0 g/l), and HCO_3–SO_4 water to HCO_3 water at Wujiabao area and Xiaodian area (with an average TDS of more than 1.0 g/l).

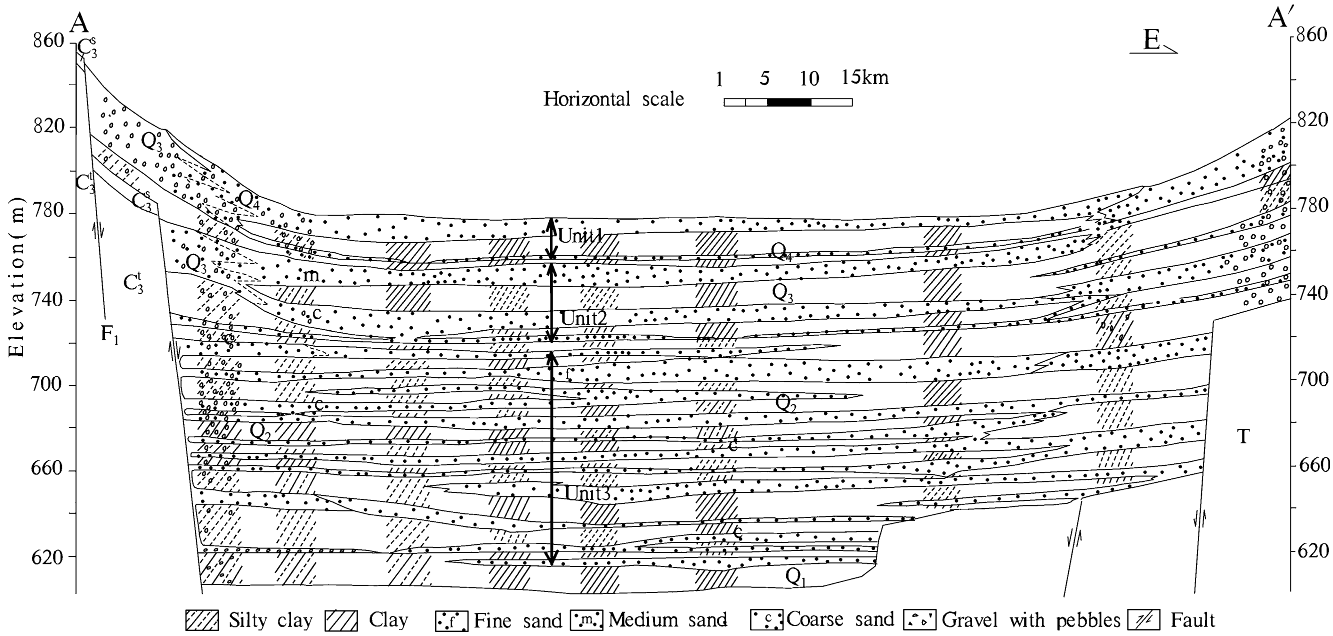

Fig. 2 Schematic hydrogeological profile *A–A′* of Taiyuan city. The profile line is indicated in Fig. 1. Units 1, 2 and 3 correspond respectively to upper, middle and lower water-bearing zone. Stratigraphic notations: *T* Triassic; C_3^t Taiyuan Formation (upper Carboniferous); C_3^s Shanxi Formation (upper Carboniferous); Q_1 Lower Pliocene; Q_2 Upper Pliocene; Q_3 Pleistocene; Q_4 Quaternary

Spatial–temporal distribution of land subsidence

According to the data from 114 second-order bench marks in Taiyuan city, the region affected by land subsidence is from Shanglan town in the north to Haocun village in the south, and from Xizhen town in the west to Xihebao village in the east, with a total area of about 585 km^2. There are four land subsidence centers, namely Xizhang, Wanbolin, Xiayuan, and Wujiabao center (Fig. 3c, d). The maximum subsidence with accumulated subsidence of 2,960 mm and an average subsiding rate of 63.0 mm/a by 2003 is in Wujiabao village. Monitoring data indicate that land subsidence in Taiyuan city has the following three stages.

Initial stage (1956–1981)

There was no obvious land subsidence before 1965; a slow subsidence in 1965–1970; a non-uniform subsidence in 1970–1981 when the land subsidence center of Wujiabao was formed (Fig. 3b). The bench mark at Wujiabao indicated an accumulative subsidence of 827 mm from 1956 to 1981, with an average subsiding rate of 33.08 mm/a which is obtained by dividing the total subsidence 827 mm with 25 a.

Developing stage (1981–1989)

By the end of this period, the four land subsidence centers had been formed (Fig. 3c), with an affected area of about 441.8 km^2. The bench marks at Xizhang, Wanbolin, Xiayuan, and Wujiabao indicated subsidence rate of 43.38, 46.75, 55.25, and 114 mm/a, respectively.

Affected-area extension stage (1989–2000)

The area affected by land subsidence quickly extended, up to an area of 585 km^2 (Fig. 3d). The average rate of land subsidence was 25, 46.73, 86, and 96.18 mm/a at Xizhang, Wanbolin, Xiayuan, and Wujiabao, respectively.

Causes of land subsidence

First-order leveling altitude data from the Jinci seismic monitoring station (BM1–BM3 leveling sites) on both sides of the Jinci fault (F_1 fault in Fig. 2) show that the downward side of the fault had subsided 21.88 mm from 1981 to 2000, accounting for 1% of the total land subsidence volume at Taiyuan. Therefore, although tectonic subsidence is one cause for land subsidence at Taiyuan, it is not the major cause.

The changes of groundwater exploitation, groundwater level, and land subsidence with time at Taiyuan (Fig. 4) indicate that in the first period (1956–1981), groundwater exploitation was not intensive, groundwater level declined gently while land subsidence developed slightly. From 1981 to 1989, groundwater was substan-

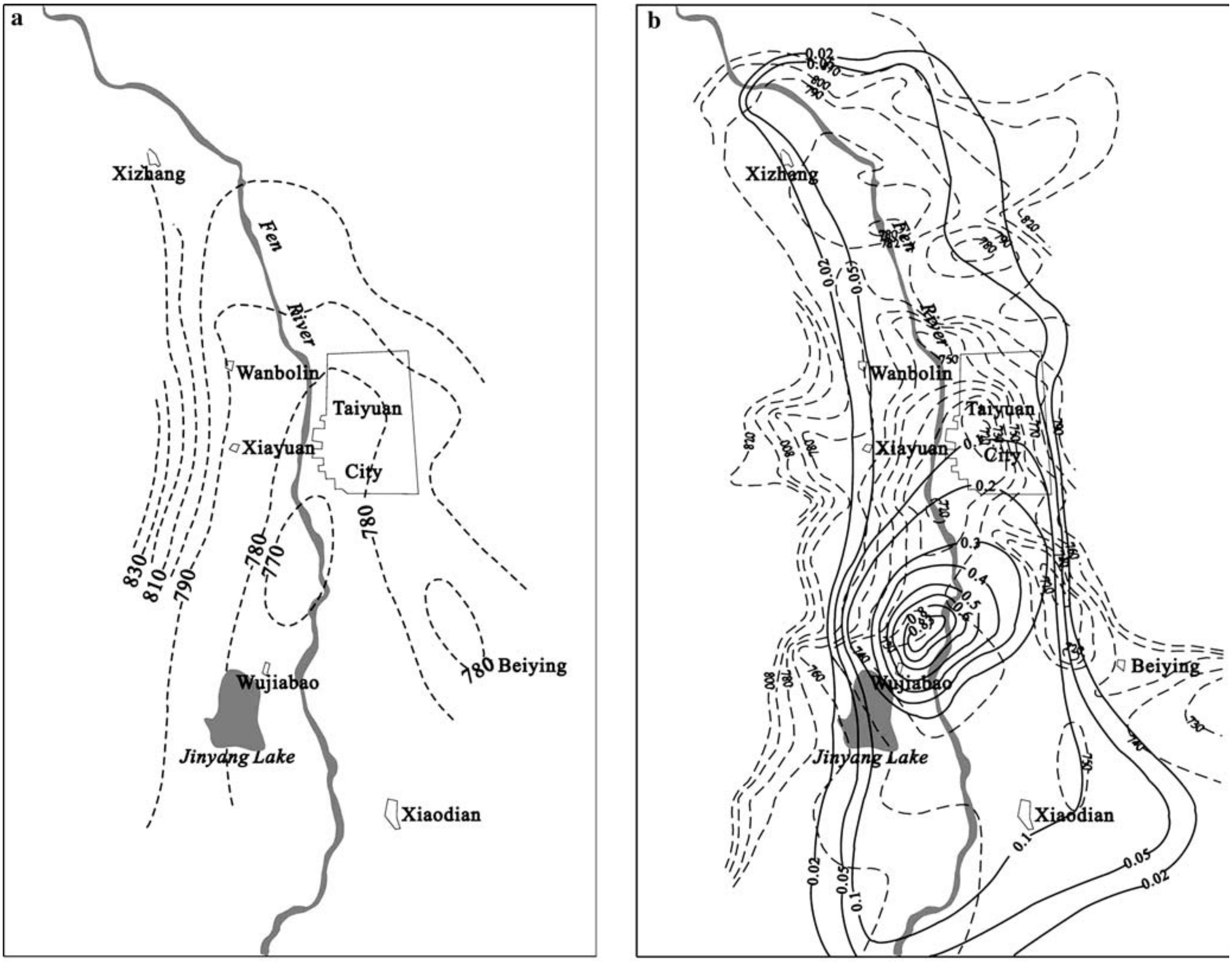

Fig. 3 Contour maps of accumulated land subsidence (*dashed lines*) and groundwater level of confined water-bearing zone (*solid lines*) in Taiyuan city: **a** groundwater level in 1965, **b** both in 1981, **c** both in 1989, and **d** both in 2000. The unit for both subsidence and groundwater level is meter. The range of each map is the same as in Fig. 1. Since there was no obvious land subsidence in 1965, only the groundwater level contour is given for 1965

tially extracted and water level declined to a great extent, and accordingly, land subsidence developed fast. From 1989 to 2000, groundwater exploitation and water level decline slowed down, but the land subsidence was still occurring due to the lagging effect between groundwater decline and land subsidence.

Figure 3 shows that groundwater depression cones spatially match with land subsidence centers. There were five groundwater depression cones in Taiyuan city by 2000, at Xizhang, Wanbolin, Xiayuan, Wujiabao, and Beiying, respectively. The land subsidence centers occur in the sub-zones of Xizhang, Wanbolin, Xiayuan, and Wujiabao, one to one correspondence with the groundwater depression cones except the Beiying. The expanding process of groundwater depression cones and land subsidence centers can be also seen on Fig. 3. The occurrence of land subsidence always lags behind the formation of groundwater depression cones.

Effect of formation characteristics on spatial pattern of land subsidence

It is excessive exploitation of groundwater that caused land subsidence in Taiyuan city, but the spatial pattern of land subsidence is not only controlled by groundwater withdrawal, but also affected by formation characteristics and geological structures. The monitoring data in the period of 1956–2000 show that land subsidence spatially coincides with the groundwater depression on the whole, but there are some discrepancies. Firstly, the groundwater depression cones do not match exactly with the land subsidence centers. Secondly, the rate of

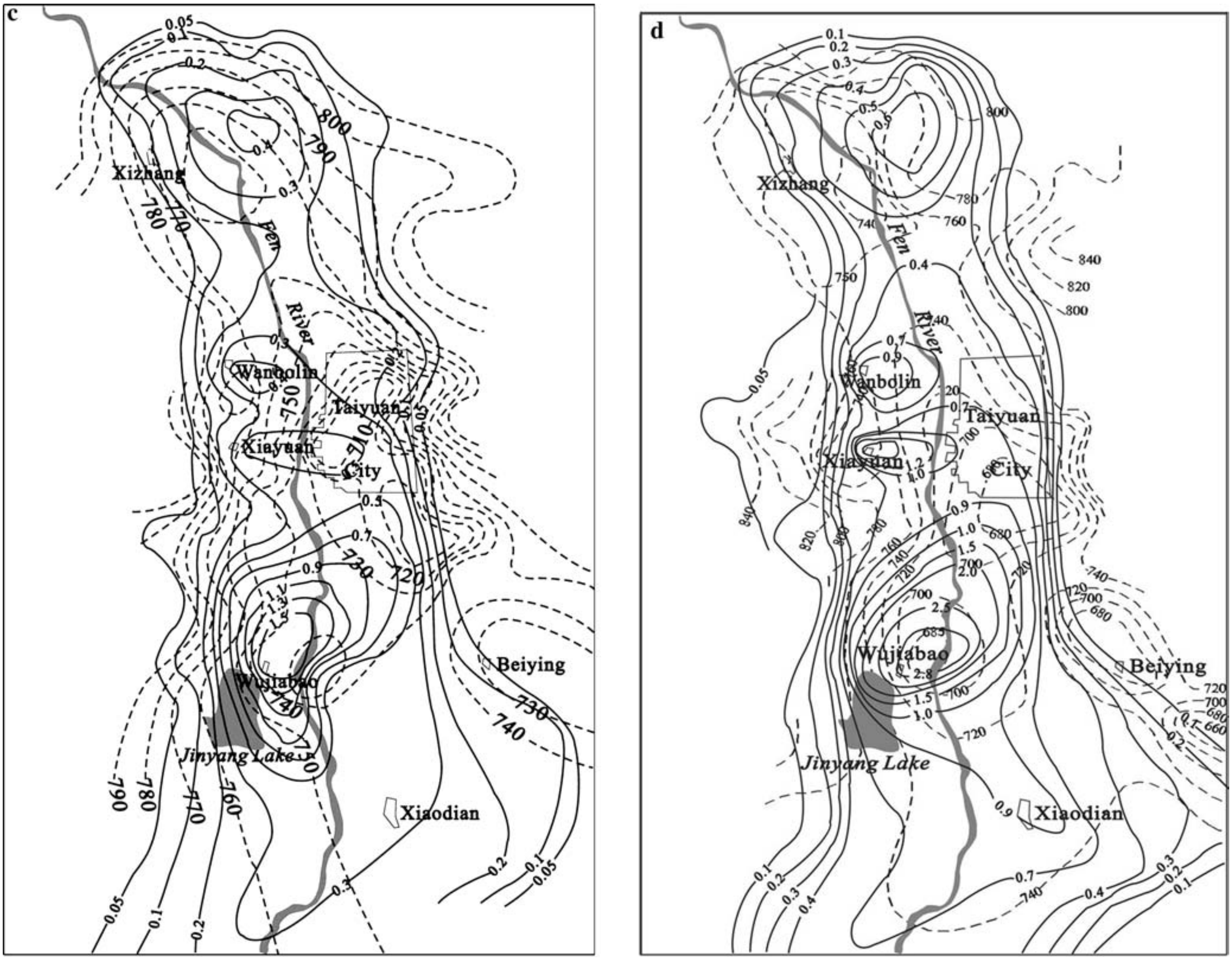

Fig. 3 (Contd.)

groundwater table decline is not proportional to land subsidence. Thirdly, the land subsidence only occurs in the alluvial plain, not in pluvial sediments. In the present study, formation heterogeneity is considered as the major reason for the phenomena, and the following factors were taken into account: clay layer thickness, stratigraphy, and physical properties of clay soils at different places and depths.

Effect of the clay layer thickness

It is well known that compaction of clay soil contributes mostly to land subsidence (Terzaghi 1925; Longfield 1932; Poland and Davis 1969). Clay soil thickness in deposits is the main factor controlling subsidence under the same conditions (Meinzer 1928; Jacob 1940; Prokopovich 1991; Liu et al. 2001; Hu et al. 2002; Sato et al. 2003).

Comparing the accumulated land subsidence contour in Fig. 3 with the accumulated clay thickness contour in Fig. 5, it can be seen that the land subsidence centers at Xizhang and Wanbolin-Xiayuan shift from the corresponding groundwater depression cones to the east and southwest respectively, where there are thicker clay soils.

Effect of stratigraphy

The pressure causing compaction of clay soil is from the change in groundwater head due to dewatering, the rate of which depends on the hydraulic characteristics of the strata. The low hydraulic conductivity of clay layers would result in slow drainage and a long-term head pressure commutation. This would make the rate of compaction lower than that of groundwater withdrawal, and cause a time lag between them (Terzaghi 1925, 1943; Riley 1970; Jorgensen 1980; Epstein 1987; Pavelko 2004). The thicker the individual clay layer is, the longer the lag time. Under the impact of the same intensity of

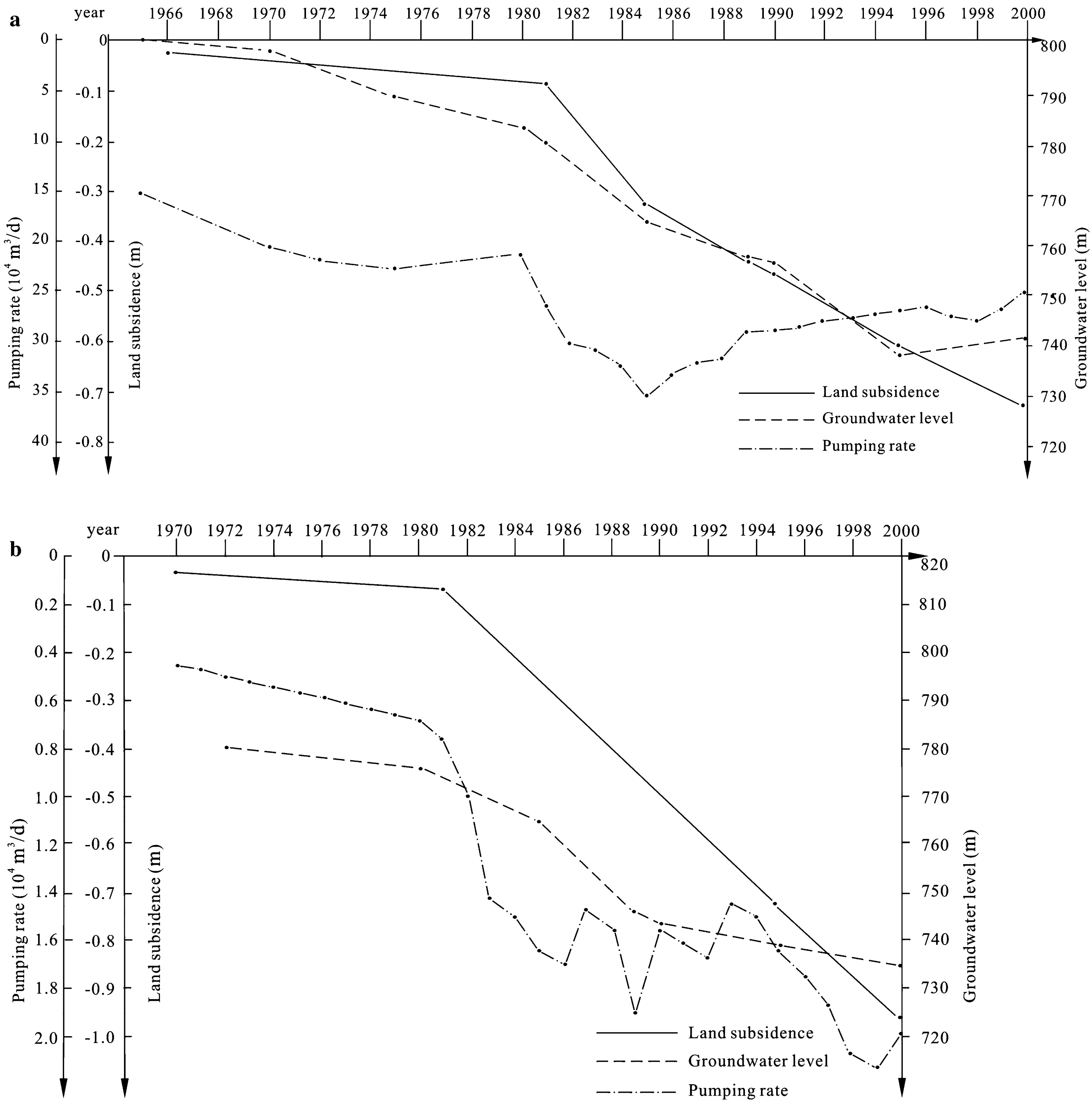

Fig. 4 Changes of groundwater exploitation, groundwater table, and land subsidence with time at Xizhang (**a**), Wanbolin (**b**), Xiayuan (**c**), and in Wujiabao (**d**)

groundwater withdrawal, subsidence is usually greater where there are more clay interlayers and the individual interlayer is thinner. When there are a lot of thin clay interlayers in deposits, water can be drained off through both sides or in different directions. Consequently, as the groundwater head declines, the clay interlayers drain relatively quickly, the time lag between drainage and soil compaction will be comparatively short, and proportionately greater subsidence. If, however, there are few but very thick clay layers, drainage will be slower, the time lags longer, and comparatively smaller subsidence.

At Wujiabao, cumulative thickness of the clay layers is large but the individual clay layer is thin (Fig. 6c). When groundwater is pumped, it drains quickly, and the lag time between the permanent head decline and subsequently land subsidence is short. Therefore, the groundwater level decline at Wujiabao is not greater than other locations, but the subsidence is, and the

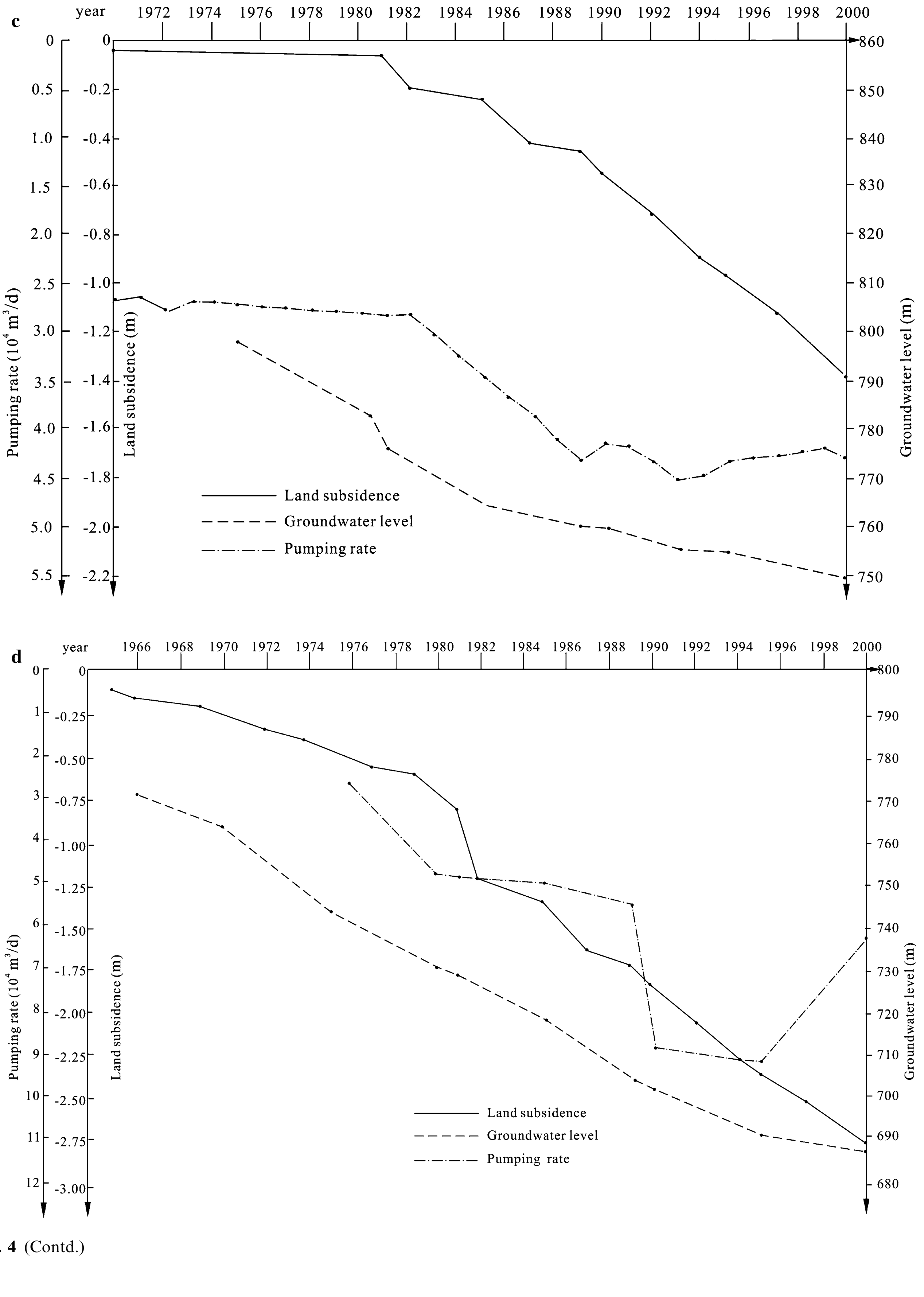
c
year
1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000
Pumping rate (10^4 m^3/d)
Land subsidence (m)
Groundwater level (m)
Land subsidence
Groundwater level
Pumping rate
d
year
1966 1968 1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000
Pumping rate (10^4 m^3/d)
Land subsidence (m)
Groundwater level (m)
Land subsidence
Groundwater level
Pumping rate

Fig. 4 (Contd.)

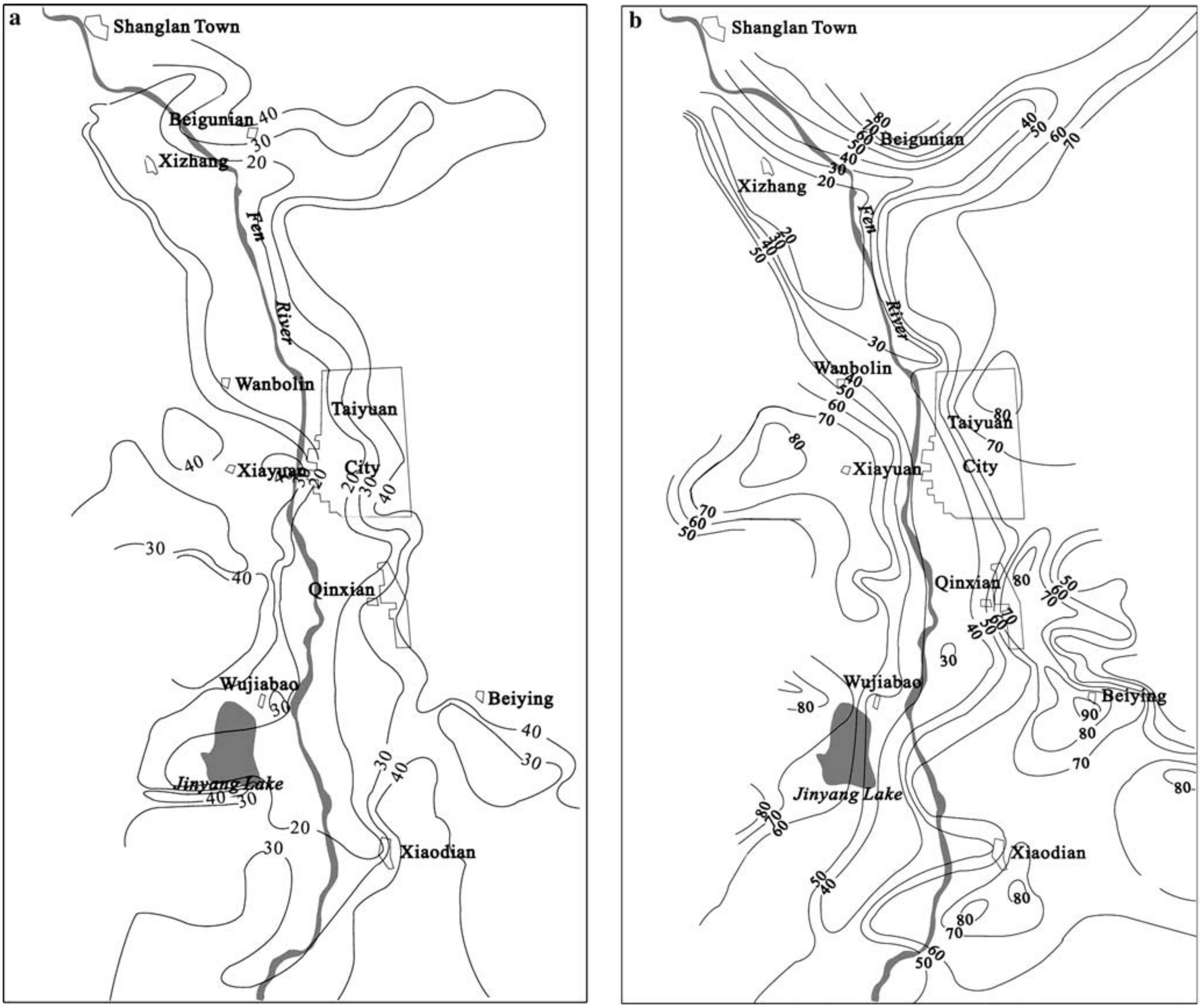

Fig. 5 Contours of accumulative thickness of clay interlayers found in the depth ranges of 0–50 m (**a**) and 50–150 m (**b**) below ground surface in Taiyuan City

subsidence center develops almost simultaneously with the groundwater depression cones. In contrast, at Beiying, the clayey sediments form thick individual clay layers (Fig. 6d). In this case, the drainage of water is relatively sluggish and the compaction slow. As a result, the land subsides only in small amounts though groundwater decline is excessive. At Xizhang, where the cumulative thickness of clay soils is small (Fig. 6a), land subsidence is comparatively small though the groundwater declined significantly. However, the lag time is the shortest because the clay interlayers is very thin. At Wanbolin-Xiayuan, where clay layers are more than those at Xizhang but less than those at Wujiabao and the cumulative clay soil is thicker than that at Xizhang and Wujiabao (Fig. 6b), the total land subsidence is greater than that at Xizhang but much less than that at Wujiabao.

Effect of clay soil physical properties

According to the data from 32 boreholes in Taiyuan city, the physical properties of clay soils from different subsidence centers and depths were studied (Table 1). The clay soils from Xizhang and Urban areas have the lowest porosity ratios, becoming higher at Beiying, Wanbolin and Xiayuan, and even higher at Wujiabao. Though the clay soils from all sites are mildly compressible, the compressibility at Wujiabao is relatively large. The clay soils from Xizhang have the lowest liquid limit value, becoming higher at Wanbolin, Xiayuan and Urban areas, and the highest at Wujiabao, which is in soft plasticity state. It can be seen that the clay soil is the

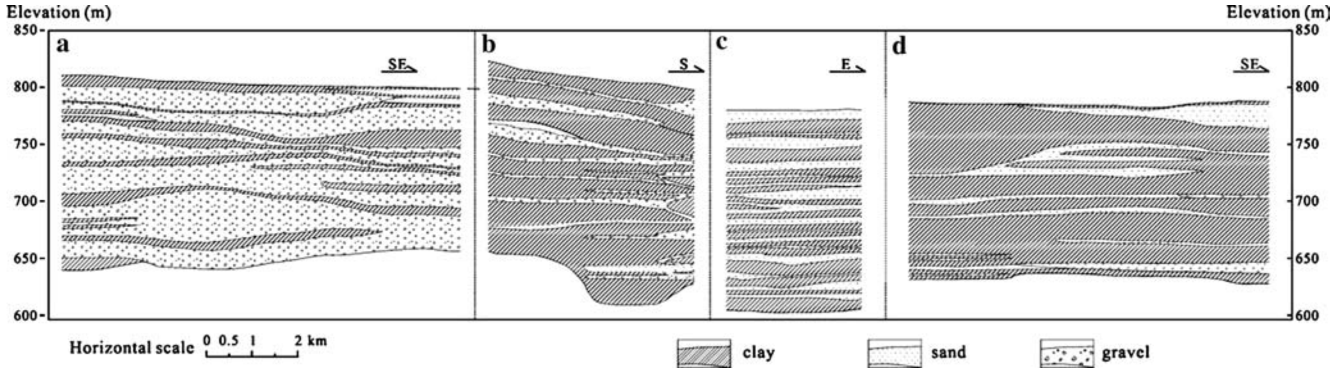

Fig. 6 Simplified cross-sections of the land subsidence centers at Xizhang sub-zone (**a**), Wanbolin and Xiayuan sub-zone (**b**), Wujiabao sub-zone (**c**) and Beiying sub-zone (**d**), showing the different clay layer stratigraphy

most compressible and plastic at Wujiabao, where the maximum land subsidence occurred. The heterogeneity of clay soil in compressibility and plasticity in different places at different depths is also an important factor controlling the spatial pattern of land subsidence.

Numerical modeling

The land subsidence at Taiyuan was simulated using a modular subroutine of MODFLOW (McDonald and Harbaugh 1988) called Interbed Storage Package-1 (IBS1) (Leake and Prudic 1991). The IBS1 package is based on the one-dimensional consolidation theory of Terzaghi. The principle of effective stress provides the link between groundwater withdrawal and subsidence. The IBS1 package calculates compaction based on changes in effective stress.

The major shortage of the IBS1 package in modeling land subsidence is its inability to directly consider the time lag of compaction. It is sufficient for aquifer systems with very thin compressible units and large model time steps, but thicker clay layers require a significant amount of time for pore pressures to dissipate. The same result can be achieved numerically by dividing the larger low conductivity units vertically into a number of smaller units (Larson et al. 2001). This approach was employed in this study.

Model cross-section

The following factors were considered in conceptualization of vertical model layers: stratigraphy, physical properties of sediments, deformation characteristics of soil layers, and hydrodynamic regime of groundwater. The strata were conceptualized as three sand layers and seven clay layers (Fig. 7). The 4th, 5th, 6th, and 7th clay layers were further subdivided into two sub-layers, respectively. In this way, 14 generalized layers were obtained in the model. The flow domain was discretized into 96 rows and 54 columns with an uneven nodal spacing of 250–1000 m in both the x- and y-directions. Groundwater depression cones and land subsidence centers were discretized with the densest grids.

Hydraulic conductivity of the boundary between the basin and surrounding mountains changes in different parts. The lateral recharge amount was estimated according to the hydrogeological parameters in different parts. In this way, the east, west, and north boundaries were treated as constant head boundaries, while the

Table 1 Statistical characteristic values for physical mechanics of the soils in different sub-zones and depths in Taiyuan city

Site	Depth	Natural water content (%)	Porosity ratio	Compression coefficient	Compression modulus	Plasticity index	Liquidity index
Xizhang	< 50 m	17.3–23.3	0.508–0.647	0.13–0.2	Not determined	7.6–8.1	0.42–0.66
	> 50 m	12.04–23.3	0.528–0.718	0.16–0.22	12.02–15.5	7.2–10.5	-0.99–0.42
Xiayuan-Wanbolin	< 50 m	Not determined	0.617–0.698	0.021–0.054	77.9–88.6	7.8–8.4	0.22–0.54
	> 50 m	17.5–23.1	0.546–0.82	0.021–0.18	53.2–81.2	8.2–13.8	0.43–0.62
Wujiabao	< 50 m	23.2–28.8	0.653–0.98	0.15–0.42	6.67–11.39	8.6–13.9	0.48–0.73
	> 50 m	20.3–26.7	0.662–0.89	0.14–0.35	8.1–15.75	9.7–16.2	0.49–0.97
Urban	< 50 m	22.4–29.3	0.488–0.759	0.07–0.24	6.73–11.37	9.5–14.4	0.57–0.74
	> 50 m	22.9–28.1	0.583–0.736	0.14–0.23	6.87–14.93	10.8–14.7	0.43–0.72
Beiying	> 50 m	17.9–24.8	0.656–0.765	0.15–0.19	9.7–12	8.5–14.8	0.5–0.6

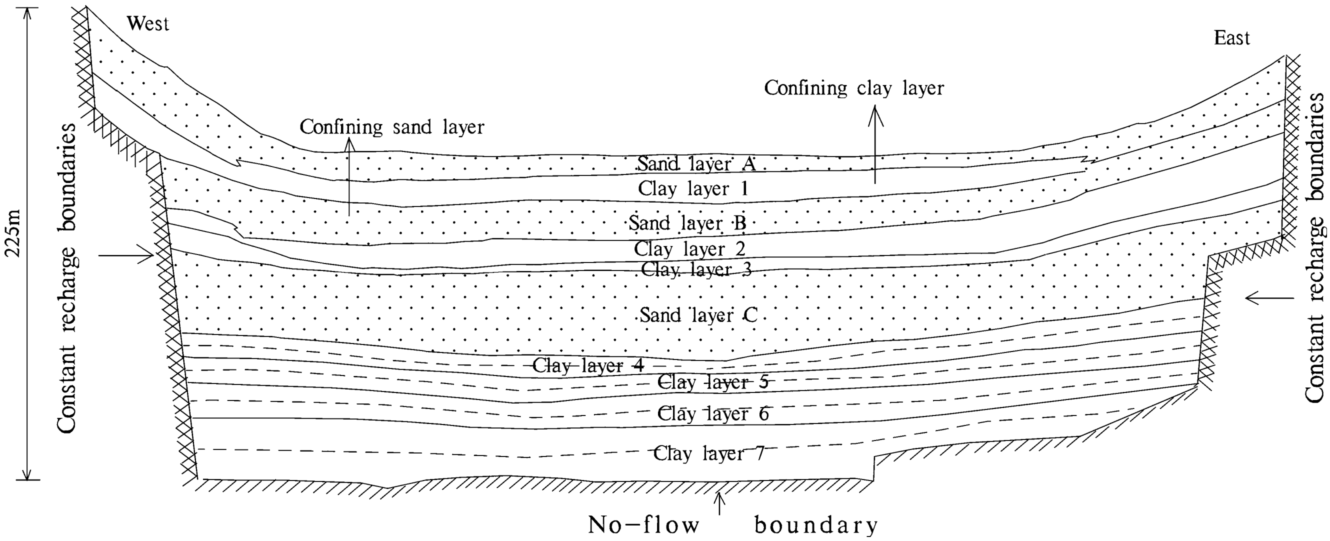

Fig. 7 Schematic model cross-section of Taiyuan city. The *dashed lines* inside the four bottom layers are dividing lines of sub-layers

south variable water head boundary. The bottom of the 225 m thick sedimentary sequence simulated is treated as a no-flow boundary, allowing drainage to occur only through the confined aquifers.

Model calibration

The model constructed in this study uses yearly stress periods because most of the data (water levels, subsidence rates, etc.) are only available at yearly intervals. Matching simulated piezometric head levels did calibration of the model and land subsidence with corresponding observed values at yearly intervals across the study area.

Most of the deep wells in Taiyuan penetrate more than one confined aquifer. The water level information from these wells is a mixed water level and the piezometric head data of individual aquifer are not available. Therefore, only the mixed water level was matched in the water level calibration. The calibration results for six monitoring wells located respectively in different groundwater depression cones of Taiyuan are satisfactory, as shown in Fig. 8.

Land subsidence at Taiyuan has been documented by bench marks, which only provide information about the total compaction of all layers, but not of individual layers. Accordingly, the present study only matches the simulated total compactions with corresponding observed values at each location. Only the data in 1981, 1982, 1985, 1987, 1989, 1992, 1994, 1997, and 2000 were available over the entire time period (1981–2000) because bench mark monitoring was conducted at irregular intervals. Fortunately, the time without observation data corresponds to a time of relatively persistent subsidence and shows no trend to rebound, and therefore it was assumed that the subsidence rate is equal to the average of the previous available rate data and the next available one. Calibrated model results versus observed subsidence for six monitoring wells are shown in Fig. 9.

Areal distribution of individual layer compression

As the layered subsidence data are unavailable, there has been no observed data about the areal distribution of individual layer compression at Taiyuan. To solve the problem, the above model is used to characterize areal distribution characteristics of compaction of different layers.

Under the same conditions, clay layer compaction is inelastic and much more compressible than sand layer. Therefore, only the clay layer is taken into consideration in the modeling. The results for the conceptualized seven clay layers are shown in Fig. 10.

Clay layer 1 Compression is up to 0.53 m, with the maximum at Wanbolin and Xiyuan.

Clay layer 2 Compression is up to 0.64 m. There are four compression centers for this layer: Xizhang, Wanbolin, Wujiabao, and Xiaodian. The maximum compression in Xiayuan and Wujiabao is 0.5 m and 0.64 m, respectively.

Clay layer 3 Compression is up to 0.2 m, with the maximum at Xizhang.

Clay layer 4–clay layer 7 Compressions are respectively up to 0.34, 0.41, 0.47, and 0.58 m. The major compression center is Wujiabao.

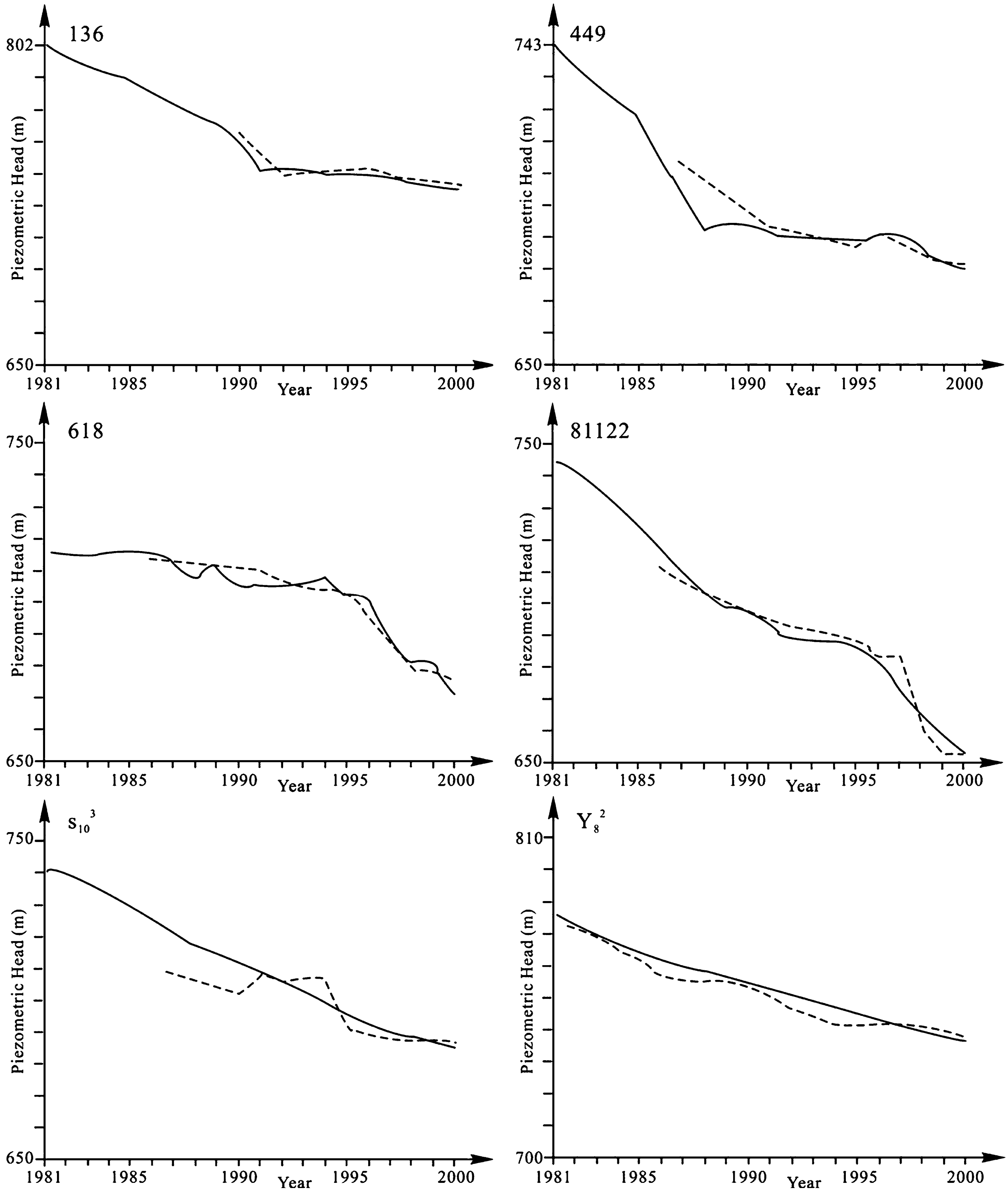

Fig. 8 Observed (*dashed lines*) and simulated (*solid lines*) piezometric heads at six monitoring wells at Taiyuan. The well locations are shown in Fig. 1

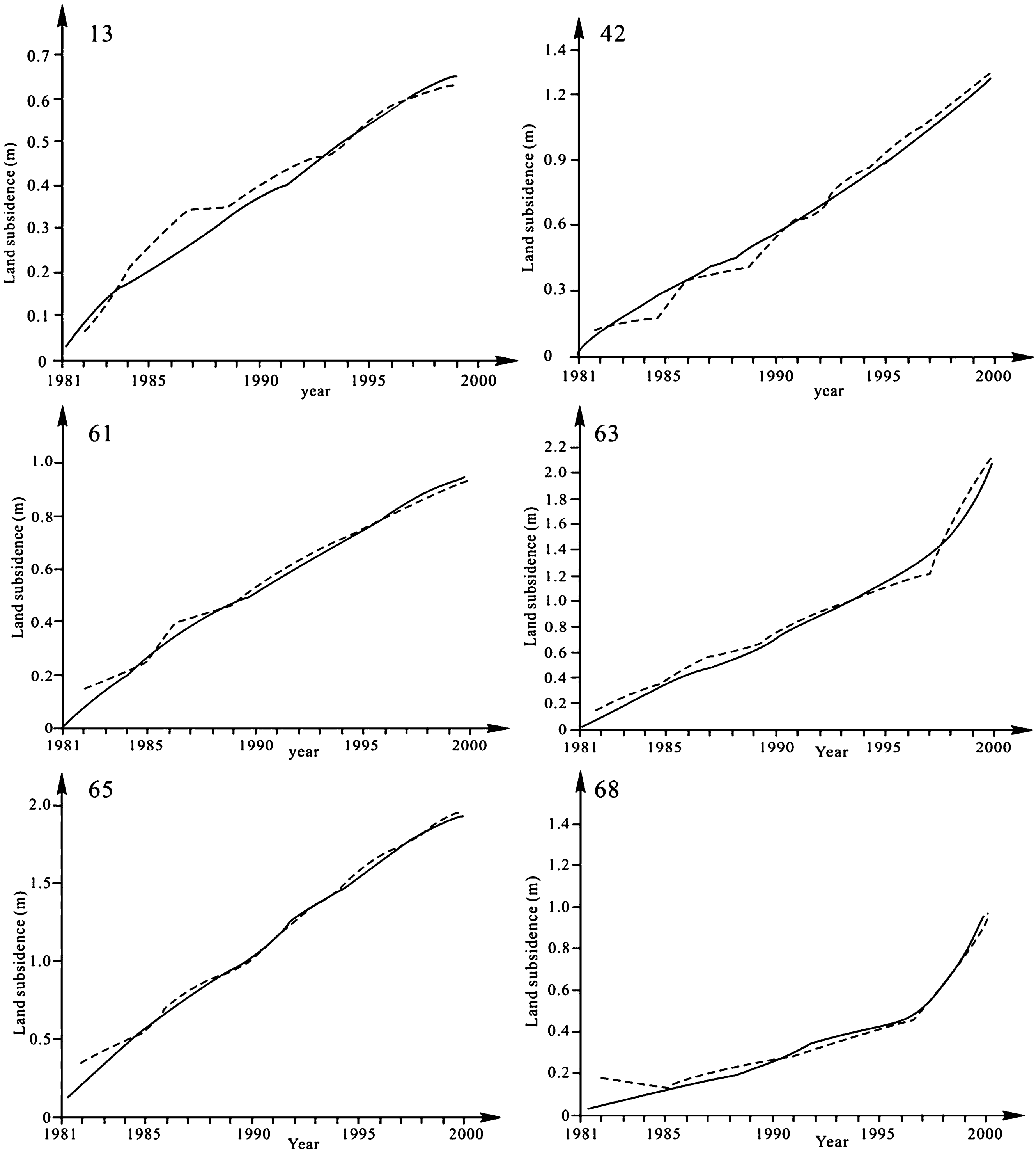

Fig. 9 Observed (*dashed lines*) and simulated (*solid lines*) land subsidence at six bench marks at Taiyuan. The locations of the bench marks are shown in Fig. 1

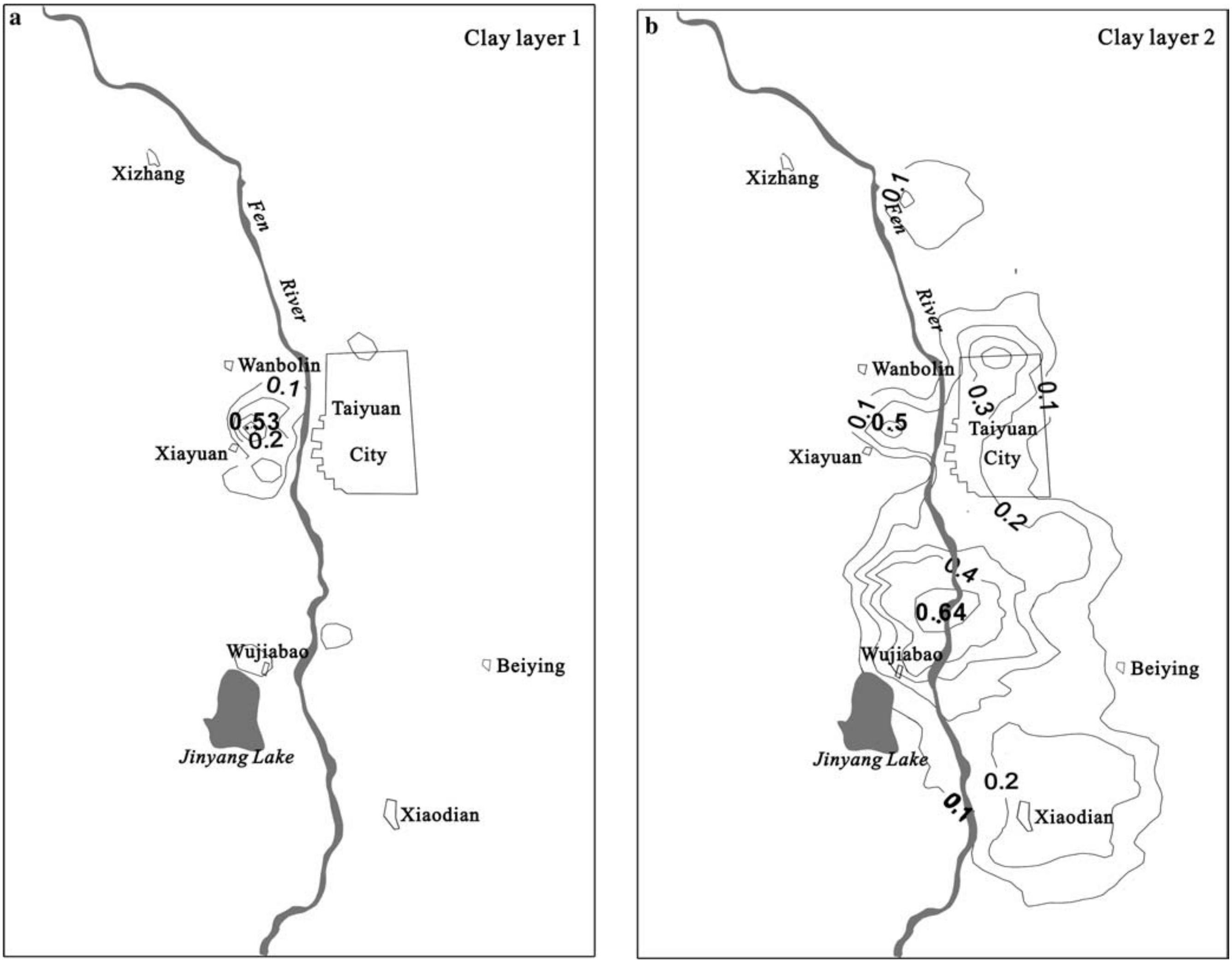

Fig. 10 Areal distribution of compression (m) of the seven conceptualized clay layers

Implications for groundwater management based on modeling results

It can be seen from Fig. 10 that compression of clay layers 1, 2, and 7 is greater than that of the other layers. Layer 3, layers 1 and 2, and layers 4, 5, 6, and 7 make major contribution, respectively, to the land subsidence at Xizhang, Wanbolin-Xiayuan, and Wujiabao-Xiaodian. Thus, in addition to water pumping, land subsidence depends on the properties, thickness, and configurations of clay layers.

To control land subsidence in Taiyuan, pumping wells should be more carefully managed. At Xizhang, pumping from the middle water-bearing zone should be avoided or strictly controlled as the zone is close to clay layer 3, which is the major contributor to land subsidence at Xizhang. At Wujiabao and Xiaodian where there occurs the maximum land subsidence, pumping from lower water-bearing layer close to clay layers 4, 5, 6, and 7 that are the major contributors to land subsidence should be avoided or controlled.

Conclusions

Land subsidence in Taiyuan city is caused mainly by over exploitation of groundwater from mid-lower aquifers. The spatial pattern of land subsidence, however, is not only controlled by the spatial distribution of groundwater withdrawal, but also affected by stratigraphic heterogeneity and properties of the geological formation. The major findings of this study on the control of stratigraphic heterogeneity on the spatial pattern of land subsidence at Taiyuan are as follows:

1. Land subsidence centers shift from the corresponding groundwater depression cones to the sides with thicker accumulated clay layers.

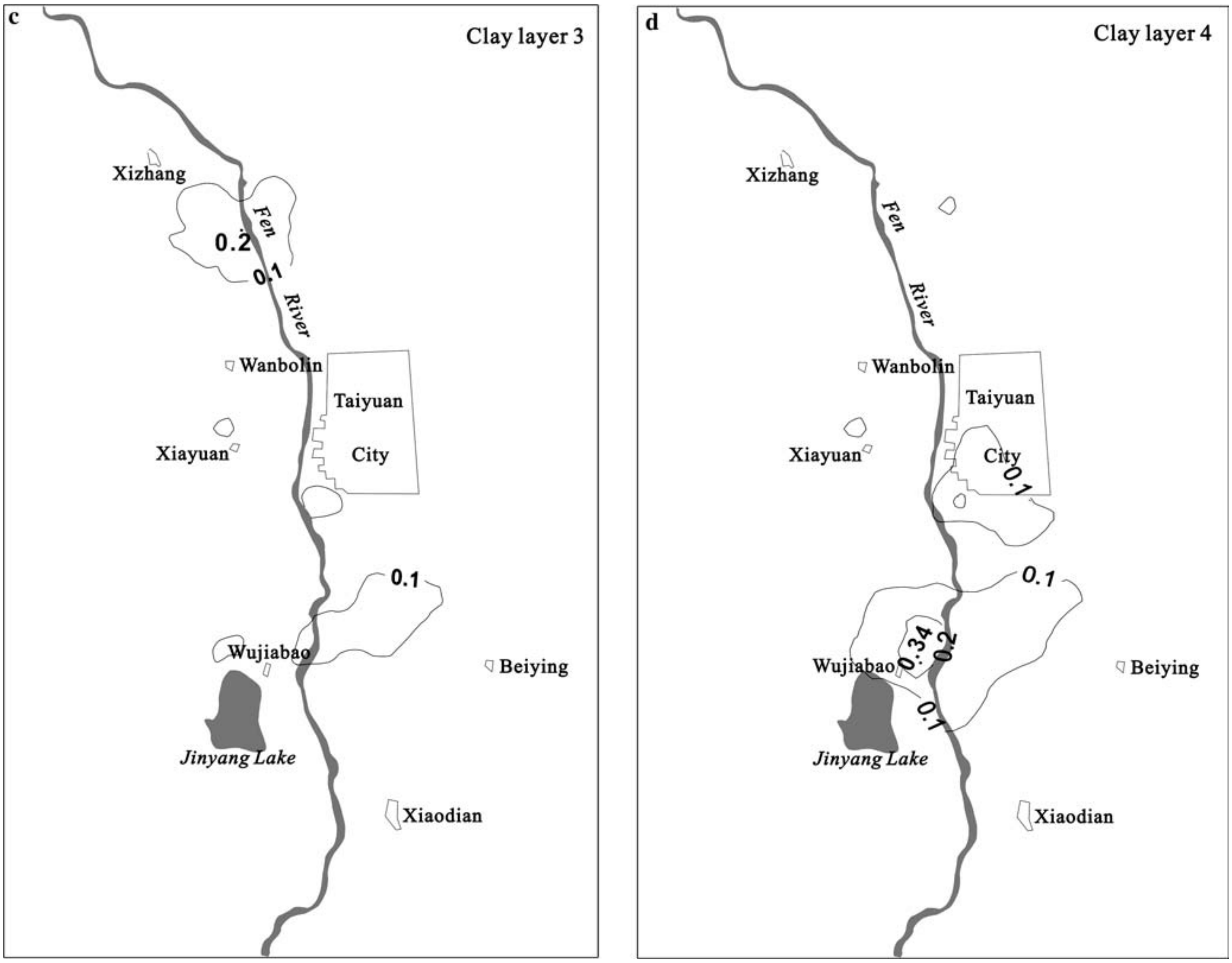

Fig. 10 (Contd.)

2. Under the same pumping rate, land subsidence at places with more thinner clay individual interlayers is greater and the lag time shorter.
3. Land subsidence is closely related with the physical properties of clay layers.

Simulation results of the areal distribution of individual clay layer compression using IBS1 show that the conceptualized clay layer 3, layers 1 and 2, and layers 4, 5, 6, and 7 make major contribution, respectively, to the land subsidence at Xizhang, Wanbolin-Xiayuan, and Wujiabao-Xiaodian. Pumping of groundwater from middle water-bearing zone in Xizhang and from the lower water-bearing zone in Wujiabao and Xiaodian should be under control or avoided.

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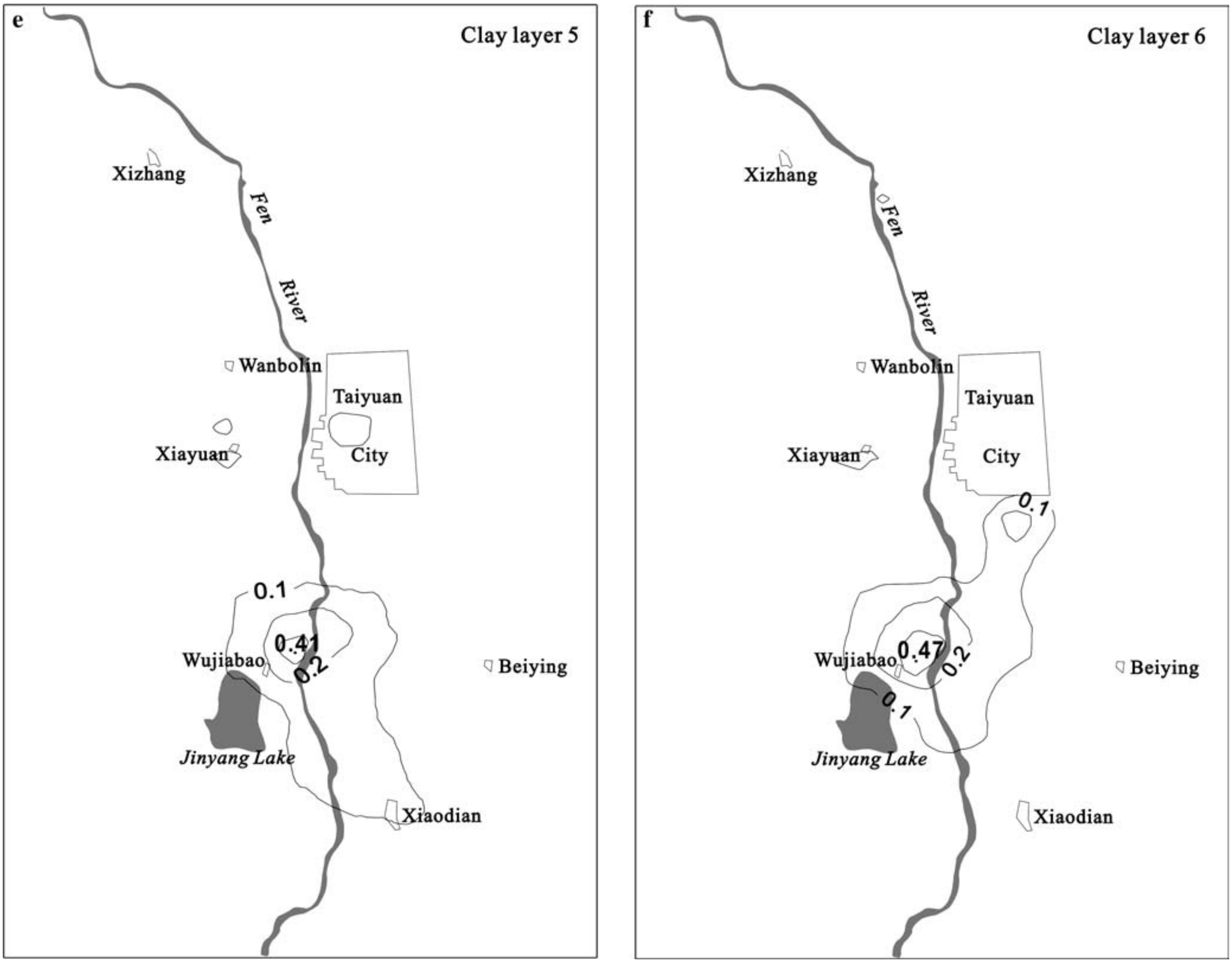
e
Clay layer 5
Xizhang
Fen
River
Wanbolin
Taiyuan
City
Xiayuan
0.1
0.41
0.2
Wujiabao
Beiying
Jinyang Lake
Xiaodian
f
Clay layer 6
Xizhang
Fen
River
Wanbolin
Taiyuan
City
Xiayuan
0.1
0.47
0.2
Wujiabao
0.1
Beiying
Jinyang Lake
Xiaodian

Fig. 10 (Contd.)

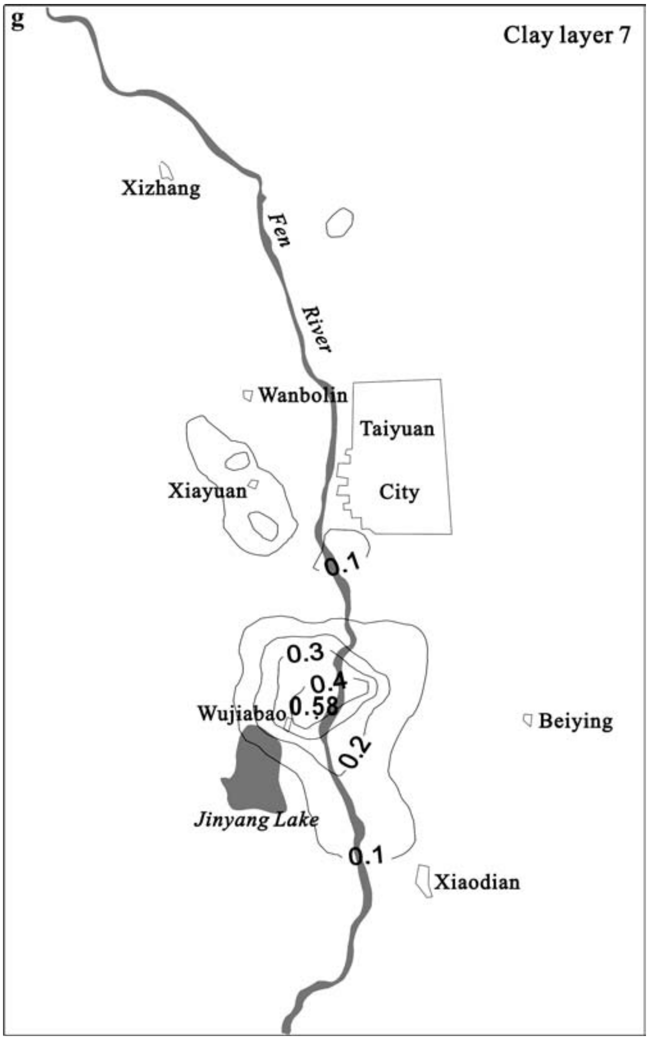

Fig. 10 (Contd.)

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