Land subsidence caused by groundwater exploitation in the Hangzhou-Jiaxing-Huzhou Plain, China

Changjiang Li · Xiaoming Tang · Tuhua Ma

Abstract Hangzhou-Jiaxing-Huzhou Plain in northern Zhejiang Province, located between the Yangtze and Qiantang Rivers, is one of the regions where economic development is most rapid in China. Geological and hydrogeological surveys reveal a multi-layered aquifer system beneath the plain, which includes Holocene phreatic water layers and Pleistocene confined aquifers. Based on the historical records of groundwater extraction, groundwater levels, and ground settlement from 1964 to 2000, it is shown that ground subsidence has resulted from the continuously increasing extraction of groundwater from deep confined aquifers, and that the evolution of land subsidence can be characterized by a multifractal model. Based on this model, a set of empirical power-law relations have been established between: the land subsidence velocity and the annual groundwater extraction; groundwater drawdown and the annual land subsidence velocity; and the amount of land subsidence and the associated area of land. A set of indices are proposed for evaluating dynamic evolution of groundwater exploitation and land subsidence for the Hang-Jia-Hu Plain, from which the critical degree of evolution of land subsidence in the near future can be estimated using data on groundwater exploitation and water level changes.

Résumé La plaine de Hangzhou-Jiaxing-Huzhou, située au Nord de la Province de Zhejiang, entre les rivières Yangtze et Qiantang, constitue l'une des régions de Chine où le développement économique est le plus rapide. Les reconnaissances géologiques et hydrogéologiques indiquent l'existence d'un système aquifère multicouche sous la Plaine, qui comprend les nappes phréatiques de l'Holocène et les aquifères captifs du Pléistocène. Les chroniques de prélèvements en eau souterraine, de niveaux piézométriques et de tassement des sols de 1964 à 2000 permettent de démontrer que les affaissements résultent de l'exploitation croissante des aquifères captifs profonds, et que leur évolution peut être caractérisée par un modèle multifractal. Un ensemble de fonctions puissance empiriques a été établi sur la base de ce modèle, entre la vitesse d'affaissement et les prélèvements en eau souterraine, entre les rabattements et la vitesse annuelle d'affaissement, et entre l'affaissement total et la surface concernée. Une série d'indices est proposée pour évaluer l'évolution des prélèvements en eau souterraine et des affaissements sur la Plaine de Hang-Jia-Hu. Ils permettent d'estimer le niveau critique d'évolution des affaissements à court terme, à partir des données de prélèvements en eau souterraine et de suivi des niveaux piézométriques.

Resumen La Planicie Hangzhou–Jiaxing–Huzhou ubicada al norte de la Provincia Zhejiang y que se localiza entre los ríos Yangtze y Qiantang es una de las regiones donde el desarrollo económico es más rápido en China. Los levantamientos geológicos e hidrogeológicos muestran un sistema de acuíferos de varias capas que subyace la Planicie el cual incluye capas acuáticas freáticas Holocénicas y acuíferos confinados Pleistocénicos. En base a registros históricos de explotación de agua subterránea, niveles de agua subterránea, e información sobre colonización de 1964 a 2000 se muestra que la subsidencia del terreno ha sido ocasionada por la continua y ascendente extracción de agua subterránea en acuíferos confinados profundos, y que la evolución del hundimiento del terreno puede caracterizarse mediante un modelo multifractal. En base a este modelo se han establecido un conjunto de relaciones empíricas de potencia-ley entre: la velocidad de subsidencia del terreno y la extracción anual de agua subterránea; descenso de agua subterránea y velocidad anual de subsidencia del terreno; y la cantidad de hundimiento del terreno y el área asociada del terreno. Se ha propuesto un grupo de índices para evaluar la evolución dinámica de la explotación de aguas subterráneas y el hundimiento del terreno en el futuro cercano

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para la Planicie Hang–Jia–Hu. Los índices elaborados permiten estimar, usando datos de explotación de agua subterránea y cambios en niveles de agua, el grado crítico de evolución de subsidencia del terreno en el futuro cercano.

Keywords Subsidence · Numerical modeling · Over-abstraction · Fractal analysis · Zhejiang Province

Introduction

Land subsidence caused by heavy exploitation of groundwater, oil or natural gas has brought serious environmental problems in numerous regions all over the world. These problems include but are not limited to: (1) distorting the elevation and the slope of streams, canals, and drains, resulting in serious impacts on urban planning and environment protection; (2) damaging bridges, roads, railroads, canals, sanitary sewers, and levees; (3) reducing the capacity of storm drains and flood control works in urban districts thus increasing the frequency and impact of floods; (4) damaging private and public buildings; and (5) increasing the pollution of water and soil. In some coastal areas, subsidence has resulted in tides moving into low-lying areas that were previously above high-tide levels (Leake 2004).

Land subsidence due to human activities has been extensively investigated (Pratt and Johnson 1926; Poland and Davis 1969; Lewis and Schrefler 1978; Bell et al. 1986; Geertsma 1973; Poland 1984; Finol and Sancevic 1995; Wahyudi 2000; Abidin et al. 2001; Chen et al. 2003; Ferronato et al. 2003; Leake 2004, and many others). Bell et al. (1986) and Gelt (1992) ascribed such subsidence, resulting from groundwater extraction, to the compaction and consolidation of sedimentary grains as the result of increasing effective stress. As water is pumped out from a confined aquifer, the effective pressure increases and the grains in the porous medium become more tightly packed. With continued pumping of groundwater without adequate recharge, the sediments become increasingly compressed and the land starts to settle or subside. Thus, a conclusion can be drawn that this kind of land subsidence caused by groundwater exploitation must have at least two basic conditions: presence of compressible sediment layers and a drop of the regional groundwater level. A quantitative study on the relationships between (1) the land subsidence velocity and the annual groundwater extraction, (2) groundwater drawdown and annual land subsidence velocity, (3) the amount of land subsidence and the associated area of land, is crucial for simulating land subsidence and formulating policies to prevent land subsidence hazards.

There are some important cities and districts in the southeast coast of China such as the Hang-Jia-Hu Plain (the plain area around Hangzhou, Jiaxin, and Huzhou), Suzhou, Shanghai and Tianjin. These cities and districts have reported increasingly severe land subsidence due to extensive groundwater exploitation. The Hang-Jia-Hu Plain is located between the lower reaches of the Yangtze River and the Qiantang River in the northern Zhejiang Province, south of Shanghai City and Jiangshu Province. The total area of the Plain is about 6,490 km^2 (Fig. 1).

The Hang-Jia-Hu Plain is one of the most concentrated areas in terms of population and one of the most developed areas in China. The plain has severely suffered from land subsidence. For example, Jiaxin City, located in the middle of this land subsidence area, has gone through a period from rapid to slow subsidence since the 1960s, but the subsiding area has still kept expanding in recent years. By the end of 2002, the maximum accumulative subsidence in the city zone has reached 842 mm, and the entire city has subsided at least 400 mm. The total area with an accumulative subsidence larger than 200 mm is 883 km^2, and the area with more than 100 mm is 2,500 km^2. The subsidence region of the plain is adjacent to the subsidence zones in Suzhou and Shanghai, thus it has brought great harm to the economic and social development of the Yangtze Delta area. At present, the

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Fig. 1 **a** Location of the Hang-Jia-Hu Plain in eastern China, and **b** the study area with cross-section line (see Fig. 3)

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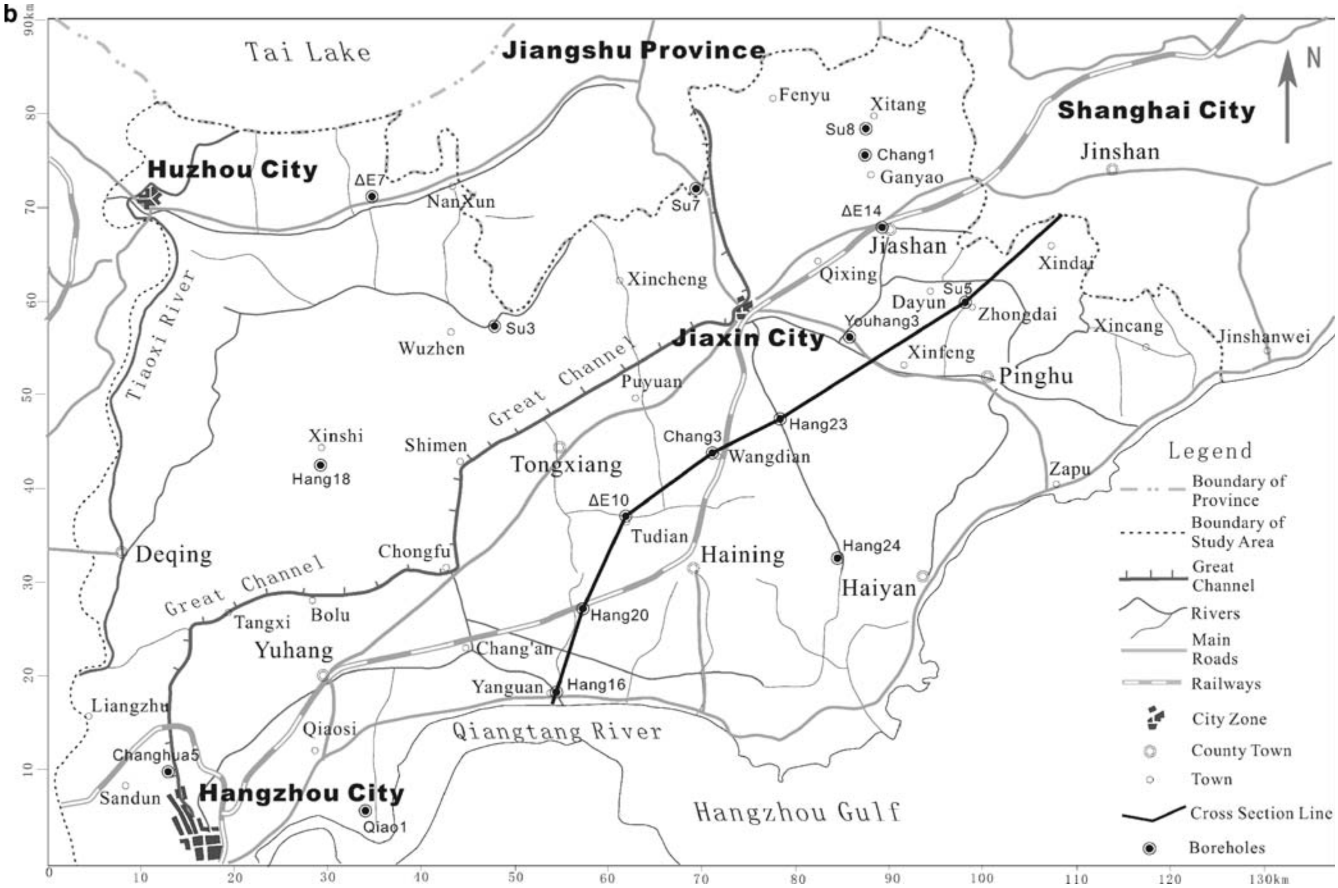
Fig. 1 (continued)



subsidence rate in most areas in the plain is over 20 mm/year. In particular, the rate at the town of Tudian and the city of Pinghu exceeds 50 mm/year. Severe land subsidence in the plain has become a major hazard, which mainly results in distorting the elevation, reducing the capacity of storm drains and flood-control works in urban districts, thus increasing the frequency and impact of floods, damaging private and public buildings, and increasing the pollution of water and soil.

Because of the annual variation in groundwater extraction as well as the heterogeneity of aquifer properties in regards to material composition, structure, and texture, and different surrounding strata; the relationships between the land subsidence rate and exploitation quantities may not be linear, and it may be difficult to describe these relationships by traditional analytical methods. Fractal geometry, developed and popularized by Mandelbrot (1983), has been widely applied to many fields of geosciences (Turcotte 1986; Bölviken et al. 1992; Barton and Scholz 1995; Crovelli and Barton 1995; Li et al. 1999, 2002–2004, among others). However, the fractal method is seldom used in the study of land subsidence resulting from groundwater exploitation. The purpose of this study is to investigate the characteristics, patterns, and mechanisms of ground subsidence in the Hang-Jia-Hu Plain and to establish some empirical power-law relationships among some factors related to land subsidence, using the fractal method.

Geologic and hydrogeologic background

Quaternary strata

The Hang-Jia-Hu Plain is mainly covered by Quaternary sediments which are characterized by coarse-grain alternated with fine-grain, one sediment layer overlapping another from the bottom to the top. The thickness of Quaternary sediments is controlled tectonically by a series of down-warped areas separated by uplifts and increases from the southwest to the northeast (Figs. 2 and 3). For instance, the thickness varies from 50 m in Hangzhou-Deqing-Huzhou districts in the plain to more than 300 m in areas nearby Shanghai and Jiangshu.

According to surface surveys, boreholes logs and subsurface geophysical investigation (Zhejiang Geological and Environmental Monitoring Station 2000), the Quaternary sediments in the plain can be divided into four stratum units (from the deepest to the land surface): Lower Pleistocene Series (Q_1), Middle Pleistocene Series (Q_2), Upper Pleistocene Series (Q_3), and Holocene Series (Q_4). The main geologic and hydrogeologic characteristics of the stratum system are summarized in Table 1 and Fig. 3.

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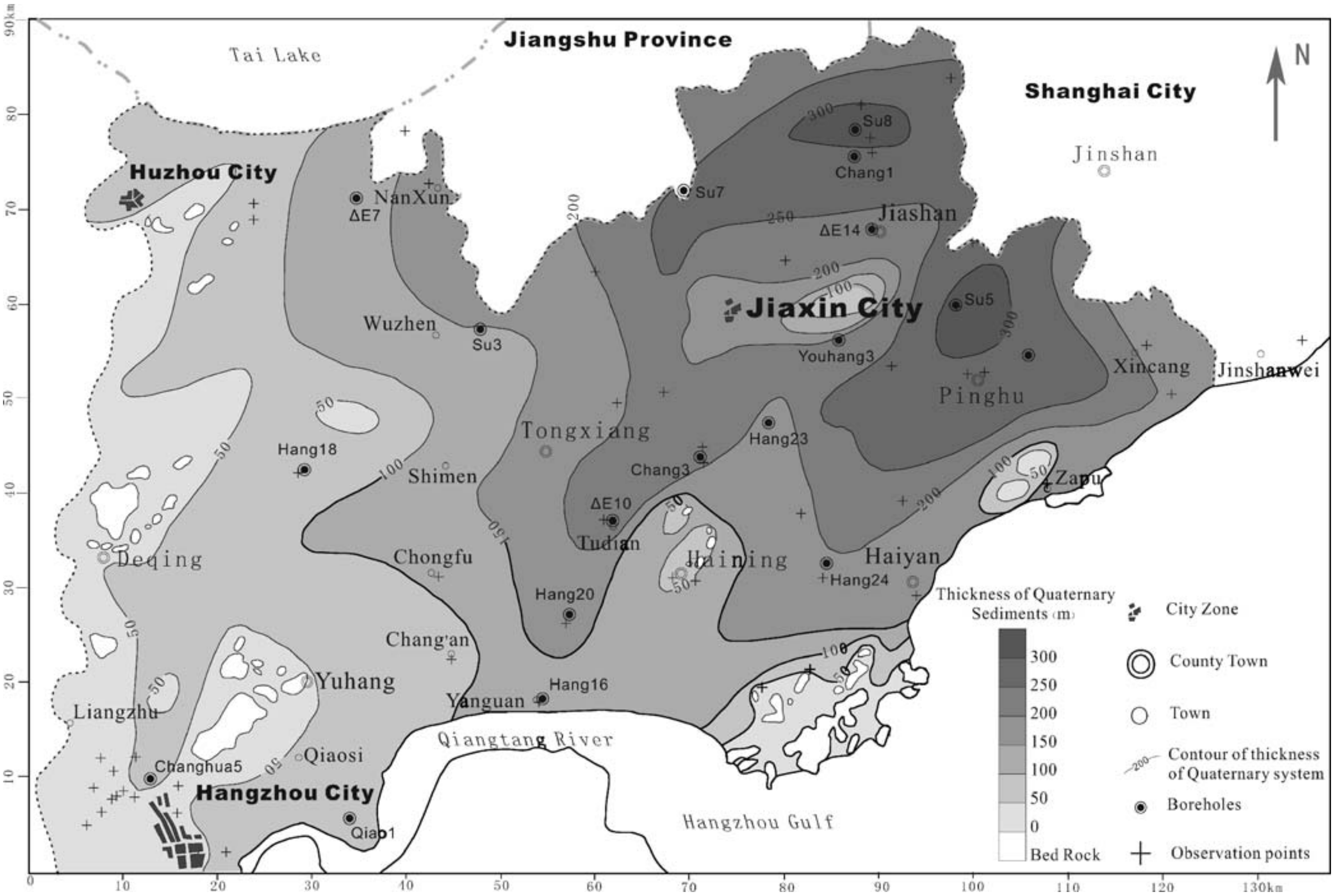

Fig. 2 Contour map of thickness of Quaternary sediments in the Hang-Jia-Hu Plain, Zhejiang, China (modified after Zhejiang Province Dept. of Land and Resources 2002)

Spatial characteristic of aquifers

Figure 3 and Table 1 show the spatial distribution of four aquifers from the superficial to the deep, i.e., Holocene phreatic water layers, Upper Pleistocene confined aquifer, Middle Pleistocene confined aquifer, and Lower Pleistocene confined aquifer. There are two Holocene phreatic water layers (unconfined aquifers) in the area. Both the aquifers are widely distributed in the plain with a thickness of 0.5–5 m and low water yield. These pore phreatic water layers mainly consist of mild clay, silty clay, sandy clay, and silt and fine sand, which are deposited in the mouth of the river and in fluvio-lacustrine environments.

The spatial distribution of the Upper Pleistocene confined aquifer (confined aquifer I in Fig. 3) is controlled by three ancient stream channels distributed along the northeast direction. The first starts at Hangzhou, passes along Bolu, Xinshi, Wuzhen, Xincheng, Fenyu, and finally reaches Jiangshu. The second branches off from the first at Puyuan, Tongxiang, passes through Jiaxing, Dayun, Xindai, and enters Shanghai. The third starts at Yanguan, passes Haiyan, and finally enters into the Gulf of Hangzhou. The depth of the upper boundary of this aquifer varies from 23 to 60 m. The confined aquifer, comprising mainly silt, medium to fine sand, sandy clay, and silty clay with gravel, can be divided into two sub-aquifers by silty clay and clay zones with thickness ranging from 10 to 30 m. The two sub-aquifers range from 2 to 38 m and from 3 to 26 m in thickness, respectively.

The Middle Pleistocene confined aquifer (confined aquifer II) is also under the control of ancient stream channels, and has three water-yield zones. The first is an ancient stream channel of Qiangtang River and Tiaoxi River starting at Yanguan and Puyuan, ending at Xitang via Jiaxing. The second is an ancient stream channel going south to Qingtang River and the Gulf of Hangzhou, passing through Pinghu and entering Shanghai. The third is an ancient stream channel of Tiaoxi River along Tangxi, Shimen, Wuzhen, and Xincheng, finally reaching Jiangshu. The depth of upper boundary of this aquifer varies from 60 to 120 m. The aquifer mainly consists of sand with gravel and fine to mild sand, and is separated by a low permeability clay zone of 10–50 m in thickness into two sub-aquifers with thickness ranging from 5 to 32 m and from 10 to 40 m, respectively. The Middle Pleistocene confined aquifer is the main aquifer of groundwater exploitation in the plain.

Lower Pleistocene confined aquifer (confined aquifer III) has two water-rich zones: one from Jiaxin, Qixing, Ganyao to Shanghai, and the other from Xinfeng, Pinghu,

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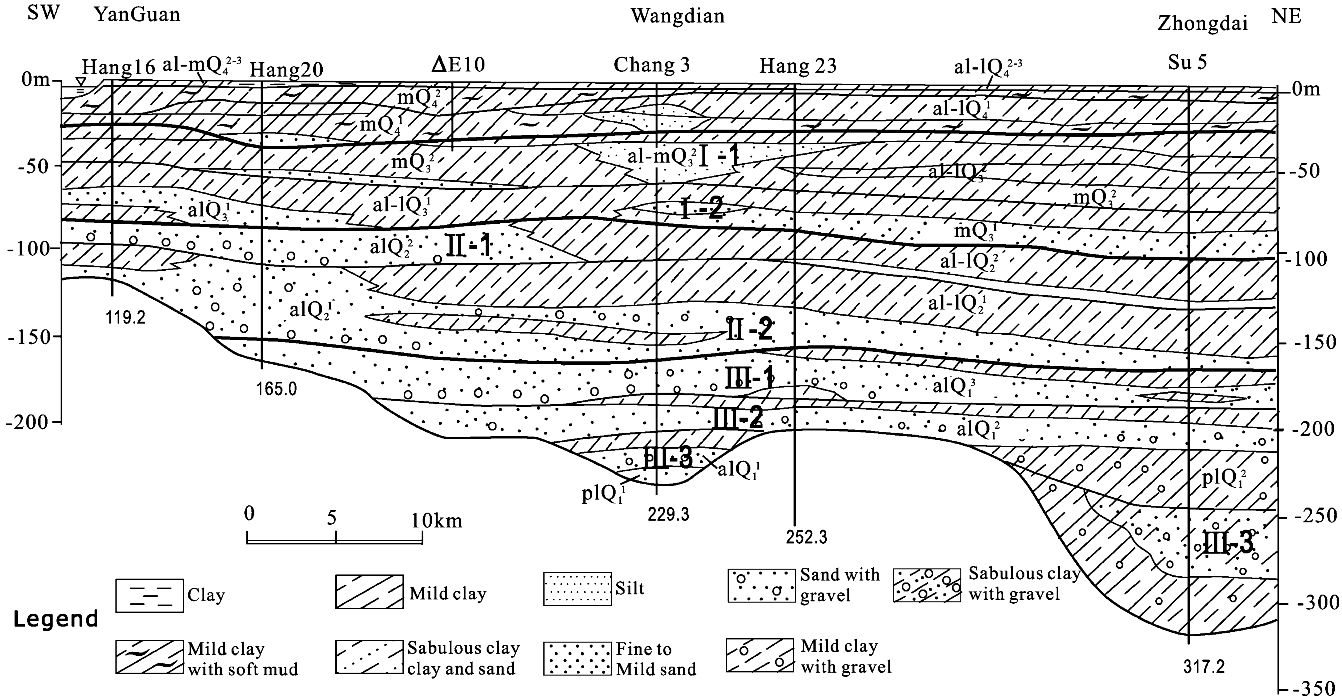

Fig. 3 Hydrostratigraphy along the cross section of Yanguan-Wangdian-Zhongdai (modified after Zhejiang Province Dept. of Geology and Mineral Resources 1987). The location of the cross section is given in Fig. 1b

Xincang to Shanghai. The depth of upper boundary of this aquifer varies from 140 to 170 m. The aquifer comprises mainly medium to fine sand, gravel, and clay-bearing gravel, and can be separated into three sub-aquifers by two lower permeability clay zones (with thickness ranging from 2 to 8 m and from 30 to 62 m, respectively). The three sub-aquifers exhibit great variations in thickness, ranging from 3 to 20, 8 to 51, and 13 to 60 m, respectively.

Recharge and discharge of groundwater system

Located in the subtropical monsoon zone, the weather in the Hang-Jia-Hu Plain is mild and humid. Abundant annual rainfall of 1,000–1,300 mm in the plain makes it possible for the precipitation seepage to become the main recharge to shallow groundwater (unconfined aquifers), and numerous lakes and rivers spreading in the plain, including the Great Channel, also supply water to the unconfined aquifers.

According to Zhejiang Geological and Environmental Monitoring Station (2000), ^{14}C ages of two water samples from the confined aquifer II are 20935±90 years and 21,335±185 years, respectively, and those from the confined aquifer III are 26,950±530 years and >37,000 years, respectively. It is shown that the groundwater in those two aquifers belongs to “palaeowater” trapped before the Holocene Epoch.

The three confined aquifers are separated by quite stable aquitards and covered by widely distributed, thick, less permeable clay layers of soft mud sediments (permeability of 10^{-5}–10^{-7} m/day in the direction perpendicular to bedding). These aquitards and clay layers obstruct the infiltration of surface water and phreatic water. The confined aquifers have no escape orifice toward the sea and lower reaches. The confined aquifers II and III have slightly permeable boundaries with some piedmont sediment in upper reaches or basement rocks. Though the confined aquifer I has a little connection with phreatic water along some river valleys, its seepage velocity is extremely low due to a very small hydraulic gradient, resulting only in a very slight leak. Accordingly, these confined aquifers in the plain belong to a kind of sealed hydrogeologic structure without adequate recharge, and, therefore, exploitation using deep wells is the main draining mode of water in these confined aquifers. From 1964 to 2000, 268,405×10^4 m^3 groundwater had been pumped from the confined aquifer system for industrial, domestic, and agricultural purposes.

Monitoring regional groundwater level and land subsidence

For confined aquifers that are almost sealed in natural conditions, deep well pumping becomes a main discharge path and is the main reason for the drying up of groundwater resources in these areas. Table 2 lists the statistical data of groundwater withdrawal in the Hang-Jia-Hu Plain from 1954 to 2000. However, monitoring the groundwater level and the land subsidence was not carried out until 1964 by Zhejiang Provincial Bureau of Geology and Minerals. There are a total of 58 wells for monitoring

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Table 1 Quaternary sedimental strata and hydrostratigraphy in Hang-Jia-Hu Plain (see Fig. 3)

Series	Symbol	Deposition environment	Description	Aquifer type	Thickness (m)
Holocene	Q_4^{3-2}	River mouth	Gray yellow mild clay, silty clay, sandy clay, and silt	Unconfined aquifer (pore phreatic water)	0.5–5
	Q_4^{3-1}	Littoral	Gray green to brown yellow mild clay, soft to plastic		2–10
	Q_4^{2-2}	Fluvio-lacustrine	Gray yellow mild clay, silty clay, silt, and fine sand	Unconfined aquifer (pore phreatic water)	0.5–5
	Q_4^{2-1}	Epeiric sea	Gray mild clay and silty clay, soft to plastic		4–20
	Q_4^{1}	Fluvio-lacustrine Epeiric sea	Gray yellow mild clay, soft to plastic Gray silt and silty clay, plastic		5–28
Upper Pleistocene	Q_3^{2-2}	Fluvio-lacustrine	Gray green and brown yellow mild clay, hard		3–18
	Q_3^{2-1}	River mouth	Gray silt, medium to fine sand, and silty clay with gravel	Confined aquifer I-1	2–38
	Q_3^{1-2}	Fluvio-lacustrine	Gray silty clay and clay, hard		10–30
	Q_3^{1-1}	Fluvial and littoral	Gray silt, medium to fine sand, and sandy clay with gravel	Confined aquifer I-2	3–26
Middle Pleistocene	Q_2^{2-2}	Fluvio-lacustrine	Motley clay, hard		15–37
	Q_2^{2-1}	Fluvial	Gray medium to fine sand and gravel	Confined aquifer II-1	5–32
	Q_2^{1-2}	Fluvio-lacustrine	Motley clay, hard		10–50
	Q_2^{1-1}	Fluvial	Gray to gray yellow gravel-bearing medium to coarse sand, and gravel	Confined aquifer II-2	10–40
Lower Pleistocene	Q_1^{3-2}	Fluvio-lacustrine	Motley clay, hard		6–18
	Q_1^{3-1}	Fluvial	Gray yellow to dark yellow gravel-bearing medium to coarse sand, and gravel	Confined aquifer III-1	3–20
	Q_1^{2-2}	Fluvio-lacustrine	Motley clay, hard		2–8
	Q_1^{2-1}	Fluvial	Gray medium to fine sand, gravel, and clay-bearing gravel	Confined aquifer III-2	8–51
	Q_1^{1-2}	Fluvio-lacustrine	Motley clay, hard		30–62
	Q_1^{1-1}	Diluvial and proluvial	Gray yellow to dark yellow medium to fine sand, gravel, clay-bearing gravel	Confined aquifer III-3	13–60

Data resource: modified after Zhejiang Geological and Environmental Monitoring Station (2000)

the groundwater level, with 22, 29 and 7 wells in the first, second, and third confined aquifers, respectively. The water level is measured every 10 days at observation boreholes as shown in Fig. 2. All the extraction wells are gauged and the pumping rates have been recorded since 1964. About 45 ground-level marks, most of which are located in Jiaxin City, are surveyed every year. The annual groundwater withdrawal and the rate of land subsidence from 1964 to 2000 in Jiaxin City are shown in Fig. 4. The figure shows that the trends of two curves are similar, indicating that the land subsidence in the plain is certainly related to groundwater exploitation and such a relation is nonlinear. The change of the annual land subsidence rate obviously lags behind that of the annual groundwater mining. For example, the amount of groundwater mining reached its maximum in 1982 (2077×10^4 m^3), while the maximum rate of land subsidence in 1989 (greater than 50 mm/year). This phenomenon can be explained as follows. Because the widely distributed, thick, low-permeability clay layers lie on the confined aquifers that are separated by quite stable aquitards, there is a time lag between the drop of regional groundwater level and the volume reduction of soft clay stratum (i.e., land subsidence) resulting from the release of water in those clays. As discussed by Jacob (1940), because of the low permeability of clays (or shales), there is a time lag

Table 2 Groundwater extraction in the Hang-Jia-Hu Plain from 1954 to 2000

Exploitation phases (year)	Total pumping (10^4 m^3)	%	Six major towns		Small towns and villages	
			Pumping (10^4 m^3)	%	Pumping (10^4 m^3)	%
1954–1963	4,455	1.6	4,129	93.7	326	7.3
1964–1972	15,616	5.7	12,389	79.3	3,227	20.7
1973–1988	97,008	35.6	58,296	60.1	38,712	39.9
1989–1996	10,4522	38.3	38,914	37.2	65,608	62.8
1997–2000	51,259	18.8	10,731	20.9	40,528	79.1
Total	272,860	100	124,459	45.6	148,401	54.4

Data source: (Zhejiang Geological and Environmental Monitoring Station 2000)

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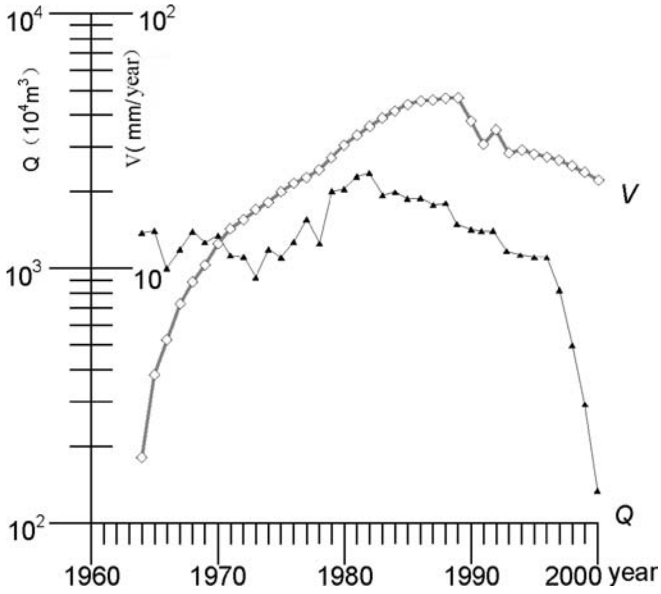

Fig. 4 Comparison between the amount of groundwater mining (Q) and the velocity of land subsidence (V) from 1964 to 2000 in Jiaxin City, Zhejiang, China (source of raw data: Zhejiang Geological and Environment Monitoring Station 2000)

between the lowering of pressure within the aquifer and the appearance of that part of the water which is derived from storage in those clays (or shales). Moreover, because clay layers are highly compressible compared to the clastic sand or sand and gravel of the aquifers and this compaction is an irreversible inelastic deformation, though the amount of groundwater mining is rapidly reduced after 1996, the rate of land subsidence did not respond as quickly to the decrease of groundwater extraction (see Fig. 4).

According to available monitoring data, it is believed that the original regional groundwater levels in all confined aquifers are about the same in the whole plain and they are near the land surface. Because these confined aquifers lack significant recharge, unplanned groundwater exploitation leads to continual lowering of groundwater levels. Figure 5 shows the water level contours for the second aquifer (II) and the third aquifer (III) in 1980. The contour map of the accumulative land subsidence in the plain from 1964 to 2001 (Fig. 6) shows that there are obvious subsidence centers at Jiaxin, Tongxiang, and Chongfu.

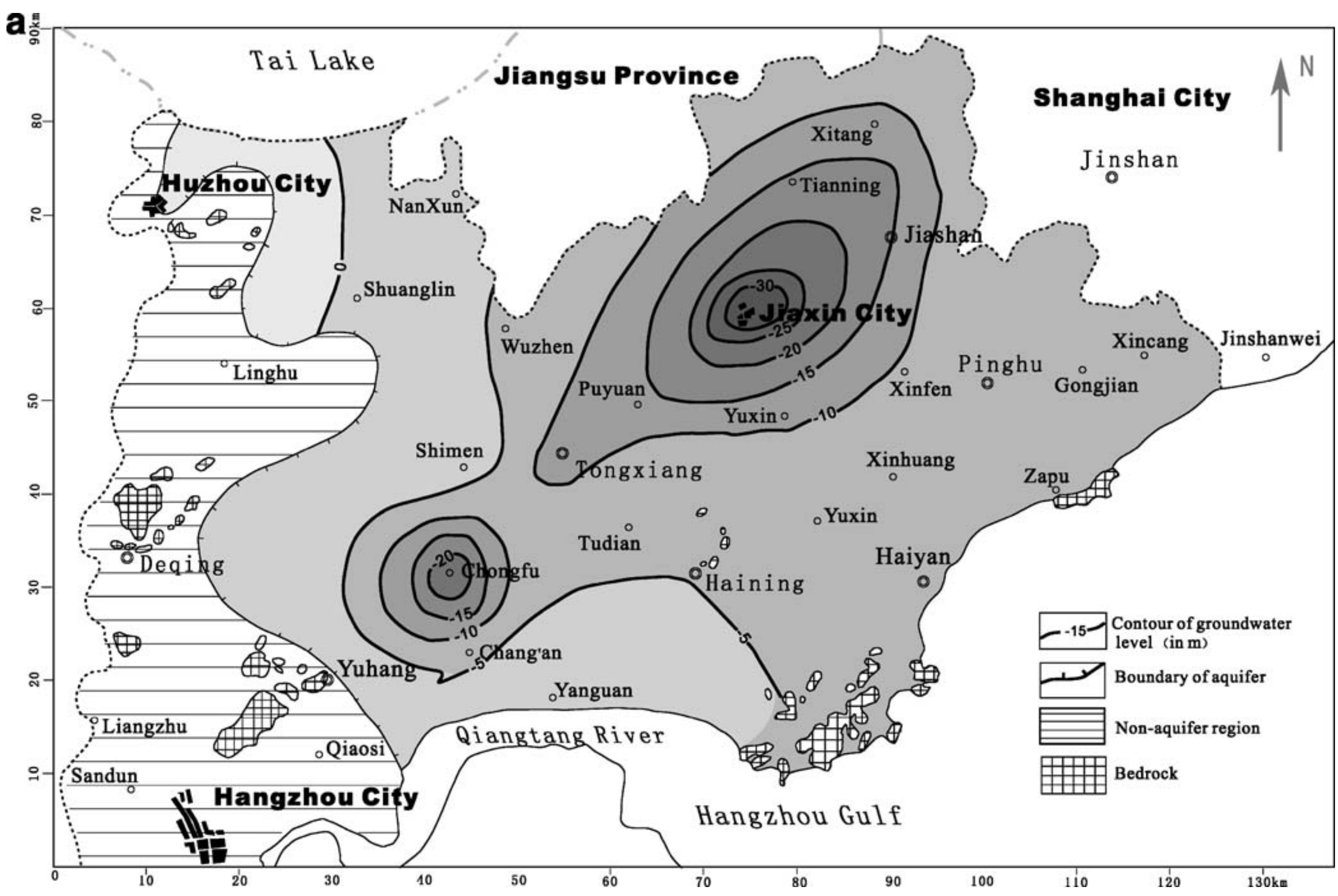

Fig. 5 Contour maps of the water level (in meters relative to sea level, Yellow Sea height system) for **a** confined aquifer II and **b** confined aquifer III in 1980 in the Hang-Jia-Hu Plain, Zhejiang, China (data source: Zhejiang Geological and Environmental Monitoring Station 2000)

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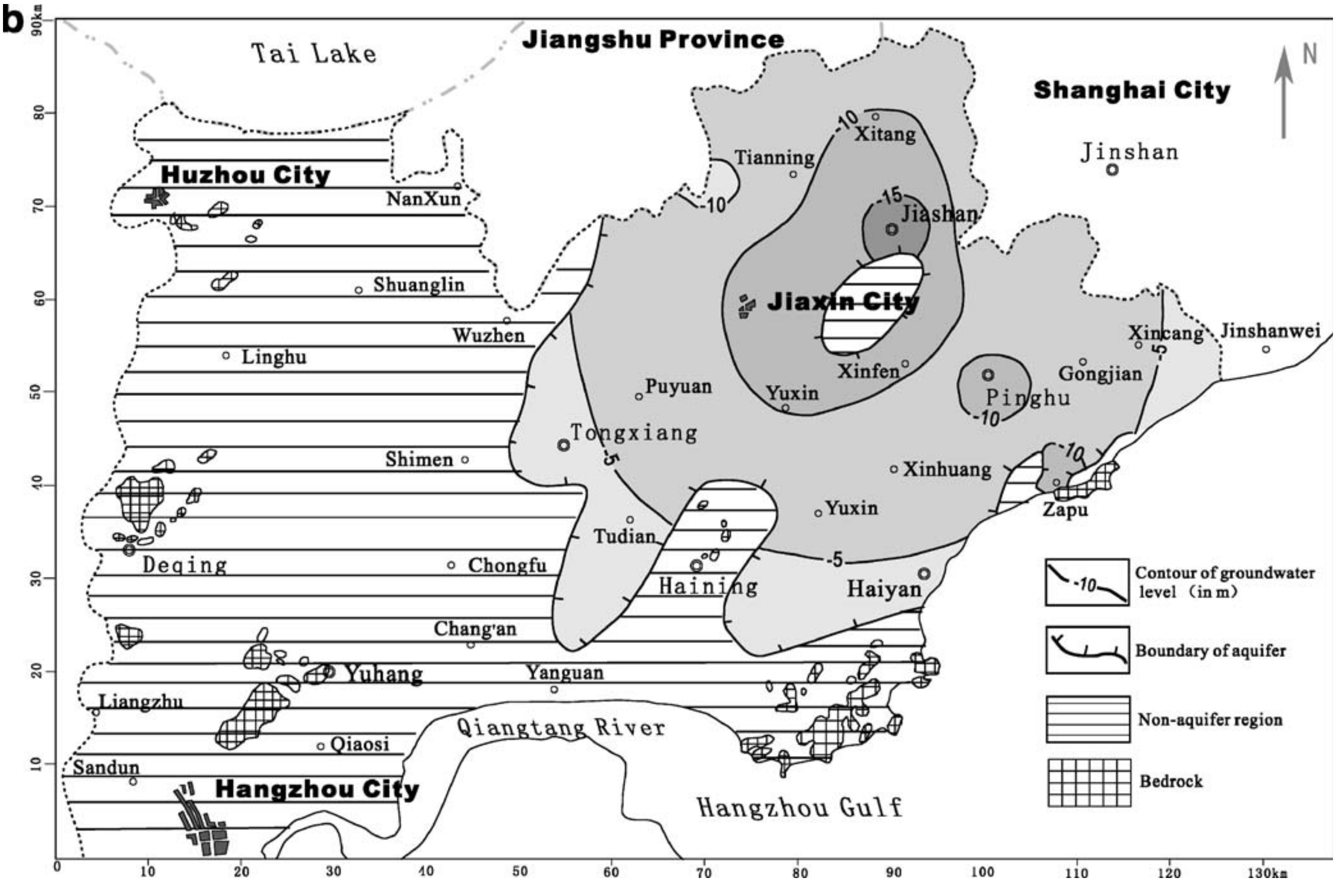
Fig. 5 (continued)



Fractal analyses on the relation of land subsidence to groundwater exploitation

The existing methods for predicting land subsidence are based mainly on the mechanics of continuous medium (De Waal and Smits 1985, among others). Moreover, many statistical procedures including fitting of quadratic function, exponential or logarithmic function, and some semi-theoretical approaches (Vega and Yamamoto 1984), have also been used to evaluate the relationship between groundwater exploitation and land subsidence and to estimate the subsidence rate in the near future.

However, regional subsidence caused by groundwater extraction is a complex phenomenon. Table 2 shows that the annual groundwater extraction in the Hang-Jia-Hu Plain is temporally and spatially non-uniform. As stated above, there are several aquitards with clays among the confined aquifers that are covered by widely distributed, thick, soft mud layers (see Table 1 and Fig. 3). Due to the complexities of the materials involved, whose mechanical parameters are anisotropic, and the lack of knowledge on the mechanical properties of the materials and groundwater flow field, it may be difficult to describe quantitatively the dynamic relationship between the groundwater exploitation and the land subsidence using those traditional methods. For these reasons, in this study, the concept of fractal statistics was applied to investigate these relationships.

Since Mandelbrot introduced the concept of fractal geometry, it has been applied to many geological research fields (Turcotte 1986; Bölviken et al. 1992; Barton and Scholz 1995; Li et al. 1999, 2002–2004, and many others). Based on the concept of fractal statistics (Mandelbrot 1983), a fractal is an object made of parts that are similar to the whole in some ways (either exactly the same except for scale or statistically the same); so therefore in general, self-similarity is equivalent to scale invariance. A fractal relationship is of the form (Crovelli and Barton 1995)

$$\text{Number} = \text{prefactor} \times (\text{quantity})^{\text{exponent}} \tag{1}$$

where the exponent could be a fraction, which defines or is related to a fundamental measure, the fractal dimension D. In many natural systems, one encounters different power-law expressions of this form.

There are two major types of fractals: geometric fractals and probabilistic fractals (Crovelli and Barton 1995). Geometric fractals are geometric shapes that comprise a length, an area, or a volume. Probabilistic

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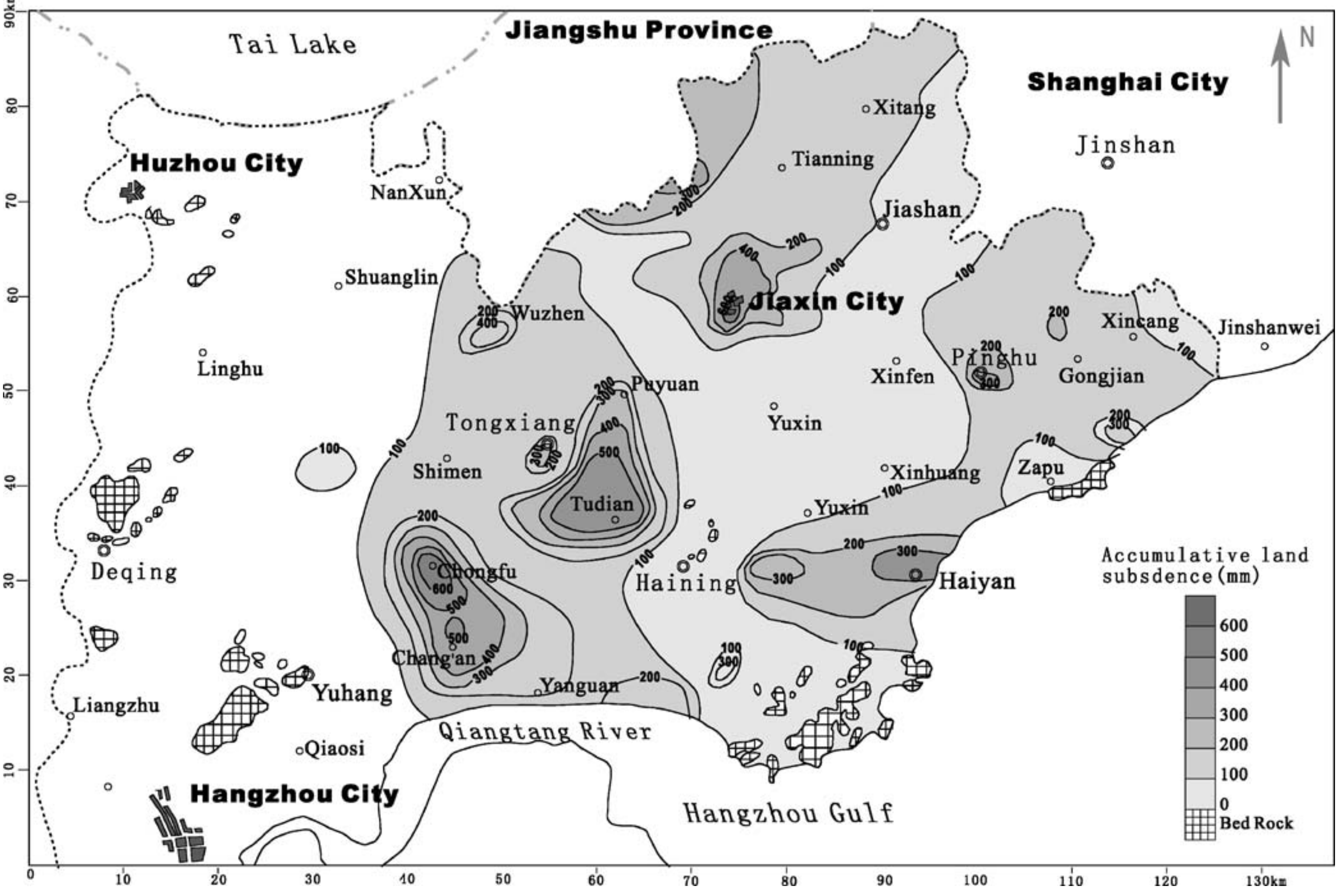

Fig. 6 Contour map of accumulative land subsidence from 1964 to 2001 in Hang-Jia-Hu Plain, Zhejiang, China (modified after Zhejiang Province Dept. of Land and Resources 2002)

fractals are random variables, or, equivalently, probability distributions that are self-similar (or scale-invariant). No matter whether geometric fractals or probabilistic fractals, the scaling of any measure of fractal objects will follow power-law distributions.

Many fractals found in nature, however, usually cannot be characterized by a single exponent. Thus, multifractals were introduced by Mandelbrot in the context of describing turbulent flows (Mandelbrot 1974). Usually multiplicative cascades of random processes generate multifractal structures, while additive processes generally produce simple fractals (monofractals; Stanley and Meakin 1988; Bunde and Havlin 1991). A multifractal may be thought of as an interwoven set of fractals associated with an object, and roughly speaking, it is characterized by several separate power law relations between the variables of interest. In general, multifractals describe phenomena that have structures with more than one scaling exponent (Schroeder 1991).

In this study, as an application of the fractal concept, the fractal relationships given in Eq. (1) are introduced to statistical analyses on the relation of land subsidence to groundwater exploitation. Let *P(δ)* be a variable of interest, i.e., the rate of land subsidence or the amount of accumulative subsidence, and let δ represent the measure of groundwater extraction, i.e., annual exploitation, exploitation intensity, or the drop of the groundwater level. The relationship between P and δ may be described mathematically as

$$\begin{array}{ll} P(\delta) \propto \delta^{\alpha}, & i = 0, 1, 2, .., m, \\ \delta \in (\beta_i, \beta_{i+1}), & \beta_{\min} \leq \beta_i \leq \beta_{\max} \end{array} \quad (2)$$

where β_i is the inflexion value of function $P(\delta)$ and α is an exponent that may have several values for different ranges of δ value. On log–log paper, the value of $P(\delta)$ against δ may be fitted by a number of straight lines. The break(s) of the straight lines and their corresponding β_i values can be considered as characteristic values for evaluating the development of land subsidence resulting from groundwater extraction.

The groundwater monitoring system in the Hang-Jia-Hu Plain was established in 1964 and the amount of groundwater extraction before 1964 is only about 1.6% of the accumulative amount from 1964 to 2000 (see Table 2). As a result, the impact of groundwater extraction before 1964 upon the land subsidence as a whole is negligible. In the following analyses, the discussion focuses on the data from 1964 to 2000.

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Relation of ground settlement velocities (V) to annual groundwater extraction quantity (Q)

As shown in Fig. 7, the amount of groundwater exploitation (Q) and the settlement velocity (V) at a land subsidence center during 1964 to 2000 are shown as a log–log plot, where four straight lines are fitted using Eq. (2) and the inflexion values and ranges of scale invariance are shown clearly. Based on the fractal concept, the fractal dimension D is related to the slope of a straight line on the log–log graph of V vs. Q. The straight lines on both sides of a break point exhibit different slopes (Fig. 7). It is shown that the change in the velocity of land subsidence caused by groundwater exploitation may be characterized by a multfractal pattern. The difference in D values indicates that the increasing of the effective pressure and the compaction of aquitards and aquifers resulting from groundwater withdrawal are not the same throughout the aquifer system but show variability on different scale ranges. The variability may be associated to the annual variation in groundwater extraction and the heterogeneity of aquifers and interbedded aquitards in material composition, structure and texture.

The values of Q and V corresponding to three break points are respectively Q=0.2×10^8 m^3, V=16.7 mm/year (1972); Q=1.2×10^8 m^3, V=51.1 mm/year (1988); Q=1.5×10^8 m^3, V=25.5 mm/year (1996), which correspond to groundwater exploitation intensity (defined as the volumetric pumping rate over a unit area, denoted as Q_i) of 0.3×10^4 m^3/km^2 year^{-1} (1972); 1.8×10^4 m^3/km^2 year^{-1} (1988); 2.3×10^4 m^3/km^2 year^{-1} (1996), respectively. According to Fig. 7 and Table 2, the evolution of land subsidence in the Hang-Jia-Hu Plain from 1964 to 2000 can be divided into four phases as described in the following.

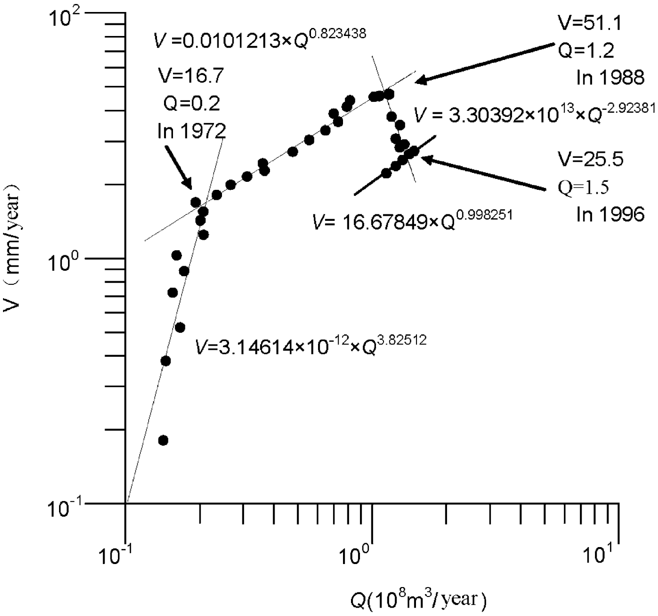

Fig. 7 A log–log plot of the land subsidence velocity (V) vs. the annual groundwater extraction (Q) during 1964–2000 in the Hang-Jia-Hu Plain, Zhejiang, China

Phase 1 (1964–1972): the annual groundwater extraction increased from 1,426×10^4 in 1964 to 2,070×10^4 m^3 in 1972, of which about 79.3% were pumped from six major towns (including Jiaxing) and the rest from many small towns in the area. At this phase, the land subsidence velocities increased greatly (in a power-law model), and the slope of the Q–V correlation line is 3.8251 in the log–log plot (Fig. 7).

Phase 2 (1973–1988): the annual groundwater extraction increased from 2,070×10^4 to 11,681×10^4 m^3, but the proportion decreased to 60.1% in the major towns. The slope of Q–V correlation line is 0.8234, which shows that the increase of settlement velocity of phase 2 at the land subsidence center is slower than that of phase 1.

Phase 3 (1989–1996): the annual groundwater extraction increased from 11,681×10^4 to 14,785×10^4 m^3, but the proportion kept on decreasing to 37.2% in the main towns and increased to 62.8% in other small towns and villages. In other words, although the total extraction kept on increasing, a large percentage of groundwater extraction took place in many small towns and villages, where a large number of new extraction wells have been installed. So the slope of the Q–V curve for this line segment is negative (−2.9238), suggesting that the settlement velocity at the land subsidence center has a descending trend.

From phase 1 to phase 3, the annual groundwater extraction has increased continuously, but the settlement velocity at the land subsidence center is gradually decreased. This phenomenon could be attributed to two major causes.

First, the compressibility of aquitards decreases with increase in effective stress (Poland 1984). The majority of the total subsidence in the Hang-Jia-Hu Plain was due to compaction of the "clay" stratum, composed of the clay beds in several aquitards between the confined aquifers and the huge thick and soft mud sediments above the confined aquifers. At the early stage of land subsidence, the compressibility (compaction coefficient) of the "clay" stratum is relatively high, that is, the particles in the original soft "clay" stratum can be easily packed due to the release of water in those clays, and thus the velocity of the land subsidence is also relatively high. However, if a large portion of water has been squeezed out of the "clay" stratum and the destruction of porous structure has occurred at the early stage of land subsidence, with continued pumping of groundwater, the compressibility of the "clay" stratum gradually decreases.

In addition, as shown in Table 2, at the early stage of groundwater extraction, pumping wells are concentrated in several major towns, but with the continued increase of demand for groundwater, most of newly installed pumping wells are distributed in many small towns and villages. This shows that the change of settlement velocity at the land subsidence center not only is related to the groundwater exploitation quantity, but also is possibly affected by the spatial distribution of the groundwater extraction.

Phase 4 (1997–2000): because of government regulations to limit groundwater extraction, the annual ground-

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water extraction decreased from $14,785\times10^4$ to $11,411\times10^4$ m^3, and the proportion of extraction from the major cities also decreased to 20.9%, while the proportion of extraction from small towns and villages increased to 79.1%. However, the decrease of the land subsidence velocity in phase 4, which appears to correspond with the slope of 0.9983, is obviously slower than that in phase 3. Moreover, it seems that the change trend line of the land subsidence velocity in phase 4 is approximately parallel with the trace of phase 2 (1973–1988), which indicates that if the groundwater extraction continuously keeps on descending henceforth, the decrease of land subsidence velocity possibly follows a similar pattern.

Relation of accumulative subsidence (ΣS) to accumulative drop of groundwater level (Σh) at land subsidence centers

In the log–log plot in Fig. 8, the accumulative subsidence (ΣS) vs. the accumulative drop of the groundwater level (Σh) at the land settlement center of Jiaxin City during 1964 to 2000 is fitted using Eq. (2). The figure shows that there are two break points on the Σh–ΣS curve. The Σh values corresponding to these break points are 8 m (1971) and 22 m (1980), respectively. That is to say, the average drop of the groundwater level at the subsidence center is 1.1 m/year during 1964 to 1971, and 1.6 m/year during 1971 to 1980. The Σh–ΣS curve is divided by two break points into three line segments (Fig. 8), and the slopes of the segments increase with the increase of Σh, from 0.1890, 1.5533, to 7.6261. This suggests that, when Σh exceeds the value on the inflexion, ΣS will increase rapidly. The Σh value on the inflexion in 1971 may indicate that the compaction of the aquifer-system came to a lower limit in response to a step increase in virgin stress (stress exceeding past maximum). Based on the historical records of regional groundwater level[1] (h), during 1964 to 2000, the elevation of the groundwater level corresponding to Σh values of 8 m (1971) and 22 m (1980) are $h = -28.5$ m and $h = -42.5$ m, respectively.

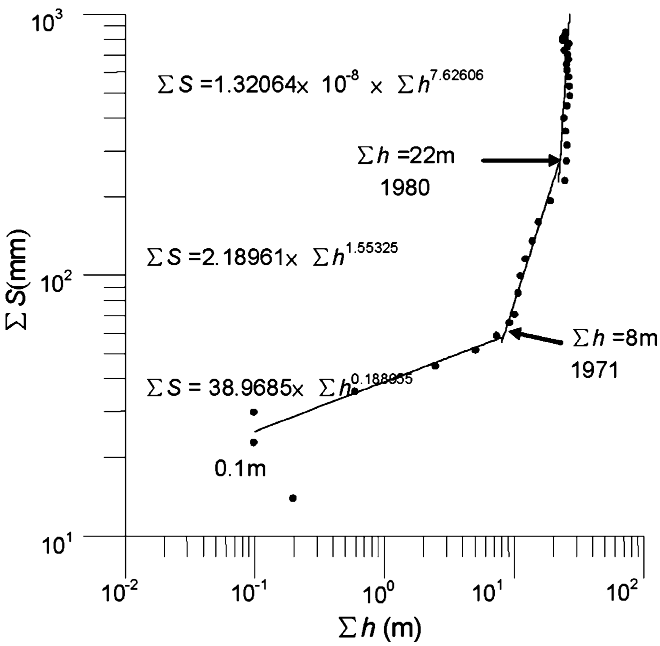

Fig. 8 A log–log plot of the accumulative subsidence at the land subsidence center (ΣS) vs. the accumulative drop of groundwater level (Σh) during 1964–2000 in Jiaxin City, Zhejiang, China

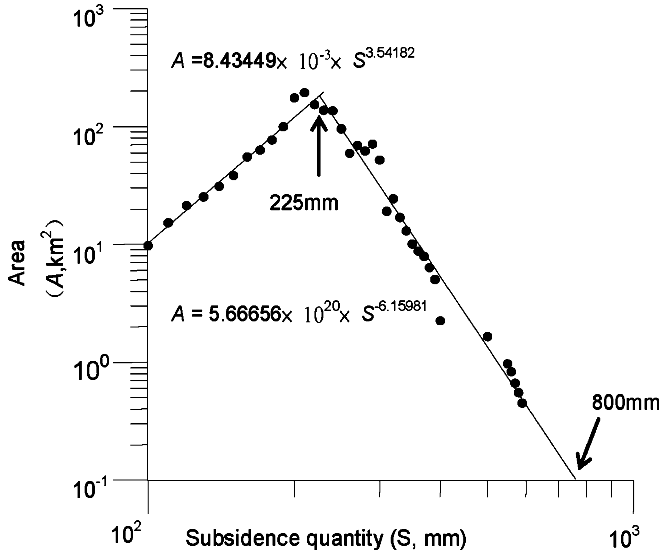

Fig. 9 A log–log plot of the area of subsidence regions (A) vs. land subsidence (S) during 1964–2000 in Jiaxin City, Zhejiang, China

Relationship between the area of subsidence regions (A) and the amount of land subsidence (S)

Figure 9 illustrates the relationship between the area of subsidence regions (A) and the amount of land subsidence (S) in Jiaxin, where A and S are shown as a log–log plot and two line segments in the figure may be fitted using Eq. (2), which approximately follows multifractal behavior. As shown in Fig. 9, at the left of inflexion (the level of land subsidence <225 mm), the slope of the A–S correlation line is positive (3.5418), and the area of subsidence region (A) varies with the level of land subsidence (following a power-law model). However, at the right of inflexion (the level of land subsidence >225 mm), the slope of A–S correlation line is negative (−0.6160), and the area of subsidence region (A) varies inversely with the level of land subsidence (following a power-law model). This suggests that the development of a subsidence region follows power-law relationships with different exponents at various levels of land subsidence. This phenomenon should be taken into account in simulating possible areas inundated during flooding and evaluating the situation of land subsidence disasters.

In the previous sections, it has been proposed that the dynamic relationship between the land subsidence and the groundwater exploitation follows fractal power-law distributions. One potential explanation for these power-law

[1] In the Yellow Sea height system

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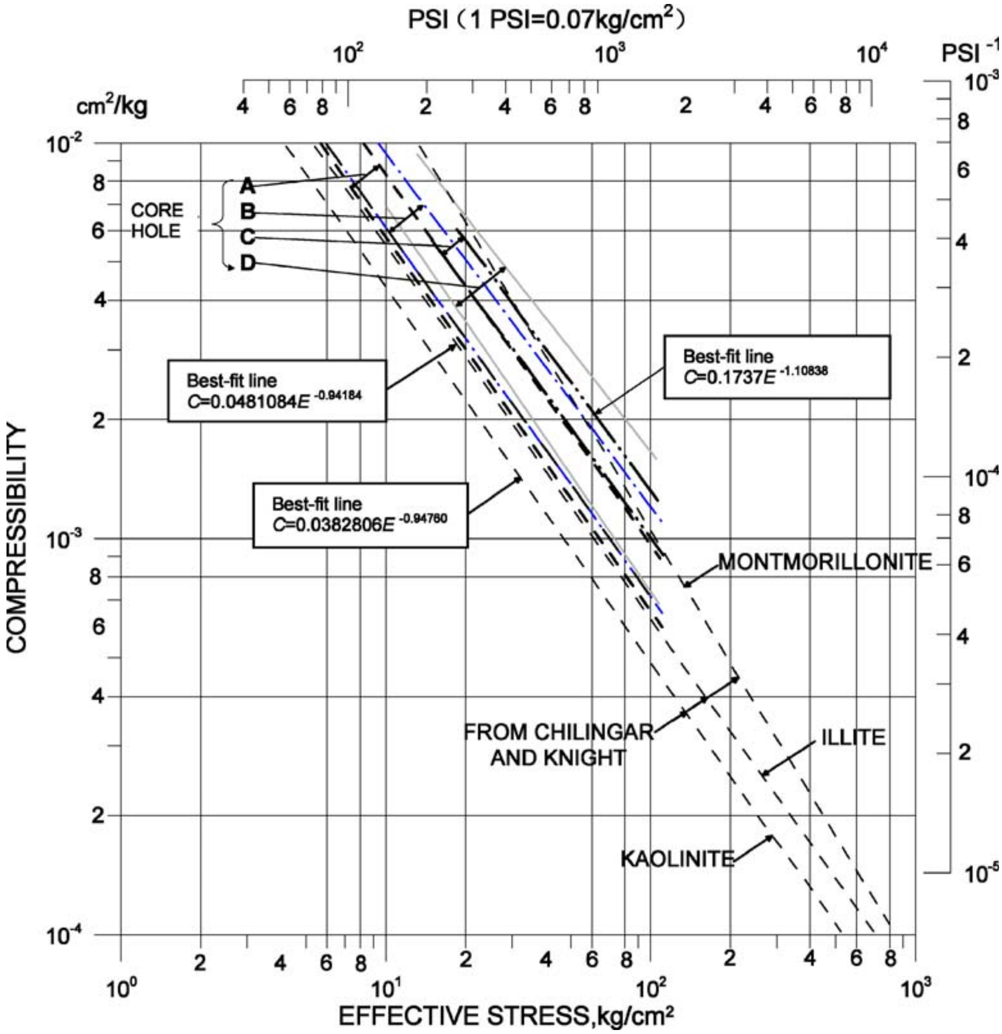

Fig. 10 A log–log plot of compressibility (*C*) vs. effective stresses (*E*) for fine-grained samples from four core holes in the southwestern United States and for pure clays tested by Chilingar and Knight (1960) (modified from Poland 1984, their Fig. 7, chapter 3). The best fit lines corresponding to Eq. (1) are shown in *rectangles*

distributions is the fractal mechanics behavior of "clay" strata (aquitards) and sediments above confined aquifers in stress. For land subsidence due to groundwater withdrawal, this subsidence is mainly associated with the compaction of aquitards (fine-grained clay interbeds) between the confined aquifers and in overlying sediments. A number of authors (Katz and Thompson 1985; Krohn and Thompson 1986; Wheatcraft and Tyler 1988; Rieu and Sposito 1991; Ghilardi et al. 1993) have suggested that sandstones and sediments have a fractal distribution of porosity. This porosity distribution could result in those aquitards and sediments in stress exhibiting fractal mechanics behavior. Poland (1984) made a compaction test for 30 samples from four core holes tapping alluvial and minor lacustrine deposits in southwestern United States (see Poland 1984, p. 51). The results of their tests, as well as the compaction tests of pure clays made by Chilingar and Knight (1960), are given in Fig. 10. On log–log paper, the compressibility of the samples as a function of the effective stress may be fitted by several

Table 3 Evaluation index of dynamic evolution of groundwater exploitation and land subsidence for the Hang-Jia-Hu Plain

Index		Criticality grade		
		Severe	Medium	Light
Characteristics of land subsidence	Accumulative subsidence (mm)	>800	225–800	<225
	Subsidence rate (mm/year)	>50	16–45	<16
Dynamic change of groundwater extraction	Annual exploitation(10^8 m^3/year)	>1.5	0.2–1.5	<0.2
	Exploitation intensity (10^4 m^3/km^2 $year^{-1}$)	>2.3	0.3–2.3	<0.3
	Accumulative drop of water level (m)	>22	8–22	<8
	Average rate of water level drop (m/year)	>1.6	1.1–1.6	<1.1
	Elevation of water level (m)[a]	<−42.5	−28.5 to −42.5	>−28.5

[a] Relative to sea level (Yellow Sea height system)

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straight lines which correspond to Eq. (1), with D=0.942–1.108 (see "best fit" lines in Fig. 10). It is suggested that the compressibility of the samples against the effective stress obeys fractal power-law distributions. The distribution can be characterized by multifractal structures when the increase of the effective pressure and the compaction of aquitards and aquifers are not the same throughout the aquifer system but vary on different temporal or spatial scales. However, because regional land subsidence caused by groundwater extraction is a complex phenomenon, this explanation clearly requires further testing. More tests and observations may be required, particularly information on the mechanical properties of the materials involved and the groundwater flow field.

From the above fractal power-law relations of land subsidence to groundwater exploitation, some indices may be established to evaluate the dynamic evolution of groundwater exploitation and land subsidence for the Hang-Jia-Hu Plain (Table 3). By means of Table 3, the critical degree of evolution of land subsidence in the near future for the plain can be estimated based on some data from groundwater exploitation and water level change. Moreover, these indices also provide valuable information for carrying out numerical modeling of land subsidence resulting from groundwater extraction.

Conclusions

The land subsidence in the Hang-Jia-Hu Plain is mainly caused by severe groundwater exploitation from three confined aquifers. These confined aquifers are separated by quite stable aquitards made of clay and covered by the widely distributed, thick, less permeable clay layers consisting of soft mud sediments. The aquitards obstruct infiltration of surface water and phreatic water, thus the aquifer system belongs to a kind of sealed hydrogeologic structure.

In this study, as an application of the fractal concept, the relation between land subsidence and groundwater exploitation is described by fractal power-law distributions. Based on the historical records of groundwater extraction, groundwater level, and ground settlement from 1964 to 2000 in the plain, it is suggested that relationships between the land subsidence velocity and the annual groundwater extraction, groundwater drawdown and annual land subsidence velocity, the amount of land subsidence and the area of land subsidence districts can be characterized by a multifractal model, which could be attributed to the fractal behavior possessed by aquifer-system compaction during groundwater exploitation. The values corresponding to the break points of fitted straight lines on log–log paper can be taken as characteristic indices for evaluating the development of land subsidence resulting from groundwater extraction. Based on this model, a set of indices are proposed for evaluating dynamic evolution of groundwater exploitation and land subsidence in the Hang-Jia-Hu Plain. Using these indices, the criticality grade of evolution of land subsidence in the near future for the plain can be estimated from groundwater exploitation data and water level changes.

The fractal power law distributions of land subsidence to groundwater exploitation and the related explanations presented in this report will potentially be of considerable value, even if only approximately valid, for quantifying impacts of groundwater extraction on land subsidence and simulating the subsidence.

Finally, it should be pointed out that the conclusions of this study are based on a preliminary study. It is necessary to analyze the relation among land subsidence, surface elevations, and perennial average surface water levels for evaluating environmental problems caused by land subsidence such as simulating areas inundated during different degrees of flooding that are encountered in the ground subsidence-prone districts. Further research shall focus on this topic.

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