LOWLAND TECHNOLOGY INTERNATIONAL SI, Vol. 9, No. 2, 2-7, December 2007
International Association of Lowland Technology (IALT), ISSN 1344-9656

ANALYSIS ON GROUNDWATER WITHDRAWAL AND LAND SUBSIDENCE IN SHANGHAI

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ABSTRACT: Large-scaled land subsidence due to withdrawal of groundwater in Shanghai was observed. A method based on 3D-groundwater flow model is presented at first to calculate land subsidence in this paper. The model considers the aquitard-aquifer condition of Shanghai soft ground. Based on the proposed groundwater flow model combined with the compressibility of soil layer, subsidence is calculated through unifying in a one model condition. The anisotropic characteristics of soil layer are also considered in the model. The land subsidence, groundwater flow vector, and groundwater drawdown were analyzed using the proposed method. Through comparing between the measured value and calculated value, it indicates that the model simulated the measurement value well. Groundwater flow from west to east at the beginning stage and it flows from east to west after the long-term groundwater withdrawal. Groundwater level is depressed along with groundwater withdrawal.

Keywords: Shanghai, layered aquifer-aquitard system, land subsidence, groundwater withdrawal

INTRODUCTION

Withdrawal of groundwater for industrial use started since 1920s in Shanghai. Withdrawal of groundwater caused serious land subsidence. In China, Shanghai is the earliest city where land subsidence was found, it is also one of the cities where subsidence was serious and made great damage to civil and industrial facilities and infrastructures. Simulation and analysis of land subsidence in Shanghai started 20 years ago. To predict the exploitable amount of groundwater, numerical model is used in land subsidence prediction. In Shanghai, presently the adopted land subsidence prediction method is so-called quisi-3D analysis, in which groundwater seepage in aquifer is simulated in 2D condition horizontally and compression of aquitards is simulated in 1D consolidation (Li et al. 2000). There is no equation to estimate release of groundwater from aquitard. The release of groundwater from aquitard and/or the flow between aquifers through aquitards is considered as the external source/sink flux and is estimated through leakage analysis (Li et al. 2000).

This paper analyzes groundwater flow and land subsidence in Shanghai based on a finite element model of groundwater seepage in 3D condition. This new proposed method (Shen et al. 2006) is an integrative model through coupled analysis of groundwater seepage and land subsidence in one time step. Groundwater seepage analysis is simulated in 3D condition, in which groundwater seepage equations are established both in aquifers and aquitards.

ANALYTICAL METHOD

For the saturated porous medium, basic equation for 3D groundwater flow in saturated media is expressed as the following equation (Bear 1979):

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right)-q=S_S\frac{\partial h}{\partial t} \tag{1}$$

where, K_{ij}=hydraulic conductivity; h=hydraulic head; q=external source/sink flux; S_s=coefficient of specific storage; t=time.

The release of water in soil is normally due to the compression of soil and the expansion of water. Thus, the coefficient of specific storage S_s was expressed in the following expression.

$$S_s=\gamma_w\left(m_v+n\beta\right) \tag{2}$$

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Note: Discussion on this paper is open until June 2008

where, γ_w=unit weight of water; m_v =soil coefficient of volume compressibility; n=effective porosity; β= coefficient of volume compressibility of water.

Under the condition that the pressure of groundwater is not high, the compression of water can be ignored because the compression of water is very small comparing with the compression of soil, that is to say, β=0. The diffuse of water in soil is only due to the compression of soil. The porosity change with hydraulic head can be expressed in the following formula.

$$S_s = \frac{\partial n}{\partial h} = \gamma_w m_v = \frac{\gamma_w}{1+e_0}\frac{C'}{\sigma'}\frac{1}{2.303} \tag{3}$$

where, n=porosity; h=hydraulic head; e=void ratio; σ'=effective stress; C'=the slope of e-logσ' curve.

Variation of effective stress:

$$\Delta\sigma' = -\Delta u = -\gamma_w \Delta h \tag{4}$$

Compression of soil layer:

$$S_t = m_v \Delta\sigma_z H = \frac{S_s}{\gamma_w}\Delta\sigma_z H = S_s \Delta h H \tag{5}$$

where, S_t=compression of soil layer.

Thus, we can calculate the compression of soil layer with variation of hydraulic head from specific storage S_s. The value of land subsidence can be calculated accumulating the compression of soil layers.

The consolidation compression by using the proposed approach was compared with the results from Terzaghi's 1D consolidation theory. It was confirmed that the proposed approach has enough accurateness for solving engineering problem (Shen et al. 2006).

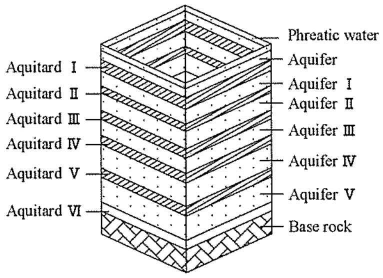
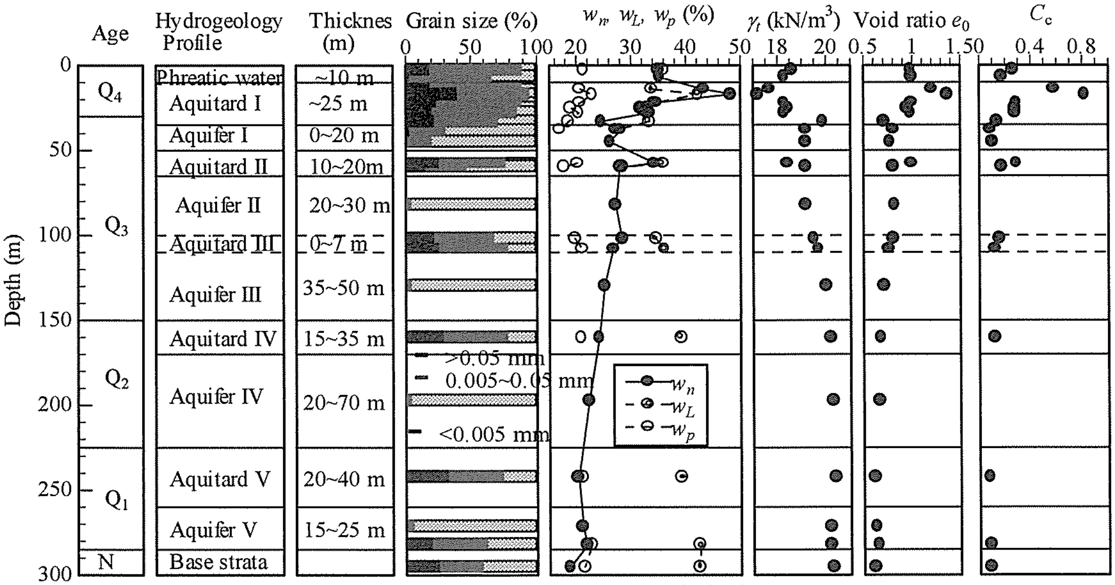


Fig. 1 3D sectional image of artesian aquifers in Shanghai (AEC 2002)

OUTLINE OF SHANGHAI HYDRO-GEOLOGY

Shanghai locates on the deltaic deposit of Yangtze River near the estuary of the same river. The Shanghai administrative region is surrounded by Jiangsu Province and Zhejiang Province at the west and north sides on land, Hangzhou Bay at the south side, and East China Sea at the east side. The exploited groundwater in Shanghai mainly comes from the aquifers of the deltaic deposit of Yangtze River. Except for several little volcanic massifs, which are at west or west-south area of Shanghai, most part of the deposit is formed in Quaternary Era. The soils of the aquifers are in uncemented state. The maximum thickness of the sediment is about 400 m. From bottom to top, the depositional environment includes five cold-periods, four warm-periods, and one glacial period (AEC 2002; Zhu et al. 1987). The deposits in cold-period and glacial period are clay or silty clay with lacustrine fine grains to form six aquitards and in warm-period, the sedimentary materials are cohesiveless material with the fluvial



Legend: $Q_{1\text{-}3}$=Pleistocene epoch; Q_4=Holocene epoch; N=Neogene bedrock.

Fig. 2 An illustrative geotechnical profile and soil properties in Shanghai coarse grains to form the five confined aquifers and one phreatic layer. These aquifers connect with groundwater reservoirs from the continental shelf of East Chian Sea. so that the groundwater level is changed seasonally with tidal influence (Lu 1994, Wang 1998, Zhang et al. 1999).

The hydro-geology of Shanghai includes phreatic water, a low-pressure artesian aquifer, five high pressure confined aquifers, and six aquitards. Figure 1 shows the sectional image of aquifers and aquitards in Shanghai. Figure 2 illustrates the hydro-geological layers of a boring hole at Huacao, west side of Hongqiao International airport. The level of phreatic water is 0.3 to 1.5 m under ground surface and it changes with raining and tide. Aquifer I has little water quantity and bad water quality; there is no groundwater withdrawal from Aquifer I for industrial use. Aquifers II and III are the main withdrawal layers. Aquifer IV is freshwater layer and its withdrawal quantity is the largest now. Aquifer V includes freshwater and tiny-salt water and it only distributes at the northern part of Shanghai; withdrawal quantity from this aquifer becomes larger recently.

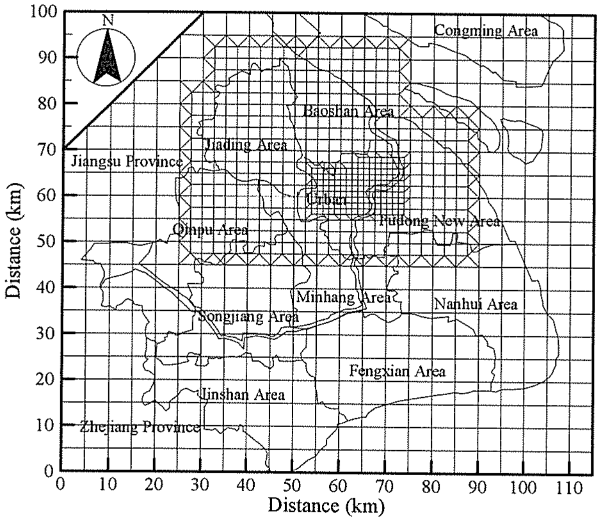


Fig. 3 Analysis range and mesh in plan

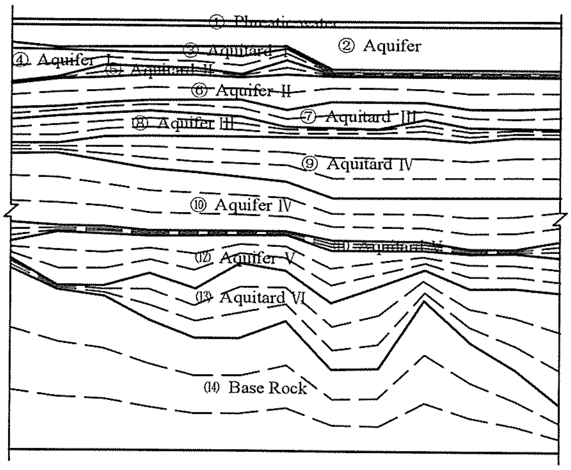


Fig. 4 Sectional drawing of aquifers and aquitards

CALCULATION MODEL OF LAND SUBSIDENCE IN SHANGHAI

Calculation Range

The analyzed range includes the whole Shanghai city and some areas of Jiangsu and Zhejiang province, as plotted in Fig. 3. FEM mesh in plan is set as 5 km size in large area (see Fig. 3). However, around outskirt and urban area it was set as 2.5 and 1.25 km size, respectively. In vertical direction, the hydro-geology includes 14 layers and the mesh is divided into 32 layers, as shown in Fig. 4. Figure 5 is the 3D finite element mesh.

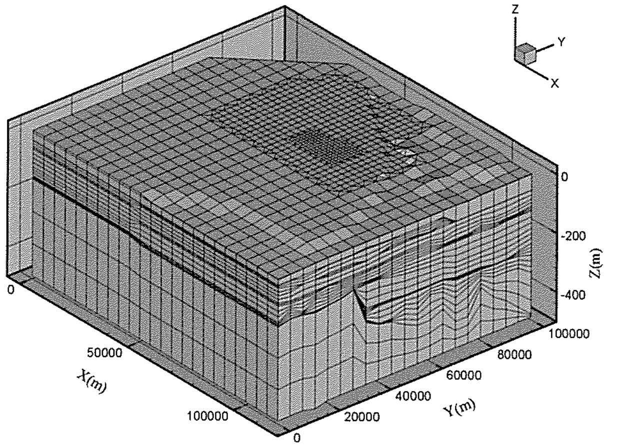


Fig. 5 3D finite element mesh

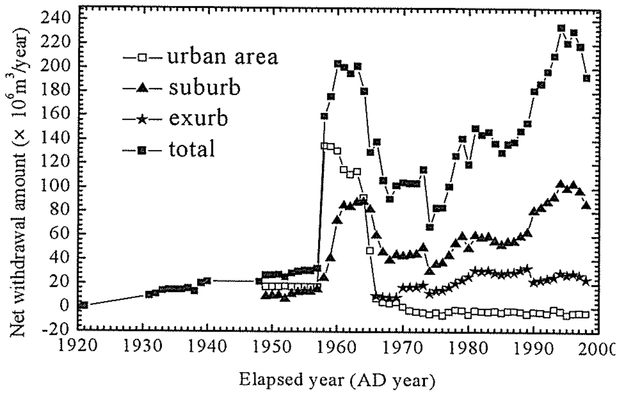


Fig. 6 Net groundwater withdrawal amount

Boundary Conditions

The phreatic water level is set as 1.0 m below the ground surface (Chai et al. 2005). Therefore, the initial hydraulic head at the top is about 2.0 m. In the sea, the water potential is at the sea surface and was set as 0.0 m. It was assumed that at 1921, the water pressure in each aquifer was the same as the static water pressure.

The amount of groundwater extracted per year is shown in Fig. 6. The place of groundwater extracted at plan is shown in Fig. 7 and groundwater was extracted from Aquifer II to Aquifer IV at each node in vertical direction. In order to compare the calculated with the measured results, two benchmarks 0-264 and 0-301 (see in Fig. 7) were selected.

Soil Parameters

Sectional view of the groundwater basin with geotechnical profile is shown in Fig. 4. Table 1 tabulates the parameters used in analysis. The values of hydraulic conductivity given in Table 1 are the recommended by Chai et al (2005). There are no data available on the value of k_v of each layer. The aquifer I is a fine sand layer with a k_v value of about 9×10^{-6} m/s. For aquifers II to V, a value of 10^{-4} m/s was assumed. There are very few test data for deeper aquitards. The k_v values of the lower aquitards were calculated from the k_v values of aquitard I (Chai et al. 2005). The horizontal hydraulic conductivity k_h is equal to 2~3 times of vertical hydraulic conductivity k_v. The coefficient of specific storage S_s is calculated from soil coefficient of volume compressibility m_v, as shown in equation (2).

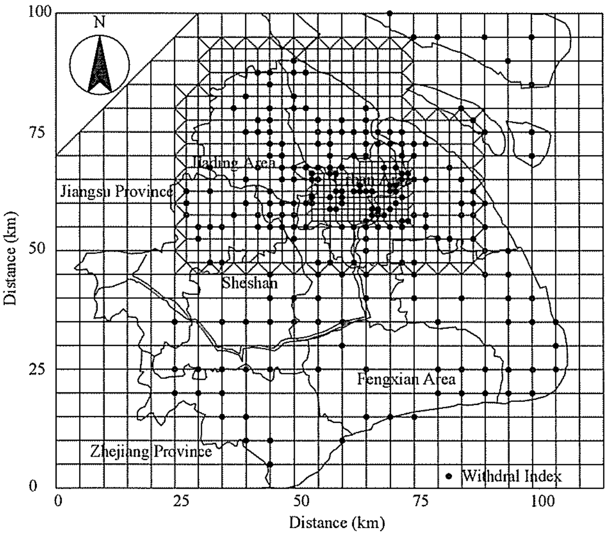


Fig. 7 Site of ground water withdrawal and FEM mesh

Results and Discussions

Figure 8 shows the calculated subsidence at bench marks 0-264 and 0-301 from 1920 to 1998. The land subsides slowly before 1949 and the subsidence rate became rapid from 1949 to 1965 due to the increase of the pumped amount of groundwater (see Fig. 6). The subsidence curve becomes gently after 1965. It shows that the subsidence rate is strongly related to the net groundwater pumping rate. A comparison between the measured value and calculated value indicates that the model simulated the measurement value fairly well. Fig. 9 shows the accumulated surface subsidence contour in 1965 and 1998. The maximum subsidence occurs at urban area. It reached 0.8 m in 1948, and 2.5 m in 1965. After 1965, since groundwater recharge was adopted, the rate of land subsidence became smaller in urban area. There is even some amount of rebound in urban. However, the subsidence range is enlarged from urban area to exurb, it is because groundwater withdrawal is undertaken throughout to the whole city.

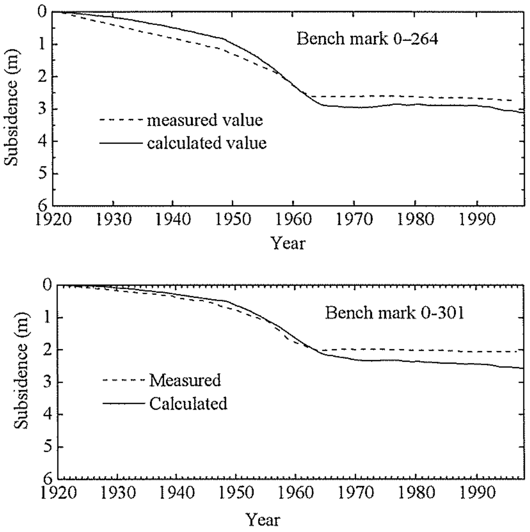


Fig. 8 Comparison between measured and calculated subsidence in Shanghai from 1920 to 1998

Table 1 Parameters used in consolidation analysis

Hydro-geological layer	e	E (kPa)	C'	k_v (m/day)	K_h (m/day)	S_s (m^{-1})
Phreatic water	1.20		0.30	4.32E-03	1.08E-02	3.75E-03
Low-pressure artesian aquifer	1.00		0.30	4.32E-03	1.08E-02	3.75E-03
Aquitard I	1.05		0.25	1.60E-03	4.01E-03	1.67E-03
Aquifer I	0.78	51300		1.04E+00	2.59E+00	9.67E-05
Aquitard II	0.85		0.21	2.34E-03	5.85E-03	6.30E-03
Aquifer II	0.82	101300		8.64E+00	2.16E+01	9.67E-05
Aquitard III	0.78		0.12	1.65E-03	4.13E-03	2.64E-03
Aquifer III	0.71	116500		8.64E+00	2.16E+01	8.41E-05
Aquitard IV	0.68		0.14	9.85E-04	2.46E-03	2.22E-03
Aquifer IV	0.66	159500		8.64E+00	2.16E+01	6.14E-05
Aquitard V	0.62		0.09	7.26E-04	1.81E-03	9.53E-05
Aquifer V	0.64	201300		8.64E+00	2.16E+01	4.87E-05
Aquitard VI	0.62		0.09	7.26E-04	1.81E-03	6.90E-05

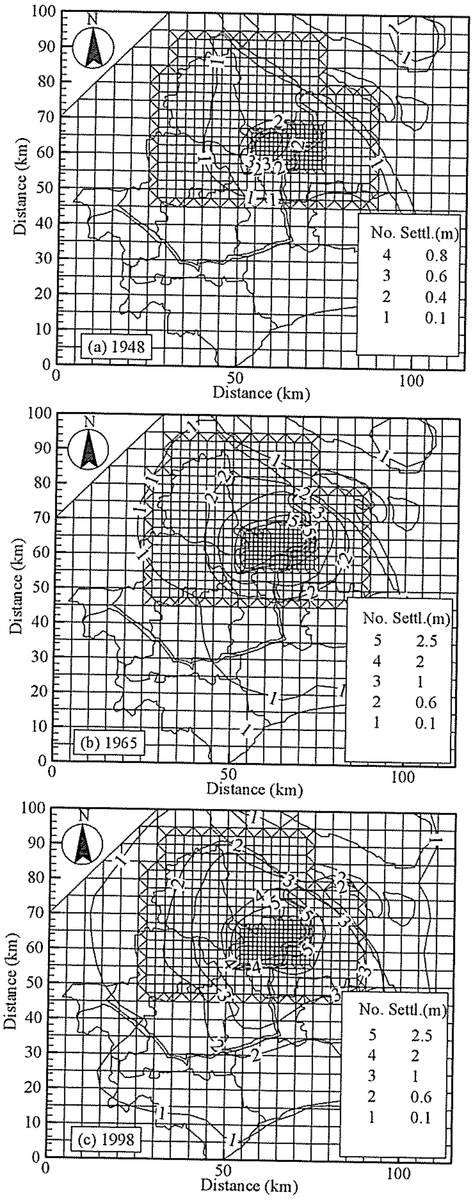


Fig. 9 Accumulated subsidence contour in 1948, 1965, and 1998, respectively

Figure 10 plots groundwater flow vector in Aquifer II in 1965 and 1998. It can be found that the groundwater flows from west to east before 1965 (Fig. 10a, Fig. 10b), and groundwater flows from east to west in 1998 (Fig. 10c). That is to say, the groundwater supply path has been changed. The natural groundwater supply in Shanghai comes from neighboring province, including Jiangsu and Zhejiang Province. After long-term groundwater withdrawal, the supply comes from groundwater reserves of east sea continental shelf. However, groundwater flows from land and sea to urban area, where land subsidence is serious. The supply area becomes larger along with groundwater withdrawal quantity and area.

Figure 10 also depicts the drawdown of groundwater in Aquifer II. As shown in the figure, after pumping groundwater for 28 year, the maximum drawdown for Aquifer II is about 3 m in 1948 (Fig. 10a). Along with large range and intensity withdrawal of groundwater, the maximum drawdown is about 14 m in 1965 (Fig. 10b). For groundwater recharge from 1966, the water level presents ascending trend in 1998, the maximum drawdown is about 10 m (Fig. 10c). Fig. 10 also shows that the maximum drawdown of groundwater occurs at urban area. It indicates that the water level variation in aquifers is closely related to the groundwater withdrawal quantity and area.

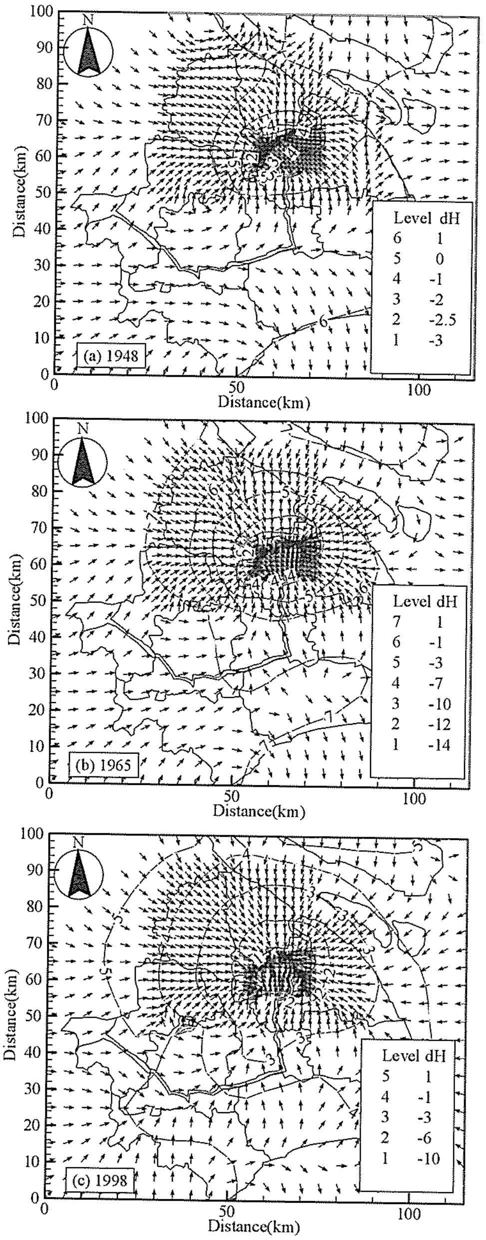


Fig. 10 Groundwater flow vector and contour of groundwater drawdown for Aquifer II in 1948, 1965, and 1998

CONCLUSIONS

The following conclusions can be drawn based on the results of this study.

1. A 3D finite element calculation model is established to estimate land subsidence due to withdrawal of groundwater in Shanghai, China. The model considers both groundwater seepage and calculation of land subsidence in one process.
2. The whole Shanghai groundwater aquifers were selected to analysis. The calculated value of land subsidence by using the proposed method simulated the measured value fairly well.
3. The maximum land subsidence value was about 2.5 m and it happened in urban area. The land subsidence in urban area is alleviated with groundwater recharge after 1966 but the subsidence range is enlarged because of large area of groundwater withdrawal.
4. The results also indicate that at the beginning groundwater flows from land to sea before 1965, however, groundwater flows from sea to land in 1998. That is to say, the supply path of groundwater was changed. Moreover, groundwater flows from land and sea to the withdrawal area during withdrawal period.
5. The simulated results show that the obvious drawdown of groundwater head is happened. The maximum drawdown of groundwater head was about 14 m after 45 years. For groundwater recharge from 1966, the water lever presents ascending trend in 1998.

ACKNOWLEDGEMENTS

The research work described herein was funded by the National Nature Science Foundation of China under Grant No. 50779035 and also supported by Shanghai Leading Academic Discipline Project (Project Number: B208). Part of the work was done during the second author staying in the Institute of Lowland Technology, Saga University as the Foreign Guest Professor from April 1 to July 1, 2006. These financial supports are gratefully acknowledged.

REFERENCES

Atlas Editorial Committee (AEC) (2002), Atlas of Geology Environment of Shanghai, Beijing, Geology Press.

Bear J. (1979). Hydraulics of Groundwater. New York, McGraw-Hill, 569p.

Chai J.C., Shen S.L., Zhu H.H., and Zhang X.L. (2005). 1D analysis of land subsidence in Shanghai, Lowland Technology International, 7(1): 33-41.

Li Q.F., Fang Z., and Wang H.M. (2000). A mathematical model and forecast of groundwater workable reserves for Shanghai. Shanghai Geology, 2: 36-43 (in Chinese).

Lu Z.J. (1994). The distribution of the confined fresh-water aquifer in Shanghai and its extension to the sea, Shanghai Geology, 1: 1-12 (in Chinese).

Shen S.L., Xu Y.S., and Hong Z.S. (2006). Estimation of land subsidence based on groundwater flow model, Marine Georesources and Geotechnology, 24(2): 149-167.

Wang W.Y. (1998). General introduction of groundwater in Shanghai, Urban Public Works, 12(3):19-21 (in Chinese).

Zhang W., Qin X.Q., and Yi L.-X. (1999). Groundwater system and its characteristics in Shanghai region. Carsologicasnica, 18(4): 343-351. (in Chinese)

Zhu S.Z., Chen Y.Y., and Sun Y.F. (1987). The geology of quaternary sediment in Shanghai and the ancient weather in recent Yangtze delta deposits, Ed. Yan and Xu, Shanghai, 1987, East China Normal University Press,: 158-173 (in Chinese).