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Research paper

Prediction maps of land subsidence caused by groundwater exploitation in Hanoi, Vietnam

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Abstract

The article presents study results of the land subsidence caused by groundwater exploitation in Hanoi, Vietnam. The study includes collection and analysis of data on geology, hydrology, soil properties and settlements observed at 10 monitoring stations as well as models of the time-dependent settlement. The calculated settlements are relatively close to actual monitoring data. The models were done for prediction of the land subsidence at 92 selected points by the finite element method. Prediction maps are made for prediction of the land subsidence in 2020 and 2030. Recommendations are proposed for potential zones of groundwater exploitation in Hanoi.

Keywords: Hanoi; Soils; Land subsidence; Settlement; Groundwater exploitation; Modeling

Hanoi, the capital of Vietnam, is one of the largest cities in Asia with a developed industry, infrastructure and high population density. After expansion of administrative boundary in August 2008, the New Hanoi has an area of 3324.9 m^2 and a population of 6.3 million people, groundwater exploitation for water supply of more than 1 million m^3 per day. Water consumption in the city is increasing annually. Continuous growth in groundwater exploitation from water supply stations created depression craters with decreasing groundwater levels in many areas: from 13 to 18 m at Thanh Cong, Ngo Si Lien, Don Thuy, Nga Tu Vong, etc.; from 18 to 32 m at Mai Dich, Ngoc Ha, Ha Dinh, Thuong Dinh, Dai Kim, Phap Van, etc. The city is located in an area with complicated natural conditions, dangerous geological processes caused by natural and man-made activities and widespread distribution of soft soils (equal to 30% of the area) that makes great difficulties in the construction and operation of engineering structures [1–3].

The land subsidence caused by intensive groundwater extraction is one of the most dangerous geological processes that occur in the Hanoi city, and accompanied by deformation and destruction of houses, buildings and objects.

Assessment and prediction of this phenomenon have great importance in the prevention and reduction of its damage to civil and industrial structures in Hanoi. Questions on the land subsidence in the Hanoi city caused by intensive groundwater extraction are answered in studies of Giao et al. [4]. One of the urgent tasks at the present time is to divide the Hanoi territory into zones with different levels of the land subsidence, and determine changes of future settlement areas.

Land subsidence due to large amounts of fluid withdrawal from an aquifer has occurred in many areas in the world, such as Venice, San Joaquin Valley, California, Mexico City, Shanghai, Bangkok etc., and has been extensively investigated both quantitatively and qualitatively. Many researchers have been dedicated to constructing mathematical models to predict the development of land subsidence and proposing measures to control land subsidence. The study results of the land subsidence caused by intensive groundwater extraction are also shown in studies of Giao and Phien-wej [5], Giao [6], Nguyen [7], Poland [8], and Terzaghi [9].

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The purpose of the article is prediction of the land subsidence in the Hanoi city and establishment of prediction map of the land subsidence caused by the groundwater extraction.

The main difficulty in achieving this goal is necessary to solve two independent groups of tasks. The first group includes hydrogeological problems for assessment and prediction of changes in groundwater levels. The second one is engineering–geological problems for assessment and prediction of the land subsidence in the geological environment with different compositions, structures and properties of soil strata. The study on the land subsidence caused by groundwater extraction was carried out by collecting and analyzing data on the geology, hydrogeology, soil properties and the observed settlements and modeling values of the land subsidence in process of groundwater exploitation. When processing, analysis and interpreting the observed data programs «MS Excel», «AutoCad», «Visual ModFlow», «Mapinfo» and others were used.

1. Analysis of data on the geology of the Hanoi area

In the profile of the Quaternary sediments in Hanoi, they can be divided into five formations according to age and origin, from bottom to top, as follows: Early Pleistocene alluvial deposits (Le Chi Formation – *a*I*lc*); Middle–Late Pleistocene alluvial and alluvial–proluvial deposits (Ha Noi Formation – *a*,*ap*II-III^1*hn*); Late Pleistocene alluvial, lacustrine, and lacustrine–bogged deposits (Vinh Phuc Formation – *a*,*l*,*lb*III^2$vp_{1,2,3}$); Early–Middle Holocene lacustrine–bogged, marine, and bogged sediments (Hai Hung Formation – *lb*,*m*,*b*IV$^{1-2}$$hh_{1,2,3}$); Late Holocene alluvial and alluvial–lacustrine–bogged deposits (Thai Binh Formation – *a*,*alb*IV^3$tb_{1,2}$).

Analysis of physical and mechanical properties of the Quaternary sediments in the Hanoi city [3] allowed dividing them into 24 layers (from top to bottom):

- **Man-made soils (*tH*):** *Layer 1* – sands, sandy clay, and clayey sand with an admixture of construction debris (fragments of brick, stone, limestone, construction mortar, etc.);
- **Upper part of Thai Binh formation (*a*IV^3tb_2):** *Layer 2* – very soft sandy clay with organic matters (bottom sediments of lakes and ponds); *Layer 3* – brown and pinkish-brown firm sandy clay, interstratified with clayey sand; *Layer 4* – saturated brownish-grey fine-grained and loose sand, some places with gravel;
- **Bottom part of Thai Binh formation (*alb*,*a*IV^3tb_1):** *Layer 5* – yellowish-grey stiff to firm clay; *Layer 6* – yellowish-grey and brown stiff to firm sandy clay; *Layer 7* – saturated brownish-grey very soft to soft sandy clay with organic matters; *Layer 8* – brownish grey firm sandy clay, interstratified with clayey sand and sand; *Layer 9* – saturated greenish-grey fine-grained medium dense sand; *Layer 10* – brownish grey firm sandy clay, interstratified with clayey sand and sand;
- **Upper part of Hai Hung formation (*amb*IV$^{1-2}$$hh_3$):** *Layer 11* – saturated dark grey very soft to soft sandy clay with organic matters;
- **Middle part of Hai Hung formation (*m*IV$^{1-2}$$hh_2$):** *Layer 12* – green grey stiff to firm clay;
- **Bottom part of Hai Hung formation (*lb*IV$^{1-2}$$hh_1$):** *Layer 13* – dark grey very soft sandy clay with organic matters;
- **Upper part of Vinh Phuc formation (*a*,*am*III^2vp_3):** *Layer 14* – light grey and yellowish-grey stiff clay; *Layer 15* – multi-coloured (brown, yellow, red) very stiff to stiff sandy clay;
- **Middle part of Vinh Phuc formation (*alb*II^2vp_2):** *Layer 16* – dark grey very soft to soft sandy clay with organic matters;
- **Bottom part of Vinh Phuc formation (*a*III^2vp_1):** *Layer 17* – yellowish-grey plastic clayey sand, interstratified with sandy clay or sand; *Layer 18* – saturated brown and yellowish-brown fine-grained medium dense to dense sand; *Layer 19* – saturated yellowish-grey and light grey medium- and coarse-grained dense to very dense sand, some places with gravel and pebbles;
- **Ha Noi Formation (*ap*,*a*II–III^1*hn*):** *Layer 20* – brownish-grey firm sandy clay, some places with organic matters; *Layer 21* – grey plastic clayey sand, some places with gravel; *Layer 22* – saturated gravel and pebbles, some places with grey and yellowish-grey very dense coarse-grained sand;
- **Le Chi formation (*a*I*lc*):** *Layer 23* – grey and brown plastic clayey sand, some places with gravel; *Layer 24* – saturated gravel and pebbles, fine-grained and coarse-grained brownish-grey and yellowish-grey very dense sand with sandy clay.

Summary of physical and mechanical properties of the Quaternary sediments in the Hanoi area according to study results of Phi H.T. is presented in Table 1.

Sediments of the upper part of the profile (Vinh Phuc, Hai Hung, Thai Binh formations) are soft soils with low bearing capacity and high compressibility (R_0 < 100 kPa and E_0 (0.1–0.2) < 5 MPa, respectively). Their thickness varies from 0.2 to 43.0 m; Their depth varies from 0 to 37.8 m. They are widely distributed in the central and southern parts of the city.

2. Analysis of data on hydrogeology and observed settlements in the city

According to the Hanoi Groundwater Extraction Company [10] the city has three main forms of groundwater extraction: public, industrial and private well fields. In Hanoi there are 10 major well fields (called water supply stations) and 11 small well fields to supply groundwater for domestic and industrial needs. They consist of 164 wells drilled in the Pleistocene complex, with an average capacity of 667,804 m^3/day in 2008. For supplying groundwater for industrial needs there are about 513 wells in total. Wells were drilled in the Pleistocene complex to a depth of 32–85 m, with an average capacity of 152,000 m^3/day in 2008. Private domestic wells consist of about 110,902 with shallow depth that use groundwater from the Holocene complex or upper part of the Pleistocene complex. The total groundwater extraction from these wells was 110,900 m^3/day in 2008.

The total groundwater extraction was 930,704 m^3/day in 2008. In the future, the daily water consumption will increase

Table 1
Summary of the physical and mechanical properties of the quaternary sediments in the Hanoi area according to the study results of Phi H.T. in 2013 [3].

Layer no.	Natural moisture content W, %	Bulk density ρ, g/cm^3	Plasticity index I_p, %	Liquidity index I_L	Internal friction angle φ, degree	Cohesion c, kPa	Deformation modulus $E_{0(0.1–0.2)}$ MPa	Bearing capacity R_0, kPa	Percentage of organic matters O, %	The number of the tested samples
2	55.8	1.64	16.9	1.12	5	7.1	1.6	50	–	52
3	32.6	1.79	15.6	0.58	10	16.5	6.9	120	–	29
4	–	–	–	–	25	–	7.2	100	–	16
5	32.8	1.85	19.0	0.35	10	29.3	11.1	170	–	87
6	29.1	1.89	14.3	0.37	12	26.8	11.6	170	–	733
7	42.6	1.72	14.8	0.89	7	12.0	4.0	70	5.7	385
8	31.2	1.82	9.7	0.74	12	14.7	7.6	110	–	249
9	–	–	–	–	27	–	10.7	130	–	545
10	34.3	1.74	12.1	0.73	10	16.1	5.4	110	–	89
11	40.1	1.76	15.6	0.96	6	9.6	3.4	60	12.2	27
12	35.1	1.80	18.6	0.47	10	24.2	8.9	140	5.3	163
13	53.3	1.61	15.9	1.26	5	9.1	1.6	50	9.7	628
14	30.6	1.87	18.5	0.25	12	30.8	15.2	180	–	196
15	26.6	1.92	13.9	0.28	14	30.4	14.8	210	–	608
16	36.4	1.76	12.8	0.88	10	12.0	4.9	90	8.0	54
17	26.0	1.85	7.5	0.77	15	14.5	11.5	140	–	167
18	–	–	–	–	33	–	19.8	290	–	195
19	–	–	–	–	36	–	30.1	370	–	215
20	27.3	1.84	10.8	0.59	9	18.2	7.0	120	–	8
21	–	–	–	–	–	–	12.4	180	–	10
22	–	–	–	–	–	–	>50.0	>500	–	80
23	–	–	–	–	–	–	15.0–20.0	>200	–	–
24	–	–	–	–	–	–	>50.0	>500	–	–

to 950,000–1,050,000 m^3/day in 2015 and 1,180,000–1,250,000 m^3/day in 2020. Most of the groundwater is taken from the Pleistocene complex (qp).

Monitoring of the land subsidence and changes in the groundwater level is managed by the Hanoi Institute of Building Technology (HIBT) at 10 monitoring stations [11].

According to analysis of monitoring data on the land subsidence and changes in the groundwater levels some conclusions can be done, as follows:

– Depending on time drawdown rate of the groundwater levels at all monitoring stations increased linearly.
– At most of the monitoring stations seasonal changes in groundwater levels were recorded clearly.
– Maximum values of the land subsidence were recorded at the monitoring station Thanh Cong, and smaller values at the monitoring stations HaDinh, Phap Van, Luong Yen.
– Levels of the land subsidence depend on the thickness of high compressive soils.
– In places with presence of soft soil layers the land subsidence is the sum of the settlement of soft soil layers overlying aquifer complex.

For the prediction of the land subsidence caused by groundwater extraction it was necessary to consider the two components of this process: (a) the prediction of changes in groundwater levels; (b) the prediction of the settlement of soil layers due to changes in its stress–strain state.

The prediction of changes in the groundwater levels in the Hanoi city was performed using the program Visual ModFlow V.4.2. According to capacity of the groundwater extraction in 2010 (see Fig. 1), in the next few years, the groundwater levels in the city will not exceed the allowable limit of drawdown. But at the water supply stations that are far from the Red River as

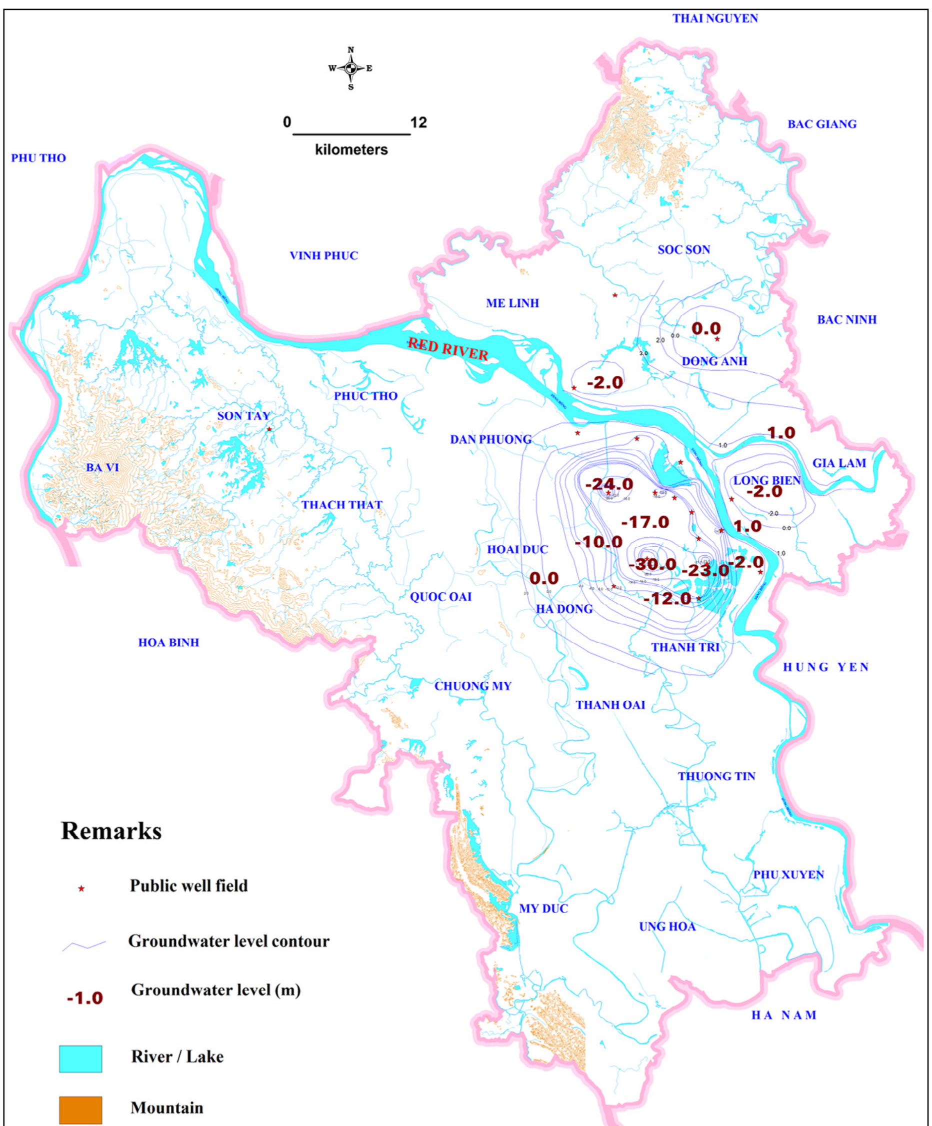


Fig. 1. Map of the groundwater level in Pleistocene complex in the Hanoi city in 2010 (Trieu DH., Pham BQ., Phi HT., 2013).

Mai Dich, Tuong Mai, Phap Van, Ngoc Ha and especially at Ha Dinh the groundwater level will still continue to go down. In 2020, the drawdown of the groundwater level in Pleistocene complex will be 27.5 m at Mai Dich and 32.0 m at Ha Dinh. In 2030 the drawdown of the groundwater level will be 28.5 m at Mai Dich and 32.8 m at Ha Dinh. As an example, Fig. 2 shows the prediction map of the groundwater level in Pleistocene complex for 2030.

To predict the land subsidence experimental and theoretical methods can be used; in this case for modeling the time-dependent surface settlement caused by groundwater extraction multifactorial correlation analysis method (MCA) and finite element method (FEM) will be used. Verification of the modeling from observed data received from 10 monitoring stations was carried out to select the optimal method of predicting the time-dependent settlement of each soil layer.

MCA allowed quantifying the impact of some geotechnical factors, such as the depth of groundwater, the average coefficient of relative compressibility, the thickness of soft soil layers, time and bulk density of the soft soil layers in formulas of the time-dependent surface settlement (S_t) due to groundwater exploitation. According to FEM, soil layers are divided into nodes and linear elements; the one-dimensional consolidation model is applied; based on changes in pore water pressure the time-dependent settlement of each soil sub-layer can be calculated.

Prediction of the time-dependent settlement (S_t) at the monitoring stations using both above methods shown that the prediction results are relatively close to the actual monitoring data. Comparison of the results obtained by these two methods together showed that in the next few years the prediction results of S_t using MCA are 20–30% bigger than prediction results using FEM in average. The reason for this deviation may relate to the short time of monitoring and a small number of monitoring stations. Therefore, MCA was used for the prediction of the land subsidence at 92 selected points. Selected points for the

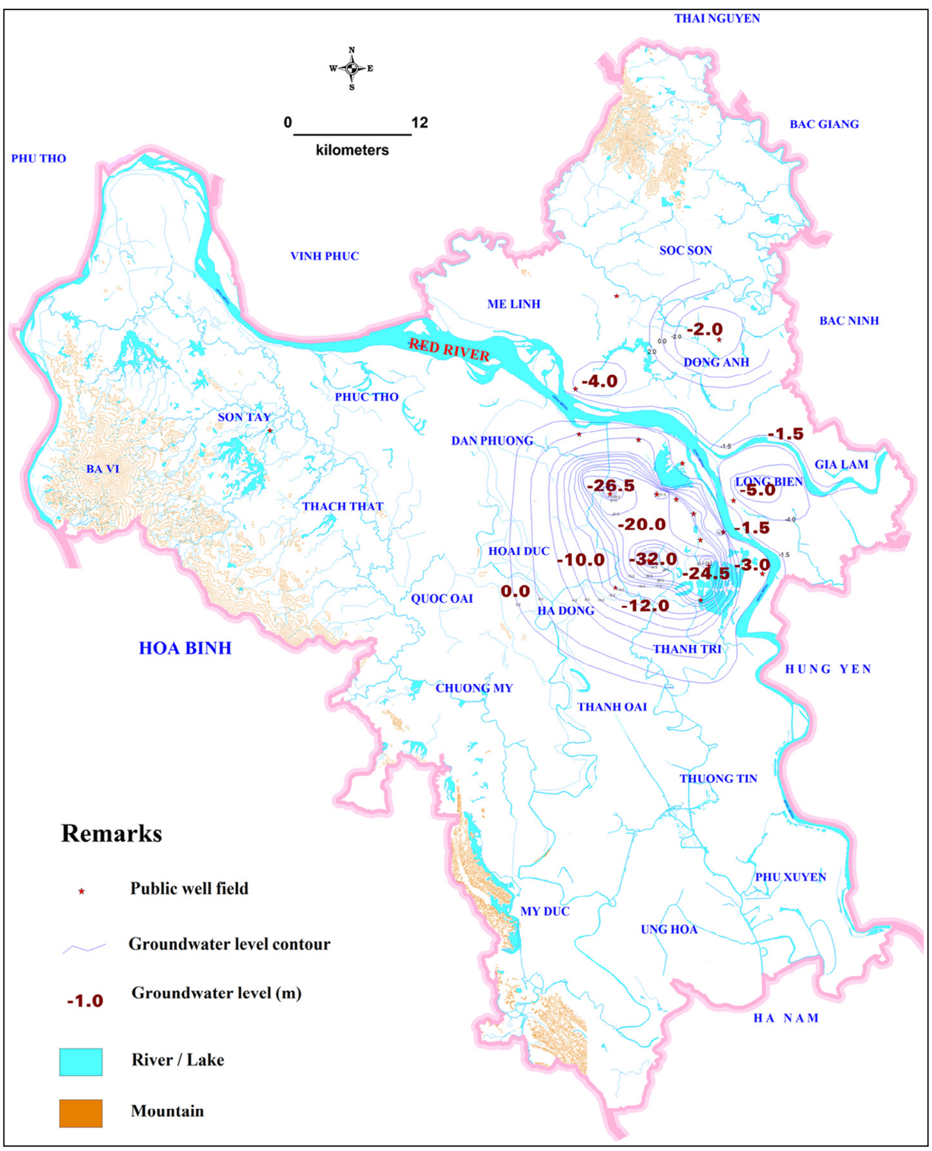


Fig. 2. Prediction map of the groundwater level in Pleistocene complex in the Hanoi city in 2030 (Trieu DH., Pham BQ., Phi HT., 2013).

calculation of the land subsidence are located in areas where the groundwater level of Pleistocene complex qp decreases due to groundwater extraction, and belongs to the different types of soil strata. The calculated results of the time-dependent settlement at selected points allowed providing prediction maps of the land subsidence in the Hanoi city caused by groundwater extraction fully and accurately.

Location of selected points for calculation of the time-dependent settlement is shown in Fig. 3.

The land subsidence at the selected points was calculated by FEM. Prediction maps of the land subsidence of the Hanoi city are caused by groundwater extraction in 2013, 2020 and 2030 (see Fig. 4). Fig. 5 is a graph showing relationship between the land subsidence and the capacity of groundwater extraction at the monitoring station Ha Dinh.

The prediction results showed that in 2013, the land subsidence in all area of the depression crater in the Pleistocene complex qp was greater than 10 cm. In there, in most of the areas of the districts Thanh Xuan, Hoang Mai, Hai Ba Trung and a part of areas of the districts Dong Da, Hoan Kiem, Ba Dinh, Tay Ho, Cau Giay, Tu Liem and Thanh Tri the land subsidence exceeded 30 cm; in the areas around the water supply stations Mai Dich, Phap Van, Tuong Mai, Ha Dinh, Luong Yen and the monitoring station Thanh Cong the land subsidence was 60–90 cm. The greatest values of the land subsidence with the value of 94 cm occurred in the area around the water supply station Bach Khoa, and in the area around the water supply station Phap Van with the value of 104 cm. This zone is located in the central part of Hanoi, and is also the center of the crater of the groundwater level in the Pleistocene complex. In the center of the depression crater the land subsidence exceeded 60 cm. This zone covered the area of water supply stations. In this zone soft soil layers have the thickness of greater than 10 m.

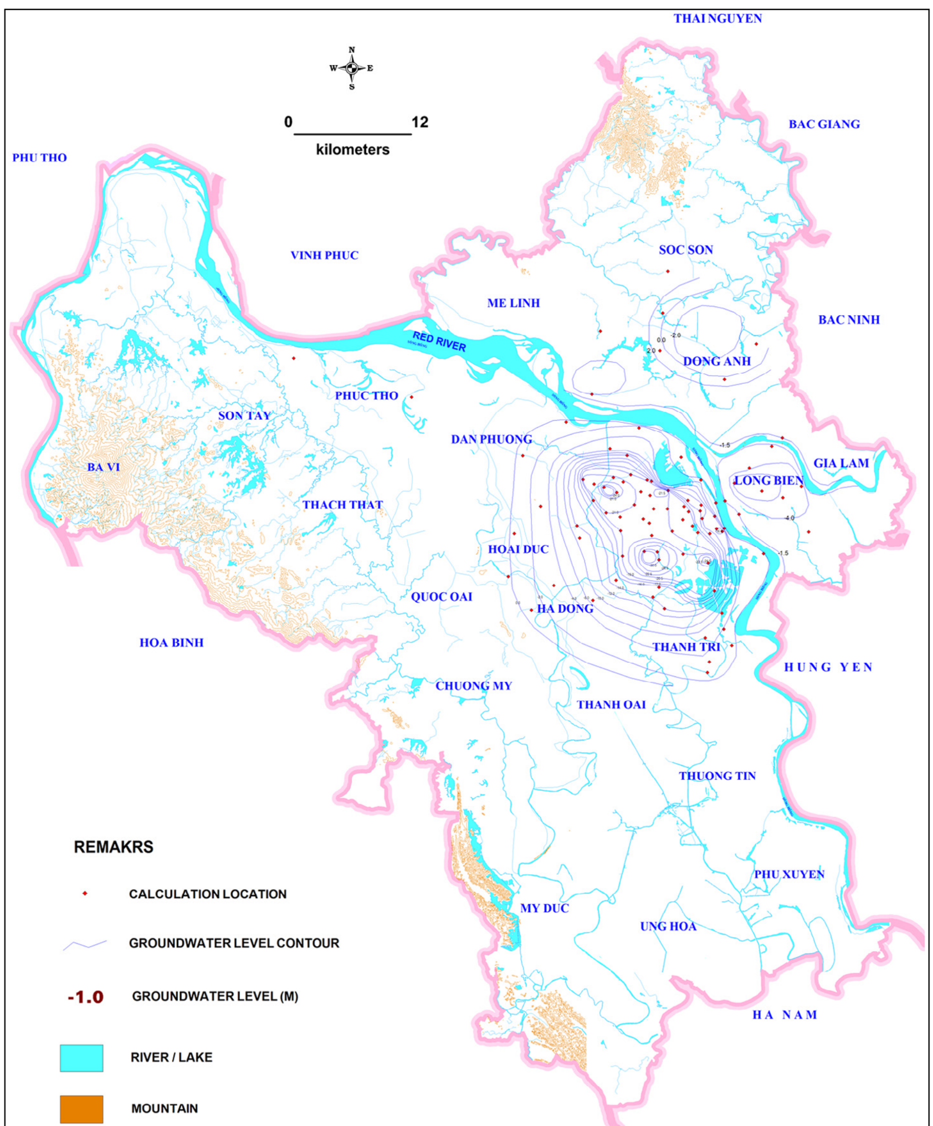
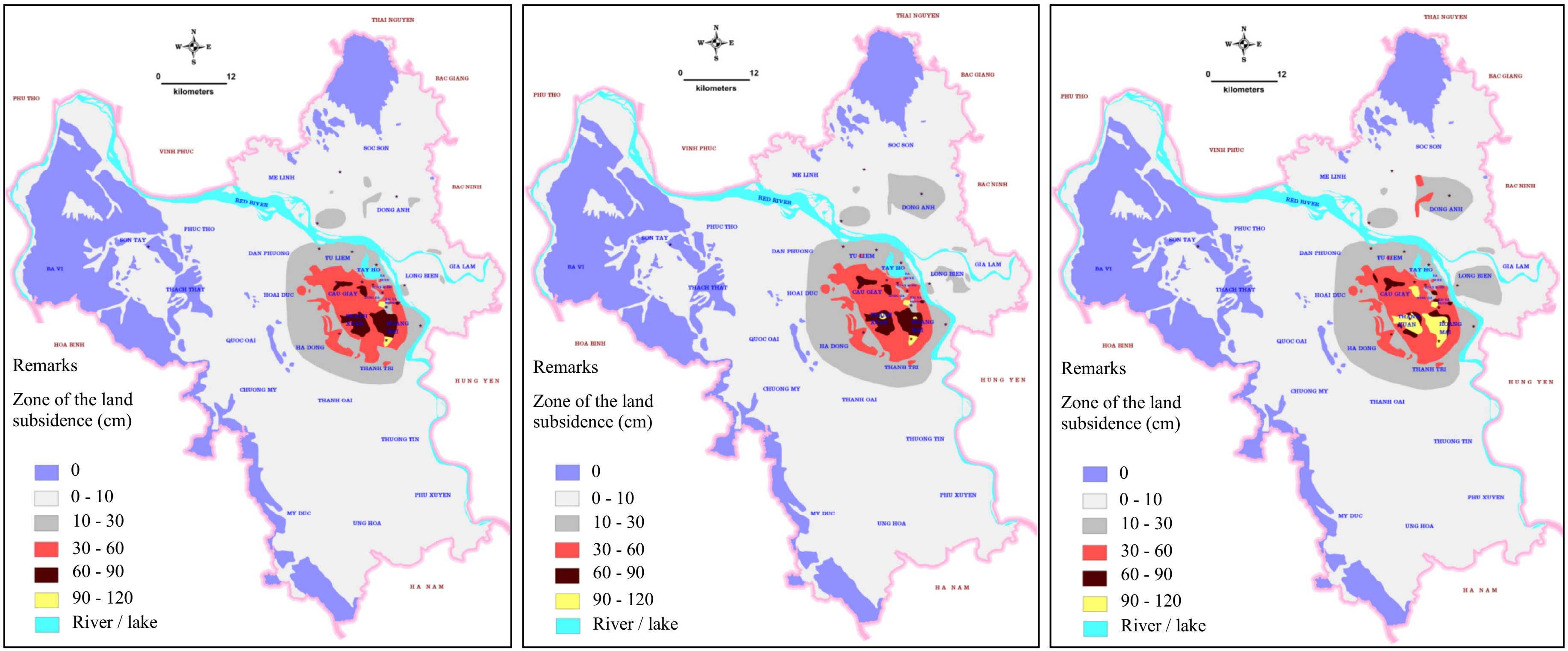


Fig. 3. Location of the selected points for calculation of the time-dependent settlement in the map of groundwater level in Pleistocene complex in the Hanoi city in 2030 (Phi HT., 2013).



a) *b)* *c)*

Fig. 4. Prediction maps of the land subsidence in the Hanoi city caused by groundwater extraction in (a) 2013; (b) 2020; (c) 2030 (Phi HT., 2013).

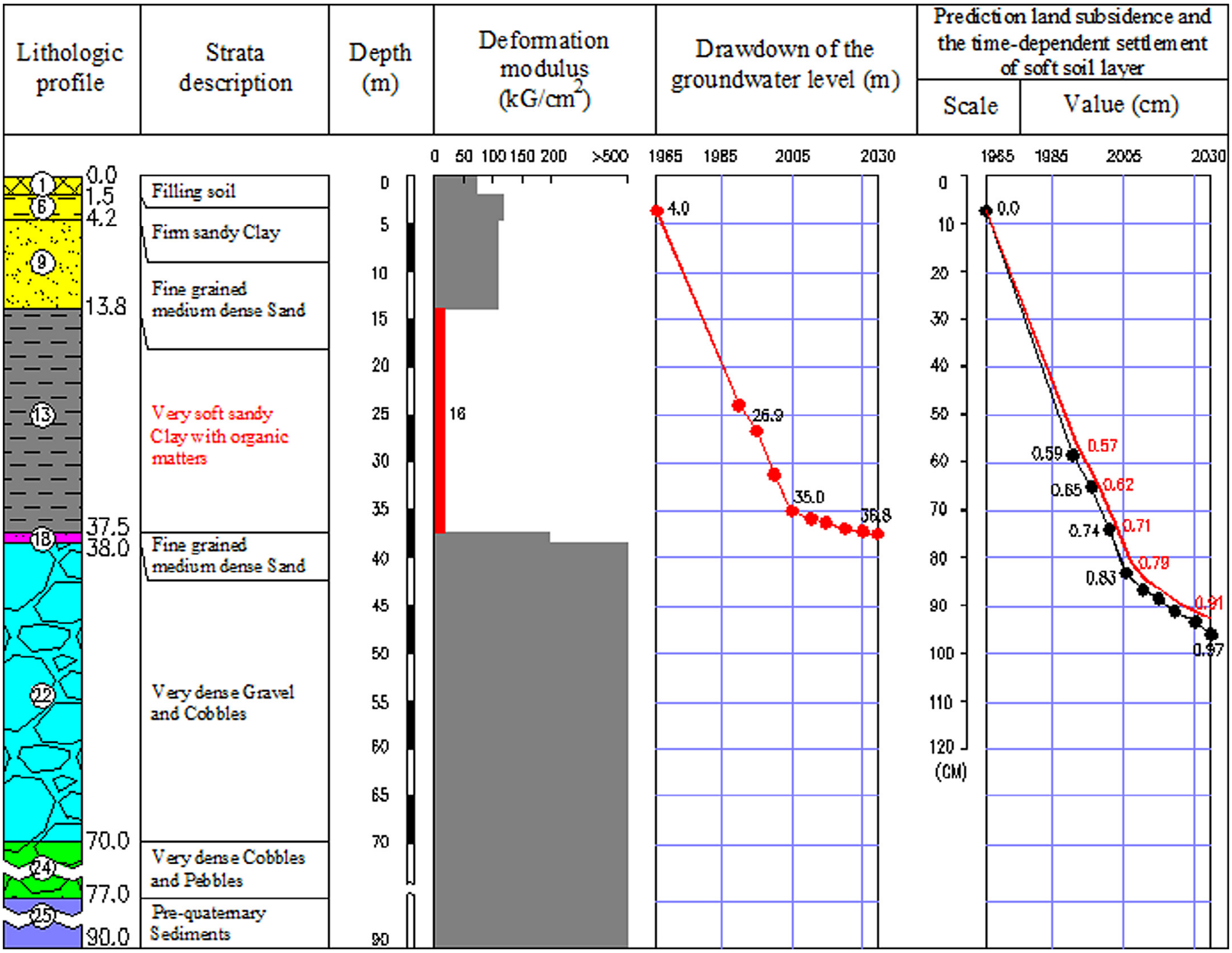


Fig. 5. Diagram shown relationship between the land subsidence and the groundwater extraction at the monitoring station Ha Dinh (Phi HT., 2013). In the diagram: black line – the land subsidence; red line – settlement of soft soil layer No. 13. Physical–mechanical properties of the other layers are shown in Table 1.

In the peripheral areas of the depression crater the land subsidence ranged from 10 to 30 cm, although in some areas of the districts Long Bien, Thanh Tri, Ha Dong, Hoai Duc the soft soil layers have the thickness of greater than 5 m.

In areas that are not in the area of the depression crater such as Phu Xuyen, Ung Hoa, My Duc, Thuong Tin, Chuong My, Quoc Oai, Thanh oai, Hoai Duc, Dan Phuong, Phuc Tho, Me Linh, Dong Anh, Soc Son, Gia Lam, Long Bien the land subsidence is predicted from 0 to 10 cm, although in many areas there are soft soil layers.

In most of the area of the districts Tu Liem, Tay Ho, Ba Dinh, Hoan Kiem, Hai ba Trung, Hoang Mai, Thanh Tri, Long Bien, Dong Anh, Me Linh that are located along the banks of the Red River and Duong River, the land subsidence was 10–29 cm, with an average of 12 cm. In these zones the soft soil layers have the thickness of less than 5 m or do not exist.

In areas covered by pre-quaternary sediments such as Soc Son, Ba Vi, Son Tay, Thach That and outlying areas in the south-western part of Hanoi, the land subsidence caused by the groundwater extraction will not occur.

The land subsidence caused by the groundwater extraction in the Hanoi city from 2006 to the present time is from 1 to 10 cm, with an average of 4 cm, which is slightly smaller than in previous years.

In comparison to 2013 some conclusions can be made as follows:

– By 2020, the area with the land subsidence of from 10 to 30 cm will be expanded, especially in the areas around the water supply stations Dong Anh and Gia Lam. Area with the land subsidence from 30 to 60 cm will be expanded on small areas around the water supply stations Mai Dich, Ha Dinh, Phap Van. Area with the land subsidence from 60 to 90 cm will not be expanded. Area with the land subsidence from 90 to 120 cm will be expanded on small areas around the water supply stations Ha Dinh and Tuong Mai.
– By 2030, the area with the land subsidence from 10 to 30 cm will continue to be expanded in the areas around the water supply stations. The area with the land subsidence from 30 to 60 cm will continue to be expanded in a small area around

the water supply station Dong Anh, where there is soft soil layer. Area with the land subsidence from 60 to 90 cm will continue to be expanded in a small area around the water supply stations Mai Dich, Ngo Si Lien, Bach Khoa, Ha Dinh. Area with the land subsidence from 90 to 120 cm will continue to be expanded in large area around the water supply stations Ha Dinh, Tuong Mai, Phap Van and Thanh Cong. In these areas, there are soft soil layers with the thickness of more than 10 m.

– By 2020 and 2030, the area of the land subsidence will be expanded, but the level of the land subsidence will be increased slightly, only from 1 to 15 cm, with an average of 6 cm. The land subsidence rate will be significantly reduced. The level of the land subsidence in many sections will reach 60–80% of the total value.

3. Recommendations

1 In order to limit the negative impact of the land subsidence some solutions can be done as follows:
   (a) Stop or reduce capacity of the groundwater extraction at the water supply stations Ha Dinh, Mai Dich, Tuong Mai, Ngoc Ha, Phap Van, Bach Khoa, Mausoleum of President Ho Chi Minh and Ngo Si Lien. The capacity of the groundwater extraction at these stations should be reviewed as shown in Fig. 6 below.
   (b) Build new water supply stations in less hazardous areas: according to the prediction results of the land subsidence, zoning geological strata (Phi HT., 2013) and zoning sketch of module of groundwater flow in the Hanoi city (National Center for Water Resources

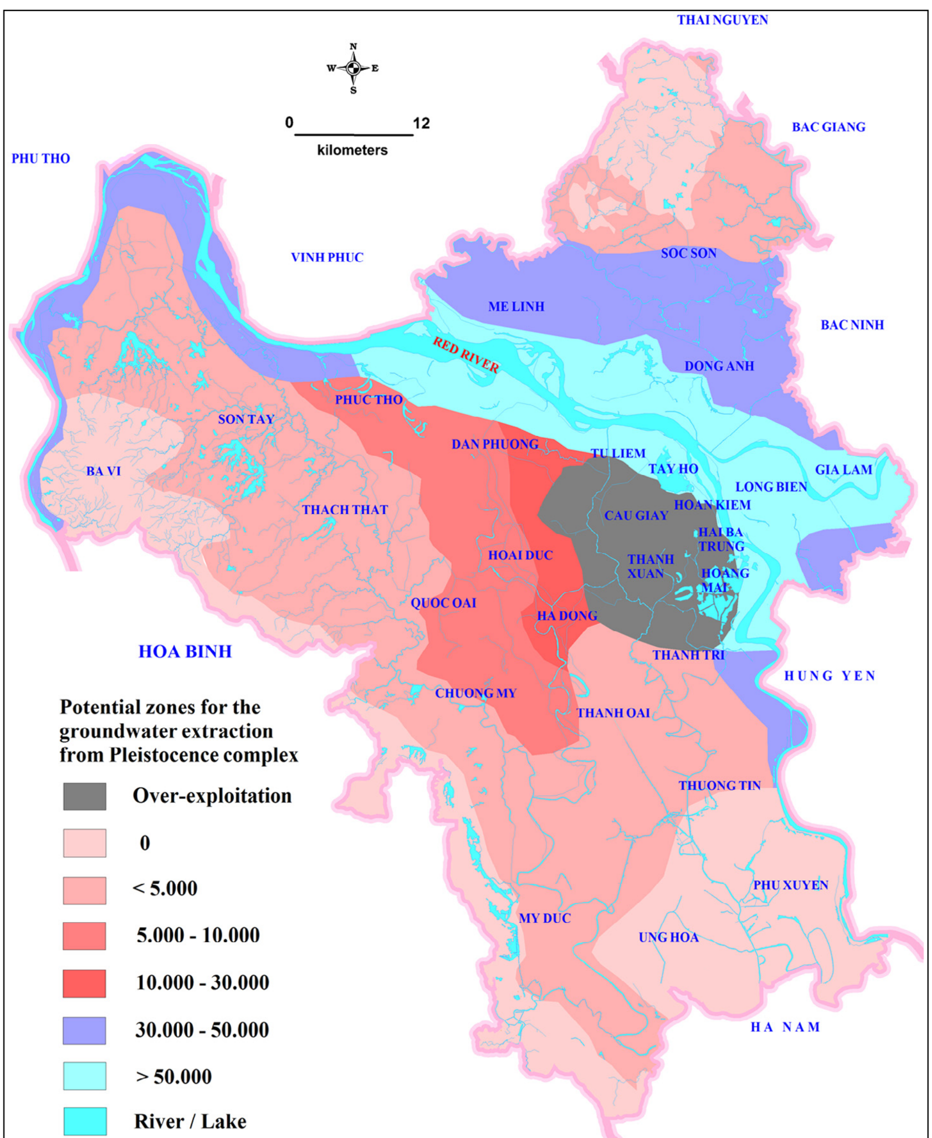


Fig. 6. Zoning sketch map of potential groundwater extraction from Pleistocene complex qp (made by NCWRPI, revised and supplemented by Phi HT., 2013).

Planning and Investigation – NCWRPI, 2011). The new water supply stations can be built at areas as shown in zoning sketch of potential groundwater extraction (see Fig. 6). In there, the area along the Red River and Duong River is the most potential zone for the groundwater extraction. In this zone there is "hydrogeological window". Groundwater is constantly replenished by surface water from the Red River and Duong River.

(c) Use the maximum capacity of the surface water supply station "Da River".

2 The surface water supply stations using water from the Red River and Duong River should not be built because of poor water quality and pollution.
3 It is necessary to build other monitoring stations for the land subsidence in the Hanoi city in order to supplement the monitoring data for timely and accurately warning the land subsidence.
4 The land subsidence caused by groundwater extraction should be considered in planning urban and designing structures.
5 It is recommended to use geophysical methods for monitoring of water resources.

4. Conclusions

The land subsidence is the result of mechanical processes, including processes of filtration consolidation and creep of soft soils, related with changes in the hydrodynamic conditions of the aquifer complex due to the groundwater extraction.

Prediction of the time-dependent settlement S_t at the monitoring stations for the land subsidence using FEM and MCA gave results relatively close to the actual monitoring data. Thus, FEM and MCA are reliable methods and can be used to predict the land subsidence caused by the groundwater extraction in Hanoi. Comparison of the prediction results obtained by these two methods shown that in the next few years the prediction results of S_t using MCA are 20–30% bigger than using FEM. The reason for this deviation may relate to the short time of monitoring and a small number of monitoring stations. Therefore, MCA was used for the prediction of the land subsidence at 10 monitoring stations, and FEM was used to predict the time-dependent settlement at all of the selected points.

The predicted results showed that:

– In 2013, in most of the area of the central part of Hanoi the land subsidence had the biggest values, from 30 to 104 cm. In this zone there is a large crater of the groundwater levels in Pleistocene complex qp. Most of the area of the zone belongs to the types of soil strata I.2.c, I.2.b with the thickness of soft soils of greater than 5 m. The biggest values of the land subsidence (70–104 cm) were observed in the center of the depression crater, covering the area around the water supply stations Ha Dinh, Phap Van, Tuong Mai, Bach Khoa. In this zone there are soft soil layers with the thickness of greater than 10 m. In suburb areas and outer part of the depression crater the land subsidence had smaller values, only from 0 to 30 cm, although in the zone there are soft soil layers with the thickness of greater than 5 m. Areas along Red River and Duong River the land subsidence had also small values, only from 10 to 29 cm. In the zones covered by pre-quaternary sediments, the land subsidence caused by groundwater extraction did not occur.
– The land subsidence caused by groundwater extraction in the Hanoi city from 2006 to the present time is from 1 to 10 cm, with an average of 4 cm, which is slightly less than in previous years.
– Comparison with 2013 shows that in 2020 and 2030 the area of surface subsidence areas will continue to be expanded, but the level of the land subsidence will increase a little, only from 1 to 15 cm, with an average of 6 cm. The land subsidence rate will be significantly reduced. The level of the land subsidence in many sections will reach 60–80% of the total values.

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