Modelling subsidence in the Hanoi City area, Vietnam

Trinh M. Thu and Delwyn G. Fredlund

Abstract: A study of land subsidence due to groundwater pumping in the city of Hanoi, Vietnam, was conducted by collecting and analyzing data on the geology, hydrology, soil properties, and observed settlements. The city of Hanoi is underlain by sediments consisting of organic and inorganic clays, silt, peat, sand, and gravel. The pumping of groundwater causes consolidation of compressible aquitard layers. The water demand for the city of Hanoi is increasing with time. The present total rate of water pumping is 450 000 m^3/day, and there is a proposal to increase the rate to 751 000 m^3/day by the year 2010. This research program involved the modelling of seepage related to pumping along with a stress–deformation analysis. The effect of surface infiltration was also modelled. The settlements computed for parts of the city of Hanoi were compared with measurements of settlement in the city area. The simulation results appear to be in fairly good agreement with the measurement results. The study showed that subsidence due to groundwater pumping is a serious problem in the city of Hanoi. It is important to continue to measure settlements and compute possible deformations associated with actual rates of pumping.

Key words: subsidence, settlement, groundwater pumping, stress–deformation modelling, seepage modelling.

Résumé : Une étude de l'affaissement de terrain causé par le pompage de l'eau souterraine dans la ville de Hanoi, Vietnam, a été réalisée au moyen de la collecte et de l'analyse des données sur la géologie, l'hydrologie, les propriétés des sols, et les tassements observés. La ville de Hanoi repose sur des sédiments comprenant des argiles organiques et inorganiques, du silt, de la tourbe, du sable, et du gravier. Le pompage de l'eau souterraine cause la consolidation des couches compressibles de l'aquitard. La demande d'eau dans la ville de Hanoi augmente avec le temps. Le taux total actuel de pompage d'eau est de 450 000 m^3/jour, et d'ici à l'an 2010, on se propose d'augmenter le taux à 751 000 m^3/jour. Le présent programme de recherche implique la modélisation de l'infiltration reliée au pompage de même qu'une analyse contrainte–déformation. L'effet de l'infiltration de surface a aussi été modélisé. Les tassements calculés dans certaines parties de la ville de Hanoi ont été comparés aux résultats des mesures du tassement sur le territoire de la ville. Les résultats de la simulation semblent être en assez bonne concordance avec les résultats des mesures. L'étude montre que l'affaissement dû au pompage des eaux souterraines constitue un problème sérieux dans la ville de Hanoi. Il est important de continuer de mesurer les tassements et de calculer les déformations possibles reliées aux taux actuels de pompage.

Mots clés : affaissement, tassement, pompage des eaux souterraines, modélisation contrainte–déformation, modélisation de l'infiltration.

[Traduit par la Rédaction]

Introduction

Hanoi, Vietnam, is a city of more than 4 million people located in the delta area of the Red River. The city is situated about 100 km from the Gulf of Tonkin. The population growth and technological developments in Hanoi have produced a continuously increasing demand for potable water. The water for domestic and industrial use in Hanoi comes from wells located within and around the city. The heavy pumping of groundwater has produced a serious settlement problem, which in turn has affected surface structures in the city of Hanoi.

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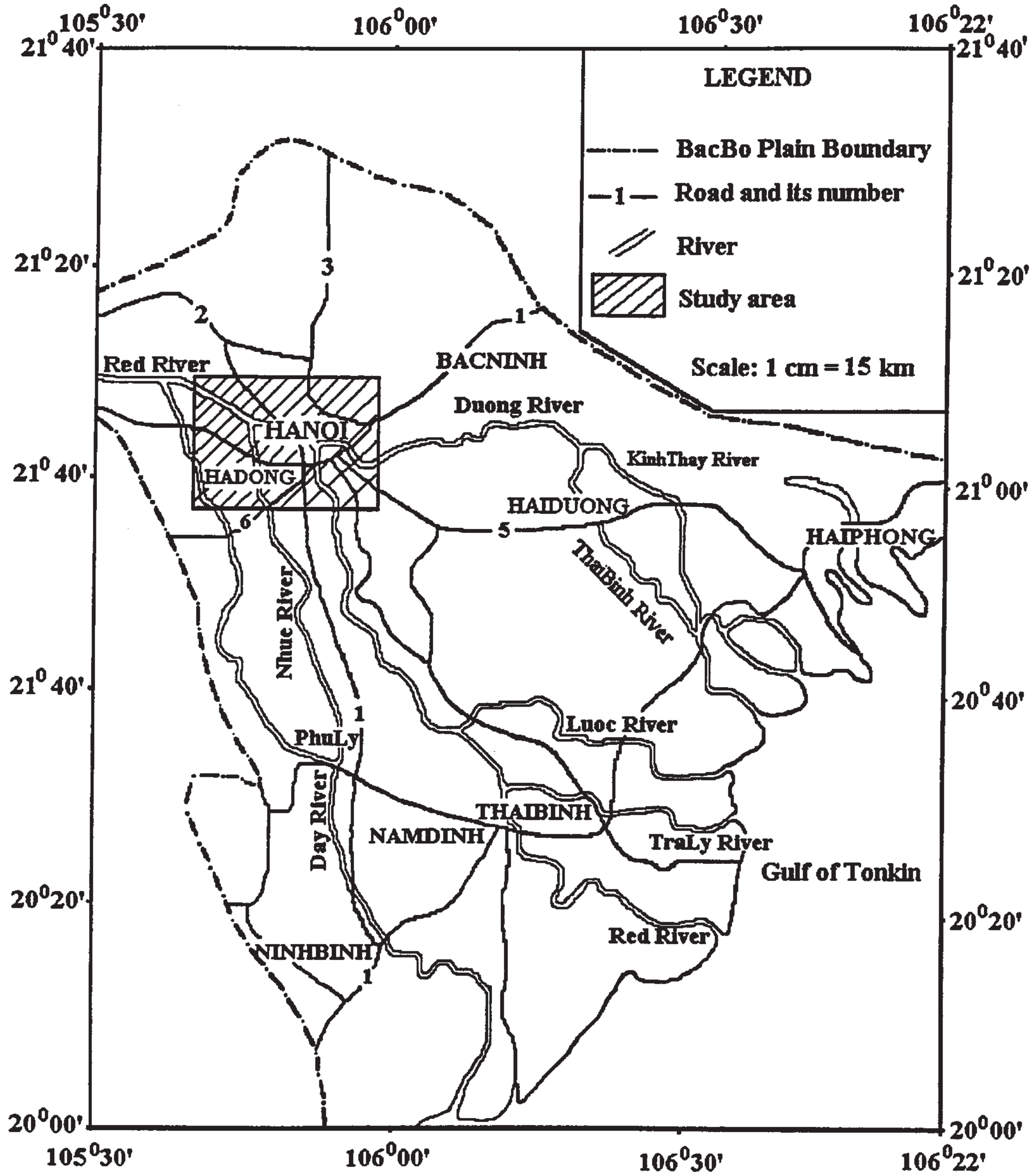
Areas experiencing land settlement are underlain by deposits of highly compressible soils. The soils are Quaternary and younger in age and are mostly alluvial and lacustrine in origin, with low coefficients of permeability and high compressibilities. The aquifers are confined and comprised of sands and gravel with high coefficients of permeability and low compressibilities. The city of Hanoi has been extracting water from aquifers since 1909. Although the present total water withdrawal is only about 450 000 m^3/day, there have been signs of distress on some of the buildings as a result of ground settlements. Some buildings, roads, and other structures in the proximity of the pumping wells have been damaged by settlement. The settlements appear to be closely related to rates of groundwater extraction.

This preliminary study of settlement due to the pumping of groundwater is based on general information related to the site conditions in Hanoi and soil investigations conducted at some of the well fields. The main objective of this study is

Fig. 1. Location of the study area.



to document the evidence related to the settlement problem in Hanoi (Thu 1998).

The scope of the research study is limited to the compilation and analysis of existing field data due to the difficulties in obtaining additional relevant data. The amount of available data does not allow for a detailed analysis of all of the water extraction well fields. As a result, there is a limit to the results that can be obtained related to possible settlements in various parts of Hanoi.

Figure 1 provides a plan view of Hanoi and the surrounding Red River basin. Figure 2 shows the locations of the well fields in Hanoi, and the arrows show the locations of two cross sections through Hanoi. Figures 3 and 4 provide the general stratigraphic cross sections that identify the upper silty clay and clayey silt that overlies the sandy gravel aquifers. The well fields extend to the sandy gravel strata where water is extracted on an ongoing basis.

Subsidence problems in other areas of the world

The worldwide exploitation of groundwater resources and the consequent water-level declines are creating many areas of land settlement and associated distress to the infrastructure. Poland and Davis (1969) summarized available pertinent information on areas of substantial known subsidence throughout the world due to fluid withdrawal as of 1963. Examples of cities and countries experiencing land subsidence are Wilmington, Texas; San Joaquin and Santa Clara Valley, California; Savannah, Georgia, U.S.A.; Lake Maracaibo, Venezuela; gas fields in Niigata, Japan; London, England; Mexico City, Mexico; Shanghai, China; Bangkok, Thailand; Venice, Italy; The Netherlands; Osaka and Tokyo, Japan; and others (Waltham 1989). Over 150 regions of contemporary settlement are known. Subsidence of up to 10 m has

Fig. 2. Location of the well field in the city of Hanoi, Vietnam.

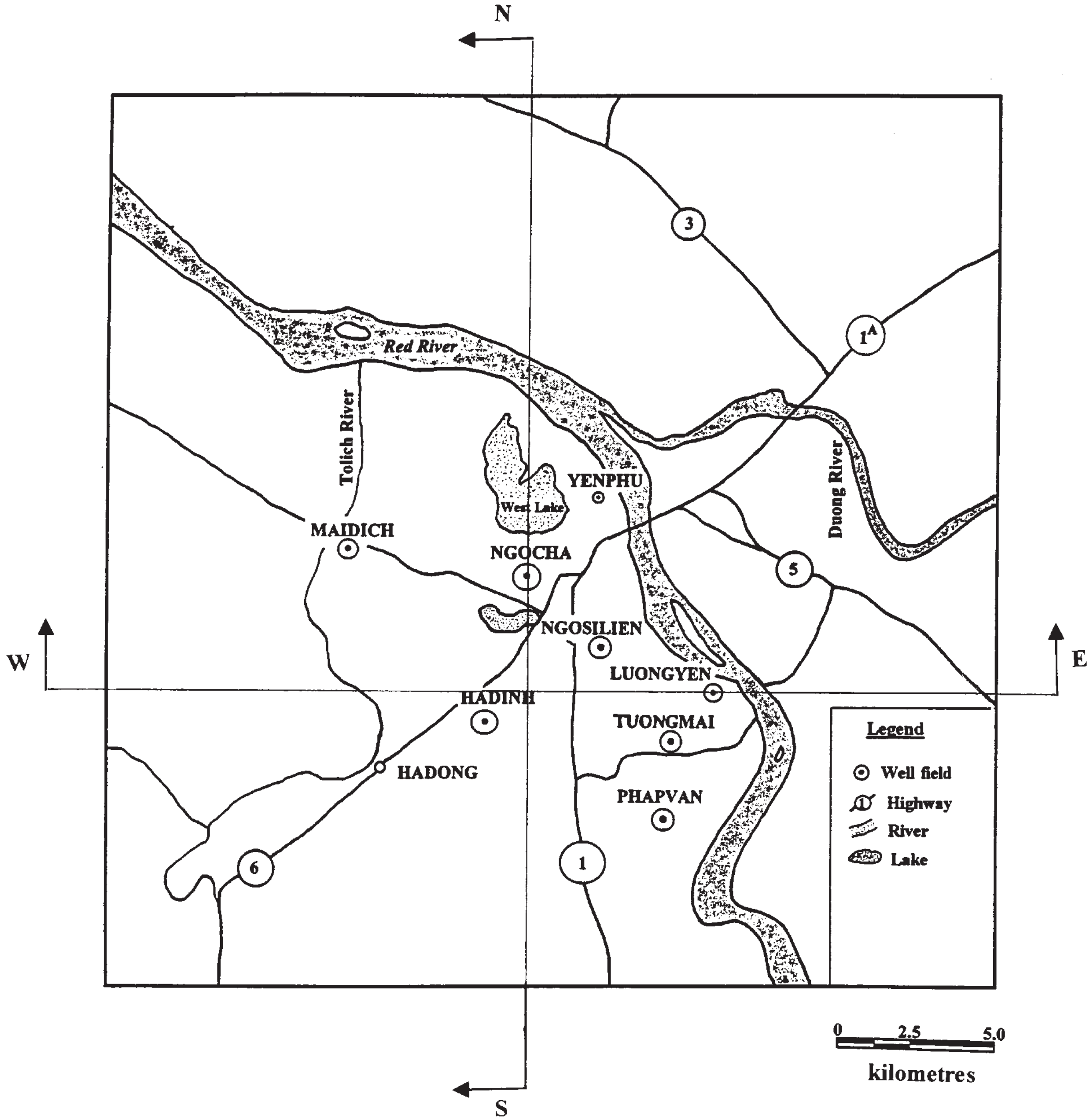


Fig. 3. Hydrogeological section from south to north through the city of Hanoi. Vertical lines indicate changing hydraulic conductivity.

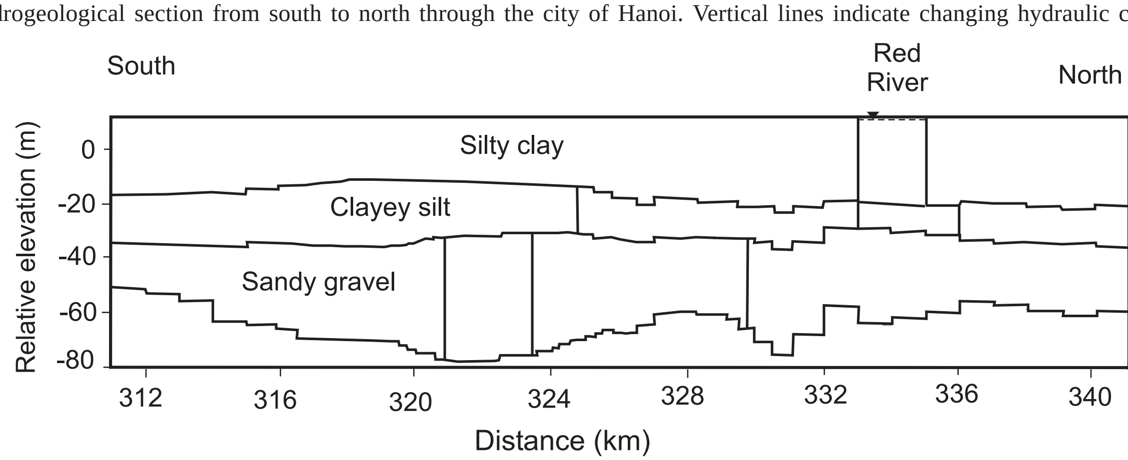
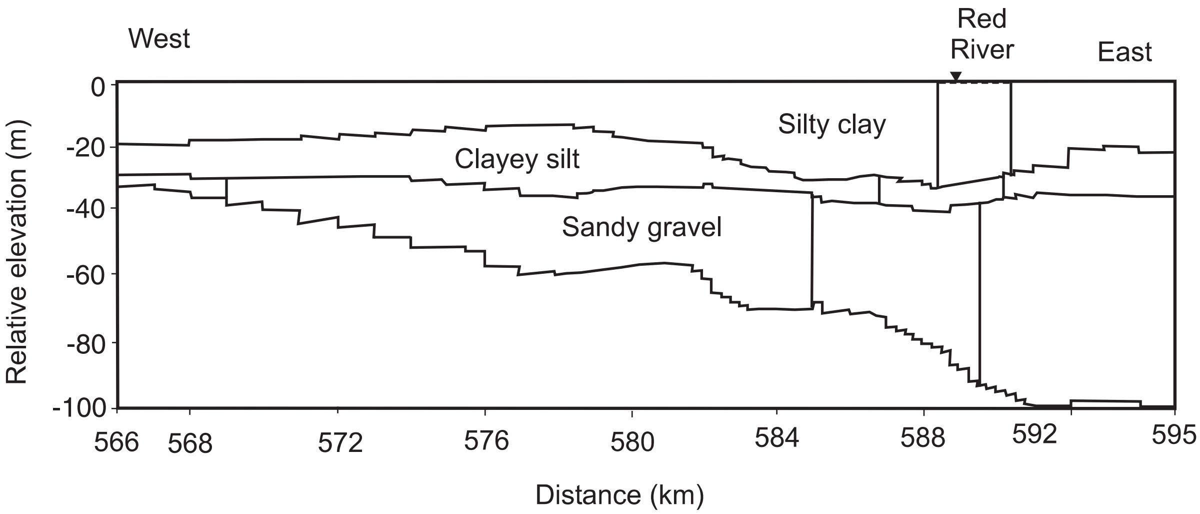


Fig. 4. Hydrogeological section from west to east through the city of Hanoi. Vertical lines indicate changing hydraulic conductivity.



been reported in Mexico. Many more areas of subsidence are likely to develop in the next few decades as a result of accelerated exploitation of water and natural resources to meet the demands of increasing populations and as developing countries expand their industries (Barends et al. 1995).

Okumura (1969) analyzed the land subsidence in the Niigata area using a one-dimensional consolidation theory. The pumping of groundwater from deep sandy layers for extracting methane gas and the subsequent increase in effective stress caused a time-dependent loading on the clay layers. An analytical consolidation solution was presented for the case of a load increasing linearly with time. A numerical method of analysis was used and solutions were developed considering various values for the consolidation and rebound parameters. The calculated results somewhat overestimated the observed measurements.

The following aspects of land subsidence in the Tokyo delta area were studied by Nakano et al. (1969): (1) land subsidence caused mainly by the consolidation of soft clayey layers within aquifers that were subjected to over-pumping of groundwater; and (2) consolidation that was progressing not only in the alluvium, but also in the deluvium. In general, most of the consolidation was in the alluvium and the layers below the alluvium. A relationship between the amount of land subsidence and the thickness of the alluvium was clearly shown. This was particularly true in the case of land subsidence due to the pumping of groundwater from the alluvium and the upper deluvium water-bearing layers. The area under consideration showed a subsidence rate of more than 100 mm/year.

The Federal District of Mexico City, one of the largest cities in North America, is well known for subsidence and settlement of its structures. The general process of subsidence of this area began long ago in pre-Spanish and Spanish times after the installation of dikes and drainage canals to cope with floods. From 1900 to about 1957 some buildings have settled about 7.6 m below original elevations. Borings in the city indicate that the soil consists of a layered system of gravel, sand, silt, and clay, the latter of which is mostly of volcanic origin and contains montmorillonite (Jumikis 1984).

Murayama (1969) constructed a model to simulate subsidence with soil layers set in a water-filled tank. The tanks were made of reinforced concrete in a rectangular shape. One series of tests was performed on the soil layers, which consisted of a clay layer placed over a sand aquifer layer. In another series of tests, two clay layers were alternated with two sand layers. The top surface of the soil was covered with free water. The following experiments were performed on the three models: (1) the settlement due to lowering and recovering of the artesian head in the aquifer was studied, and the results showed that the rate of recovery of pore-water pressures was quicker than that under consolidation; (2) the land subsidence due to repetitious change in the artesian head in the aquifer was studied, and the results showed that the longer the cycle of the repetition, the greater is the rate of land subsidence, and rebound is faster than consolidation in the clay layer; and (3) the effects of a change in the level of the surface water on land subsidence and artesian head were studied.

MacMillan et al. (1976) used an existing numerical flow model to predict drawdown. A model and an associated equation were developed to predict ultimate subsidence in the Tularosa basin, New Mexico. The equations for the model require an estimate of the specific yield, the average hydraulic conductivity of the aquifer, the aquifer thickness, and the compressibility of clay in the aquifer. The results showed the predicted drawdown and subsidence after 25 years of pumping at the assumed rates.

Theoretical aspects related to subsidence

The drawdown of the piezometric level in an aquifer will increase the effective stress in the adjacent soil strata. The decrease in pore-water pressure will cause consolidation and hence will result in settlement in accordance with the effective stress equation:

$$[1] \qquad \sigma' = \sigma - u$$

where

- σ is the total stress;
- u is the pore-water pressure; and
- σ' is the effective stress.

Table 1. Summary of the hydraulic parameters used in the calibrated flow model Modflow.

Layer	Area	Hydraulic conductivity (m/s)	Specific yield S_y	Specific storage S_s (l/m)
Unconfined		6.2×10^{-7}	0.0018	0.0180
Confining	Hadinh, Tuongmai, Phapvan, Luongyen, Hadong, Ngosilien	8.5×10^{-9}	0.00023	0.0023
Confined	Maidich, Ngocha	6.4×10^{-9}	0.00023	0.0023
	Red River, Xenphu	6.2×10^{-7}	0.00180	0.0180
	Maidich, Ngocha	5.1×10^{-4}	0.00250	0.0250
	Hadinh, Tuongmai	2.3×10^{-4}	0.01600	0.1600
	Hadong, Phapvan	6.0×10^{-4}	0.02000	0.2000
	Xenphu, Ngosilien, Luongyen	1.2×10^{-3}	0.02100	0.2000
	North of the Red River	2.5×10^{-4}	0.00300	0.0300

Note: Specific yield S_y is determined from the equation $n = S_y + S_r$, where S_r is the specific retention, and n is the porosity. Specific storage is defined as $S_s = \rho g(\alpha + n\beta)$, where ρ is the density of the water, g is the acceleration due to gravity, α is the compressibility of the soil, and β is the compressibility of water.

The increase in vertical effective stress is equal to the change in pore-water pressure:

$$[2] \qquad \Delta\sigma' = -\Delta u$$

When the pore-water pressures are in excess of equilibrium boundary conditions, a consolidation process is initiated. As a first level of estimation, the change in pore-water pressure (and subsequently the magnitude of settlement) can be computed using Terzaghi's one-dimensional consolidation theory:

$$[3] \qquad \frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2}$$

where c_v is the coefficient of consolidation. Settlement can then be estimated through a knowledge of the coefficient of volume change, m_v:

$$[4] \qquad s = Hm_v\Delta\sigma'$$

where

s is the settlement;
H is the thickness of the settlement layer; and
$\Delta\sigma'$ is the increase of the effective stress.

The same theoretical principles apply for the axisymmetric case and for two- and three-dimensional seepage modelling.

Numerical modelling of subsidence

The modelling of ground subsidence due to groundwater pumping can be achieved through a combined seepage analysis and a stress–deformation analysis along with a ground surface moisture-flux model. The computer software programs Modflow[1] (Waterloo Hydrogeologic, Inc. 1997) and Seep/W[2] (Geo-Slope International Ltd. 1994*a*) were used to model seepage through the soil strata as a result of groundwater pumping.

Modflow analysis

The assessment of land subsidence in the Hanoi area is closely related to the study of groundwater flow. Modflow has been recognized as a general purpose, three-dimensional, finite-difference, groundwater flow model. Modflow allows for a variety of input and boundary-condition options.

The Modflow groundwater model was applied to the entire city of Hanoi. The ground surface and the stratigraphic layers in the model were synthesized based on well logs and geological and topographic information. In the area where the pumping wells are located, a square cell 125 m by 125 m was chosen for discretization. For the peripheral area, which is not influenced significantly by pumping, the discretization cells sizes are 250 m by 250 m, 500 m by 500 m, and 1000 m by 1000 m. The discretized flow model consisted of about 42 840 cells with three layers covering an area of 30 km by 29 km.

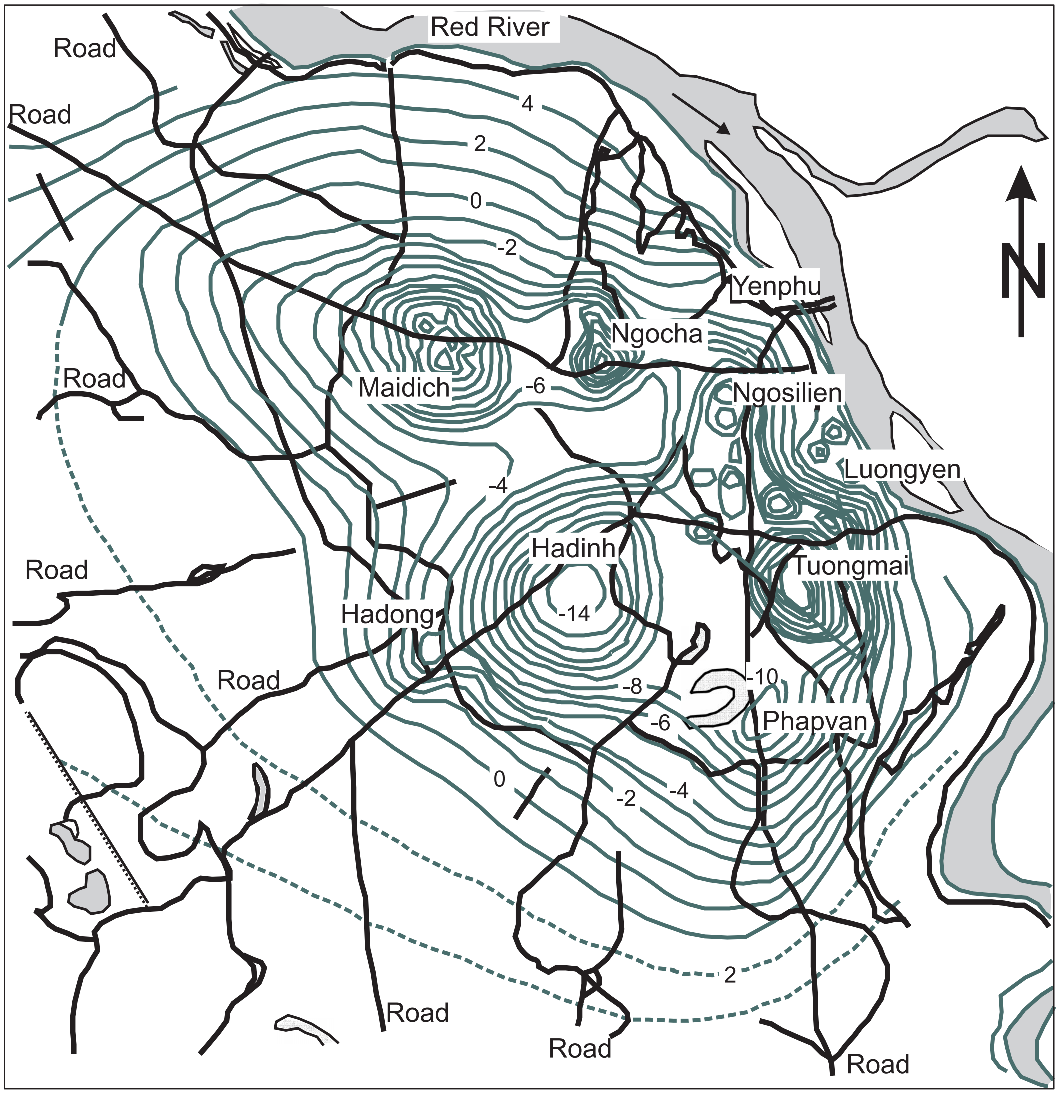
Pumping from the aquifer layer was simulated using the "Well" package of Modflow for individual cells located within the southern part of the Red River basin in Hanoi. Well extraction rates were assigned to cells representing the pumping wells in the sandy gravel aquifer. Future groundwater exploitation from within Hanoi was also simulated. The capacity of the well fields and the locations of the well fields were adopted from the proposal of the City Council Water Master Plan Hanoi up to year 2010 when the proposed total extraction will be 751 000 m^3/day.

Well measurements for the period from 1988 to 1995 were used for calibration of the model. The calibration of the groundwater pumping model was an integrative process. The surface infiltration and material properties for each stratigraphic unit were refined until the simulated hydraulic head distribution closely approximated measured values. The calibrated hydraulic parameters are those values which produced a flow model that most closely represented the measured regional hydrogeologic conditions and responses. The calibration parameters fell within the range of values measured on soil samples. The hydraulic parameter values that best simulated field responses are shown in Table 1.

A transient-flow analysis was performed for the study area. The hydraulic head and drawdown were computed for the period from 1974 to 2015. It was assumed that the initial head was constant in each layer at an elevation of 3.8 m

[1] Modflow is a software program for pseudo-three-dimensional groundwater modelling.
[2] Seep/W is a proprietary product and trade secret.

Fig. 5. Contour map of the observed heads (in metres) for the aquifer layer in 1990 for the city of Hanoi.



above mean sea level. Figure 5 shows the observed contours of head for the aquifer layer in 1990, and Fig. 6 shows the contours of head calculated using Modflow. The Modflow results show depressions in the pumping well regions that are similar to the measured values.

A comparison between the measured and the computer-simulated heads is shown in Fig. 7 for several of the well fields for the year 1995. The data show that the calculated and measured values are similar.

Axisymmetrical analysis of seepage into wells

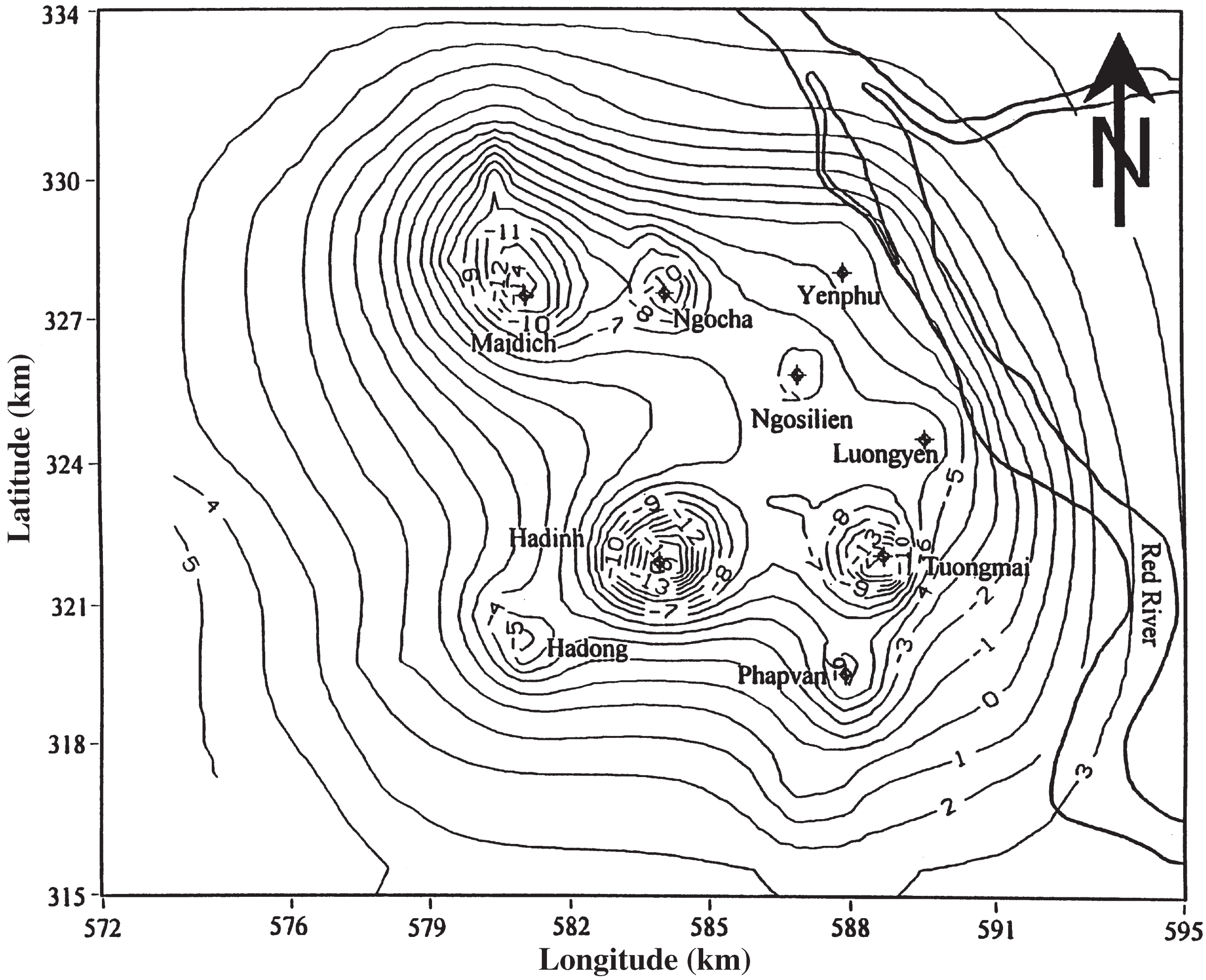
The Phapvan and Maidich well fields in Hanoi were selected for an axisymmetric seepage analysis using Seep/W. The axisymmetric simulations were performed to determine the magnitude of settlement. Numerical simulations of subsidence can be conducted using either a coupled or an uncoupled consolidation theory approach. The modelling results presented in this study are uncoupled with respect to continuity and equilibrium. The axisymmetric modelling of individual well fields does not provide a good simulation of drawdown with distance from the pumping location. However, the results of the Seep/W axisymmetric analysis can readily be combined with an axisymmetric stress analysis using the program Sigma/W[3] (Geo-Slope International Ltd. 1994*b*). The purpose of the stress analysis is to predict settlements in the immediate vicinity of the pumping well. It was reasoned that the uncoupled analysis of seepage and stress would be adequate as a first estimate based on the limited information available. The pore-water pressure change results from the seepage analysis were used as input for the stress–deformation analysis model (i.e., Sigma/W) to calculate settlements near each pumping site.

The characterization of pore-water pressure conditions is essential to the prediction of settlement due to groundwater pumping. Pore-water pressures were estimated through the use of steady-state and transient analyses. The pore-water pressure results were then imported into the stress–deformation analysis to compute settlement.

The governing partial differential equation for axisymmetric seepage is as follows:

[3] Sigma/W is a proprietary product and trade secret.

Fig. 6. Contour map of the calculated heads (in metres) for the aquifer layer in 1990 for the city of Hanoi.



$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad [5]$$

where

h is the total head;
k_x is the hydraulic conductivity in the x direction;
k_y is the hydraulic conductivity in the y direction;
Q is the applied boundary flux;
θ is the volumetric water content; and
t is the time.

The change in storage of water in the soil goes to zero under steady-state seepage conditions, and eq. [5] becomes

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + Q = 0 \quad [6]$$

The matrix form of the axisymmetric seepage analysis for a finite element analysis is as follows:

$$[K]\{H\} + [M]\{H\},\ t = \{Q\} \quad [7]$$

where

$[K]$ is the element characteristic matrix;
$[M]$ is the mass matrix; and
$\{Q\}$ is the applied flux vector.

For a steady-state analysis, the finite element seepage equation can be written as

$$[K]\{H\} = \{Q\} \quad [8]$$

Steady-state flow model

The characterization of the initial and final pore-water pressure profiles is an essential part of a stress–deformation analysis. Steady-state and transient conditions were considered. The results from the seepage analysis were imported into the stress–deformation analysis to estimate the subsidence due to groundwater pumping. The steady-state condition provided an initial data file for the transient flow simulations. Steady-state, axisymmetric analyses were conducted for the Phapvan and Maidich well fields.

Boundary conditions

The geometric meshes for the Phapvan and Maidich model are shown in Figs. 8 and 9, respectively. All elements in the mesh are quadrilaterals with four or eight nodes and triangular with three nodes. The elements at the edge of the

Fig. 7. Calculated heads versus observed heads for 1995, in the Hanoi City area.

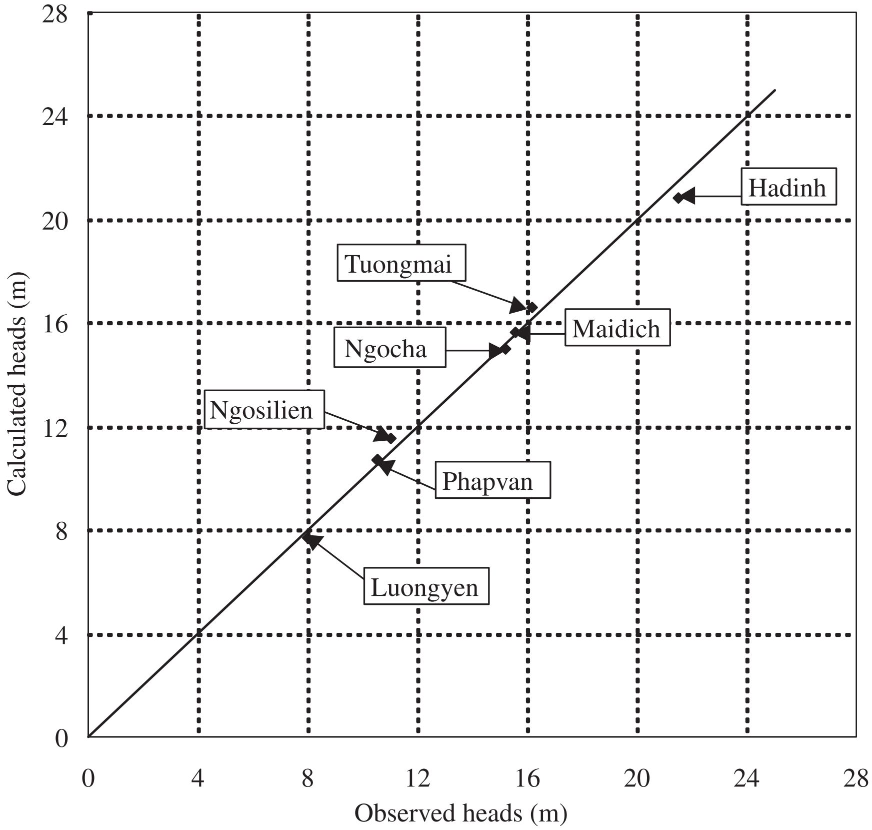


Table 2. Summary of calibrated and measured values of the coefficient of permeability, *k*, used in the axisymmetric seepage analysis at the Phapvan well field.

Material	Calibrated *k* (m/s)	Measured *k* (m/s)		
		Mean	Max.	Min.
Silty clay	3.0×10^{-7}	6.1×10^{-7}	3.4×10^{-6}	1.1×10^{-7}
Clayey silt	7.5×10^{-9}	8.7×10^{-9}	1.04×10^{-8}	3.4×10^{-9}
Sandy gravel	5.5×10^{-4}	6.6×10^{-4}	6.9×10^{-4}	5.8×10^{-4}

Table 3. Summary of calibrated and measured values of the coefficient of permeability, *k*, used in the axisymmetric analysis at the Maidich well field.

Material	Calibrated *k* (m/s)	Measured *k* (m/s)		
		Mean	Max.	Min.
Silty clay	2.0×10^{-7}	8.73×10^{-7}	3.46×10^{-6}	1.09×10^{-7}
Clayey silt	4.0×10^{-9}	4.28×10^{-9}	2.30×10^{-8}	3.35×10^{-9}
Sandy gravel	5.1×10^{-4}	4.50×10^{-4}	5.92×10^{-4}	3.61×10^{-4}

vertical boundary on the right side (i.e., farthest away from the well) were considered to be infinite elements.

The computer program SoilCover[4] (Wilson 1997) was used to model the surface-flux boundary as a percentage of the mean annual precipitation. The net infiltration from SoilCover is only about 2% of the annual precipitation or 7.93×10^{-10} m/s. A constant (precipitation) flux of 7.93×10^{-10} m/s was applied across the surface of the model.

The vertical head boundaries at both sides of the model (i.e., right and left side) were assumed to be constant head boundaries below the water table. The heads were assumed to be equal to the elevation of the initial heads from the Modflow model. The vertical head boundaries at the left- and right-hand sides of the model were 3.80 and 3.75 m, respectively.

Quantitative information concerning aquifer characteristics is available from the results of pumping tests carried out at various locations in Hanoi (Minh and Tam 1993). The coefficients of permeability of the aquitard layers were based on data from the soils reports and laboratory testing of undisturbed soil samples at the University of Saskatchewan, Saskatoon. The coefficients of permeability indicate that the aquitards have a low coefficient of permeability (i.e., approximately 4×10^{-9} m/s), and the aquifer has a high coefficient of permeability (i.e., approximately 6×10^{-4} m/s).

The calibrations for the coefficients of permeability were achieved by selecting a series of values within the range of field-measured values. The coefficient of permeability values that best simulated field responses were chosen for the steady-state and transient-flow model. Tables 2 and 3 provide a comparison of the calibrated model parameters and the measured values. In general, the values appeared to be slightly lower than the mean of the measured values. In general, however, the measured and model-calibrated values are similar. It should be noted that the axisymmetric and three-dimensional modelling simulations were conducted independently.

[4] SoilCover is a computer program developed at the University of Saskatchewan, Saskatoon, to model soil–atmospheric flux.

Fig. 8. The geometric mesh and boundary conditions for the axisymmetric seepage analysis at the Phapvan well field.

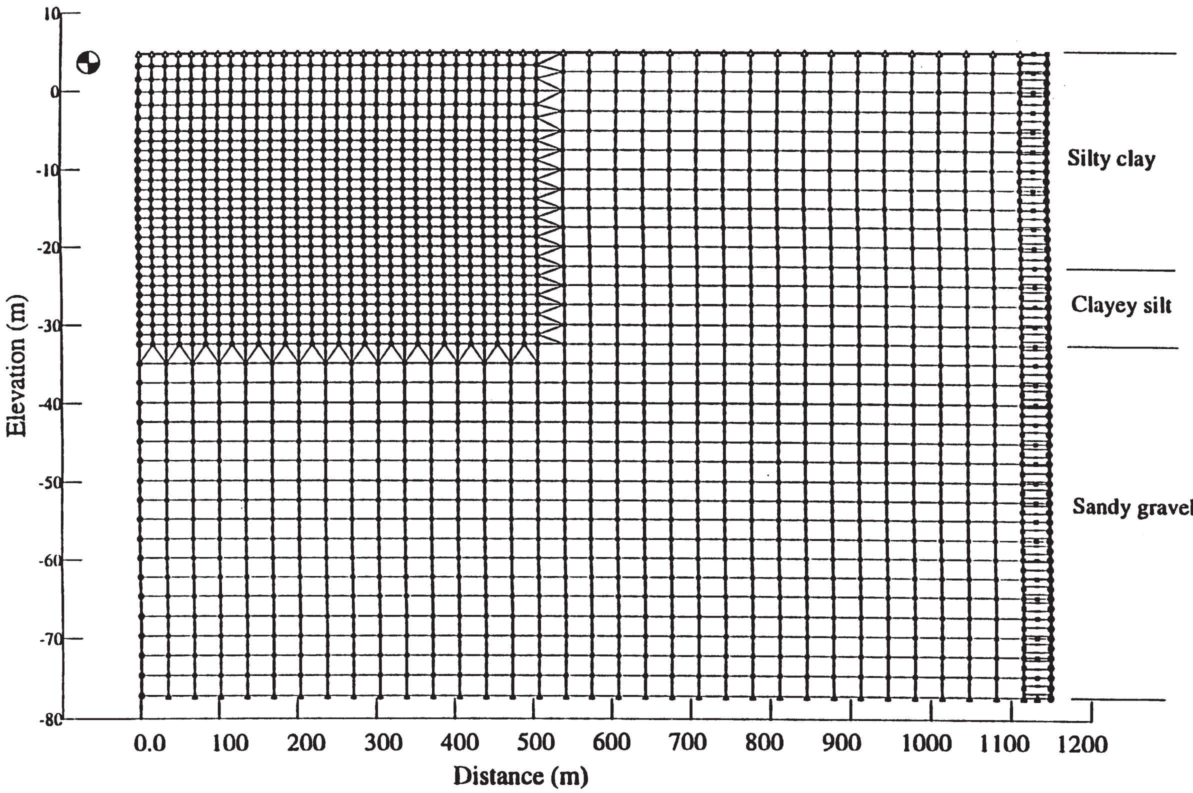


Fig. 9. The geometric mesh and boundary conditions for the axisymmetric seepage analysis at the Maidich well field.

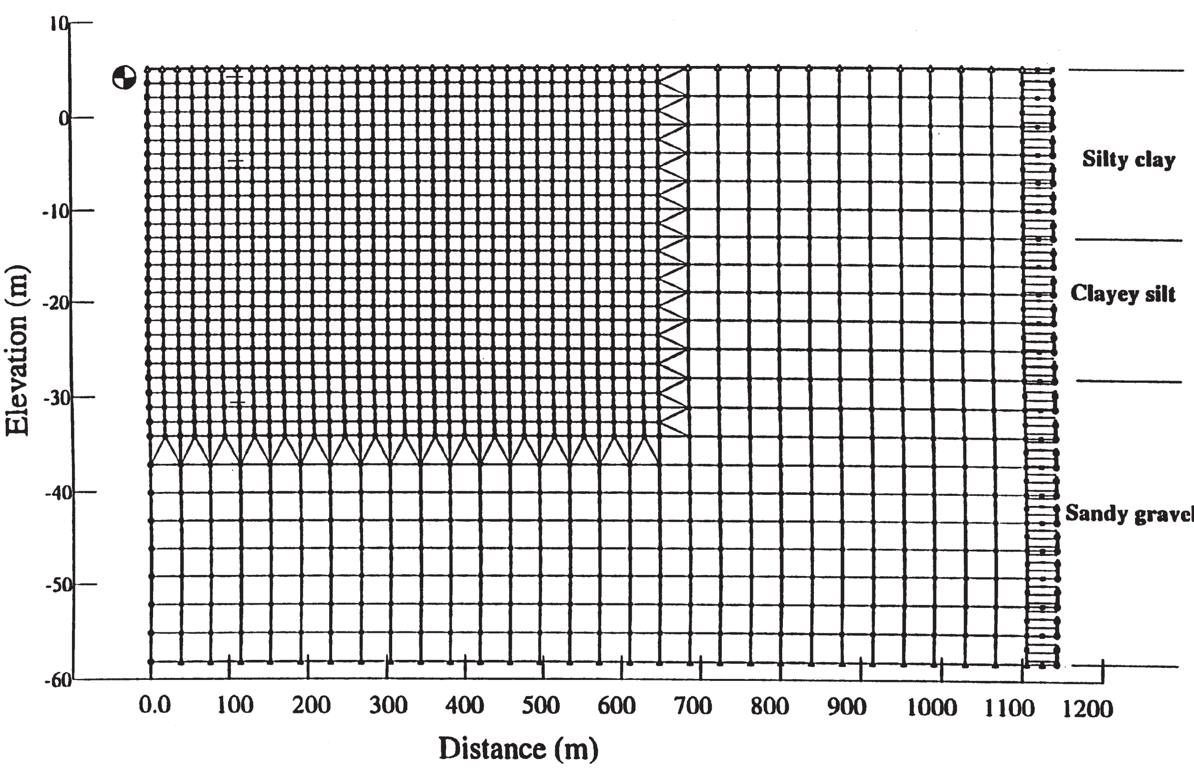


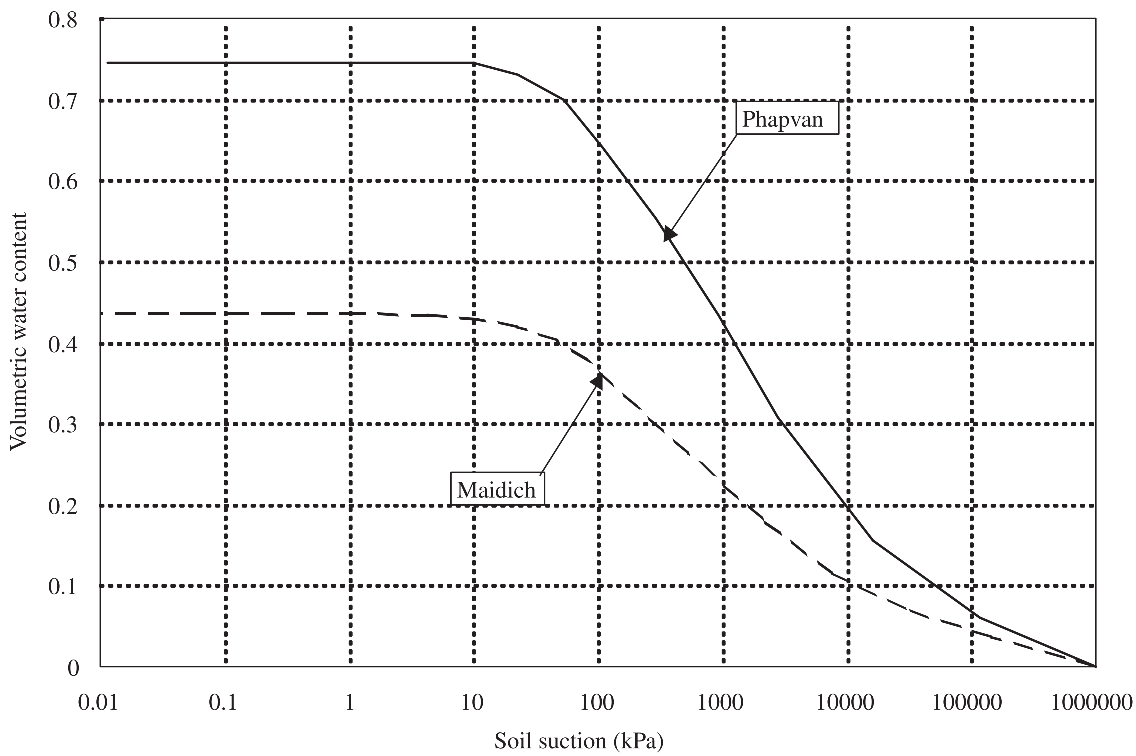
Table 4. Summary of the heads used in transient analyses at the Phapvan well field.

Year	Head at the well (m)
1988	–6.312
1989	–6.609
1990	–6.806
1991	–7.013
1992	–7.331
1993	–7.556
1994	–7.870
1995	–8.211
2000	–9.673
2005	–11.270
2010	–12.950
2015	–14.460

Table 5. Summary of the heads used in transient analyses at the Maidich well field.

Year	Head at the well (m)
1988	–14.70
1989	–14.87
1990	–14.91
1991	–15.00
1992	–15.09
1993	–15.20
1994	–15.31
1995	–15.45
2000	–16.71
2005	–17.95
2010	–19.36
2015	–20.84

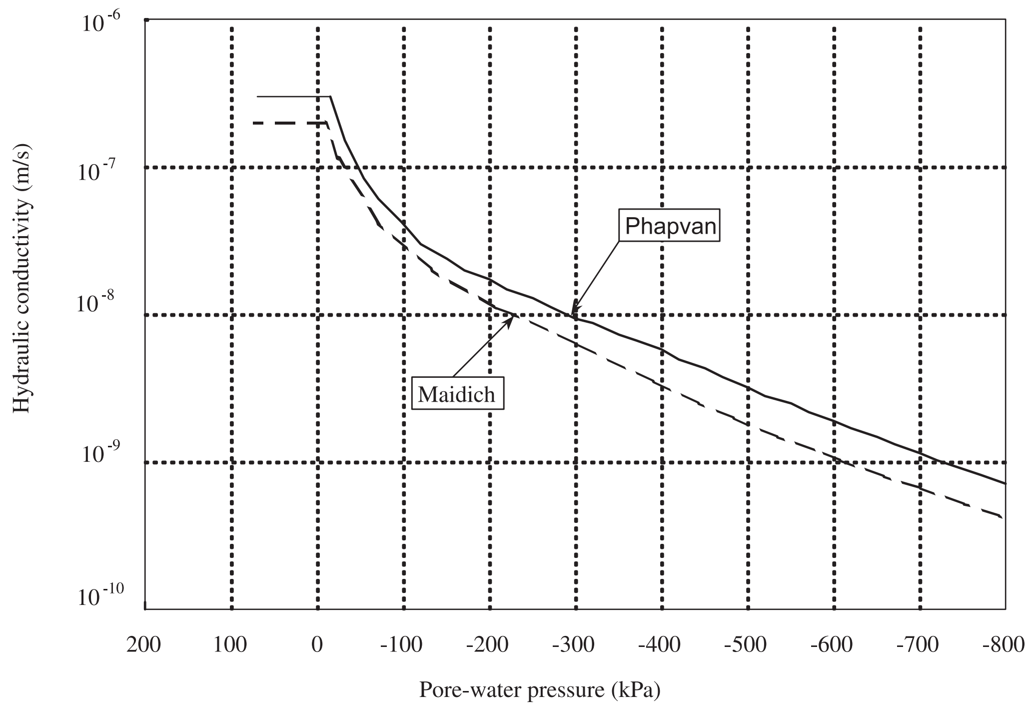
Fig. 10. Soil-water characteristic curve for silty clay for the Maidich and Phapvan well fields predicted by the method of Fredlund and Xing (1994).



Soft soil layers compress as a result of groundwater withdrawal. The pore-water pressures drop in the soil and cause an increase in effective stress. Therefore, pore-water pressures are basic to the evaluation of ground subsidence. A transient groundwater analysis was performed to determine the pore-water pressure dissipation with time and the subsequent subsidence due to groundwater lowering. The boundary conditions in the transient model are the same as those described for the steady-state model with the exception that heads are used along the vertical boundaries. The boundary condition at the well (i.e., left-hand side of the model) were taken from results of the Modflow model. The head boundaries at the Phapvan and Maidich well fields are summarized in Tables 4 and 5, respectively.

The material properties used in the steady-state analysis were also used in the transient analysis. A storage function for the silty clay layer was estimated. The storage functions were estimated using the method described by Fredlund and Xing (1994). The storage functions used in the transient-flow model at the Phapvan and Maidich well fields are shown in Fig. 10. The coefficient of permeability of the materials that remain saturated was represented as a constant value. The coefficient of permeability function for the unsaturated, upper silty clay layer was estimated using an approximate

Fig. 11. Hydraulic conductivity function for silty clay for the Phapvan and Maidich well fields predicted by the method of Fredlund and Xing (1994).



soil-water characteristic curve and the method described by Fredlund and Xing (Fig. 11).

Results of the transient analysis

The results of the seepage analysis are presented in the form of pore-water pressure contours. The pressure-head profiles generated due to the lowering of groundwater at the Phapvan well field are shown in Fig. 12. The pressure-head profiles are consistent with consolidation theory results assuming single drainage of the layer. Figure 13 presents the profiles of total head for the period from 1988 to 1995 at the Phapvan well field. The pressure heads in the sandy gravel are compared with those in the aquifer layer obtained from the Modflow simulation (Fig. 14). There is some difference between the three-dimensional Modflow analysis and the Seep/W, axisymmetric seepage analysis because of the differences in the boundary conditions. The boundary condition for the axisymmetric seepage analysis was a constant head at the well, whereas in the Modflow analysis there was a constant rate of pumping. The differing boundary conditions appear to be the primary reason for the variation in results presented in Fig. 14.

Stress–deformation analysis in the vicinity of the well fields

The withdrawal of water from the wells reduces the pore-water heads in the aquifers and increases the effective stresses. There are many assumptions and estimations that must be made when performing the seepage and stress analysis. This section describes how the stress–deformation analysis was performed using Sigma/W. The results show a first approximation of behavior of the soil near the well site. A more accurate modelling simulation requires the use of a fully coupled, three-dimensional seepage and stress analysis with a better understanding of the soil properties.

Stress–deformation modelling for the Phapvan and Maidich well fields

The well-field models were analyzed to calculate subsidence due to pumping of the groundwater at the Phapvan and Maidich well fields.

Boundary conditions for stress–deformation modelling

The geometric mesh for the stress–deformation model Sigma/W was *imported* from the seepage model Seep/W as shown in Figs. 8 and 9. The following boundary conditions were assumed: (1) displacements were zero in both the x and y directions along the bottom of the geometric mesh (i.e., between the aquifer and the hard stratum); (2) along the vertical boundary of the geometric mesh (i.e., at both the left and right sides), the soil cannot move in the x direction but is free to move in the y direction; and (3) along the exposed ground surface, the soil was free to move in both the x and y directions.

The material properties used in the stress–deformation analysis were determined from a combination of the laboratory test results and values published in geotechnical reports in Vietnam (Minh and Tam 1993). A drained Young's modulus, E, of the silty clay and clayey silt with organics was calculated based on the one-dimensional consolidation test results. Young's modulus was computed using the following equation:

$$[9] \qquad m_{\mathrm{v}} = \frac{(1+\mu)(1-2\mu)}{(1-\mu)E}$$

Fig. 12. Pressure head versus elevation profiles at the Phapvan well field for the period from 1988 to 1995.

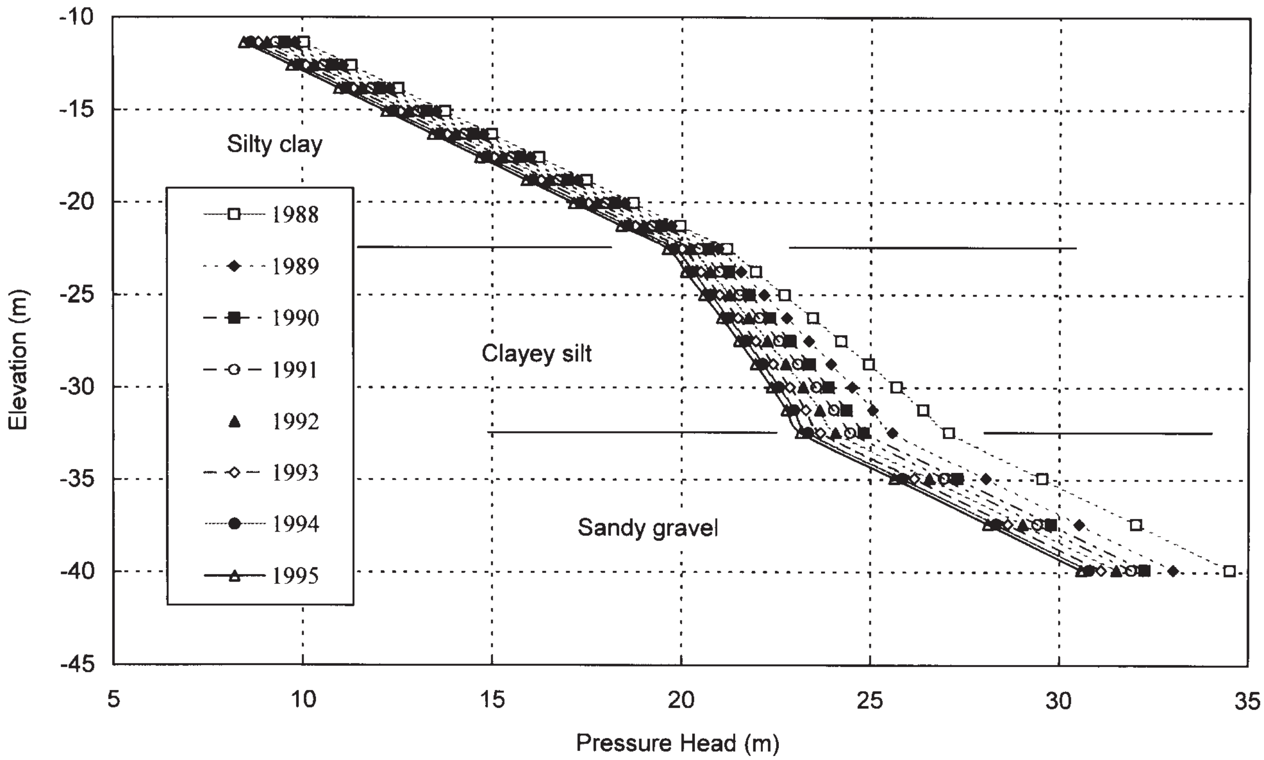


Fig. 13. Total head versus elevation profiles at the Phapvan well field for the period from 1988 to 1995.

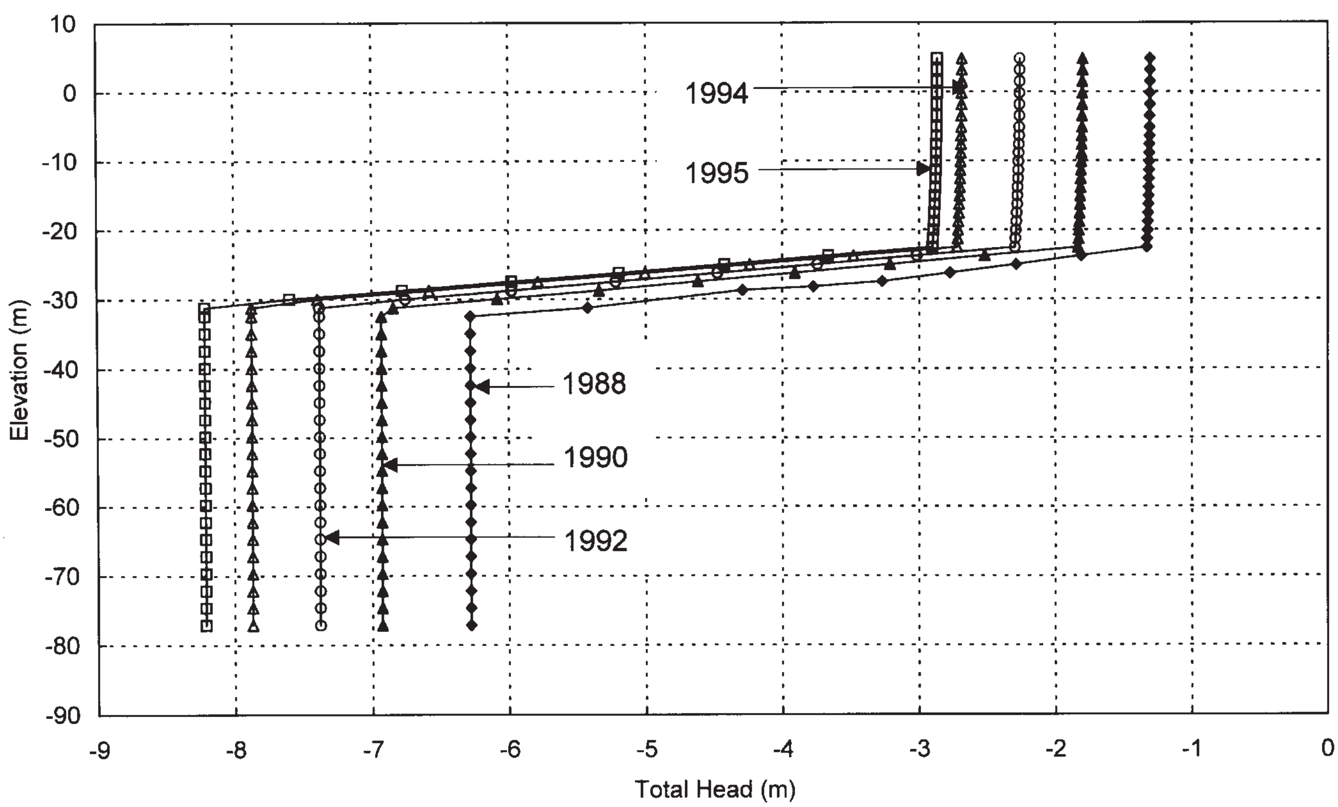


Fig. 14. Comparison between the pressure heads obtained from the Modflow and Seep/W analyses for the aquifer layer in 1995 at the Phapvan well field.

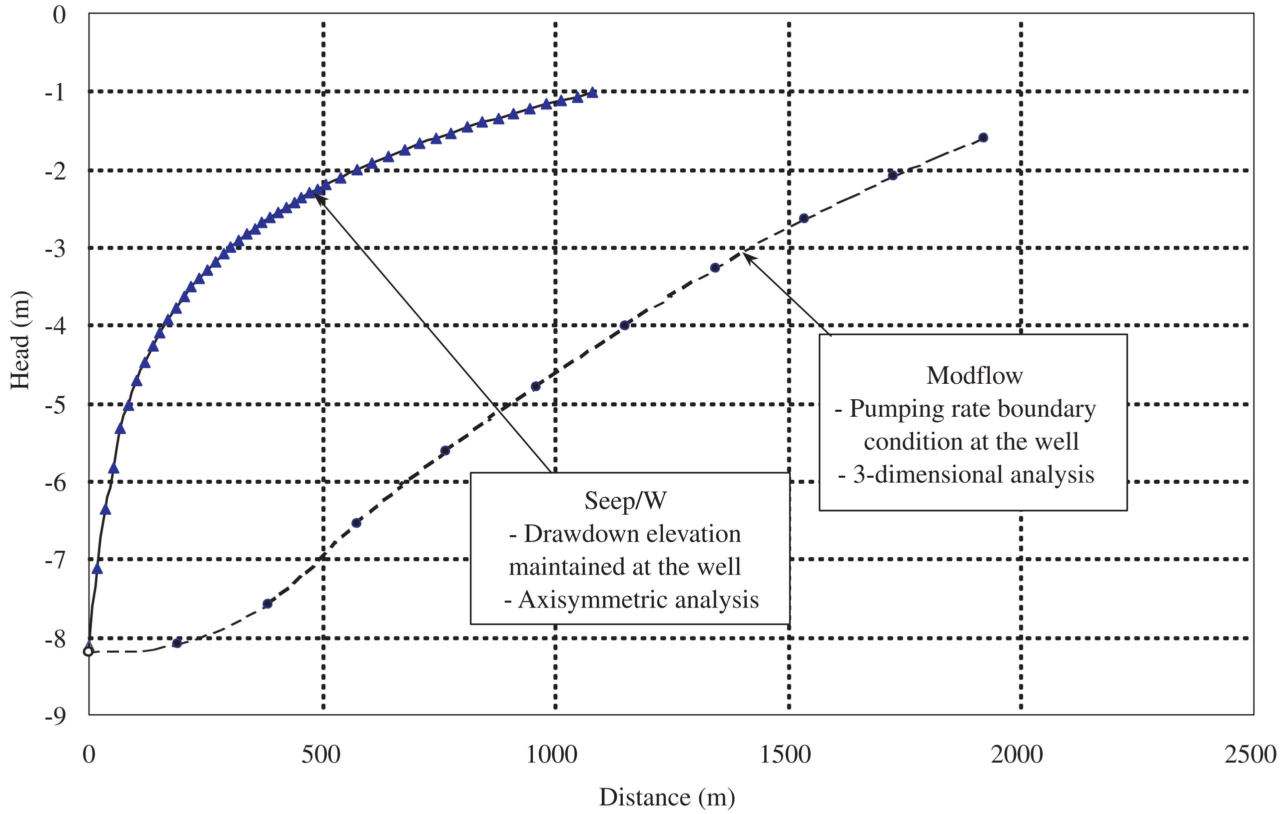


Table 6. Soil properties used in the stress–deformation analysis for the Phapvan and Maidich well fields.

Material	Values of E from the models (kPa)	Values of E from the consolidation tests (kPa)			Poisson's ratio μ
		Mean	Max.	Min.	
Phapvan					
Silty clay	1 200	854	1405	813	0.33
Clayey silt	3 150	2177	3328	1985	0.33
Sandy gravel	100 000	—	—	—	0.29
Maidich					
Silty clay	2 200	1128	2327	549	0.33
Clayey silt	4 130	2813	4557	1776	0.33
Sandy gravel	100 000	—	—	—	0.29

where

m_v is the coefficient of volume change;
μ is Poisson's ratio (assumed); and
E is Young's modulus.

The analysis of the consolidation test data provided a drained-type E modulus for the stress–deformation analysis. Rearranging eq. [9], Young's modulus can be computed provided a value of Poisson's ratio is assumed:

$$[10] \quad E = \frac{(1+\mu)(1-2\mu)}{(1-\mu)m_v}$$

Young's modulus for the sandy gravel layer was selected from Jumikis (1984). Poisson's ratio for the model was assumed and values are presented in Table 6. The values of Young's modulus that best simulated the field-measured values were chosen for the stress–deformation analysis. The material properties (i.e., E and μ) used for the stress–deformation analysis model are summarized in Table 6. The elastic properties used for Young's modulus fall within the general range of values computed from the one-dimensional consolidation tests.

Results of numerical modelling studies

The numerical simulation for the Phapvan and Maidich well fields was conducted for the period from 1988 to 2015. The numerical results of calculated subsidence along with the observed values at the Phapvan and Maidich well fields

Fig. 15. Calculated and observed subsidence at the Phapvan well field for the period from 1988 to 1995.

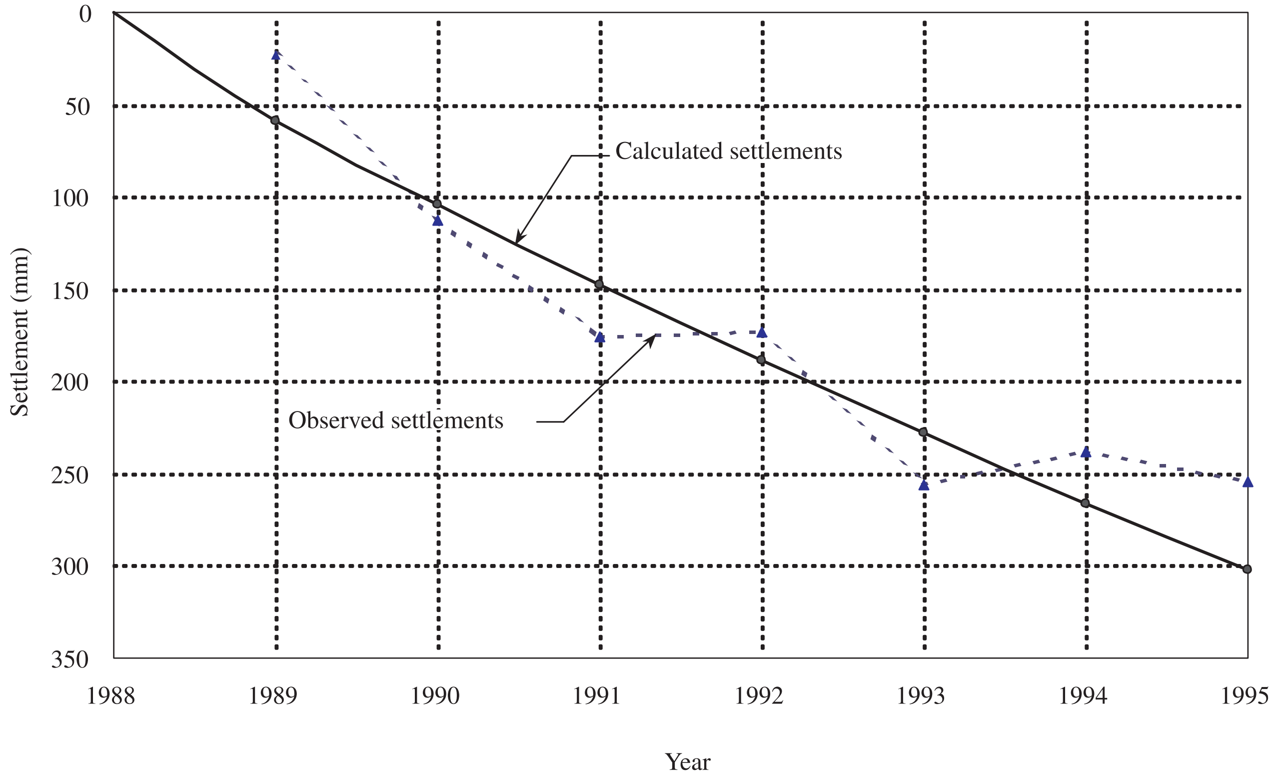
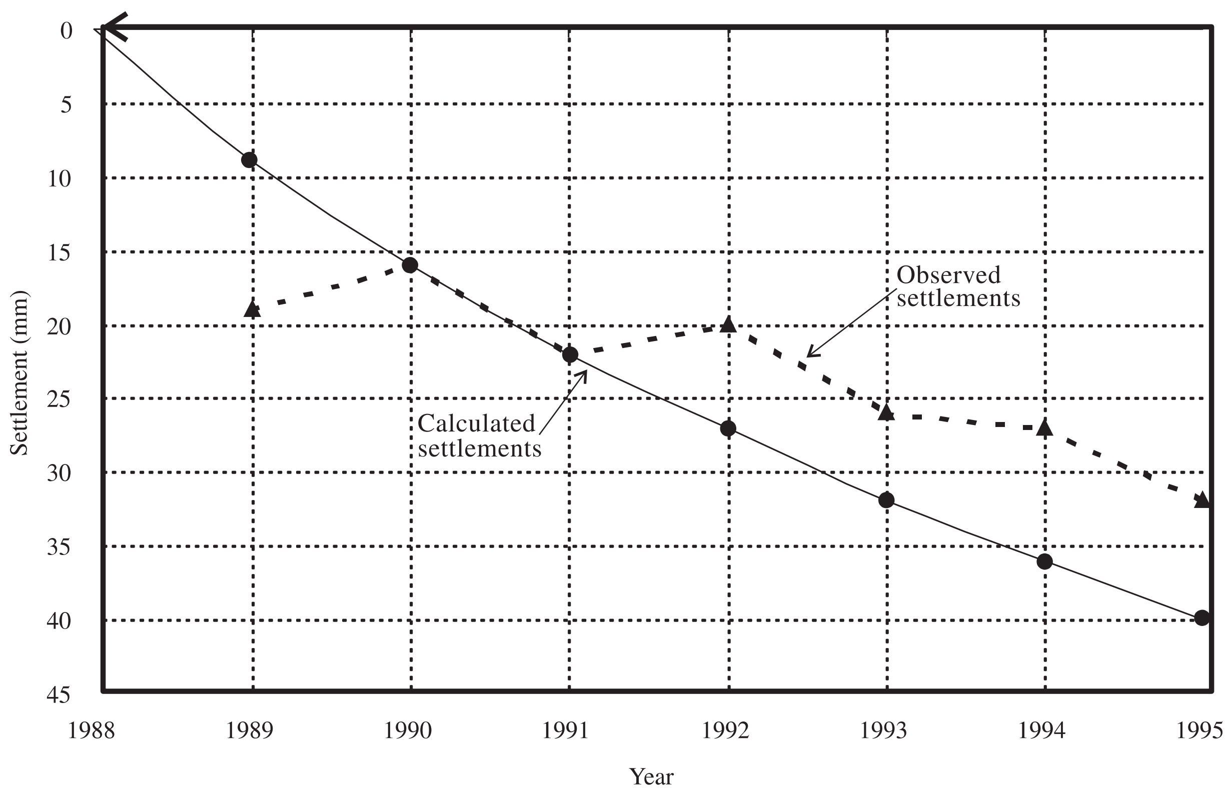


Fig. 16. Calculated and observed subsidence at the Maidich well field for the period from 1988 to 1995.



for the period from 1988 to 1995 are presented in Figs. 15 and 16, respectively. The total settlement from 1988 to 1995 is about 300 mm at the Phapvan well field and 40 mm at the Maidich well field. The rate of settlement at the Phapvan

Fig. 17. Vertical deformation contours (in metres) at the Phapvan well field for 1995.

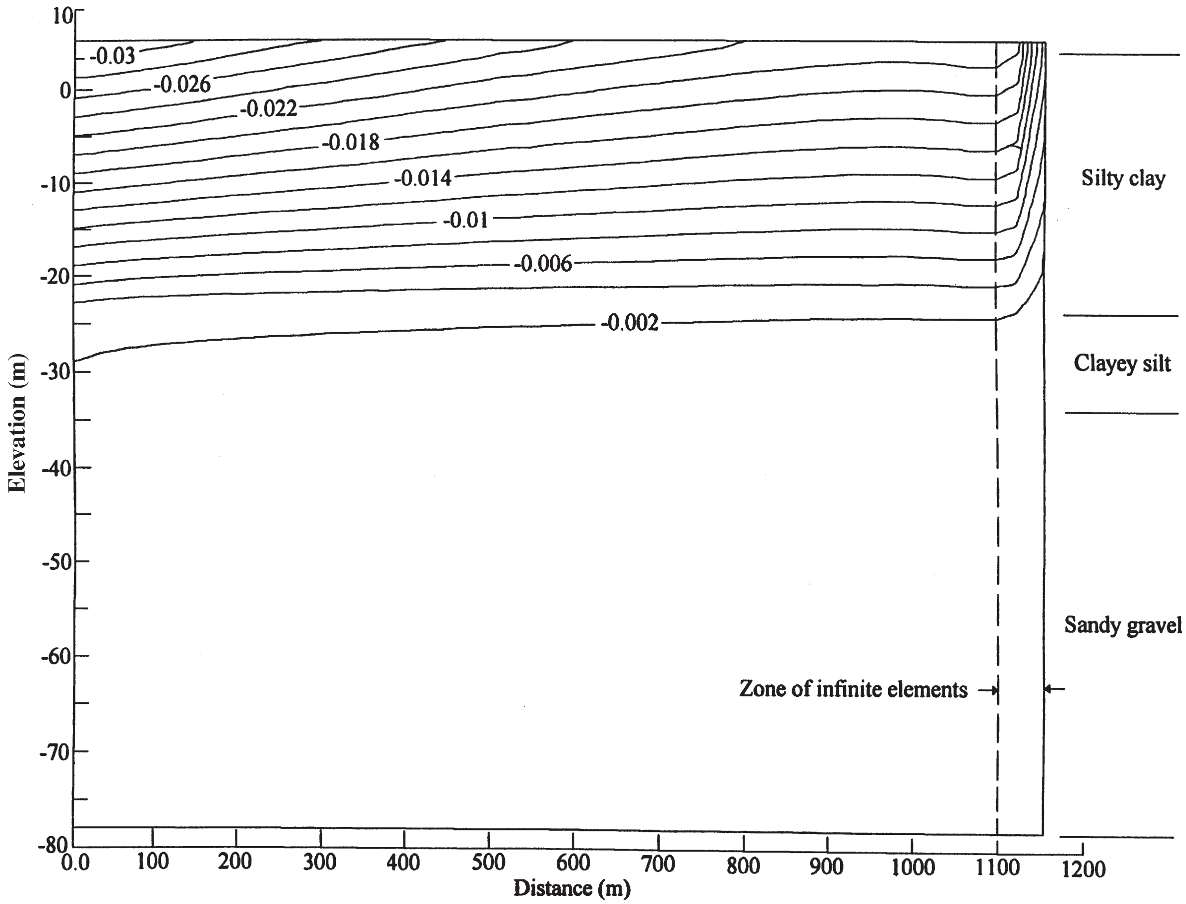


Table 7. Summary of calculated and observed settlement values at the Phapvan and Maidich well fields for the period from 1989 to 1995.

	Phapvan		Maidich	
Year	Observed settlement (mm)	Calculated settlement (mm)	Observed settlement (mm)	Calculated settlement (mm)
1989	23	55	19	9
1990	90	52	–3	7
1991	63	43	6	6
1992	–3	42	–2	5
1993	83	41	6	5
1994	–18	37	1	4
1995	16	32	5	4

Note: The negative values indicate that the measured settlements showed a rebound of the soil during this year

well field in 1995 was about 30 mm/year (Table 7). Figures 17 and 18 present typical contours of the vertical deformation in 1995 at the Phapvan and Maidich well fields, respectively. Figure 19 provides a cross section of the simulated ground-surface settlements due to the pumping of groundwater in 1995.

Future subsidence at the Phapvan and Maidich well fields was predicted by assuming the proposed pumping schemes up to the year 2015. The numerical simulations show the

Table 8. Summary of the predicted settlements (mm) at the Phapvan and Maidich well fields for the period from 1996 to 2015.

Year	Phapvan	Maidich
1996	32	6
1997	25	4
1998	27	5
1999	24	4
2000	22	5
2001	18	5
2002	19	6
2003	22	4
2004	15	5
2005	16	4
2006	18	6
2007	15	6
2008	12	4
2009	16	5
2010	17	5
2011	35	8
2012	28	7
2013	32	5
2014	23	5
2015	25	4

Fig. 18. Vertical deformation contours (in metres) at the Maidich well field for 1995.

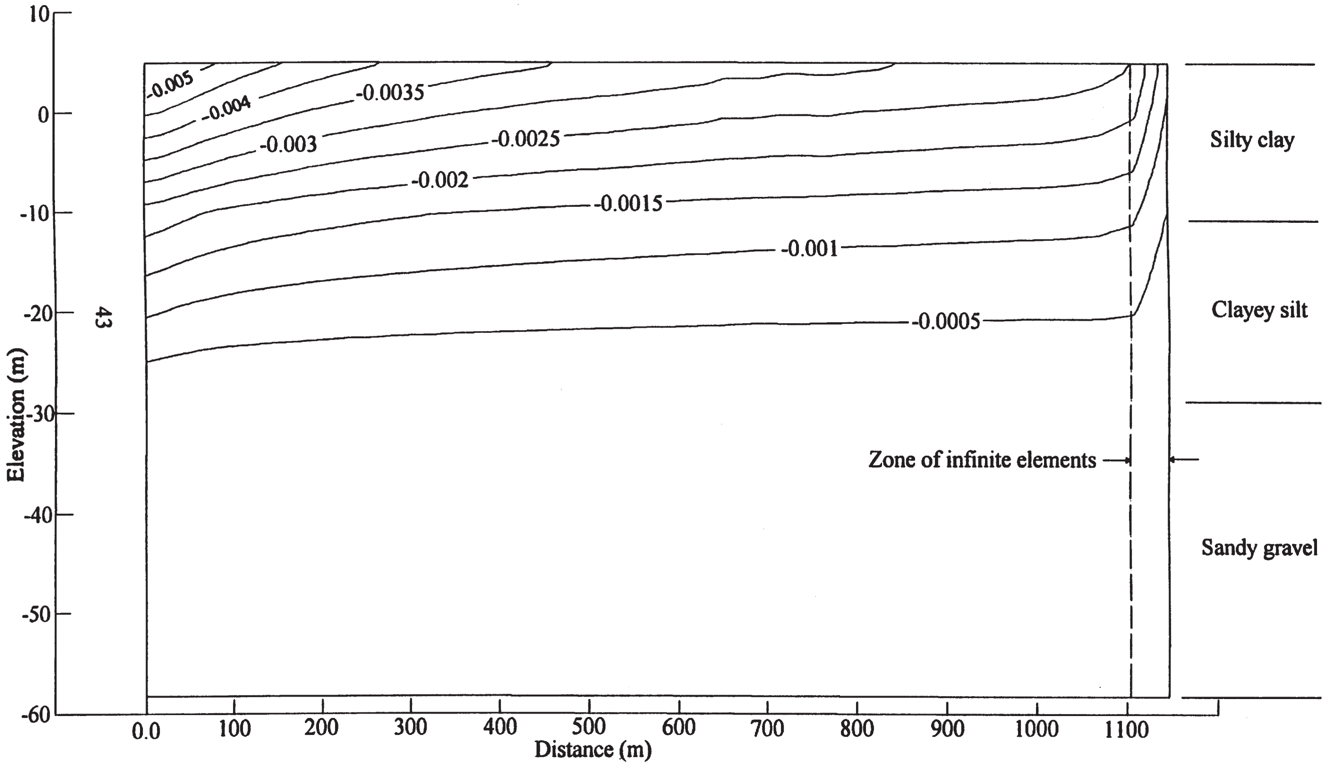
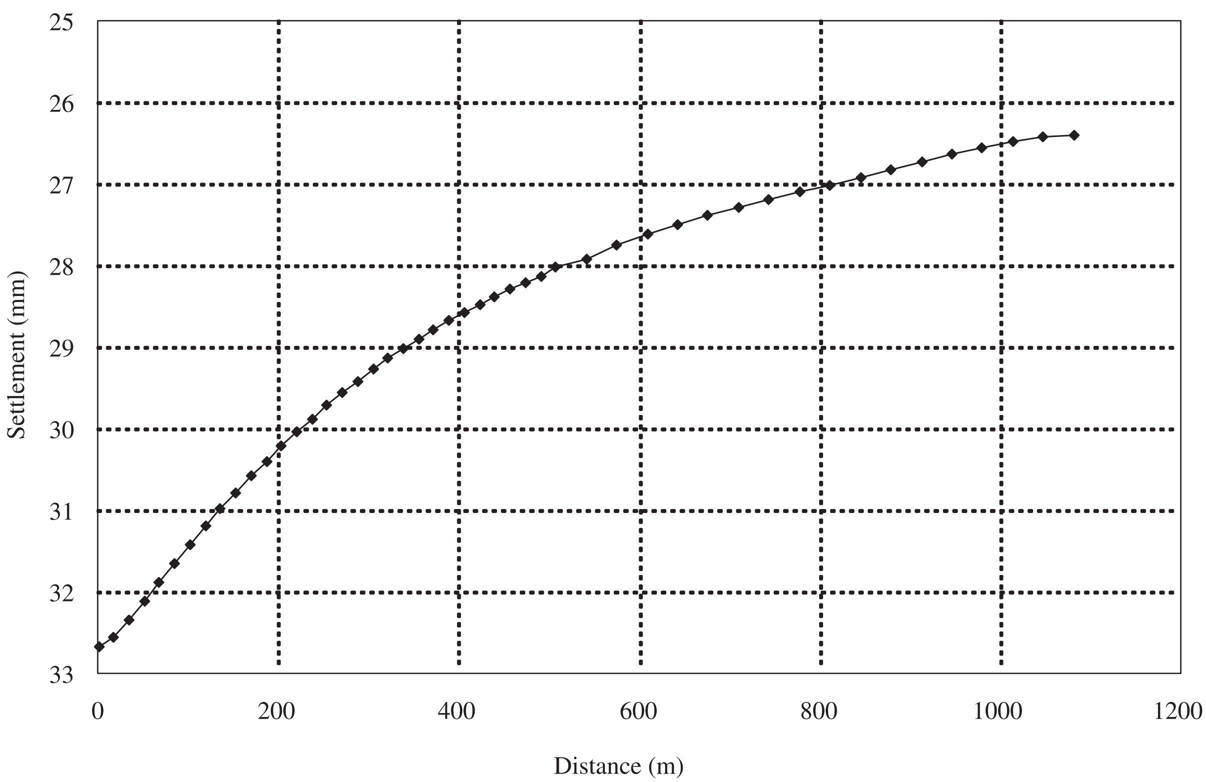


Fig. 19. Vertical ground surface subsidence at the Phapvan well field in 1995 computed using Sigma/W.



drop in the groundwater table for each year (Table 8). The model predicts a total settlements of 743 mm at the Phapvan well field and 144 mm at the Maidich well-field from 1988 to 2015.

Summary and conclusions

The findings from studying land subsidence due to the pumping of groundwater in the city of Hanoi are as follows:

(1) Subsidence in the central and southeastern part of Hanoi (i.e., Phapvan well field) was quite serious (i.e., subsidence rate is about 20–35 mm/year). The soil strata are composed of thick, compressible soils (e.g., peat, organic and inorganic clay, and silt), and there is the potential for significant settlements in the vicinity of the well field.

(2) The process of subsidence due to the pumping of groundwater and heaving of the land surface due to a rise in the groundwater table or rainfall is complicated. The prediction depends primarily on the accuracy of the boundary conditions and the accuracy of the input soils information used in the models. The results obtained from numerical modelling of the well fields are close to the observed (or measured) results. The calibrated numerical modelling method provides a reasonable tool to estimate future subsidence due to further groundwater pumping.

(3) Groundwater lowering can cause considerable land subsidence in the Hanoi area. It is expected that settlements will be uneven because of nonhomogeneous soil conditions and because the coefficient of permeability varies both horizontally and vertically.

(4) An intermediate step in the numerical estimation of subsidence is the prediction of the distribution of the pore-water pressures throughout the aquifer system. The model can be calibrated by comparing actual pore-water pressure distributions with the predictions based on the present pumping pattern. At present, there are insufficient data to define piezometric conditions in all areas of Hanoi. Limited available data indicate a general decline in the water table.

(5) The pattern of drawdown and subsidence based on numerical modelling is reasonable. However, the magnitude of the predicted subsidence at a specific location may not be very accurate due to a lack of information on the soil geometry and soil properties. Simulations with variable well field pumping schemes as a function of time can be utilized to test where the maximum subsidence may occur. This information can be used in planning development in Hanoi.

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