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Finite element modeling for assessment of seawater intrusion into coastal groundwater abstractions due to seawater level rise in Thai Binh province

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Abstract. Thai Binh province is the most intensively impacted by sea water level rise (SLR). It definitely causes more intensive seawater intrusion into the groundwater abstraction facilities near the coastal line. Finite element modeling of groundwater flow and seawater intrusion by advection-dispersion had been carried out for one coastal groundwater pumping field of Thuy An commune-Thai Thuy district. Seawater intrusion patterns have been obtained by the modeling technique for the present sea water level and three scenarios of SLR. For the present sea water level, the time for which the seawater intrusion with concentration of 0.66g/l reaches the pumping well is estimated to be 30 years, and for the case of high SLR of 1m, the time is much reduced and is estimated to be 16.3 years, which is approximately faster two time than present sea water level.

1. Introduction

Climate change in general and seawater level rise (SLR) in particular definitely negatively impact the water resources including groundwater, especialliy the coastal areas. Besides the IPCC reports, there are lot of reports on the SLR scenarios. Recently, a climate change researcher from Potsdam had pointed out that the SLR rates determined by various models are relatively much lower than that in the reality and summarized six IPCC's climate change scenarios and had made the conclusion that the SLR would be in the range 0.5m-1.4m.

Due to uncertainty of the prediction of climate change due to Dioxide omission, Vietnam Ministry of Natural Resources and Environment advises using of scenario of medium Dioxide omission (B2) for prediction SLR, which provide the values of 0.5m, 0.75m and 1m of SLR. The times of the SLR in Vietnam in different climate change scenarios are as follows [1].

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SLR	Scenario 1 (50 cm)			Scenario 2 (75cm)			Scenario 3 (100 cm)		
Climate change	A1FI	B2	B1	A1FI	B2	B1	A1FI	B2	B1
Time	2065	2075	2080	2083	2100		2100		

The SLR definitely effects all the socio-economic development conditions and natural water resources of Vietnam coastal areas, especially Thai Binh province which has high percentage of land surface lower than the sea water level-about 35% of the province total area. The specific impact of SLR on water resources in general and in groundwater in particular is very much essential for Thai Binh province to serve fundamental of strategy of mitigation measures.

2. Hydrogeological conditions of the study area

The aquifer system of the province is characterized by a multilayer structure, which consists of Quaternary deposits and conceptually can be presented as a three-layer aquifer system [2].

- *Upper Holocene Unconfined Aquifer qh2:* This is the first groundwater aquifer from the ground surface and consists of Thai Binh formation $Q^{IV}{}_{3}tb$. In some places it is covered by a Holocene clay layer. The materials are fine sands, sandy clay, clayey sands, some places, silt and peat of the upper part of Holocene deposits. The thickness varies from few meters to more than 20m. The permeability varies very much in the range 0.04m/day-11m/day and the specific yield is 0.10 in average. The water in this aquifer interacts with the surface streams and lakes. In places where the clay and silt of the lower part of Holocene, direct interaction with the lower confined aquifer *qh1* takes place. The water total dissolved solids (TDS) is from 0.3g/ℓ to 18.3g/ℓ. Although this is a poor aquifer, household domestic water supply is usually takes place due to the lack of other better water sources.

- *Semipervious Upper Hai Hung Formation Layer (aquitard 1):* This layer consists of silty and clayey materials of the upper part of Hai Hung formation $Q^{IV}{}_{1\text{-}2}hh2$. The thickness varies very much from few meters to more than 15m. In some places this layer is absent.

- *Confined Lower Hai Hung Formation Aquifer qh1:* The aquifer consists of silty sands and sands, in some places contains thin layers or lenses of clay or sandy clay of the lower part of $Q^{IV}{}_{1\text{-}2}hh1$ formation. The thickness varies considerably from 5m to 20m. The total dissolved solids of water is mostly more than 1g/ℓ. This aquifer has an insignificant meaning for water supply.

- *Semipervious Vinh Phuc Formation Layer (aquitard 2):* This layer consists of silty and clayey materials of the upper part of Vinh Phuc formation $Q^{III}{}_{2}vp2$. The thickness varies very much from few meters to more than 25m to more than 50m.

- *Confined Middle-Upper Pleistocene Aquifer qp:* The aquifer consists of sands and gravels of the middle and upper Pleistocene formation (Vinh Phuc $Q^{III}{}_{2}vp1$, Ha Noi $Q^{II\text{-}III}hn$ and Le Chi $Q^{I}lc$ formations). The piezometric head is near to the ground surface. The thickness varies considerably from 29m to 127m with the average 57m. The average transmissivity is 1254m^2/day, average permeability is 22m/day and the average storage coefficient is 0.007.

The TDS of the aquifer water has very complicated pattern, but two zones can be divided by TDS of 1g/l: 1) northern part of the province which includes Hung Ha, Dong Hung, Quynh Phu districts and a small western part of Thai Thuy district, with TDS from 0.3g/l to 1g/l; 2) southern part of the province which includes Kien Xuong, Tien Hai, Vu Thu districts and eastern part of Thai Thuy districts with TDS of 1g/l to more than 2g/l. Pleistocene aquifer is a rich groundwater aquifer not only for Thai Binh province, but also for the whole Bac Bo plain.

The schematic aquifer system of the area can be specifically seen for the coastal area in Thai Thuy district in Figure 2 below.

3. Assessment of SLR impact on seawater intrusion into groundwater abstraction facilities

There are existing 68 central domestic water supply systems in Thai Binh province (Figure 1), from which 15 from groundwater. The groundwater abstraction facilities near to the coastal line in Thai Thuy districts (numbering 21 and 23 in Figure 1) are the mostly threaten by seawater intrusion. Seawater intrusion to Thuy An-Thai Thuy (facility 23) groundwater abstraction shall be carried out to investigate the possible seawater intrusion since its abstraction is 750m^3/day which is much greater than of facility 21 and about 1500m from the sea coastal line. The groundwater system structure near to the facility is presented in Figure 2.

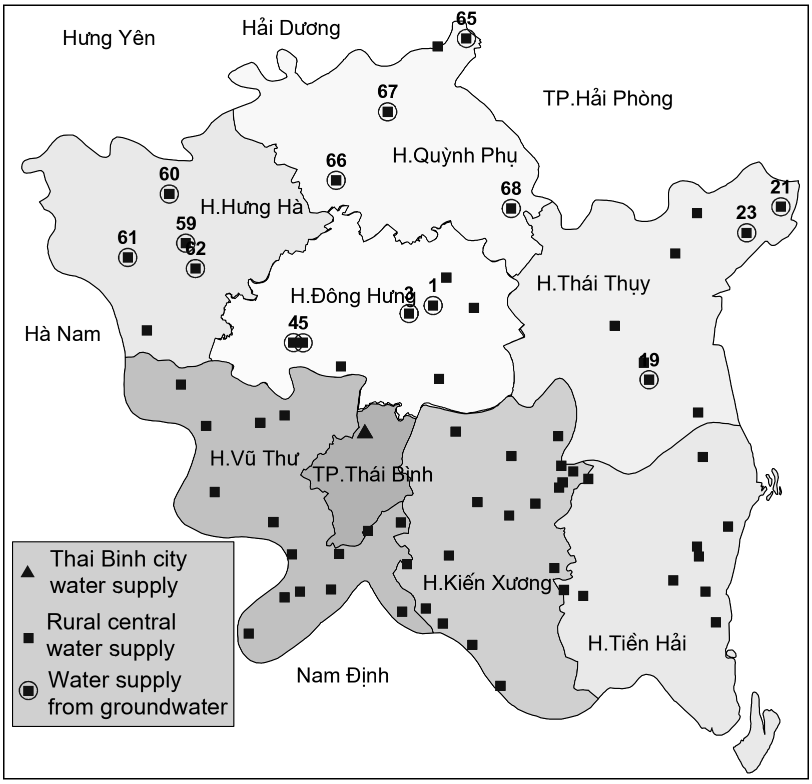

Fig. 1. Thai Binh central domestic water supply.

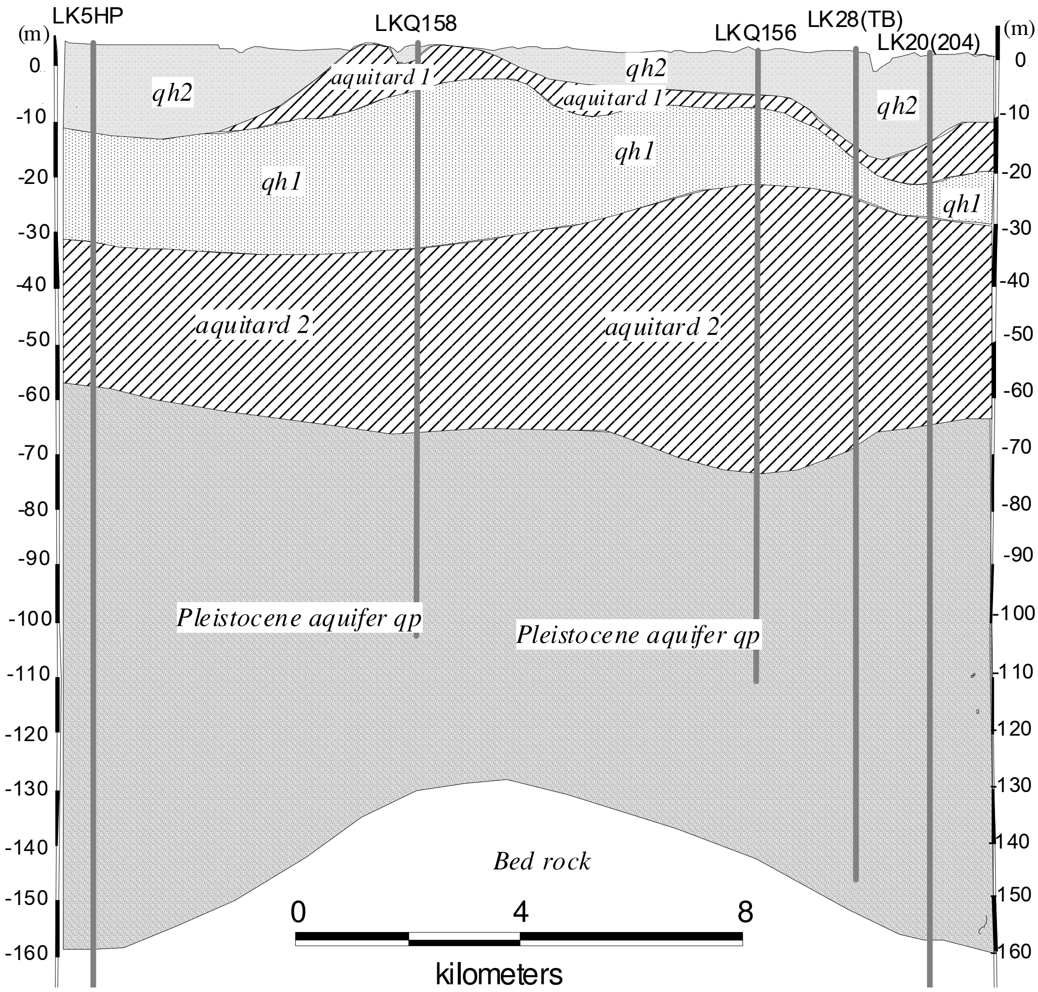

Fig. 2. Groundwater system structure of Thai Thuy district.

3.1. Groundwater movement finite element modeling

General form of the governing equation for a three-dimensional flow with the co-ordinate axes coinciding with the principle directions of the nonehomogeneous, anisotropic porous medium confined aquifer given as [3,4]:

$$\frac{\partial}{\partial x}(mK_x\frac{\partial\varphi}{\partial x})+\frac{\partial}{\partial y}(mK_y\frac{\partial\varphi}{\partial y})+\frac{\partial}{\partial z}(mK_z\frac{\partial\varphi}{\partial z})+Q=S^*\frac{\partial\varphi}{\partial t} \quad (1)$$

Where: ϕ - piezometric head, *Kx*, *Ky*, *Kz* - the hydraulic conductivities in principal directions *x*, *y* and *z*, *S** - the storativity, *m* - aquifer thickness, and *Q* - distributed and point sink (usually negative)/source (usually negative).

Applying finite element algorithm to equation (1) over a given mesh with appropriate boundary conditions, using backward difference scheme for time for *t* counted from time *t-Δt* would result in the following system of linear equations (written in matrix form) [5]:

$$\frac{[\mathrm{B}]}{\Delta t_n}\{\Phi_{n+1}\}+\left([\mathrm{A}]-\frac{\{\mathrm{B}\}}{\Delta t_n}\right)\{\Phi_n\}=\{\mathrm{F}_n\} \quad (2)$$

Matrix [A] depends upon the shape and sizes of elements and permeability K, matrix

[B] depends upon the element sizes, time step Δt and storativity, column matrix $\{\Phi\}$ denotes piezometric head at time step (n+1 and n), matrix $[F_n]$ depends upon element sizes and boundary conditions.

3.2. Advection-dispersion seawater intrusion by finite element modeling

Governing partial differential equation describing the advection-dispersion of pollutants (including salt) by groundwater flows in two dimensions (x, y) without pollutant source or sink is written as [3,4]:

$$D_{xx}\frac{\partial^2 C}{\partial x^2}+D_{yy}\frac{\partial^2 C}{\partial y^2}+D_{xy}\frac{\partial^2 C}{\partial x\partial y}-\upsilon_x\frac{\partial C}{\partial x}-\upsilon_y\frac{\partial C}{\partial y}=R\frac{\partial C}{\partial t} \quad (3)$$

where - D_{xx}, D_{yy}, D_{xy} - hydrodynamic dispersion coefficients in x, y and xy directions respectively (L^2/T), C - solute concentration (M/L^3), υ_x, υ_y - pore water velocity in x and y directions (M/T), R - retardation coefficient (dimensionless), t - time (T).

The initial condition describing the distribution of solute concentration at an arbitrary initial time $t=t_0$:

$$C = C_o(x, y) \quad (4)$$

The boundary conditions can be combination of the following three types:

- Boundary of specified concentration:

$$C = C_c \text{ on } \Gamma_c \quad (5)$$

- Neumann boundary condition (specified concentration gradient normal to the boundary):

$$\frac{\partial C}{\partial \mathbf{n}} = q \text{ on } \Gamma qc \quad (6)$$

-Cauchi condition (specified advective - dispersive flux normal to the boundary):

$$\upsilon_n C - D_n\frac{\partial C}{\partial \mathbf{n}} = \frac{\upsilon_0 C_\upsilon}{\theta} \text{ on } \Gamma q\upsilon c \quad (7)$$

where: υ_0, C_υ are known flux and solute concentration in the flux, θ - effective porosity (dimensionless).

The partial differential equation (3) describing the advection-dispersion solute transport by groundwater subject to the above initial and boundary conditions has been solved by the Finite Element Method (FEM) using quadratic elements. The FEM procedure with the Crank-Nicholson time scheme (time centered scheme) results in a system of linear equations [5]:

$$\left(\frac{1}{2}[A]+\frac{[B]}{\Delta t_n}\right)\{C_{n+1}\}+\left(\frac{1}{2}[A]-\frac{[B]}{\Delta t_n}\right)\{C_n\}=\frac{1}{2}\{F_n\}+\frac{1}{2}\{F_{n+1}\} \quad (8)$$

With the number M of unknowns [A] and [B] are M×M matrices, {C}, $\{F_n\}$ and $\{F_{n+1}\}$ are M vectors. Variable $\{C_{n+1}\}$ at time step n+1 are solved for when $\{C_n\}$ are known at previous time step n.

The size of the elements Δx, Δy and time step Δt have been chosen based on the following criteria on Peclet and Courant numbers (Huyakorn and Pinder, 1987) [5]:

$$\text{Peclet number } Pe=\frac{\upsilon_{x,i}\Delta x_i}{D_{xx,i}}\le 2 \text{ and} \qquad \text{Courant numer } Cr=\frac{\upsilon_{x,i}\Delta t}{\Delta x_i}\le 1 \quad (9)$$

and ratio R_ρ of spacing parameter ρ_{xx} to ρ_{yy} in x and y directions respectively (Huyakorn and Pinder, 1987) [5]:

$$R_\rho=\frac{\rho_{xx}}{\rho_{yy}}=\frac{\frac{D_{xx}\Delta t}{\Delta x}}{\frac{D_{yy}\Delta t}{\Delta y}}=\frac{D_{xx}\Delta y}{D_{yy}\Delta x}\le 2 \Rightarrow \Delta y\le\frac{2D_{yy}\Delta x}{D_{xx}} \quad (10)$$

3.3. Groundwater flow and seawater intrusion into Thuy An groundwater abstraction well

Seawater intrusion for Thuy An groundwater abstraction well is carried out for four different cases: 1) present sea water level;

2) SLR=0.5m (KB1) ; 3) SLR=0.75m (KB2); 4) SLR=1m (KB3).

Groundwater movement is carried out for rectangle with short size of 1.56km (parallel to sea coastal line) and long size of 2.28km (perpendicular to sea coastal line). The FEM mesh has finer elements in and around pumping well and coarser elements in outside area (Figure 3). The pumping well is in coordinate $x=y=720$m (Figure 3).

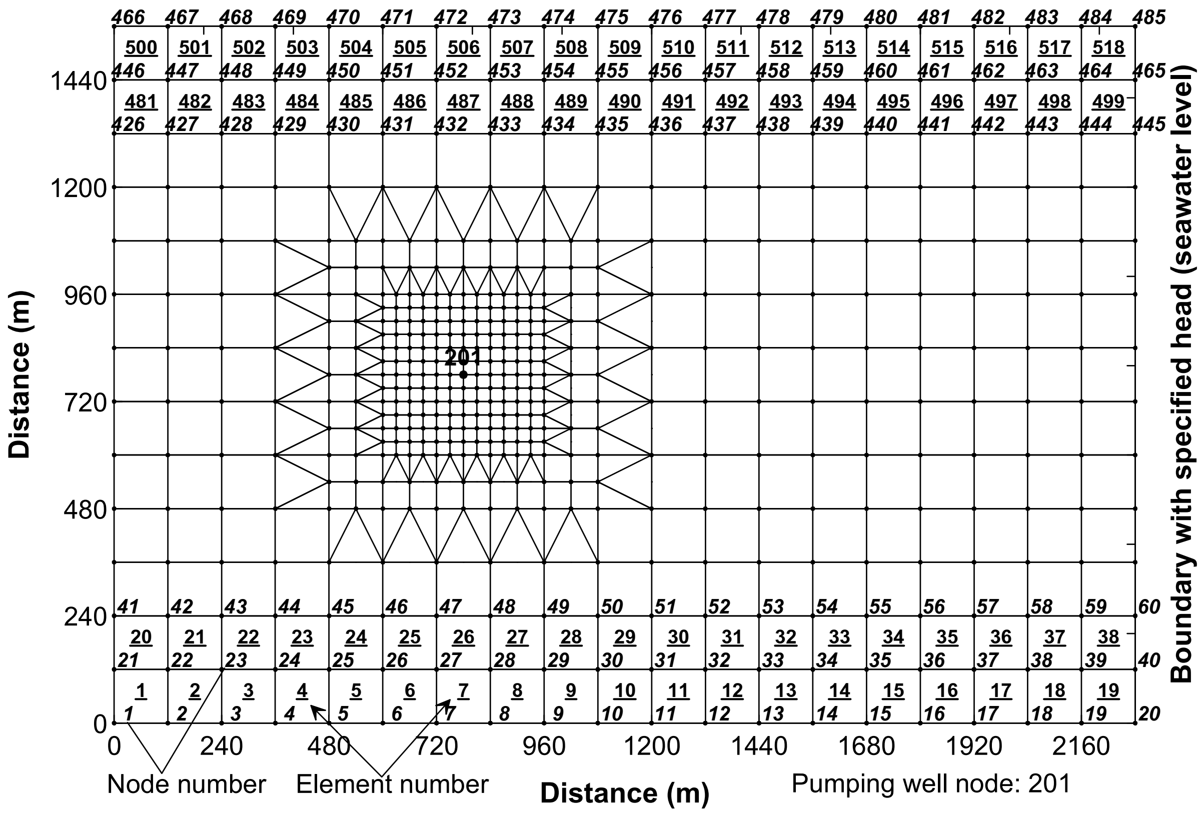

Fig. 3. FEM mesh for the model domain of Thai Thuy pumping field.

Steady state piezometric level was determined by FEM modeling for different cases of sea water level and the groundwater velocity field was determined. The flow velocity was then used in the FEM seawater intrusion modeling. Figure 4 illustrates the piezometric level over the groundwater flow model domain and velocity of the area where the seawater intrusion is carried out for the case of SLR KB3.

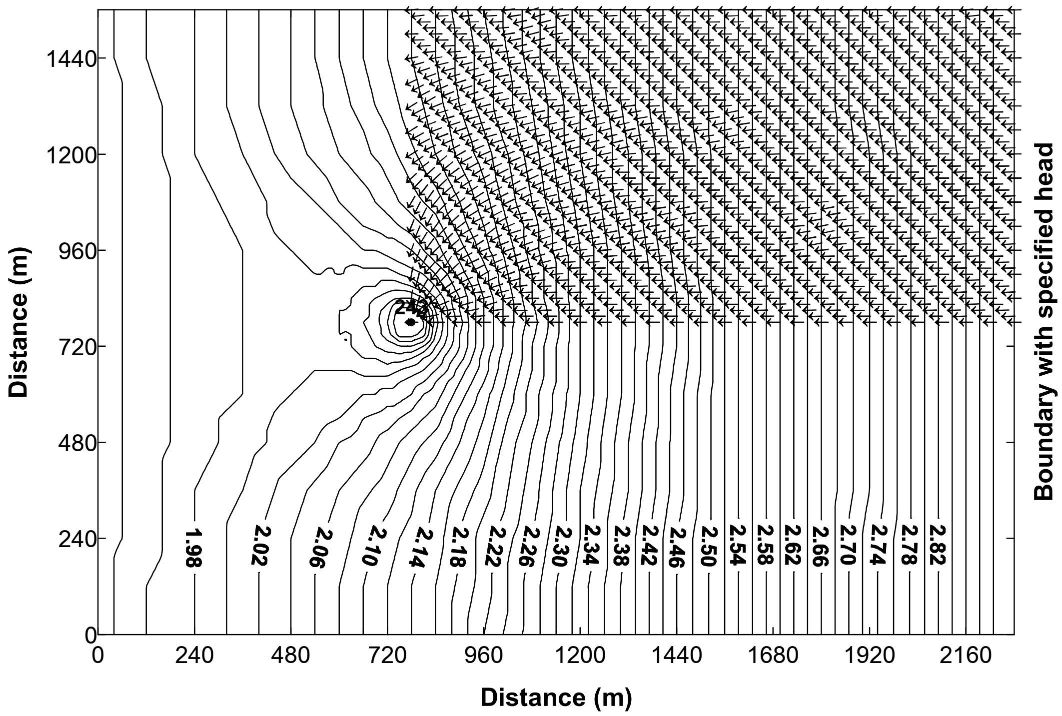

Fig. 4. Piezometric level and velocity field for SLR KB3
(the arrow length is proportional to velocity magnitude).

The seawater intrusion model domain is 780m×1500m consists of 5353 nodes and 5200 elements (Figure 5). The disspersivity in accordance with Gelhar L. W., C. Welty and K. R. Rehfeldt (1992) [6] of the Pleistocene aquifer and the field scale is taken to be a_L=15m/day. The effective porosity of the medium is taken to be 0.1. Since the aquifer consists of sands and gravels the retardation coefficient is equal to one.

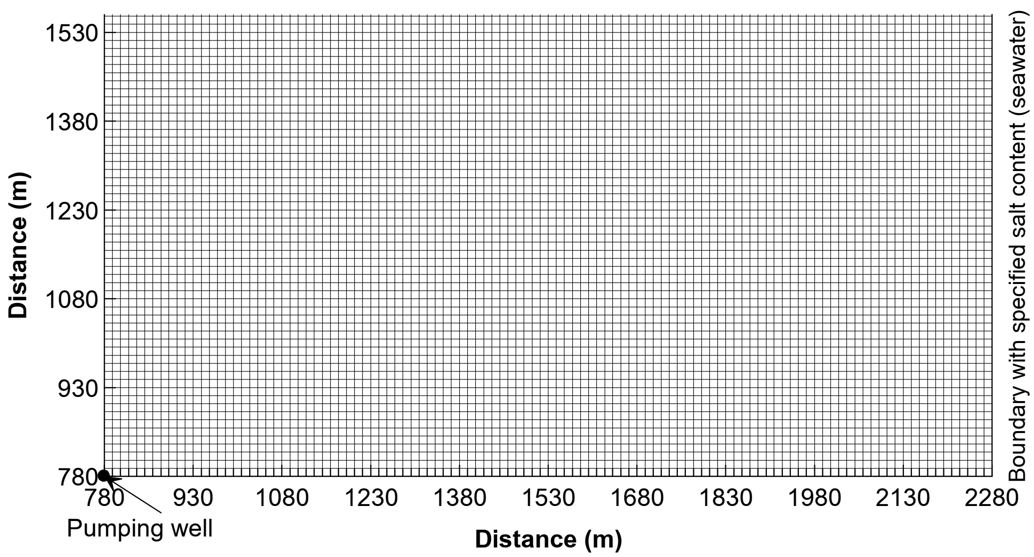

Fig. 5. Seawater intrusion FEM model mesh.

4. Results

Seawater intrusion patterns have been obtained for the four different cases of sea water levels. Figure 6 illustrates the relative salt concentration at the end of the fifth year. Relative salt concentration after five years varies from 0.02 (which corresponds to 0.66g/l since the seawater has salt concentration of 33g/) to 0.5 (16.5g/l) in all the four cases were shown in Figure 7. Figure 8 presents the relative salt concentration along the line from pumping well to the sea for four different cases, while Figure 9 and 10 present the relative salt concentrations with time and distance from the coastal line for the present sea water level and SLR KB3, respectively.

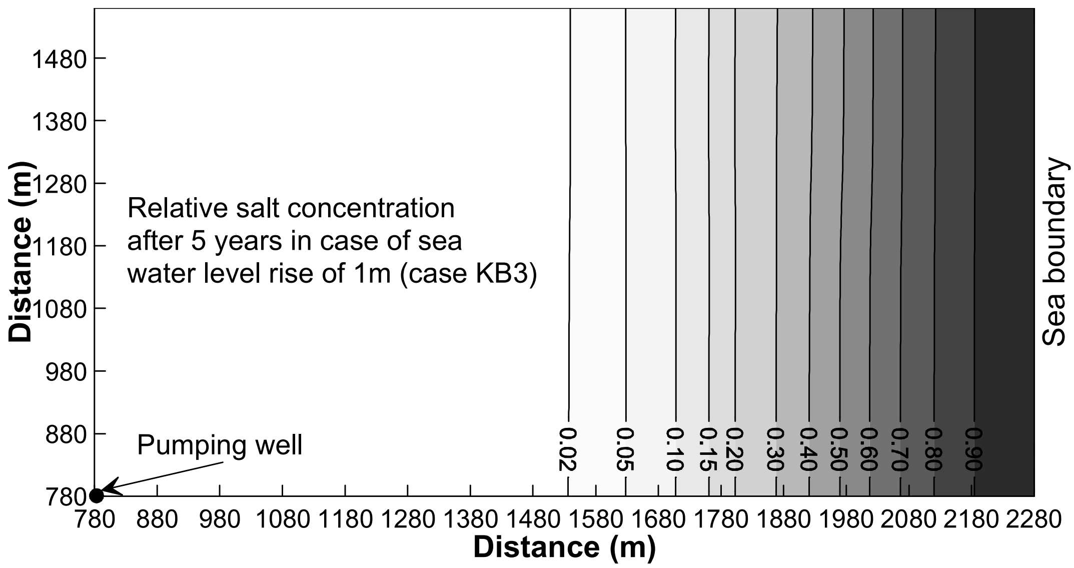

Fig. 6. Relative salt concentration-SLR KB3.

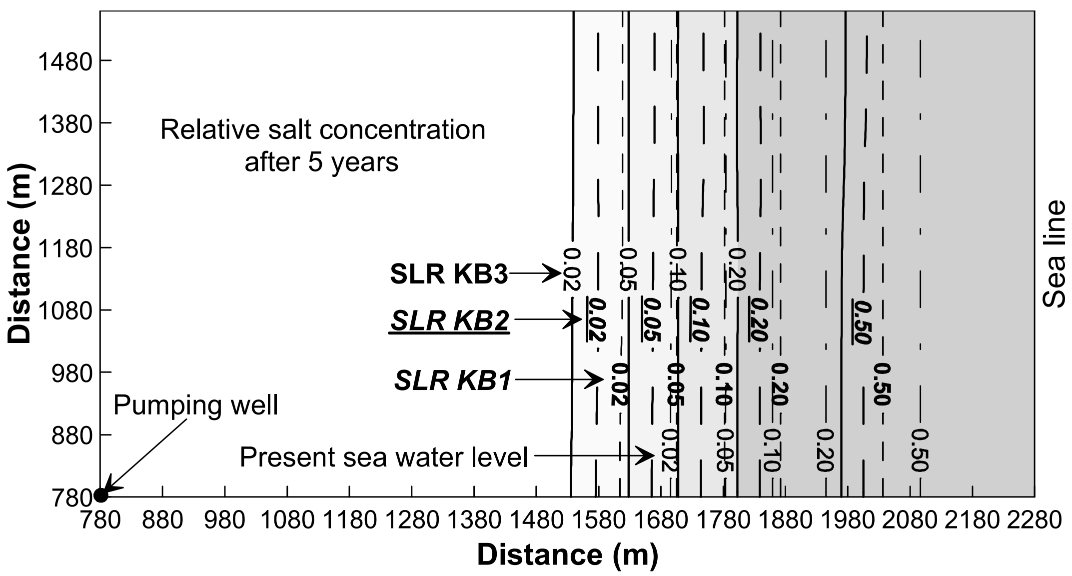

Fig. 7. Relative salt concentration-four different cases.

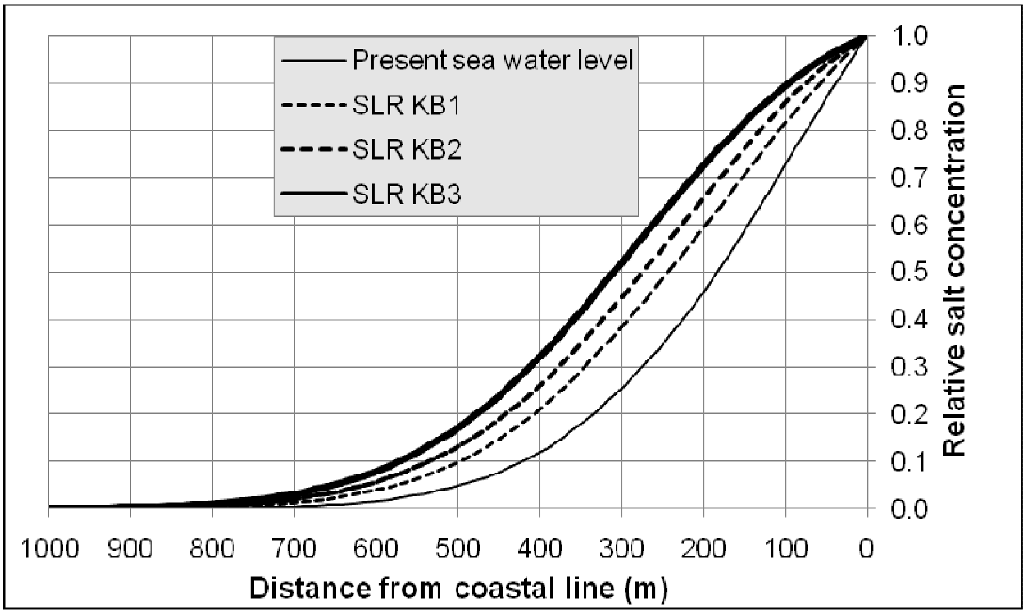

Fig. 8. Relative salt concentration from coastal line to pumping well.

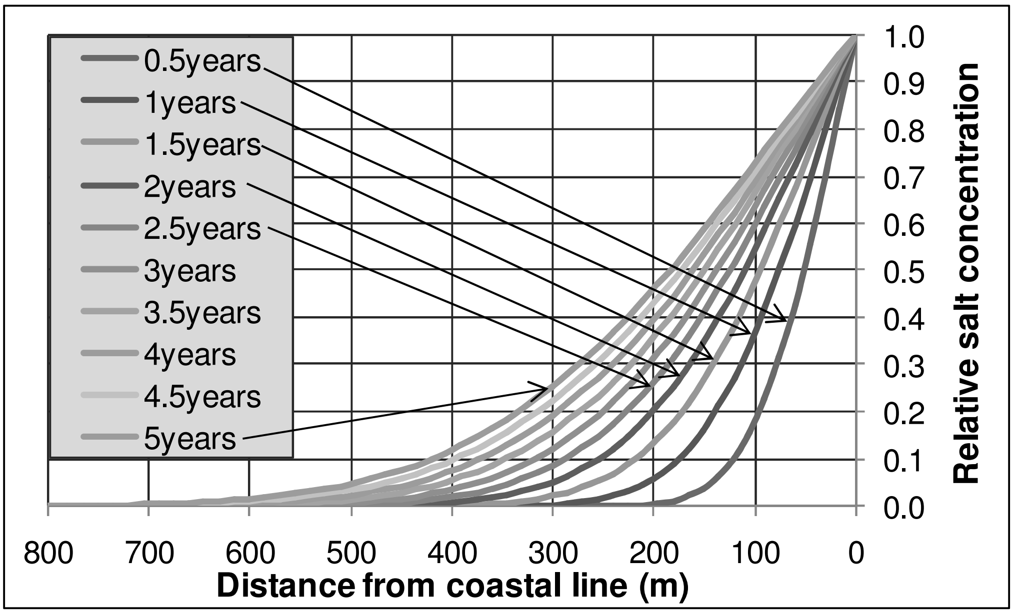

Fig. 9. Relative salt concentration from coastal line to pumping well-present sea water level.

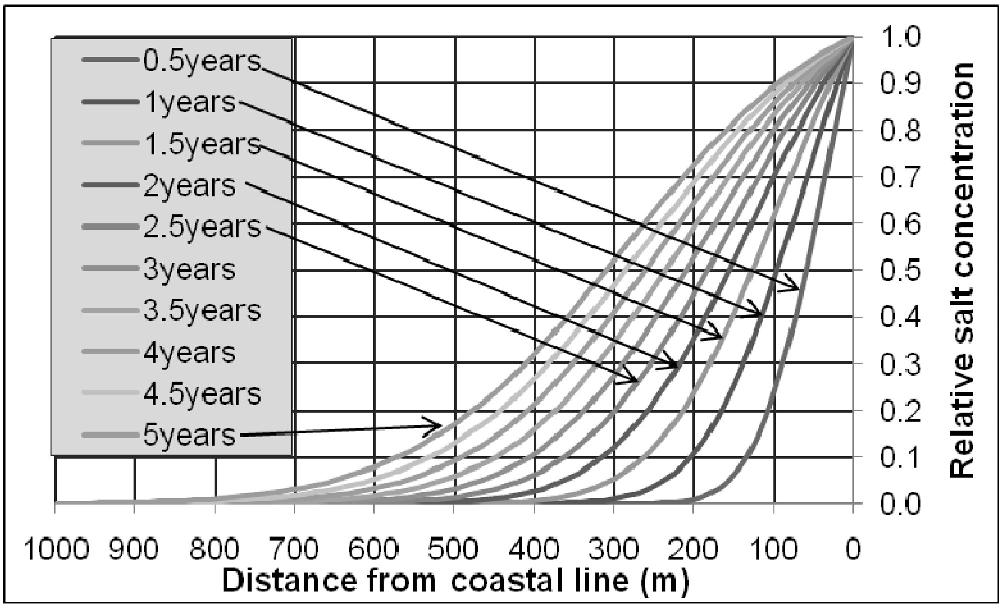

Fig. 10. Relative salt concentration from coastal line to pumping well-SLR KB3=1m.

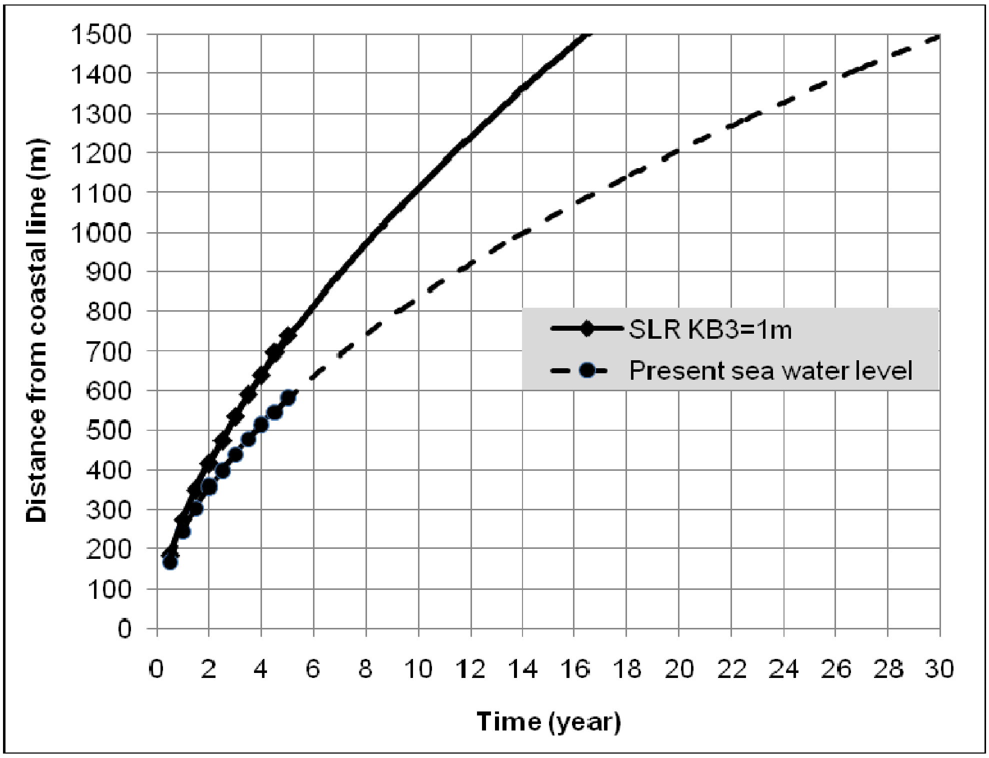

Fig. 11. Relationship between relative salt concentration of 0.02 (0.66g/l)
with time and distance from the sea.

Concluding remarks

- SLR definitely causes more intensive seawater intrusion into the groundwater abstraction facilities near the coastal line. The more abstraction rates, the more intensive seawater intrusion.

- For the present sea water level, the time for which the seawater intrusion with concentration of 0.66g/l reaches the pumping well is estimated to be 30 years for ThuyAn-Thai Thuy pumping well.

- For the case of high SLR of 1m, the time for which the seawater intrusion with concentration of 0.66g/l reaches the Thuy An-Thai Thuy pumping well is estimated to be 16.3 years, which is approximately faster two time than present sea water level.

- More detailed hydrogeological conditions should be obtained for more accurate seawater intrusion in to Thuy An-Thai Thuy pumping well and other groundwater pumping field in coastal area of Thai Binh province in order to have appropriate measures in dealing with sea water level rise.

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