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Groundwater Quality Modelling using Coupled Galerkin Finite Element and Modified Method of Characteristics Models

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Abstract— This paper presents a coupled Galerkin finite element model for groundwater flow simulation (FEFLOW) and Modified Method of Characteristics model for the simulation of solute transport (MMOCSOLUTE) in two-dimensional, transient, unconfined groundwater flow systems. The coupling factor is velocity field which is simulated by finite element technique. The study mainly focuses on groundwater quality aspects hence the flow simulation model has been kept conventional whereas the solute transport model is improvised by approximating dispersion term. This coupled model is used to obtain the space and time distribution of head and concentration for the reported synthetic test case. Further the sensitivity of model results to variation in parameters viz. porosity, dispersivity and combined injection and pumping rates is analyzed. The model results are compared with the reported solutions of the model presented by Chiang et al. (1989).

Keywords—Coupled flow and transport models, Unconfined groundwater flow, Space time distribution of head and concentration, Sensitivity of numerical models

INTRODUCTION:

Groundwater quality deterioration in many parts of the world due to poorly planned municipal, agricultural and industrial waste disposal practices has drawn the attention of researchers to develop new methods of predicting and analyzing the impact of the migration of the dissolved solutes reliably in the aquifers. The pollution of this vital water resource resulted into a serious environmental problem which may damage human health, destroy the ecosystem and cause water shortage. Thus it has become essential to assess the severity of groundwater pollution and chalk out the strategies of aquifer remediation, which are made possible by the use of the numerical models. The groundwater pollution problem becomes severe because of the migration of solutes by advection and hydrodynamic dispersion from the point of its introduction in aquifers [Freeze and Cherry, 1979].

Numerical models of groundwater flow and solute transport are properly conceptualized version of a complex aquifer system which approximates the flow and transport phenomena. The approximations in the numerical models are effected in through the set of assumptions pertaining to the geometry of the domain, ways the heterogeneities are smoothed out, the nature of the porous medium, properties of the fluid and the type of the flow regime. The complex aquifer system is treated as a continuum, which implies that the fluid and solid matrix variables are continuously defined at every point in the aquifer domain. The continuum is viewed as a network of several representative elementary volumes, each representing a portion of the entire volume of an aquifer with average fluid and solid properties taken over it and assigned to the nodes of superimposed grid used for the discretization of the domain.

Numerical models are applied either in an interpretive sense to gain insight into controlling the aquifer parameters in a site-specific setting or in generic sense to formulate regional regulatory guidelines and act as screening tools to identify regions suitable for some proposed action e.g. artificial recharge and aquifer remediation.

Pinder and Frind (1972) developed the Galerkin finite element model to simulate two-dimensional groundwater flow in a leaky aquifer. The accuracy of model results is compared with the finite difference results and it is found that both the results are in close agreement with each other.

Garder et al (1964) proposed a method of characteristic technique for the solution of the solute transport equation. The method uses moving points for calculating the concentration change at a given point in the domain for each time step. This method properly takes into account the physical dispersion. Form the various numerical experiments carried out using this technique the effect of number of moving points and their spacing is analyzed over the accuracy of the numerical solutions.

Cheng et al. (1984) proposed an Eulerian- Lagrangian scheme which uses Lagrangian concept in an Eulerian computational grid system. The values of the dependent variable i.e. solute concentration are interpolated by second order Lagrangian polynomial. The numerical solutions obtained by this method are found to be free from artificial numerical dispersion. This concept is further extended for the treatment of anisotropic dispersion in the natural coordinates by relating the anisotropic properties of the dispersion to the properties of the flow field.

Chiang et al. (1989) presented a comprehensive numerical model for solute transport simulation in groundwater flow system by combining modified method of characteristics for solution of advection-dispersion equation with finite element method for the solution of groundwater flow equation. The model allows arbitrary placement of injection and pumping wells within or on the boundaries of the domain together with different boundary conditions such as specified hydraulic heads or no-flow boundaries

Yu and Singh (1995) presented five major modifications to the existing Galerkin finite element simulation of solute transport. These include a mixed formulation for the time derivative term by combining Galerkin finite element method with collocation method, formulation of both advection and dispersion terms by Green's theorem, simpler expressions for leaky and surface flux conditions by using unit step function, expressions for the source and sink terms derived by Dirac delta function and the finite integration solution scheme for solving the system of ordinary differential equations. The effects of these five modifications on numerical solutions are also investigated.

Kulkarni N.H et al used the modified method of characteristics model for the chosen test case of Chu(1989) and analyzed the effect of porosity and dispersivity variation on model results.

GROUND WATER FLOW EQUATION:

The governing equation of two-dimensional, horizontal, and transient groundwater flow in homogeneous, isotropic and unconfined aquifer is given as [Illangasekare and Doll, 1989]

$$S_y \frac{\partial h}{\partial t} = T_{xx} \frac{\partial^2 h}{\partial x^2} + T_{yy} \frac{\partial^2 h}{\partial y^2} + \sum_{i=1}^{n_w} Q_i \delta(x_o - x_i, y_o - y_i) + \sum_{j=1}^{n_p} q_j \quad (1)$$

where S_y is the specific yield, [dimensionless]; h is the hydraulic head averaged over vertical, [L]; t is the time, [T]; T_{xx} and T_{yy} are components of the transmissiviy tensor, [L^2/T] which are approximated as $T_{xx} \approx K_{xx} h$ and $T_{yy} \approx K_{yy} h$, provided the change in the head in unconfined aquifer is negligible as compared to its saturated thickness [Illangsekare and Doll, 1989]; K_{xx} and K_{yy} are components of the hydraulic conductivity tensor, [L/T]; x and y are spatial coordinates, [L]; Q_i is the pumping rate when ($Q_i < 0$) and injection rate when ($Q_i > 0$) at i th pumping and / or injection well, [L^3/T]; n_w is the number of pumping and/or injection wells in the domain; n_p is the number of nodes in the domain with distributed discharge and/or recharge; $\delta(x_o - x_i, y_o - y_i)$ is the Dirac delta function; x_o and y_o are the Cartesian coordinates of the origin , [L]; x_i and y_i are the coordinates of i th pumping and / or injection well, [L]; q_j is the distributed discharge rate when ($q_j < 0$)and recharge rate when ($q_j > 0$) at j th nodes with distributed discharge and/or recharge, [L/T].

Equation (1) is subject to the following initial condition which is given as

$$h(x, y, 0) = h_0 \qquad (x, y) \in \Omega \qquad (2)$$

Where h_0 is the initial head over the entire flow domain, [L] and Ω is the flow domain, [L^2]. Equation (1) is subject to the Dirichlet type of boundary condition which is given as

$$h(x, y, t) = h_1 \qquad (x, y) \in \Gamma_1 ;\ t \geq 0 \qquad (3)$$

Where h_1 is the prescribed head over aquifer domain boundary Γ_1, [L].The Neumann boundary condition with zero groundwater flux can be given as

$$\left[\{q_b(x, y, t)\} - [T]\nabla h(x, y, t)\right]'.\{n\} = 0 \qquad (x, y) \in \Gamma_2 ;\ t \geq 0 \qquad (4)$$

Where q_b is the specified groundwater flux across boundary Γ_2 ,[L/T]; $[T]\nabla h$ is the groundwater flux across the boundary Γ_2 , [L/T] and n is normal unit vector in outward direction.

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ADVECTION-DISPERSION EQUATION:

The governing equation of solute transport in two-dimensional transient unconfined groundwater flow system referred to as advection-dispersion equation is given as [Illangsekara and Doll, 1989].

$$R\frac{\partial c}{\partial t} = D_{xx}\frac{\partial^2 c}{\partial x^2} + D_{xy}\frac{\partial^2 c}{\partial x\,\partial y} + D_{yx}\frac{\partial^2 c}{\partial y\,\partial x} + D_{yy}\frac{\partial^2 c}{\partial y^2}$$
$$-V_x\frac{\partial c}{\partial x} - V_y\frac{\partial c}{\partial y}$$
$$+\sum_{i=1}^{n_w}\frac{(c - c_i^{'})}{\theta b}Q_i\,\delta(x_o - x_i, y_o - y_i)$$
$$+\sum_{j=1}^{n_p}\frac{q_j}{\theta}(c - c_j^{'}) + \frac{c\,S_y}{\theta b}\frac{\partial h}{\partial t} \qquad (5)$$

where R is the retardation factor, [dimensionless]; c is solute concentration, $[M/L^3]$; D_{xx}, D_{xy}, D_{yx}, and D_{yy} are hydrodynamic dispersion coefficients, $[L^2/T]$; V_x and V_y are the components of average linear groundwater velocity, $[L/T]$; $c_i^{'}$ is solute concentration of the injected water at i th injection well, $[M/L^3]$; n_w is the number of injection wells in the domain; θ is the effective porosity of the aquifer, [percent]; b is the saturated thickness of the aquifer, $[L]$; $c_j^{'}$ is solute concentration of the recharge water at j th node with distributed recharge, $[M/L^3]$ and n_p is the number of nodes with distributed recharge .

Equation (5) is subject to the following initial condition which is given as

$$c\,(x, y, 0) = c_0 \qquad (x, y) \in \Omega \qquad (6)$$

Where c_0 is the initial solute concentration over the entire aquifer domain, $[M/L^3]$. Equation (5) is subject to the Dirichlet boundary condition which is given as

$$c(x, y, t) = c_1 \qquad (x, y) \in \Gamma_1; t \geq 0 \qquad (7)$$

Where c_1 is the prescribed solute concentration over aquifer domain boundary Γ_1, $[M/L^3]$. Equation (5) is subject to the Neumann boundary condition which is given as

$$\left[\{cq_b(x,y,t)\} - [D]\nabla c(x,y,t)\right]'.\{n\} = 0 \quad (x,y) \in \Gamma_2;\ t \geq 0 \qquad (8)$$

Where cq_b is the specified solute flux across the boundary Γ_2, [M/L3/T] and $[D]\nabla c$ is the dispersive flux across the boundary Γ_2, $[M/L^3/T]$.

FEFLOW MODEL:

Applying the numerical integration for the various terms of Equation (1) the following system of linear equations is obtained and the same can be written as

$$\left([\boldsymbol{G}] + \frac{1}{\Delta t}[\boldsymbol{P}]\right)\{h_{i,j}^{t+\Delta t}\} = \left(\frac{1}{\Delta t}[\boldsymbol{P}]\right)\{h_{i,j}^{t}\} + \{\boldsymbol{B}\} + \{\boldsymbol{f}\} \qquad (9)$$

Where $[\boldsymbol{G}]$ is the global conductance matrix which is formed by assembling the elemental conductance matrices $\left[G_L^e\right]$ that can be expressed as

$$[G_L^e] = \iint_e \left(\frac{\partial \hat{h}_L^e}{\partial x}\frac{\partial N_L^e}{\partial x} + \frac{\partial \hat{h}_L^e}{\partial y}\frac{\partial N_L^e}{\partial y}\right) dx\,dy = \qquad (10)$$
$$\frac{1}{4A^e}\begin{bmatrix} b_i^e b_i^e & b_i^e b_j^e & b_i^e b_k^e \\ b_j^e b_i^e & b_j^e b_j^e & b_j^e b_k^e \\ b_k^e b_i^e & b_k^e b_j^e & b_k^e b_k^e \end{bmatrix} + \begin{bmatrix} c_i^e c_i^e & c_i^e c_j^e & c_i^e c_k^e \\ c_j^e c_i^e & c_j^e c_j^e & c_j^e c_k^e \\ c_k^e c_i^e & c_k^e c_j^e & c_k^e c_k^e \end{bmatrix}$$

$[\boldsymbol{P}]$ is the global storage matrix which is assembled from elemental storage matrices $\left[P_L^e\right]$ that can be given as

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$$\left[P_L^e\right]=\iint_e \frac{\partial \hat{h}_L^e}{\partial t} N_L^e \frac{S_y{}^e}{T^e} dx\,dy=\iint_e N_L^e N_L^e \frac{S_y{}^e}{T^e} dx\,dy= \frac{S_y{}^e}{T^e}\frac{A^e}{12}\begin{bmatrix}2 & 1 & 1\\ 1 & 2 & 1\\ 1 & 1 & 2\end{bmatrix} \quad \because L=i\neq j\neq k \tag{11}$$

$\{B\}$ is the global load vector which is assembled from elemental load vectors $\{B_L^e\}$ that can be given as

$$\{B_L^e\}=\iint_e \begin{pmatrix} \sum_{i=1}^{n_w} Q_i^e \delta\left(x_o - x_i, y_o - y_i\right) \\ + \sum_{j=1}^{n_p} q_j^e \end{pmatrix} N_L^e\, dx\, dy = \left(\frac{Q^e}{3T^e}+\frac{q^e A^e}{3T^e}\right)\begin{bmatrix}1\\1\\1\end{bmatrix} \tag{12}$$

$\{f\}$is the global boundary flux vector which is assembled from the elemental boundary flux vectors $\{f_L^e\}$ that can be given as

$$\{f_L^e\} = \int_\Gamma \frac{1}{T}\left(T^e \frac{\partial \hat{h}_L^e}{\partial x} n_x + T^e \frac{\partial \hat{h}_L^e}{\partial y} n_y\right) N_L^e\, d\sigma^e = \left(\frac{b\, q_{bx}{}_L^e}{T^e}\left(\frac{d\sigma_y^e}{2}\right)+\frac{b\, q_{by}{}_L^e}{T^e}\left(\frac{d\sigma_x^e}{2}\right)\right)\begin{bmatrix}1\\1\\1\end{bmatrix} \tag{13}$$

From the known head distribution at previous time level the unknown head distribution at the next time level is obtained by recursively solving the set of algebraic equations given in Equation (9).

MMOCSOLUTE MODEL:

This model is proposed as a variant of the conventional USGS-MOC model. Unlike the conventional USGS-MOC model, real solute particles are used for the simulation of the advective transport. Each solute particle has definite volume which is equal to the volume of the cell accommodating that particle and it drifts through the groundwater flow system due to the average linear groundwater velocity. The second order hydrodynamic dispersion term is handled by finite element method. This model considers the Equation (5) in its material derivative form so as to replace the hyperbolic form of equation due to advection terms with the parabolic form of equation containing hydrodynamic dispersion terms and discharge and/or recharge terms and the same is given as

$$\frac{Dc}{Dt}\cong\left(\frac{\partial c}{\partial t}+V_x\frac{\partial c}{\partial x}+V_y\frac{\partial c}{\partial y}\right)=D_{xx}\frac{\partial^2 c}{\partial x^2}+D_{xy}\frac{\partial^2 c}{\partial x\partial y}+D_{yx}\frac{\partial^2 c}{\partial y\partial x} + D_{yy}\frac{\partial^2 c}{\partial y^2}+\sum_{i=1}^{n_w}\frac{(c - c_i')}{\theta b}Q_i\,\delta(x_o - x_i, y_o - y_i)+ \sum_{j=1}^{n_p}\frac{q_j}{\theta}(c - c_j')+\frac{c\,S_y}{\theta b}\frac{\partial h}{\partial t} \tag{14}$$

The advection term of the Equation (14) is solved separately using backward in time particle tracking along characteristic curves. The solution of the advection term is the solution of the equations of characteristic curves which are given as

$$\frac{dx}{dt}=V_x, \frac{dy}{dt}=V_y \quad \frac{dc}{dt}=\frac{\partial c}{\partial t}+\frac{dx}{dt}\frac{\partial c}{\partial x}+\frac{dy}{dt}\frac{\partial c}{\partial y} \tag{15}$$

Thus the location of the base of the characteristic curve which represents the probable location of the drifting particle at the previous time level from which it has come to the nodal location during a time step is obtained by using following equations:

$$\delta x_{i,j}^t = V_{x_{i,j}} \times \Delta t, \delta y_{i,j}^t = V_{y_{i,j}} \times \Delta t \tag{16}$$

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Where $\delta x_{i,j}^{t}$ and $\delta y_{i,j}^{t}$ are the advective displacements in x-and y-directions, respectively. For the particle residing in third quadrant after advective transport, the concentration at the drifted location of the solute particle which happens to be the base of the characteristic curve is computed by using following equation:

$$c^{a\,t+\Delta t}_{i,j} = c_R^{a\,t} = (1-f_y)\{(1-fx)(c_{i,j}^t)+(f_x)(c_{i-1,j}^t)\}+ (f_y)\{(1-fx)(c_{i,j-1}^t)+(f_x)(c_{i-1,j-1}^t)\} \quad (17)$$

where $c^{a\,t+\Delta t}_{i,j}$ is the concentration at the node after advective movement which is same as that of the concentration at the base of the characteristic curve i.e. $c_R^{a\,t}$, $[M/L^3]$; R is the location of the base of the characteristic curve; $f_x = (\Delta x - \delta x_{i,j}^t)/\Delta x$ and $f_y = (\Delta y - \delta y_{i,j}^t)/\Delta y$ are factors of bilinear interpolation; $(i-1, j;\ \ i-1, j-1;\ \ i, j-1;\ \ i, j)$ are the indices of the closest nodes to the drifted location of the particle. The change in nodal concentration at next time level i.e. $c^{d\,t+\Delta t}_{i,j}$ is computed by approximating the second-order hydrodynamic dispersion term.

$$A_L^e = \iint_e \left(D_{xx} \frac{\partial \hat{c}_L^e}{\partial x}\frac{\partial N_L^e}{\partial x} + D_{xy} \frac{\partial \hat{c}_L^e}{\partial y}\frac{\partial N_L^e}{\partial x} + D_{yx} \frac{\partial \hat{c}_L^e}{\partial x}\frac{\partial N_L^e}{\partial y} + D_{yy} \frac{\partial \hat{c}_L^e}{\partial y}\frac{\partial N_L^e}{\partial y} \right) dx\, dy =$$

$$\frac{D_{xx}}{4A^e}\begin{bmatrix} b_i^e b_i^e & b_i^e b_j^e & b_i^e b_k^e \\ b_j^e b_i^e & b_j^e b_j^e & b_j^e b_k^e \\ b_k^e b_i^e & b_k^e b_j^e & b_k^e b_k^e \end{bmatrix} + \frac{D_{xy}}{4A^e}\begin{bmatrix} b_i^e c_i^e & b_i^e c_j^e & b_i^e c_k^e \\ b_j^e c_i^e & b_j^e c_j^e & b_j^e c_k^e \\ b_k^e c_i^e & b_k^e b_j^e & b_k^e c_k^e \end{bmatrix} + \frac{D_{yx}}{4A^e}\begin{bmatrix} c_i^e b_i^e & c_i^e b_j^e & c_i^e b_k^e \\ c_j^e b_i^e & c_j^e b_j^e & c_j^e b_k^e \\ c_k^e b_i^e & c_k^e b_j^e & c_k^e b_k^e \end{bmatrix} + \frac{D_{yy}}{4A^e}\begin{bmatrix} c_i^e c_i^e & c_i^e c_j^e & c_i^e c_k^e \\ c_j^e c_i^e & c_j^e c_j^e & c_j^e c_k^e \\ c_k^e c_i^e & c_k^e c_j^e & c_k^e c_k^e \end{bmatrix} \quad (18)$$

In every time step the results obtained from Equation (17) are used as initial condition for Equation (18) and vice versa. Thus the changed nodal concentration after advective and dispersive transport is given as

$$c_{i,j}^{t+\Delta t} = c^{a\,t+\Delta t}_{i,j} + c^{d\,t+\Delta t}_{i,j} \quad (19)$$

RESULTS AND DISCUSSION:

An example problem [Chiang et al. 1989] is considered presently. It is chosen to study the changes in solute concentration distribution due to the combined effect of the extraction and injection of groundwater from the aquifer. A pumping well situated at a location (1.8 m, 1.8 m) extracts the groundwater at the constant pumping rate of 0.279 m^3/d. The injection well situated at the location of (7.2 m, 7.2 m) recharges the aquifer at the constant rate of 0.279 m3/d. The aquifer domain of 9.14 m × 9.14 m size is discretized into 30 × 30 grid system as shown in Fig. 1. The dimension of each square cell is 0.31 m.

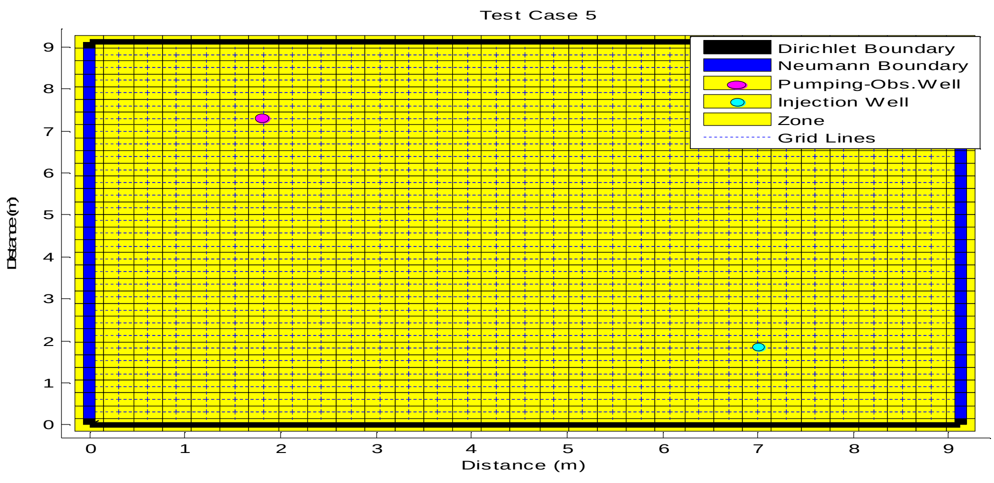

Figure 1 Schematic of aquifer modeled in Test Case for the simulation of solute transport in two-dimensional transient groundwater flow in unconfined aquifer under the combined injection and pumping well conditions

The concentration breakthroughs are observed for the total simulation period of 20 days at the observation well which is situated at the location of the pumping well and the reported solutions are shown in Fig. 2[*Chiang et al. 1989*]. The observation well is selected at the location of the pumping well to investigate the constrained conditions for the spread of the solute from its point of introduction to the aquifer.

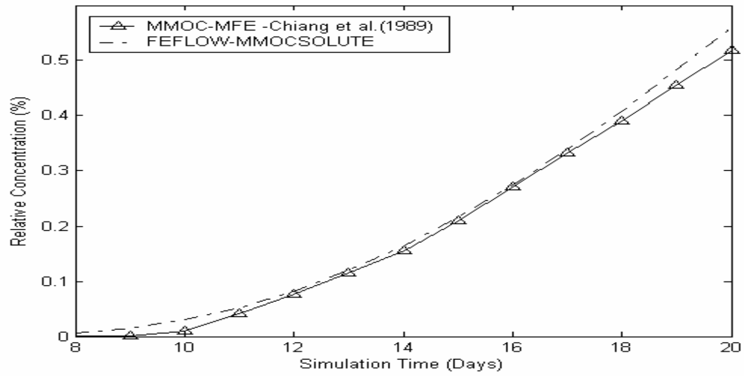

Figure 2 *Comparison of concentration breakthrough curves obtained by FEFLOW-MMCSOLUTE*

The concentration is continuously rising with the simulation period and the maximum concentration reached to 56% of the injected solute concentration. The concentration breakthroughs simulated at the observation well under the condition of the combined pumping and injection well system are plotted against the simulation time of 20 days. It is found from the Fig. 2 that both the curves match very closely during the period from 12 to 17 days. However in the early as well as later stages of the simulation the FEFLOW-MMCSOLUTE breakthrough curve experiences very small numerical dispersion. After 20 days of the simulation the FEFLOW-MMCSOLUTE breakthrough curve deviates by 10% from the reported solution. Fig. 3 shows the velocity field simulated under the condition of combined injection and pumping well system with these wells located diagonally at the distance of 7.2 m. It is observed from the velocity vectors that the divergent and convergent flow zones are formed around injection and pumping well, respectively. The maximum x-and y-velocity components are almost same and calculated as 1.57 and -1.8 m/d, respectively. It can be seen from the concentration contours that the 50% of the input concentration is observed in the vicinity of the pumping well as shown in Fig. 4.

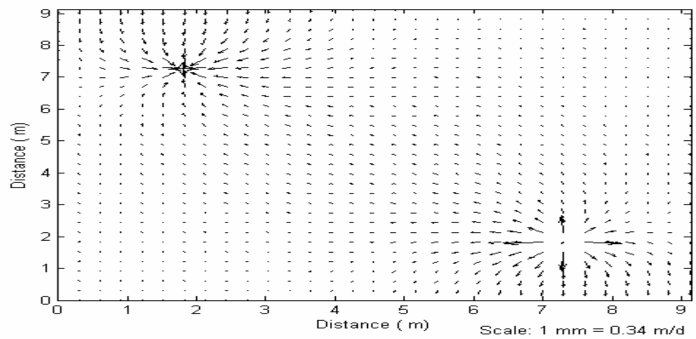

Figure 3 *Simulated velocity field by FEFLOW model under the combined injection and pumping well system for Test Case*

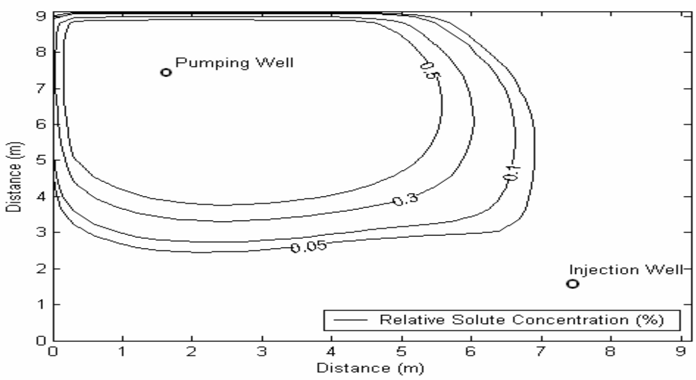

Figure 4 Solute concentration distributions by FEFLOW-MMOCSOLUTE model under the combined injection and pumping well conditions for Test Case

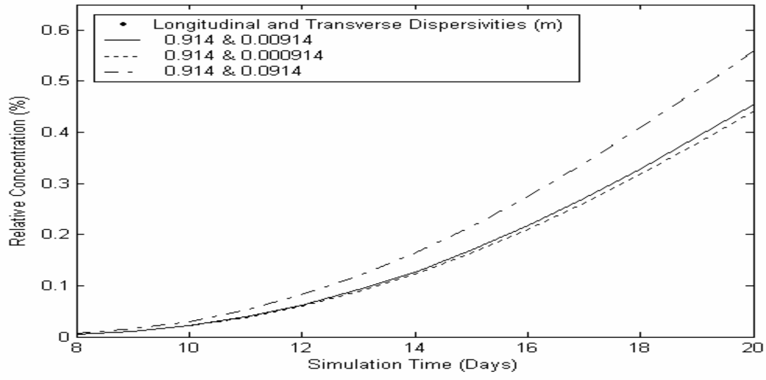

Figure 5 Effect of dispersivity on FEFLOW-MMOCSOLUTE model solutions under the combined injection and pumping well conditions for Test Case

It is observed that all the concentration contours are affected by boundary conditions. The maximum value of the concentration is observed at the node situated at the location (1.8 m, 6.6 m) from the origin which is almost equal to the input concentration. The longitudinal dispersivity is kept unchanged and only transverse dipersivity is varied by one order less and one order higher respectively compared to its initial value (0.00914) i.e. 0.0914 and 0.000914 m, respectively. It is found from Fig. 5 that the concentration breakthrough simulated with the dispersivity of 0.0914 deviates from the breakthrough curve simulated with the initially chosen dispersivity value by 7%. The concentration breakthrough simulated with the dispersivity of 0.000914 m deviates from the breakthrough curve simulated with the initially chosen value of the dispersivity by 22%.

EFFECT OF POROSITY ON FEFLOW-MMOCSOLUTE SOLUTIONS UNDER THE COMBINED INJECTION AND PUMPING WELL SYSTEM:

Fig. 6 shows the comparison of three concentration breakthrough curves simulated by FEFLOW-MMOCSOLUTE model with three different values of the effective porosity. These values are 0.085, 0.10, and 0.15 respectively. It is observed from the Figure 6 that the breakthrough curve simulated with 0.085 porosity varies from the breakthrough simulated with the porosity of 0.15 at the end of 20 days period by an order of 65% whereas the breakthrough curve simulated with 0.1 percent effective porosity dips down from the breakthrough curve for the initially chosen value of the effective porosity by an order of 55%.

EFFECT OF COMBINED INJECTION AND PUMPING RATE ON FEFLOW-MMOCSOLUTE SOLUTIONS:

Fig. 7 shows the comparison of the three concentration breakthrough curves at the observation well. The initial pumping rate of 0.279 m^3/d varied to its half (0.1395 m^3/d) and double value of 0.418 m^3/d. Due to high pumping rate the concentration goes down and due to low pumping rate the less concentration mass is taken out from the contaminated aquifer resulting into the occurrence of higher concentrations at the observation well.

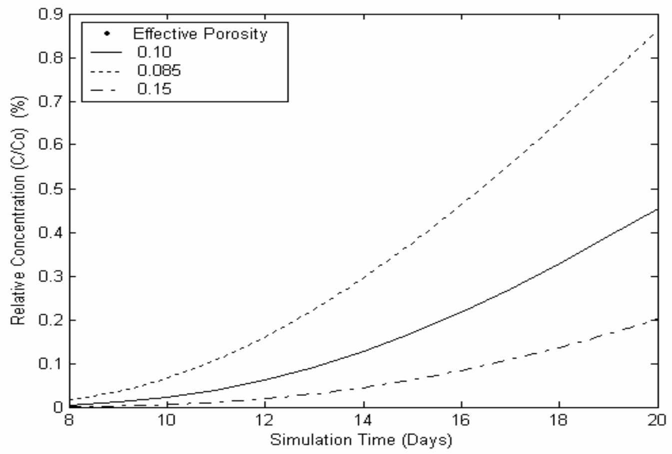

Figure 6 Effect of porosity on FEFLOW-MMOCSOLUTE model solutions under the combined injection and pumping well conditions for Test Case

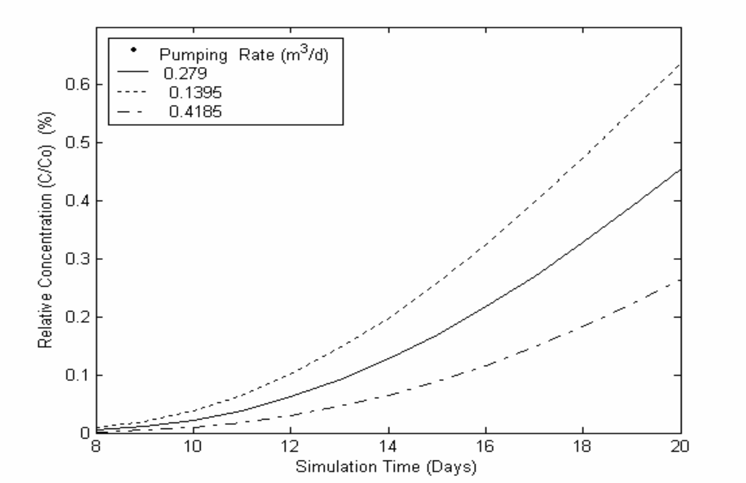

Figure 7 Effect of combined injection and pumping rate on FEFLOW-MMOCSOLUTE model solutions for Test Case

This physical condition is adequately simulated by numerical models. The concentration breakthrough simulated with increased pumping rate drops down to 46 % of that of the concentration for the given pumping rate and for decreased pumping rate the breakthrough concentration rises to 35 % of that of the concentration for the given pumping rate.

CONCLUSIONS:

A coupled Galerkin finite element model for groundwater flow simulation (FEFLOW) and Modified Method of Characteristics model for the simulation of solute transport (MMOCSOLUTE) in two-dimensional, transient, unconfined groundwater flow systems with velocity field as coupling factor. This model is compared with the Chiang et al. (1989) model for a synthetic test case. Following noteworthy conclusions are derived: Due to approximation in hydrodynamic dispersion term by finite element technique the corresponding solute concentration breakthrough curves deviate by about 10% at the end of simulation period i.e. 20 days as per Fig.2. If the location of pumping well is diagonally opposite to the injection well then the observed solute concentration in the vicinity of pumping well is 50% of the concentration of injected water. The effect of variation of magnitude of transverse dipersivity by one order less and one order higher respectively compared to its base value (0.00914) i.e. 0.0914 and 0.000914 m, respectively caused deviation in solute concentration breakthrough curve at the end of simulation period by 7% and 22% respectively. The solute concentration breakthrough curve simulated with 0.085 porosity varies by an order of 65% whereas the breakthrough curve simulated with 0.1 percent effective porosity dips down by an order of 55%. The solute concentration breakthrough simulated with increased pumping rate drops down to 46 % of that of the concentration for the given pumping rate and for decreased pumping rate the breakthrough concentration rises to 35 % of that of the concentration for the given pumping rate. Thus it is felt that the model results are comparable with the reported solutions of the model presented by Chiang et al. (1989) and the developed model can be used for real life problem involving combined pumping and injection schemes from which aquifer remediation strategies can be evolved.

REFERENCES:

[1] Garder, A. O., Peaceman, D. W., and Pozzi, A. L. Jr., 1964, Numerical calculation of multidimensional miscible displacement by the method of characteristics, *Society of Petroleum Engineers Journal*, 4(1):26-36.

[2] Pinder, G. F., and Frind, E. O., 1972, Application of Galerkin's procedure to aquifer analysis. *Water Resources Research*, 8(1):108-120.

[3] Freeze, R. A., and Cherry, J. A. 1979, Groundwater, Prentice- Hall, Englewood Cliffs, New Jersy.

[4] Anderson, M. P., 1983, Using models to simulate the movement of contaminants through groundwater flow systems, Critical Review in Environmental Control, 9(2): 97-156.

[5] Cheng, R. T., Casulli, V., and Milford, S. N., 1984, Eulerian-Lagrangian solution of the convection-dispersion equation in natural coordinates, *Water Resources Research*, 20(7): 944-952.

[6] Illangasekare, T. H., and Doll, P., 1989, A discrete kernel method of characteristics model of solute transport in water table aquifers, *Water Resources Research*, 25(5): 857-867.

[7] Chiang, C. Y., Wheeler, M. F., and Bedient, P. B., 1989, A modified method of characteristics technique and mixed finite elements method for simulation of groundwater solute transport, *Water Resources Research*, 25(7): 1541-1549.

[8] Yu, F. X., and Singh, V. P., 1995, Improved finite-element method for solute transport, *Journal of Hydraulic Engineering*, 121(2): 145-158.

[9] Kulkarni N.H., and Rastogi A.K., 2012, Numerical Experiments on Solute Transport in Groundwater Flow System, International *Journal of Emerging Technology and Advanced Engineering*, 2(8): 408-416.