

# Influence of Various Dispersion Coefficients on Contaminant Migration in a Fracture-matrix System with Skin Formation

**N. Natarajan**

Department of Civil Engineering, Dr. Mahalingam College of Engineering  
Pollachi, Tamil Nadu – 642003, India  
✉ itsrajan2002@yahoo.co.in

*Received August 16, 2016; revised and accepted March 19, 2017*

**Abstract:** Subsurface contamination due to transient migration of chemicals through weathered fractures is a serious problem in hard rock terrains. In this paper, a numerical model has been used to analyse the effect of various dispersion coefficients on the movement of contaminants in a fracture-matrix system with skin formation. A constant continuous source of contaminants is considered at the inlet of a set of parallel fractures and an implicit finite difference technique has been used to solve the model. The transport of contaminants with constant dispersion coefficients were compared with those subjected to distance and time dependent dispersion. Sensitivity analysis has been conducted to study the effect of different fluid velocities, fracture-skin porosities, fracture-skin diffusion coefficients, fracture aperture, retardation factors, and dispersivity–distance ratio on solute transport mechanism within the system. Results suggest that the solute mass retained in the fracture is higher when time-dependent dispersion coefficients are used which may be due to seasonal conditioning of the rocks. When constant dispersion coefficient is considered, the reduction in the solute mass with increment in the fracture-skin porosity is gradual unlike other cases. The solute mass retained in the fracture increases with increase in dispersivity–distance ratio for time-dependent dispersion coefficients.

**Key words:** Fracture-skin, time-dependent dispersion, distance-dependent dispersion, solute transport, numerical model.

## Introduction

Flow and transport through fracture porous media is a hot topic of research for many researchers including geologists and hydro-geologists. This field has gained momentum over the last few decades as it enhances the understanding of the migration of contaminants in the subsurface porous media. The movement of contaminants in fractured porous media plays a major role in many areas such as groundwater, petroleum, geothermal, nuclear, gas, etc. Significant research has been carried out on solute transport in a coupled fracture-matrix system (Freeze and Cherry, 1979; Grisak

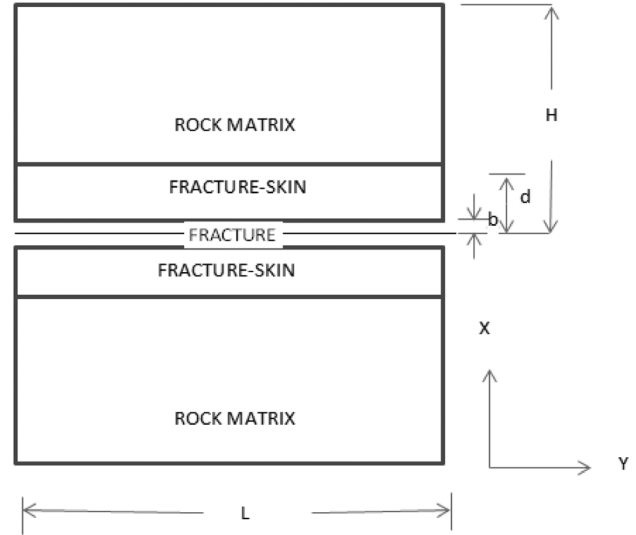
and Pickens, 1980; Tang et al., 1981; Maloszewski and Zuber, 1990; Wallach and Parlange, 1998; Sekhar et al., 2006; Suresh Kumar, 2008; Suresh Kumar et al., 2008; Moreno and Rasmuson, 2010; Natarajan and Suresh Kumar, 2011a, b, c; Suresh Kumar et al., 2011; Natarajan and Suresh Kumar, 2012a; Natarajan and Suresh Kumar, 2015; Natarajan and Suresh Kumar, 2016a). While many of the studies have considered dispersion phenomenon to be a constant, a few of them have considered dispersion coefficient to be either distance-dependent (Pickens and Grisak, 1980; Pang and Hunt, 2001; Gao et al., 2010) or time-dependent (Srivastava et al., 2002; Zhou and Selim, 2003; Sharma

and Srivastava, 2012). Sharma et al. (2014) conducted a numerical study to compare the effect of usage of distance and time-dependent dispersion models with constant dispersion models in the coupled fracture-matrix system.

Recent studies have reported the deposition of a low permeability material known as fracture-skin on the walls of the fracture walls which hinders the mass transfer between the high permeability fracture and the low permeability rock matrix (Moench, 1984, 1995; Kriesel and Sharp, 1996). The fracture-skin material can be either in the form of clay filling (Driese et al., 2001), mineral precipitation (Fu et al., 1994), or organic material (Robinson and Sharp, 1997). Thus the presence of fracture skin can either mitigate or enhance the mass transfer at the fracture-matrix interface and thereby influence the migration of contaminants in fractured porous media (Sharp, 1993; Fu et al., 1994; Sharp et al., 1995; Kriesel and Sharp, 1996; Robinson et al., 1998; Landrum, 2000; Phyu, 2002; Zimmerman et al., 2002). Only a few studies have been conducted on solute and colloidal transport in a coupled fracture-matrix system with skin formation (Natarajan and Suresh Kumar, 2010, 2012b, 2012c, 2012d; Nair and Thampi, 2010; 2011, 2012; Natarajan and Suresh Kumar, 2014; Natarajan, 2014; Natarajan and Suresh Kumar, 2016b). As far as the authors' knowledge is concerned, these preliminary studies have considered dispersion coefficient to be a constant. As per the conclusion of Sharma et al. (2014), the concentration profiles obtained by using constant dispersion coefficient should definitely differ from that obtained by using distance-dependent and time-dependent dispersion coefficients. Although the effect of distance- and time-dependent dispersion coefficients have been incorporated in a coupled fracture-matrix system, the effect of the same is yet to be studied in the fracture-skin-matrix system. Therefore, the present study aims to analyse the behaviour of non-reactive contaminant migration when subjected to different dispersion coefficients in a fractured porous system with skin formation.

### Physical System and Governing Equations

The conceptual model illustrating a coupled fracture-skin-matrix system (Robinson et al., 1998) is illustrated in Figure 1. A set of parallel fractures with aperture of size  $2b$  is separated by a distance of  $2H$ . The fracture-skin having thickness  $d-b$  lies between the fracture and the rock-matrix. The principal transport mechanisms considered within the fracture entails the following:



**Figure 1: Schematic representation of the fracture-matrix system with skin formation.**

advection, hydrodynamic dispersion, sorption and first-order radioactive decay, accompanied with mass transfer to the adjacent skin by diffusion. Molecular diffusion, sorption and decay have been considered within the fracture-skin and rock-matrix.

The governing equations for contaminant transport in fracture, fracture-skin and rock-matrix are expressed as (Robinson et al., 1998);

$$R_f \frac{\partial C_f}{\partial t} = D \frac{\partial^2 C_f}{\partial x^2} - V \frac{\partial C_f}{\partial x} - \lambda C_f + \frac{\theta_s D_s}{b} \frac{\partial C_s}{\partial y} \Big|_{y=b} \quad (1)$$

As mentioned earlier, both distance-dependent and time-dependent dispersion coefficients have been considered for this study. Yates (1990) provided the expression for distance-dependent dispersion coefficient:

$$D(x) = \alpha(x) V + D_0 = \varepsilon x V + D_0 \quad (2)$$

where  $\alpha(x)$  is the distance-dependent dispersivity,  $\varepsilon$  is the slope of the dispersivity–distance relationship,  $x$  is the distance from the source, and  $D_0$  is free molecular diffusion coefficient.

The time-dependent dispersion coefficient can be represented as (Yates, 1990)

$$D(t) = \alpha(t) V + D_0 = \varepsilon \bar{x} V + D_0 \quad (3)$$

where  $\alpha(t)$  is the time-dependent dispersivity,  $\bar{x}$  is the mean travel distance and it is represented as  $V \times t$ .

$$R_s \frac{\partial C_s}{\partial t} = D_s \frac{\partial^2 C_s}{\partial y^2} - \lambda C_s \quad (4)$$

$$R_m \frac{\partial C_m}{\partial t} = D_m \frac{\partial^2 C_m}{\partial y^2} - \lambda C_m \quad (5)$$

Here  $C_f$ ,  $C_s$  and  $C_m$  represent the concentration of solute in high-permeability fracture, low-permeability fracture-skin and low-permeability rock-matrix,  $x$  is the space coordinate along the direction in the fracture,  $y$  is the space coordinate perpendicular to the fracture,  $t$  is the time coordinate,  $D$  is the hydrodynamic dispersion coefficient in the fracture,  $V$  is the velocity of the fluid,  $\theta_s$  is the fracture skin porosity,  $D_m$  is the matrix diffusion coefficient,  $D_o$  is the molecular diffusion coefficient of solute in free water,  $D_s$  and  $D_m$  are effective diffusion coefficients in fracture-skin and rock-matrix respectively, and  $\lambda$  is first order radioactive decay constant.  $R_f$ ,  $R_s$  and  $R_m$  are the retardation factors in fracture, fracture-skin and rock-matrix respectively.

The initial and boundary conditions associated with equations (1), (4) and (5) are:

$$C_f(x, t = 0) = C_s(x, y, t = 0) = C_m(x, y, t = 0) = 0 \quad (6)$$

$$C_f(x = 0, t) = C_0 \quad (7)$$

$$C_f(x = L, t) = 0 \quad (8)$$

$$C_f(x, t) = C_s(x, y = b, t) \quad (9)$$

$$\theta_s D_s \frac{\partial C_s(x, y = d, t)}{\partial y} = \theta_m D_m \frac{\partial C_m(x, y = d, t)}{\partial y} \quad (10)$$

$$C_s(x, y = d, t) = C_m(x, y = d, t) \quad (11)$$

$$\frac{\partial C_m(x, y = H, t)}{\partial y} = 0 \quad (12)$$

Following assumptions have been made in this study:

1. The fracture aperture is very small in magnitude compared to length of the fracture.
2. Permeability of fracture-skin and rock-matrix is ignored as there is no advection within fracture-skin and rock-matrix.
3. Concentrations at the fracture-skin interface, i.e., concentration along the fracture walls and along the lower boundary of the fracture-skin is assumed to be equal.
4. Concentrations at the skin-matrix interface, i.e., concentration along the upper boundary of the fracture-skin and lower boundary of the rock-matrix is assumed to be equal.

5. Due to symmetry, only one half of a high permeability fracture, its adjacent low permeability fracture-skin and its associated one half of rock-matrix has been considered for simulation.
6. Fracture-skin thickness is assumed to remain constant with time.

## Numerical Method

The physical system is described by a set of three partial differential equations: one for the fracture, another for the fracture-skin and the final one for the rock-matrix, formulated as a one-dimensional framework. The coupled non-linear equations are solved using implicit finite difference technique: Upwind scheme for advection and second-order central difference for the dispersion. The continuity of fluxes at the interface of the fracture-skin is satisfied by iterating the solution at each time step. The grid size in the fracture is maintained uniform whereas a varying grid size is adopted at the fracture-skin interface to capture the concentration flux at the interface of the fracture and the fracture-skin. The last term on the right hand side of Eq. (1) is discretized as follows:

$$\frac{\partial C_s}{\partial y} = \frac{C_{s2}^{n+1} - C_{s1}^{n+1}}{\Delta y(1)} \quad (13)$$

where  $\Delta y(1)$  represents the width of the first cell at the fracture-skin interface. The contaminant concentration in the first node in the fracture-skin, i.e.  $C_{s1}^{n+1}$  will be equal to the corresponding fracture concentration  $C_{f1}^{n+1}$  at  $i = 1$  perpendicular to the fracture satisfying the boundary condition. The contaminant concentration at the second node of the fracture-skin  $C_{s2}^{n+1}$  is unknown at the  $(n + 1)^{\text{th}}$  time level in Eq. (1). The value of this unknown is assumed and iterated until convergence. The Thomas algorithm or otherwise known as Tri-diagonal matrix algorithm (TDMA) is used to solve the three unknowns in Eq. (1) at the  $i^{\text{th}}$  node,  $(i + 1)^{\text{th}}$  node and  $(i - 1)^{\text{th}}$  node at  $(n + 1)^{\text{th}}$  time level.

## Results and Discussion

In this study, an implicit finite difference numerical model has been used to analyse the effect of distance-dependent and time-dependent dispersion coefficients on the contaminant transport mechanism in a coupled fracture-matrix system with skin formation. The input parameters used in the present study has been adopted

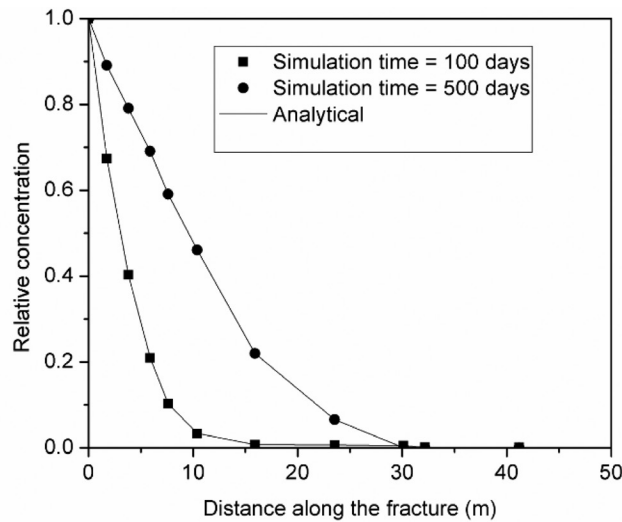
from Robinson et al. (1998). Table 1 provides the list of parameters used in the simulation of this study.

**Table 1: Parameters used in the present study**

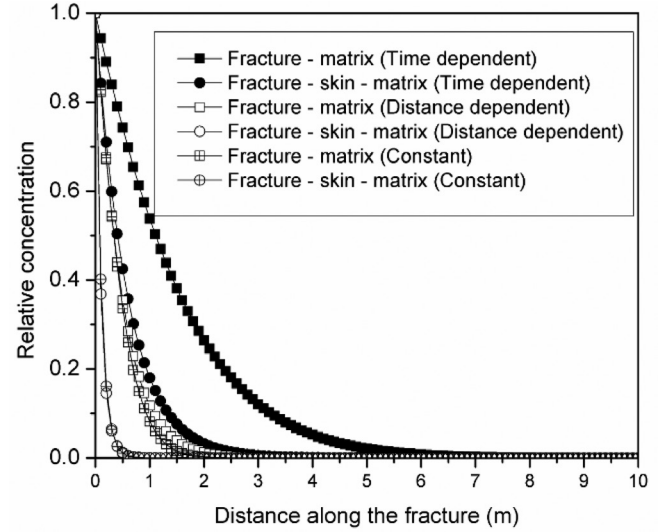
Parameter	Value
Fluid velocity in the fracture (V)	1 m/d
Half fracture aperture (b)	100e-06 m
Fracture-skin porosity ( $\theta_s$ )	0.035
Fracture-skin diffusion coefficient ( $D_s$ )	4e-06 m <sup>2</sup> /d
Rock-matrix diffusion coefficient ( $D_m$ )	4e-06 m <sup>2</sup> /d
Free molecular diffusion coefficient ( $D_0$ )	1e-06
Rock-matrix porosity ( $\theta_m$ )	0.145
Length of the fracture (L)	100 m
Half-fracture spacing (H)	0.15 m
Fracture skin thickness (d-b)	0.0018 m
Total simulation time	100 days
Decay in the fracture ( $\lambda_f$ )	6.33e-05 d <sup>-1</sup>
Retardation factor in the fracture	6
Retardation factor in the fracture-skin	673
Retardation factor in the rock-matrix	141

Figure 2 shows the comparison of the results obtained from the numerical model with the analytical solution provided by Robinson et al. (1998) for solute transport in a fracture-matrix coupled system with skin formation.

Figure 3 shows the comparison of the solute concentration in a coupled fracture-matrix system with and without fracture-skin. The concentration profiles obtained by using three different dispersion coefficients (namely, constant, distance-dependent and



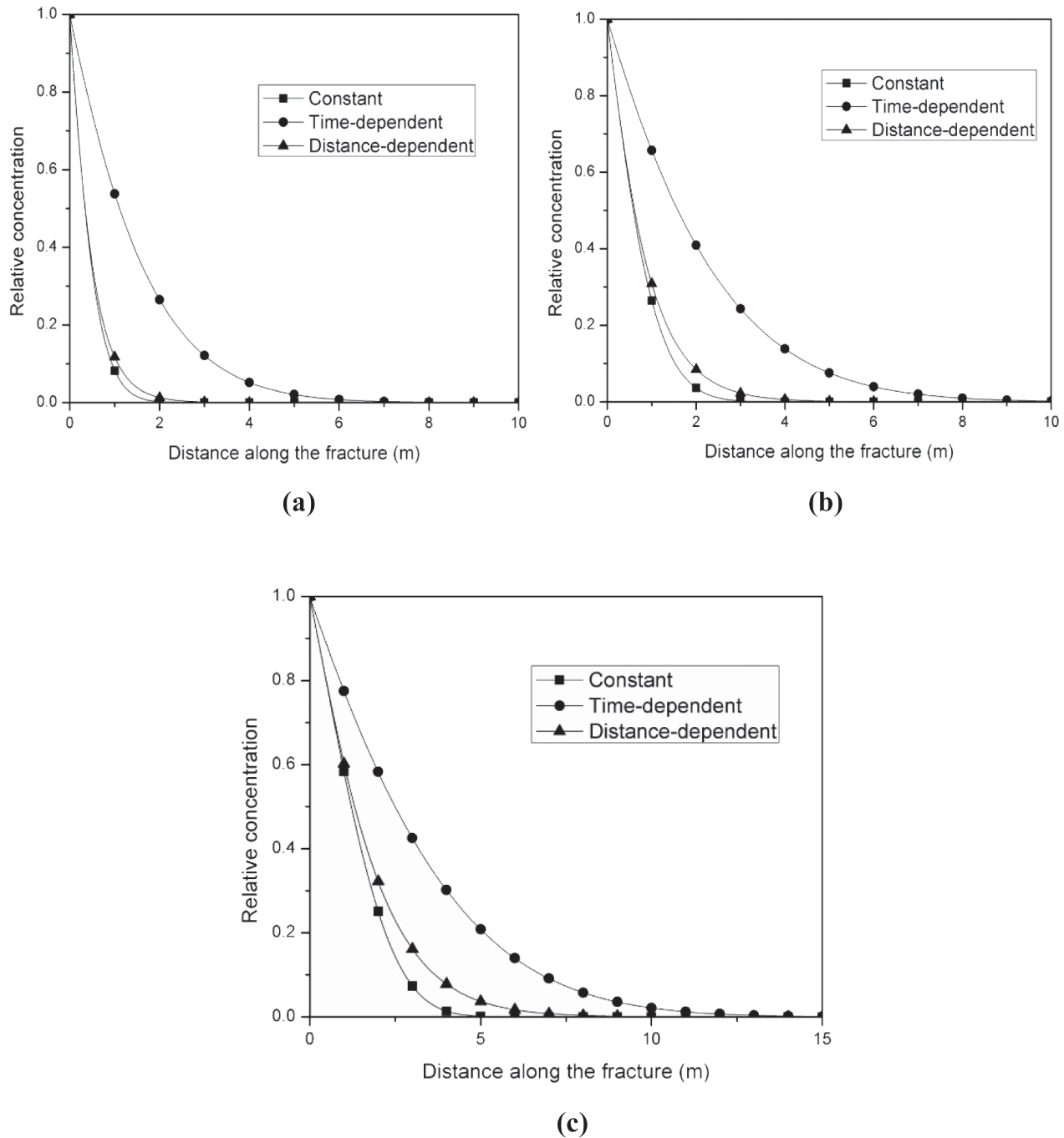
**Figure 2: Validation of the numerical model with analytical solution.**



**Figure 3: Comparison of solute concentration in a coupled fracture-matrix system with and without skin formation for various dispersion coefficients.**

time-dependent) for the coupled fracture-matrix system has been compared with that of the coupled fracture-skin-matrix system. It is observed from the plot that the concentration of the solute retained in the fracture is higher in case of the fracture-matrix system (i.e. in the absence of fracture-skin) irrespective of the type of dispersion coefficient adopted as the fracture-skin enhances the diffusion of solute from the fracture into the rock-matrix. Moreover, the solute mass retained in the fracture is much higher when time-dependent dispersion coefficient is used as compared to other dispersion coefficients. This observation is quite different from that of Sharma et al. (2014) who concluded that distance-dependent and time-dependent dispersion models behave similarly. The solute concentration in the fracture-matrix as well as fracture-skin-matrix system is very much similar when distance-dependent and constant dispersion coefficients are used.

Figure 4 shows the comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for different half fracture apertures of 100  $\mu$ m, 200  $\mu$ m and 500  $\mu$ m. It is observed from the plot that the dispersion coefficient is independent of the size of the half fracture aperture. Furthermore, the mass of solute retained in the fracture increases in increment in the half fracture aperture (Figure 4c). This is because the coupling between the fracture and the fracture-skin becomes weaker as the half fracture aperture size increases and thus the concentration of the solute is high for large fracture apertures. The concentration profiles for constant and distance-dependent dispersion coefficients are very



**Figure 4: Comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for half fracture aperture of (a) 100  $\mu\text{m}$ , (b) 200  $\mu\text{m}$  and (c) 500  $\mu\text{m}$ .**

much similar for half fracture apertures of 100  $\mu\text{m}$  and 200  $\mu\text{m}$  (Figures 4a and 4b). For half fracture aperture of 500  $\mu\text{m}$ , the concentration profiles obtained for constant and distance-dependent dispersion coefficients vary marginally. It can also be observed from the plots that the rate at which solute mass decreases in the fracture for various dispersion coefficients is different. The same

phenomenon is observed irrespective of the size of the half fracture aperture.

Figure 5 shows the comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for different fluid velocities of 1 m/d, 2 m/d and 5 m/d. When fluid velocity is 1 m/d (Figure 5a), the solute concentration reaches zero



at 2 m from the inlet of the fracture for constant and distance-dependent dispersion coefficients. The solute concentration reaches zero only at 6 m from the inlet for time-dependent dispersion coefficient. When fluid velocity is 5 m/d (Figure 5b), the solute concentration reaches zero at 10 m from the inlet of the fracture for constant and distance-dependent dispersion coefficients but the concentration becomes zero at 30 m from the inlet for time-dependent dispersion coefficient. Similarly, when the fluid velocity is very high (i.e. 10 m/d, Figure 5c), the solute travels a longer distance

(55 m) before reaching zero concentration when time-dependent dispersion coefficient is used. The reason for such behaviour is that the mechanical dispersion increases significantly for high fluid velocities, which in turn causes the hydrodynamic dispersion to increase, resulting in higher concentration in the fracture. Furthermore, when time-dependent dispersion coefficient is considered, the mass of solute retained in the fracture for high fluid velocities is much higher when compared to the mass retained for other dispersion coefficients.

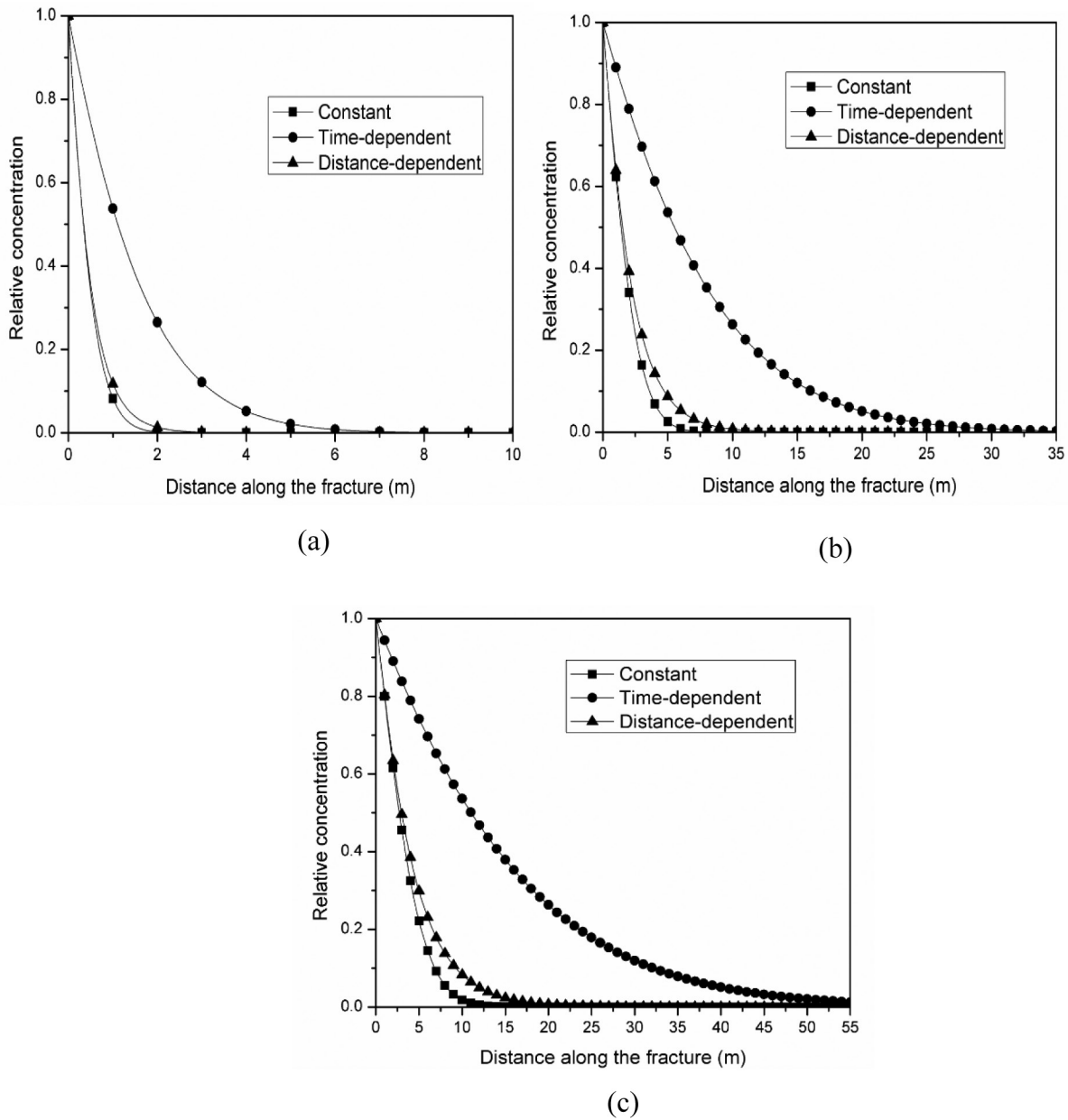


Figure 5: Comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for fluid velocities of (a) 1 m/d, (b) 5 m/d and (c) 10 m/d.

Figure 6 shows the comparison of the solute concentration obtained with different dispersion coefficients for various fracture-skin porosities. It is observed from the plot that the mass retained in the fracture is high when the porosity of the fracture-skin is low (Figure 6a). On the other hand, the mass retained in the fracture decreases with increment in the fracture-skin porosity (Figures 6b and 6c), as the high porosity of the fracture-skin facilitates the transfer of solutes from the fracture into the fracture-skin. When constant dispersion coefficient is considered, the reduction in the solute mass with increment in fracture-skin porosity is gradual but for distance and time-dependent dispersion

coefficients, the reduction in the solute mass is rapid. Another interesting observation is that when the fracture skin porosity is very low (i.e. 0.005), the porous medium surrounding the fracture becomes practically insignificant and the fracture plays a major role. This is the reason why in Figure 6(a), the concentration profile for constant dispersion coefficient has an advective part in addition to the dispersive component, while for distance-dependent and time-dependent cases, an exponentially decaying curve is observed.

Figure 7 shows the comparison of the solute concentration obtained with different dispersion coefficients for various fracture-skin diffusion

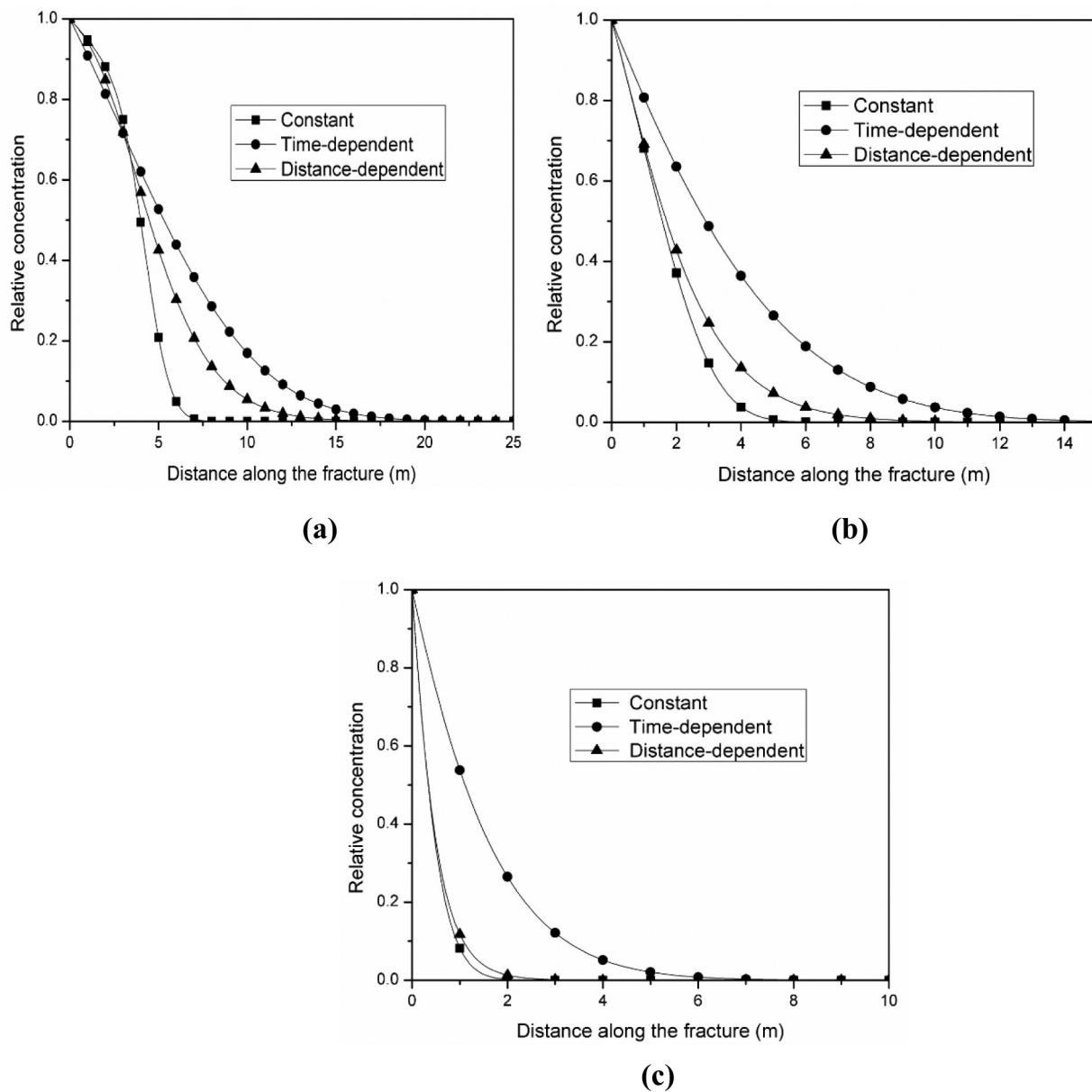
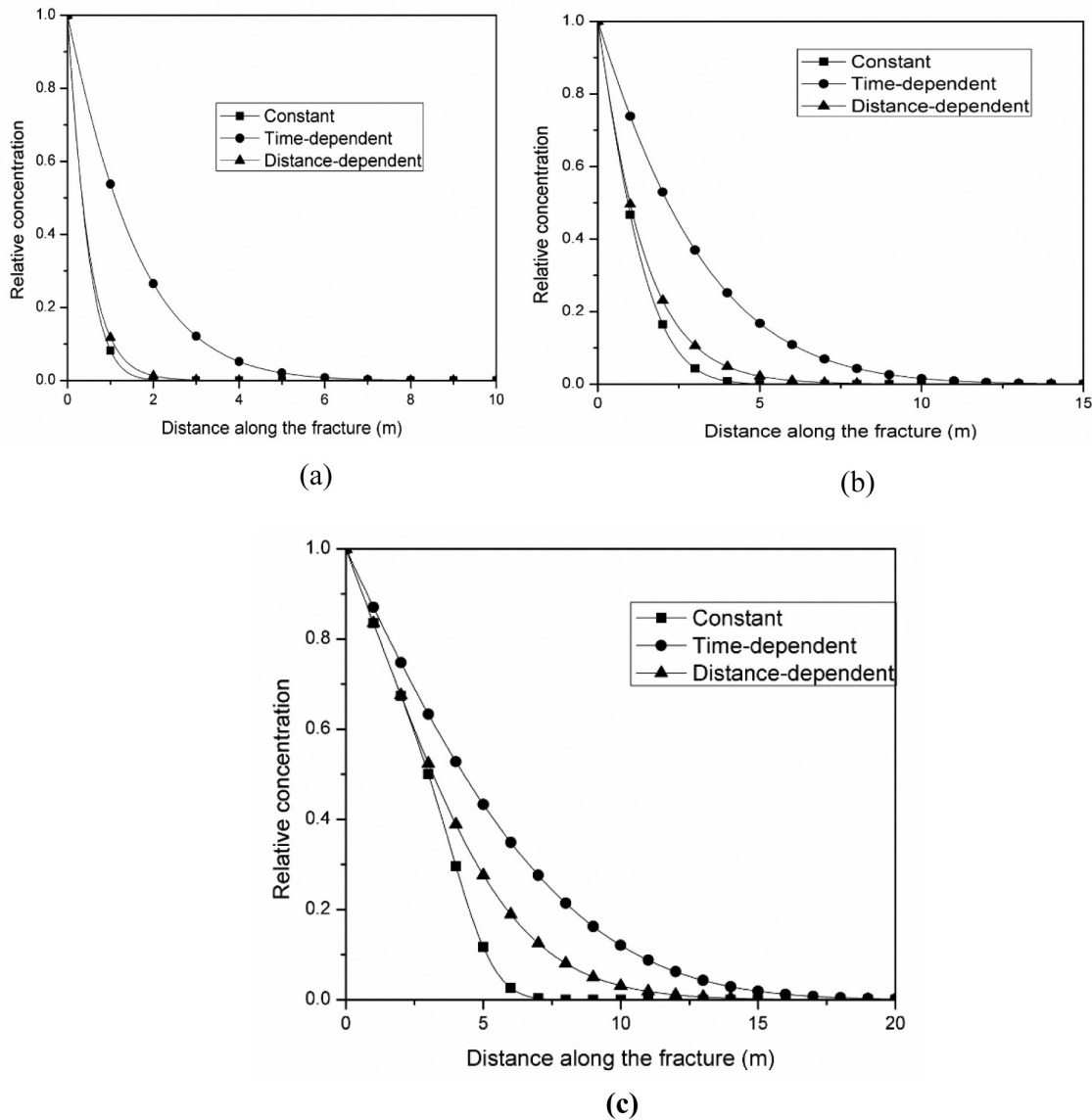


Figure 6: Comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for fracture-skin porosities of (a) 0.005, (b) 0.01 and (c) 0.035.

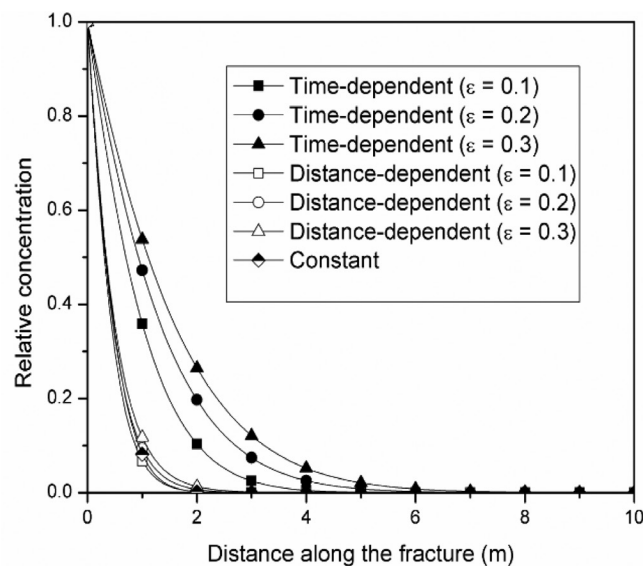
coefficients. It is observed from the plot that the mass retained in the fracture is high when the fracture-skin diffusion coefficient is low (Figure 7c). On the other hand, the mass retained in the fracture decreases with increment in the fracture-skin diffusion coefficient (Figures 7a and 7b), as the high fracture-skin diffusion coefficient facilitates the mass transfer of solutes. From plots 7a and 7b, it can be observed that concentration profile is very much similar for constant and distance-dependent dispersion coefficients for high fracture-skin diffusion coefficients such as  $1e-06$  m/d and  $1e-07$  m/d. On the other hand, for low skin diffusion coefficient, both of them behave differently as the solute mass retained is different (Figure 7c).

Figure 8 shows the concentration profile obtained by using constant, distance-dependent and time-dependent dispersion coefficients with various dispersivity-ratios for a half fracture aperture of  $100\text{ }\mu\text{m}$ . As observed earlier, in this plot also, the concentration profile obtained for constant and distance-dependent dispersion coefficient merge with each other. The variation in the dispersivity-distance ratios has very insignificant effect on the solute transport migration when distance-dependent dispersion coefficient is used. On the other hand, when time-dependent dispersion coefficient is used, the solute mass retained in the fracture is more for dispersivity-distance ratio of 0.3.



**Figure 7: Comparison of solute concentration in the fracture-skin-matrix system with different dispersion coefficients for fracture-skin diffusion coefficients of (a)  $1e-6$  m/d, (b)  $1e-07$  m/d and (c)  $1e-08$  m/d.**





**Figure 8: Comparison of concentration profiles for constant, distance-dependent and time-dependent dispersion coefficients with various dispersivity-distance ratios.**

## Conclusion

The effect of distance-dependent and time-dependent dispersion coefficients on the solute migration in a coupled fracture-matrix system with skin formation has been analysed in this study. The implicit finite difference technique was adopted for solving the coupled non-linear equations. A constant continuous source was assumed at the inlet of the fracture. The influence of distance-dependent and time-dependent dispersion coefficients on the solute movement was analyzed for different fluid velocities, half-fracture apertures, fracture-skin porosities, and fracture-skin diffusion coefficients. The effect of different dispersivity-distance ratios on the solute migration was also analysed for the base case parameters (Table 1). The conclusions for this study based on the above analysis are as follows:

1. The behaviour of the solute migration in the fracture-matrix system with skin is quite different from the fracture-matrix system for different dispersion coefficients.
2. The solute mass retained in the fracture is higher when time-dependent dispersion coefficient is used, when compared to constant and distance-dependent dispersion coefficients.
3. Irrespective of the size of the fracture aperture, the rate at which the solute mass decreases in

the fracture is different for the various dispersion coefficients.

4. When time-dependent dispersion coefficient is considered, the mass of solute retained in the fracture for high fluid velocities is much higher when compared to the mass retained for other dispersion coefficients.
5. When constant dispersion coefficient is considered, the reduction in the solute mass with increment in fracture-skin porosity is gradual but for distance and time-dependent dispersion coefficients, the reduction in the solute mass is rapid.
6. The mass retained in the fracture is significant for low fracture-skin diffusion coefficients when time-dependent dispersion coefficient is considered.
7. The solute mass retained in the fracture increases with increase in dispersivity-distance ratio in the case of time-dependent dispersion coefficients but the variation of the same has insignificant impact when constant and distance-dependent dispersion coefficients are used.

## References

- Driese, S.G., McKay, L.D. and C.P. Penfield (2001). Lithologic and pedogenic influences on porosity distribution and groundwater flow in fractured sedimentary saporolite: A new application of environmental sedimentology. *Journal of Sediment Research*, **71**(5): 843-857.
- Freeze, R.A. and J.A. Cherry (1979). *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.
- Fu, L., Milliken, K.L. and M. Sharp Jr. (1994). Porosity and permeability variations in fractured and liesegang-banded Breathirr sandstones (middle Pennsylvanian), eastern Kentucky: Diagenetic controls and implications for modeling dual-porosity systems. *J Hydrology*, **154**(1): 351-381.
- Gao, G., Zhan, H., Feng, S., Fu, B., Ma, Y. and G. Huang (2010). A new mobile-immobile model for reactive solute transport with scale-dependent dispersion. *Water Resour Res.*, **46**(8): 1-16.
- Grisak, G.E. and J.F. Pickens (1980). Solute transport through fractured media: 1. The effect of matrix diffusion. *Water Resour Res.*, **16**(4): 719-730.
- Kreisel, I. and M. Sharp Jr. (1996). Fracture skins in the brushy canyon formation. In: *The Brushy Canyon Play in Outcrop and Subsurface: Concepts and Examples*. DeMis, W.D. and Cole, A.G. (Eds), PBS-SEPM No. 96-38, Midland, Texas, 147-152.
- Landrum, M.T. (2000). Hydrogeologic properties of fracture skins and their effects on radionuclide transport. MSc Thesis: The University of Texas at Austin, Texas, USA.

- Maloszewski, P. and A. Zuber (1990). Mathematical modeling of tracer behavior in short-term experiments in fissured rocks. *Water Resour Res.*, **26(7)**: 1517-1528.
- Moench, A.F. (1995). Convergent radial dispersion in a double-porosity aquifer with fracture skin: Analytical solution and application to a field experiment in fractured chalk. *Water Resour Res.*, **31(8)**: 1823-1835.
- Moench, A.F. (1984). Double-porosity models for a fissured groundwater reservoir with fracture skin. *Water Resour Res.*, **20(7)**: 831-846.
- Moreno, L. and A. Rasmuson (2010). Contaminant transport through a fractured porous rock: Impact of the inlet boundary condition on the concentration profile in the rock matrix. *Water Resour Res.*, **22(12)**: 1728-1730.
- Nair, V.V. and S.G. Thampi (2011). A triple continuum one-dimensional transport model for colloid facilitated contaminant migration in sets of parallel fractures with fracture skin. *Colloids Surf A: Physio Eng Asp.*, **373(1-3)**: 74-81.
- Nair, V.V. and S.G. Thampi (2012). A triple continuum transport model for colloid migration in fractured formations. *KSCE J Civil Eng*, **16(3)**: 293-297.
- Nair, V.V. and S.G. Thampi (2010). Numerical modeling of colloid transport in sets of parallel fractures with fracture skin. *Colloids Surf A: Physio Eng Asp.*, **364(103)**: 109-115.
- Natarajan, N. and G. Suresh Kumar (2010). Radionuclide and colloid co-transport in a coupled fracture-skin-matrix system. *Colloids Surfaces A: Physio Eng Asp.*, **370**: 49-57.
- Natarajan, N. and G. Suresh Kumar (2011a). Numerical modeling of bacterial facilitated contaminant transport in fractured porous media. *Colloids and Surfaces A: Physico Eng Asp.*, **387**: 104-112.
- Natarajan, N. and G. Suresh Kumar (2011b). Effect of fluid velocity on matrix diffusion in a coupled fracture-matrix system. *Int J Eng Simulation*, **11(3)**: 9-17.
- Natarajan, N. and G. Suresh Kumar (2011c). Spatial moment analysis of colloid facilitated radionuclide transport in a coupled fracture-matrix system. *Int J Energy Environ*, **2(2)**: 491-504.
- Natarajan, N. and G. Suresh Kumar (2012a). Effect of non-linear sorption on multi-species solute transport in a coupled fracture matrix system. *Int J Res Chem Environ*, **2(2)**: 96-101.
- Natarajan, N. and G. Suresh Kumar (2012b). Evolution of fracture permeability due to co-colloidal bacterial transport in a coupled fracture-skin-matrix system. *Geoscience Frontiers*, **3(4)**: 503-514.
- Natarajan, N. and G. Suresh Kumar (2012c). Aperture variation and pressure change due to thermal stress and silica precipitation/dissolution accompanied by colloidal transport in a coupled fracture-skin-matrix system. *Int J Energy Environ*, **6(1)**: 1-15.
- Natarajan, N. and G. Suresh Kumar (2012d). Effect of fracture-skin on virus transport in fractured porous media. *Geoscience Frontiers*, **3(6)**: 893-900.
- Natarajan, N. and G. Suresh Kumar (2014). Effect of fracture skin formation in clay fractured porous media. *ISH J Hydraul Eng.*, **20(3)**: 2663-2673.
- Natarajan, N. and G. Suresh Kumar (2015). Numerical modelling and spatial moment analysis of solute transport with Langmuir sorption in a fracture matrix-coupled system. *ISH J Hydraul Eng*, **21(1)**: 28-41.
- Natarajan, N. and G. Suresh Kumar (2016a). Effect of Sips adsorption isotherm on contaminant transport mechanism in fractured porous media. *KSCE J Civil Eng*, **20**: 1714-1720.
- Natarajan, N. and G. Suresh Kumar (2016b). Spatial moment analysis of solute transport with Langmuir sorption in a fracture-skin-matrix coupled system. *J King Saud Univ: Eng Sci*, **28(2)**: 157-164.
- Natarajan, N. (2014). Effect of time varying fracture-skin on contaminant transport in a coupled fracture-matrix system. *KSCE J Civil Eng*, **18(1)**: 124-131.
- Pang, L. and B. Hunt (2001). Solutions and verification of a scale-dependent dispersion model. *J Conta Hydrol*, **53**: 21-39.
- Phyu, T. (2002). Transient modeling of contaminant transport in dual porosity media with fracture skins. MSc Thesis. The University of Texas at Austin, Texas, USA.
- Robinson, N.I. and M. Sharp Jr. (1997). Analytical solution for contaminant transport in a finite set of parallel fractures with matrix diffusion. C.S.I.R.O. Math Info Sci CMIS-C23.
- Robinson, N.I., Sharp Jr., J.M. and I. Kriesel (1998). Contaminant transport in a set of parallel fractures with fracture skin. *J Conta Hydrol*, **31(1-2)**: 83-109.
- Sekhar, M., Suresh Kumar, G. and D. Misra (2006). Numerical modeling and analysis of solute velocity and macrodispersion for linearly and nonlinearly sorbing solutes in a single fracture with matrix diffusion. *J Hydrol Eng*, **11(4)**: 319-328.
- Sharma, P.K. and R. Srivastava (2012). Concentration profiles and spatial moments for reactive transport through porous media. *J Haz Toxic Radio Waste*, **16(2)**: 125-133.
- Sharma, P.K., Ojha, C.S.P. and N. Joshi (2014). Finite volume model for reactive transport in fractured porous media with distance and time dependent dispersion. *Hydrol Sci J*, **59(8)**: 1582-1592.
- Sharma, P.K., Sekhar, M., Srivastava, R. and C.S.P. Ojha (2012). Temporal moments for reactive transport through fractured impermeable/permeable formations. *J Hydraul Eng*, **17(12)**: 1302-1314.
- Sharp, J.M. (1993). Fractured aquifers/reservoirs: Approaches, problems, and opportunities, Hydrogeology of Hard Rocks. Memoires of the 24th Cong. Int Assoc. Hydrogeol. Banks, D. and Banks, S. (Eds). Oslo, Norway, **24(1)**: 23-38.
- Sharp Jr., J.M., Robinson, N.I., Smyth-Boulton, R.C. and K.L. Milliken (1995). Fracture skin effects in groundwater transport. Mech Joint Fault Rock. Rossmanith, H.P. (Ed.). Rotterdam, 449-454.

- Srivastava, R., Sharma, P.K. and M.L. Brusseau (2002). Spatial moments for reactive transport in heterogeneous porous media. *J Hydraul Eng*, **7(4)**: 336-341.
- Suresh Kumar, G. (2008). Effect of sorption intensities on dispersivity and macrodispersion coefficient in a single fracture with matrix diffusion. *J Hydrol Eng*, **16(2)**: 235-249.
- Suresh Kumar, G., Renu, V. and N. Natarajan (2011). Numerical modeling and spatial moment analysis on the sensitivity of decay mechanism under simultaneous matrix diffusion and non-linear sorption in a coupled fracture-matrix system. *Int J Environ Eng Sci*, **2(2)**: 213-224.
- Suresh Kumar, G., Sekhar, M. and D. Misra (2008). Time-dependent dispersivity of linearly sorbing solutes in a single fracture with matrix diffusion. *J Hydrol Eng*, **13(4)**: 250-257.
- Tang, D.H., Frind, E.O. and E.A. Sudicky (1981). Contaminant transport in a fractured porous media: Analytical solution for a single fracture. *Water Resour Res*, **17(3)**: 555-564.
- Wallach, R. and J.-Y. Parlange (1998). Modeling transport in a single crack by the dual-porosity concept with a boundary layer at the interface. *J Contam Hydrol*, **34(1-2)**: 121-138.
- Yates, S.R. (1990). An analytical solution for one-dimensional transport in heterogeneous porous media. *Water Resour Res*, **26(10)**: 2331-2338.
- Zhou, L. and H.M. Selim (2003). Scale-dependent dispersion in soils: An overview. *Adv Agro*, **80**: 223-263.
- Zimmerman, M.D., Bennett, P.C., Sharp Jr., J.M. and W.J. Choi (2002). Experimental determination of sorption in fractured flow systems. *J Contam Hydrol*, **58(1-2)**: 1-77.

# CAPITAL PUBLISHING COMPANY

## Recent and Forthcoming Publications on Climate Change and Environmental Sciences

Mohanty	Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Predictions
Rakhecha	Applied Hydrometeorology
Sundaresan	Climate Change and Island and Coastal Vulnerability
Subramanian	Coastal Environments — Focus on Asian Regions
Nagarajan	Drought Assessment
Ramachandra	Environmental Education for Ecosystem Conservation
Ghosh	Environmental Geology: Geo-Ecosystem Protection in Mining Areas
Ramesh	Fresh Water Management
Naqvi	Geology and Evolution of the Indian Plate (From Hadean to Holocene - 4 GA to 4 KA)
Sharma	Geology of Andaman - Nicobar: The Neogene
Basavaiah	Geomagnetism: Solid Earth and Upper Atmosphere Perspectives
Thakur	Geospatial Techniques for Managing Environmental Resources
Tiwari	Geospectroscopy
Raju	Geostatistical and Geospatial Approaches for the Characterization of Natural Resources in the Environment: Challenges, Processes and Strategies
Mitra	Global Environmental Changes in South Asia: A Regional Perspective
Varma	Green Energy: Biomass Processing and Technology
Thangarajan	Groundwater Flow and Mass Transport Modeling
Ghosh	Groundwater Governance
Ghosh	Groundwater Modelling and Management
Thangarajan	Groundwater: Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management
Ray	High Impact Weather Events over the SAARC Region
Machiwal	Hydrologic Time Series: Theory and Practice
Beheim	Integrated Watershed Management
Chatterjee	Macro-Economics of Mineral and Water Resources—Important Issues
Ramanathan	Management and Sustainable Development of Coastal Zone Environments
Krecek	Management of Mountain Watersheds
Raju	Management of Natural Resources in a Changing Environment
Raju	Management of Water, Energy and Bio-Resources in the Era of Climate Change: Emerging Issues and Challenges
Kayal	Microearthquake Seismology and Seismotectonics of India
Talapatra	Modelling and Geochemical Exploration of Mineral Deposits
Murthy	Modelling and Monitoring of Coastal Marine Processes
Mohanty	Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change
Jha	Natural and Anthropogenic Disasters: Vulnerability, Preparedness and Mitigation
Nagarajan	Natural and Mad-made Disasters: Assessment and Management
Subramanian	Rivers of South Asia
Ramanathan	Safe and Sustainable Use of Arsenic Contaminated Aquifers in the Gangetic Plain: A Multi-Disciplinary Approach
Datta	Theory and Principles of Simulation Modelling in Soil-Plant System
Kurisu	Trends in Asian Water Environmental Science and Technology
Mohapatra	Tropical Cyclone Activity over the North Indian Ocean
Nagarajan	Water: Conservation, Use and Management for Semi-arid Regions

For more detailed information on individual titles, please log on to our website [www.capital-publishing.com](http://www.capital-publishing.com)