Simulation of Stream Pollutant Transport with Hyporheic Exchange for Water Resources Management

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1. Introduction

Stream channel irregularities, meandering and hyporheic zones, is commonly seen in many riparian streams. These irregular channel geometries often influence the pollutant transport. The stagnation or dead zones are the pockets of stagnant water or water having very low velocities, which trap pollutants and release them at later time to mainstream flow at a rate that depends upon the concentration gradient of the pollutants between the two domains. The stagnation zones are formed near the concave banks of the stream and behind the irregular sand dunes formed on the bed of the stream. The stagnation zones may also be formed due to irregular stream boundaries and also due to localized channel expansions (Bencala & Walters, 1983). The hyporheic zone is a transition zone between terrestrial and aquatic ecosystems and is regarded as an ecologically important ecotone (Boulton et al., 1998; Edwards, 1998). The term hyporheic is derived from Greek language – hypo, meaning under or beneath, and rheos, meaning a stream (Smith, 2005). A number of definitions for the hyporheic zone exist (Triska et al., 1989; Valett et al., 1997; White, 1993), however, the most common connotations are: it is the zone below and adjacent to a streambed in which water from the open channel gets exchanged with interstitial water in the bed sediments; it is the zone around a stream in which fauna characteristic of the hyporheic zones are distributed and live; it is the zone in which groundwater and surface water mix (Smith, 2005). The physical process, of hyporheic exchanges, as described by many investigators (Stanford and Ward, 1988; Stanford and Ward, 1993; Triska et al., 1989; Valett et al., 1997; Brunke and Gonser, 1997, White, 1993) suggest that significant amounts of water are exchanged between the channel and saturated sediments surrounding the channel. Such exchanges have the potential to cause large changes in stream water chemistry and retard the transport of pollutants. The rates of biogeochemical processes and the types of processes governed by flow hydraulics may be fundamentally different. When the groundwater component is negligible, this is possible if there is a fine silt or clay formation underneath the hyporheic zone, the exchanges between the mainstream flow and the hyporheic zone for such condition shall be similar to the stagnation or dead zone processes, i.e., the stream water that enters the subsurface eventually re-enters the stream at some point downstream. The pollutant transport processes for such circumstances can be regarded as hyporheic exchange. Fig. 1 represents a stream with hyporheic zone.
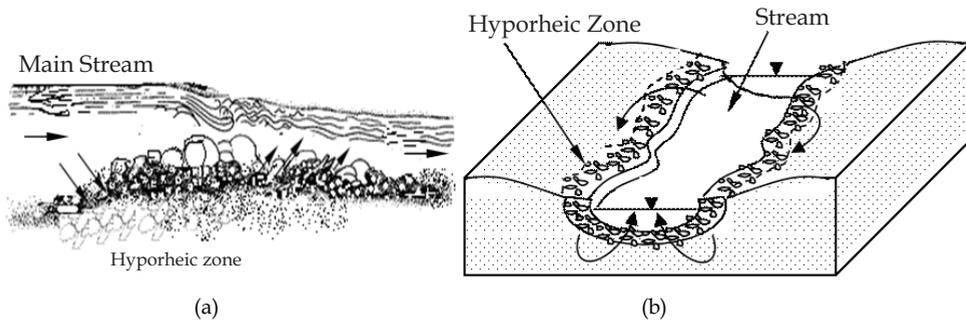
Fig. 1. Representations of a stream with underlying hyporheic zone

In the hyporheic zone, a fraction of stream water containing pollutants is temporarily detained in small eddies and stagnant water that are stationary relative to the faster moving water near the center of the stream. In addition, significant portions of flow may move through the coarse gravel of the streambed and porous areas within the stream banks (Runkel, 2000). The pollutants detained in the hyporheic zone as buffer is released back slowly to the mainstream when the concentration gradient reverses. The travel time for pollutants carried through these porous areas may be substantially longer than that for pollutants travelling within the water column. Streams with intact hyporheic zone provide more temporary storage space and residence time for water with pollutant than streams without them (Bencala & Walters, 1983, Berndtsson, 1990; Castro & Hornberger, 1991; Harvey et al., 1996; Runkel et al., 1996). The hyporheic exchange thus retards the transport of pollutants. The rate of exchange of pollutants between two domains may vary from constituent to constituent. The phenomena, that trap pollutants from the mainstream and hold into the buffer at the beginning and release them back to the mainstream water at later time, shall generate C-t profile representing characteristics of delayed transport, shifted time to peak, reduced peak concentration and also a long tail. To simulate the temporal variations of pollutant concentrations, a hybrid model which appends the retardation component with advection-dispersion pollutant transport has been conceptualized in this study. In this study, the hybrid model has been formulated for both equilibrium and non-equilibrium exchange of pollutant mass between main stream and underlying soil media. Efficacy of model was tested with the results of well known Advection Dispersion Equation and with field data collected from River Brahmani, India.

2. Formulation of the model considering equilibrium mass exchange

Let us consider a straight stream reach of length, Δx, having irregular porous geomorphology. This irregular porous geomorphology is comprised of uniform formations of stagnation or dead or hyporheic zones along streambed and banks. These zones represent the hyporheic exchange, and are hydraulically connected with the mainstream flow. Further, there are exchanges of pollutants with the flow through the interface between the mainstream flow and the hyporheic zones. The stream reach has a steady flow rate, Q and initial concentration of pollutants C_i both in the mainstream as well as in the hyporheic zone. Let a steady state concentration of pollutant, C_R, be applied at the inlet boundary of the stream at a time, t_0. It is assumed that the river reach be composed of series of equal size hybrid units. It is required to derive the model that can simulate the

response of injected pollutant concentration, C_R at the exit of Δx of the mainstream due to the affects of the hyporheic exchange using a hybrid model. The hybrid model has three compartments all connected in series; first compartment represents the plug flow cell of residence time, α; whereas second and third compartment, represent respectively two well mixed cells of unequal residence times, T_1 and T_2. The hybrid model simulates advection-dispersion transport of pollutant in regular channel for steady and uniform flow conditions when the size of the basic process unit, Δx, is equal to or more than $4\ D_L\ /\ u$ (Ghosh et al., 2008) where u…mean flow velocity in m/s, and D_L…longitudinal dispersion coefficient in m^2/s.
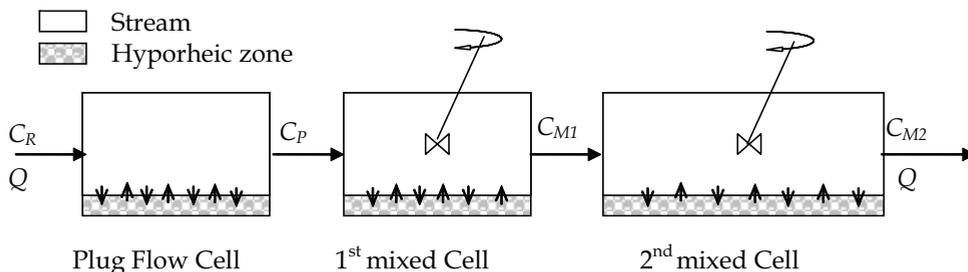

Fig. 2. Conceptual hybrid model with hyporheic zone

The arrangement of the conceptualized hybrid model and the hyporheic zone has been shown schematically in Fig. 2. It is assumed that the hyporheic zones along streambed and banks below and around the plug flow cell and two well mixed cells are in equal proportion to their ratios of: cross-sectional areas, volumes of water and also mass of solute exchanges between the hyporheic zones and the mainstream water. Let V_0, V_1, and V_2 be the volumes of the plug flow cell, and two well mixed cells in the mainstream, respectively. For stream flow Q, the residence time of pollutant in the plug flow and two well mixed cells of the main stream are $\alpha = V_0\ /\ Q$, $T_1 = V_1\ /\ Q$ and $T_2 = V_2\ /\ Q$ respectively.

Let V_0^*, V_1^*, and V_2^* be the volumes of the hyporheic zones below the plug flow and two well mixed cells of the mainstream water columns respectively. These volumes can be given by, $V_0^* = (\phi\ A_P\ D)$, $V_1^* = (\phi\ A_{M1}\ D)$ and $V_2^* = (\phi\ A_{M2}\ D)$; where A_P, A_{M1}, and A_{M2}…the interface areas (in m^2) of the hyporheic zone and the mainstream flow respectively for the plug flow and the two well mixed cells, D is the depth (in m) of the hyporheic zone below and around the mainstream, and ϕ is the porosity of the bed materials. When this zone represents a dead or stagnant pocket with only storage of water, $\phi = 1$, and if there is no soil pores and no water storage, $\phi = 0$. If the hyporheic zone is extended all along the wetted surfaces, the A_P, A_{M1}, and A_{M2}, in such cases, are represented respectively by: $A_P = W_P\ (\alpha\ u)$; $A_{M1} = W_P\ (T_1\ u)$; and $A_{M2} = W_P\ (T_2\ u)$, in which W_P is the wetted perimeter at the interface of the mainstream and the hyporheic zone and u is the mainstream flow velocity. If the ratios of the volume of water in the hyporheic zones to the three volumes in the mainstream are in proportion and constant, the ratios $V_0^*\ /\ V_0 = V_1^*\ /\ V_1 = V_2^*\ /\ V_2$ are also constant and defined as, say F. The total residence time of pollutant in the plug flow cell would thus be: $\left(V_0 + V_0^*\right)/Q = V_0\left(1 + V_0^*/V_0\right)/Q = \alpha(1+F) = \alpha R$, where R…the retardation factor, and F…proportionality constant. Similarly, the total residence times in the two well mixed cells would respectively be: T_1R and T_2R.

It is also assumed that the retardation process of pollutants takes place in all the cells of the hybrid model due to the hyporheic exchange. In natural riparian rivers, the hyporheic exchange is a complex process which may follow non-equilibrium exchange between main stream and underlying stagnation zone. Decay of pollutant will take place both in main stream and stagnation zone, if the pollutant is of non-conservative type. It is worth trying with a conservative pollutant's equilibrium exchange between main stream channel and hyporheic zone. Hence, in this study retardation process is considered to be followed the linear equilibrium condition, which is expressed as:

$$Cs(x, t) = F\ C(x, t) \tag{1}$$

where $Cs(x, t)$…the concentration of pollutant which is trapped in the hyporheic zone in mg/L, F…the proportionality constant and $C(x, t)$…the concentration of pollutant in the main stream in mg/L.

For a steady state flow condition, performing the mass balance in a control volume within plug flow cell of hybrid model, one can get partial differential equation which governs hyporheic exchange coupled pollutant transport as given

$$\frac{\partial C(x,t)}{\partial t} + u \frac{\partial C(x,t)}{\partial x} = -\frac{\phi\,W_P D}{A} \frac{\partial C_s(x,t)}{\partial t} \tag{2}$$

where A…the cross sectional area of any control volume in the plug flow cell of the mainstream water in m^2.

Solving eqns (1) and (2), the concentration of pollutants at the end of the plug flow cell of residence time, α is given by,

$$C(x,t) = C_P(\alpha u, t) = C_R U(t - \alpha\ R) \tag{3}$$

where, $C_P(\alpha u, t)$…concentration of pollutant at the end of plug flow cell in mg/L, U(*)…the unit step function, and t…the time reckoned since injection of pollutants in min.

In the first well mixed cell, pollutants after travelling a distance of 'αu' through the plug flow cell enter and exchange to the adjoining hyporheic zone and release back to the mainstream water, before making an exit from it. The inputs to this cell are thus the outputs from the plug flow cell. The pollutants are thoroughly mixed in this cell.

Performing the mass balance in the first well mixed cell along with the hyporheic zone over a time interval t to t + Δt, one can get governing differential equation as

$$\frac{dC_{M1}}{dt} = \frac{C_R\,U(t - \alpha R)}{T_1} - \frac{C_{M1}}{T_1} - \frac{1}{V_1}\frac{dM_s}{dt} \tag{4}$$

Replacing dMs/dt by derivative of concentration, eqn (4) transforms to:

$$\frac{dC_{M1}}{dt} = \frac{C_R\,U(t - \alpha R)}{T_1} - \frac{C_{M1}}{T_1} - \frac{\phi\,W_P\,D}{A}\frac{dC_s}{dt} \tag{5}$$

Solving eqns (1) and (5), the concentration of pollutants at the end of the first well mixed cell of residence time, T_1 is given by,

$$C_{MI} = C_R\, U\left(t - \alpha R\right)\left[\, 1 - e^{-\frac{(t-\alpha R)}{R\,T_I}}\,\right] \tag{6}$$

Eqn (6) is valid for $t \geq \alpha R$ which gives the time varying concentration of pollutants at the exit of the first well mixed cell coupled with the retardation due to a unit step input, C_R applied at the inlet boundary of the plug flow cell.

The time varying outputs from the first well mixed cell form the inputs to the second well mixed cell. Alike first well mixed cell, pollutant before being exited from the cell exchanges to the adjoining hyporheic zone and release back to the mainstream water. Performing the mass balance over a time interval t to t + Δt, one can get a differential equation similar to the first one except residence time

$$\frac{dC_{M2}}{dt} = \frac{C_R\, U\left(t - \alpha R\right)\left[\, 1 - e^{-\frac{(t-\alpha R)}{R\,T_1}}\,\right]}{T_2} - \frac{C_{M2}}{T_2} - \frac{1}{V_2}\frac{dM_s}{dt} \tag{7}$$

Solving Eqns (1) and (7), the concentration of pollutants at the end of the second well mixed cell of residence time, T_2 is given by,

$$C_{M\,2} = C_R U\left(t - \alpha\, R\right)\left[\, 1 - \frac{T_1}{T_1 - T_2}e^{-\frac{(t-\alpha\, R)}{R\,T_1}} + \frac{T_2}{T_1 - T_2}e^{-\frac{(t-\alpha\, R)}{R\,T_2}}\,\right] \tag{8}$$

If $C_R = 1$, eqn (8) represents the unit step response function. Designating K(t) as the unit step response function, K(t) is given by:

$$K(t) = U(t - \alpha\, R)\left[\, 1 - \frac{T_1}{T_1 - T_2}\, e^{-\frac{(t-\alpha R)}{R\,T_1}} + \frac{T_2}{T_1 - T_2}e^{-\frac{(t-\alpha R)}{R\,T_2}}\,\right] \tag{9}$$

The unit impulse response function, k (t) is the derivative of eqn (9) with respect to 't' which is given by

$$k(t) = \frac{U(t - \alpha\, R)}{R\left(T_1 - T_2\right)}\left[\, e^{-\frac{(t-\alpha R)}{R\,T_1}} - e^{-\frac{(t-\alpha R)}{R\,T_2}}\,\right] \tag{10}$$

Eqns (9) and (10) are valid for $t \geq \alpha R$, and they respectively represent the unit step and the unit impulse response functions of a hybrid unit coupled with the retardation. If R = 1, eqns (9) and (10) respectively represent the unit step and the unit impulse response functions of the Advection-dispersion equation.

Let the stream reach downstream of a point source of pollution be composed of series of equal size hybrid units coupled with the hyporheic zone, each having linear dimension, Δx

and consisting of a plug flow cell, and two unequal well mixed cells. The stream reach has identical features all along downstream; i.e., mainstream flow and hyporheic or dead zones. The exchange of pollutant takes place in all the hybrid units. Assuming that output of pollutant from preceding hybrid unit forms the input to the succeeding hybrid unit, thus the response of the nth hybrid unit, n ≥ 2 for steady flow condition can be obtained using convolution technique, as:

$$C(n\Delta x, t) = \int_0^t C\{(n-1)\Delta x, \tau\} \; k(\alpha, T_1, T_2, R, t-\tau) \, d\tau \tag{11}$$

where $C((n-1)\Delta x, \tau)$…input of nth hybrid unit in mg/L, $k(\alpha, T_1, T_2, R, \tau)$…the unit impulse response (in mg/L. min) as given by eqn (10).

The retardation factor, R can be calculated as given

$$R = \left(1 + \frac{\phi w_p D.F}{A}\right) \tag{12}$$

Eqn (12) is a function of ratio between areas of the hyporheic zone and the mainstream flow, porosity of bed materials. The retardation coefficients have been estimated with different porosity values using eqn (12) by keeping all other parameters constant as shown in Fig. 3.

Knowing parameters α, T_1, and T_2 of the hybrid unit, and using estimated value of the retardation factor, R, one can predict concentration profiles at multiple distance downstream from source at {n Δx}, n = 1,2,3,…. in a stream having steady flow and homogeneous reach conditions making use of eqn (11).
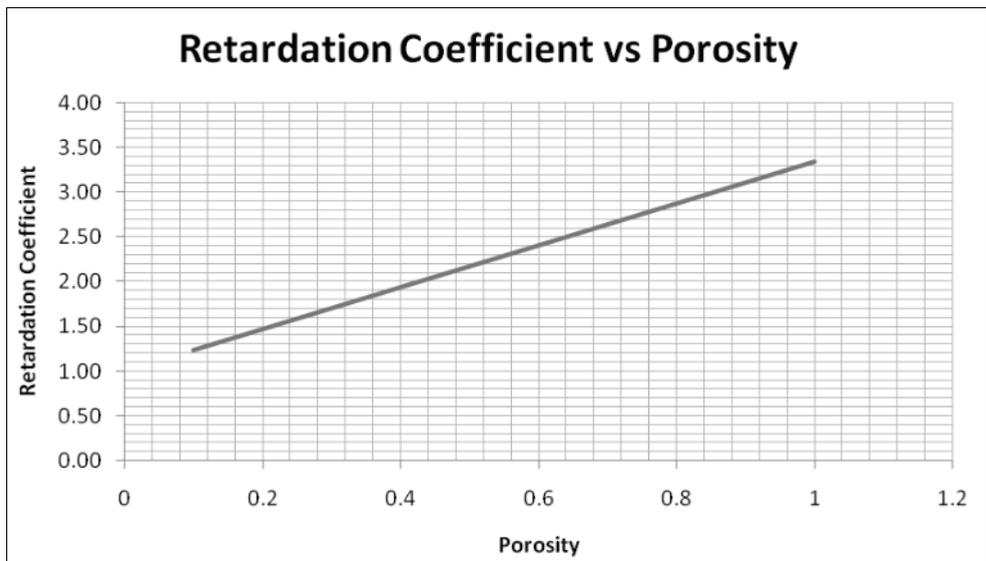

Fig. 3. Variation of retardation factor due to porosity

3. Formulation of the model considering non-equilibrium mass exchange

The pollutant exchange between the main stream and underlying subsoil is non-equilibrium in nature. It can be seen most of the mountainous streams where the water with pollutant re-enters the stream in an slower phase. Simulation of non-equilibrium exchange processes along with advection and dispersion is not a simple case due the complexity of the processes of exchange (Cameron and Klute, 1977). Numerous investigators (Bencala and Walters, 1983; Runkel and Broshears, 1991; Runkel and Chapra, 1993; Czernuszenko and Rowinski, 1997; Runkel, 1998; Worman et al., 2002) have studied exchange of the pollutant between main stream and porous soil media. The concentration-time profile of pollutant transport in such case is influenced significantly by the mass exchange. Cameron and Klute, 1977; Bajracharya and Barry, 1992; 1993; 1995 have illustrated that the pollutant exchange in the form of adsorption processes flatten more the concentration-time profile. Thus an exact pollutant transport simulation is important to correctly ascertain the assimilation capacity of streams. Consider a conceptualized hybrid model which incorporate non-equilibrium exchange of pollutant and which is expressed mathematically as follows

$$\frac{dC_s(x,t)}{dt} = R_D \left[C(x,t) - C_s(x,t) \right] \tag{13}$$

where, R_D…proportionality constant (per min), $C_s(x, t)$…concentration of pollutant adsorbed in mg/L, $C(x, t)$…concentration of pollutant in the water column in mg/L, t…the time in min.

For a steady state flow condition, performing the mass balance in a control volume within plug flow cell of hybrid model, one can get partial differential equation which governs hyporheic exchange coupled pollutant transport which will be same as eq. (2). Then Laplace transform has been used to solve it by combining eq. (13) and effluent concentration from plug flow zone is given by

$$C(x,t) = C_P(\alpha u, t) = C_R \exp(\gamma) \left[U(t-\alpha) + \sqrt{\eta} \int_0^t U(\tau-\alpha) e^{-R_D(\tau-\alpha)} \frac{1}{\sqrt{\tau-\alpha}} I_1 \left(2\sqrt{\eta(\tau-\alpha)} \right) d\tau \right] \tag{14}$$

where $\gamma = -\frac{\phi W_P D_B}{A} \left(e^{R_D x/u} - 1 \right)$; $\eta = \frac{\phi W_P D_B R_D}{A} \left(e^{R_D x/u} - 1 \right)$, $U(t - \alpha)$…step function which is zero for t < α and it is 1 for t ≥ α, so eq. (14) is valid for t ≥ α; α…residence time of plug flow cell, which is x/u. As the eq. (14) is valid for t ≥ α,.it can be considered that the pollutant concentration is zero for t < α

Effluent of plug flow zone enters to the first well mixed cell, where it gets mixed before entering into the second well mixed cell. During these transports through mixed cells too, mass exchange activities follow the non-equilibrium type. Consider a unit step input, C_R and perform the mass balance in the first thoroughly mixed zone which can be expressed as

$$\frac{dC_{M1}}{dt} = \frac{C_R U(t-\alpha)}{T_1} - \frac{C_{M1}}{T_1} - \frac{\phi W_P D}{A} \frac{dC_s}{dt} \tag{15}$$

Eq. (15) can be solved analytically and effluent from the first well mixed cell will enter second well mixed cell. Thus similar mass balance equation can be formulated. Successive convolution numerical integration can be used by combining effluent concentrations of plug flow cell and well mixed cells to get effluent concentration at the end of first hybrid cell as follows

$$K(n\Delta t) = C_2(n\Delta t) = \sum_{\gamma=1}^{n} \{C_1(\gamma\Delta t) - C_1((\gamma-1)\Delta t)\} \, \delta_{M2}\big[(n-\gamma+1), \Delta t\big] \tag{16}$$

where $C_1(n\Delta t) = \sum_{\gamma=1}^{n} \{C_P(\gamma\Delta t) - C_P((\gamma-1)\Delta t)\} \, \delta_{M1}\big[(n-\gamma+1), \Delta t\big]$; δ_{M1} & δ_{M2}…ramp kernel

co-efficients.

Eq. (16) is unit step response [K(.)] of first hybrid unit and one can get unit impulse response [k(.)] by differentiating Eq. (16). The output (Eq. 16) of pollutant from preceding hybrid unit forms the input to the succeeding hybrid unit, thus the response of the nth hybrid unit, $n \geq 2$ for steady flow condition can be obtained using convolution technique which will be similar to eq. (11) and is given by

$$C(n\Delta x, t) = \int_{0}^{t} C\{(n-1)\Delta x, \tau\} \, k(\alpha, T_1, T_2, R_D, t-\tau) \, d\tau \tag{17}$$

where C[(n-1)Δx, t)]…effluent concentration from the preceding unit, k( )…unit impulse response of a single hybrid unit.

4. Simulation of pollutant transport

4.1 Verification of model considering equilibrium exchange using synthetic data

The hybrid model simulates the advection-dispersion governed pollutant transport in a regular channel under uniform flow conditions when the size of the basic process unit, Δx, is equal to or more than 4 D_L/u. This means that the response of the hybrid model corresponding to that Δx for a specific u and D_L, should be identical to that of the response of the Advection Dispersion Equation (ADE) model for that u and D_L at the downstream distance, x = Δx.

Let the parameters,α T_1, and T_2 of the hybrid model for pollutant transport in a stream be known from the ADE model for a given value of u and D_L satisfying Peclet number, Pe ≥ 4. Let the value of the parameters of the mainstream flow in a stream having hyporheic zones along streambed and banks, be: α = 1.70 min, T_1 = 2.0 min and T_2 = 6.30 min corresponding to Δx = 200 m, u = 20 m/min and D_L = 1000 m²/min. The retardation factor, R is assumed to be 1.25. Using the above data, the unit step responses and the unit impulse responses of the hybrid model are generated at the end of the 1st hybrid unit applying eqns (9) and (10), respectively, and they are shown in figs 4 and 5.

In these figures, the C-t profiles generated by the hybrid model corresponding to the same value of α, T_1 and T_2 without the retardation component, i.e., for R = 1, are also shown for

comparison and it can be noted that the C-t profiles represented by the hybrid model with retardation shows the characteristics of delayed pollutant transport as expected. The impulse response, presented in fig. 5, represents the following; the rising limb occurred at a later time with reduction in magnitudes, the time to peak shifted, the peak concentration reduced, and the recession limb extended for a long time to that of the distributions depicted by the hybrid model with retardation.
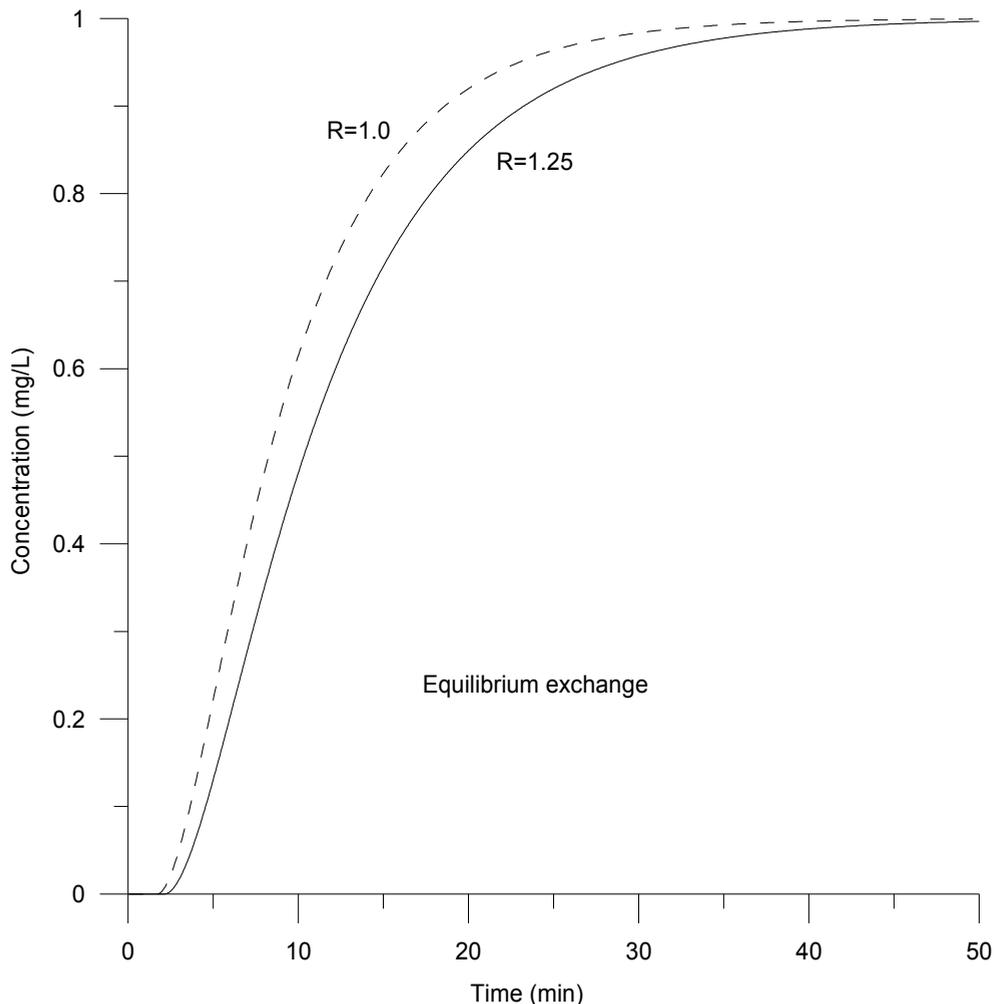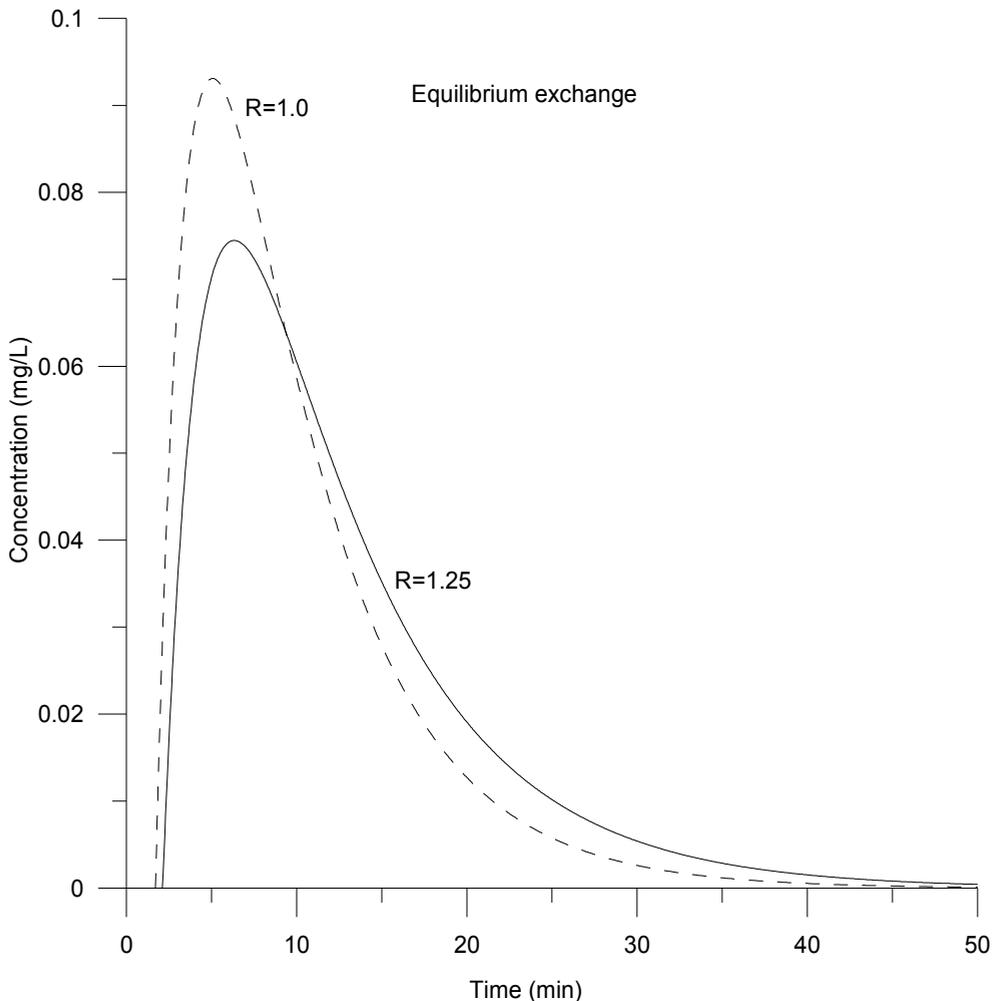

Fig. 4. Unit step responses of the hybrid model at the end of one hybrid unit of size $\Delta x = 200$ m for $\alpha = 1.7$ min, $T_1 = 2.0$ min, $T_2 = 6.3$ min

The above data are adopted again and the C-t profiles of the hybrid model for a unit impulse input have been generated for n = 3, 6, and 11 using eqn (11) and shown in fig. 6 and it can be noted from the figure that as the pollutants move from the near field to the far

field the C-t distributions of the hybrid model get more and more attenuated, elongated and delayed in terms of occurrence of the rising limbs, the times to peak, and the peak concentrations. This means that the total residence time of the hybrid unit is increased by a factor of R for one unit as compared with the hybrid unit without mass exchange. As pollutant move down stream by n units, the residence time increased by a factor of "n times R". These characteristics of the C-t profiles for a steam with retardation component are in the expected lines. This may be due to more permanent loss of pollutant within the hyporheic zone or the water along with pollutant may take very long time to re-enter stream. The model is also capable of simulating non-equilibrium exchange which has been demonstrated in section 4.2 below with synthetic data.

Fig. 5. Unit impulse responses of the hybrid model at the end of one hybrid unit of size $\Delta x = 200$ m for $\alpha = 1.7$ min, $T_1 = 2.0$ min, $T_2 = 6.3$ min
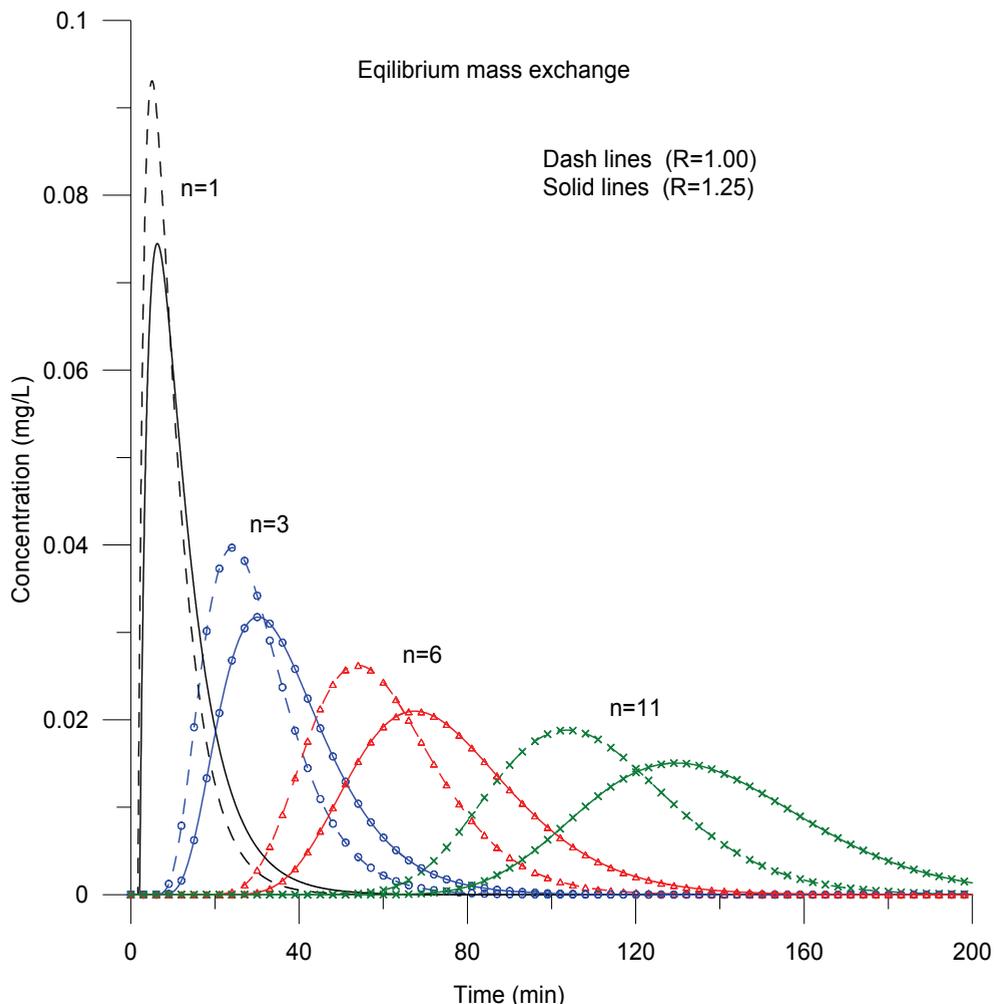
Fig. 6. Unit impulse responses of the hybrid at the end of first (n = 1), third (n = 3), sixth (n = 6) and eleventh (n = 11) hybrid units.

4.2 Verification of model considering non-equilibrium exchange using synthetic data

Let the parameters, α T_1, and T_2 of the hybrid model are being 1.7 min, 2.0 min and 6.3 min respectively. Non-equilibrium mass exchange rate R_D is assumed to be 0.25 per min which is a time reciprocal parameter. The C-t profiles of the hybrid model for a unit impulse input have been generated having parameters (α T_1, T_2 and R_D) for n = 3, 6, and 11 using eq. (17) which is presented in fig. 7. In this study, the synthetic data was used for non-equilibrium exchange because of absence of field data to calculate mass exchange rate (R_D). However, the section 4.3 explains the simulation of pollutant transport with equilibrium exchange using field data collected from a river.
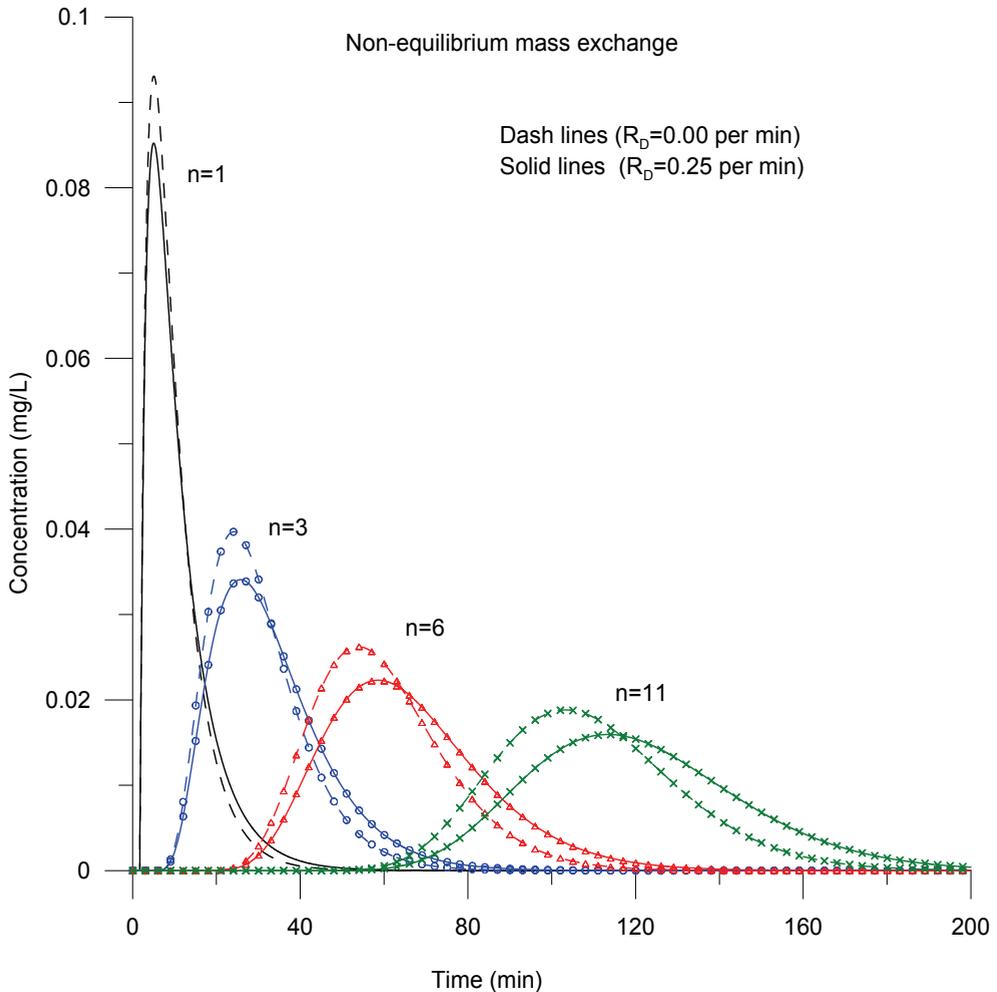
Fig. 7. Unit impulse responses of the hybrid at the end of first (n = 1), third (n = 3), sixth (n = 6) and eleventh (n = 11) hybrid units

4.3 Model verification using field data

In order to verify the performance of the model, field data from the river Brahmani, India has been collected. A river reach from Rengali dam to Talcher is affected seriously by the waste water discharged by river Tikira, tributary of the main river. The Talcher Township is located 26km downstream of Tikira confluence. Fig. 8 shows the study area with locations of sampling points. Data collections from the field have been tabulated in Table 1.

If observed *C-t* profile is available, as an inverse problem model parameters can be estimated using optimization. In absence of observed *C-t* profile, model parameters can be obtained by relating with longitudinal dispersion co-efficient, D_L, satisfying the condition of
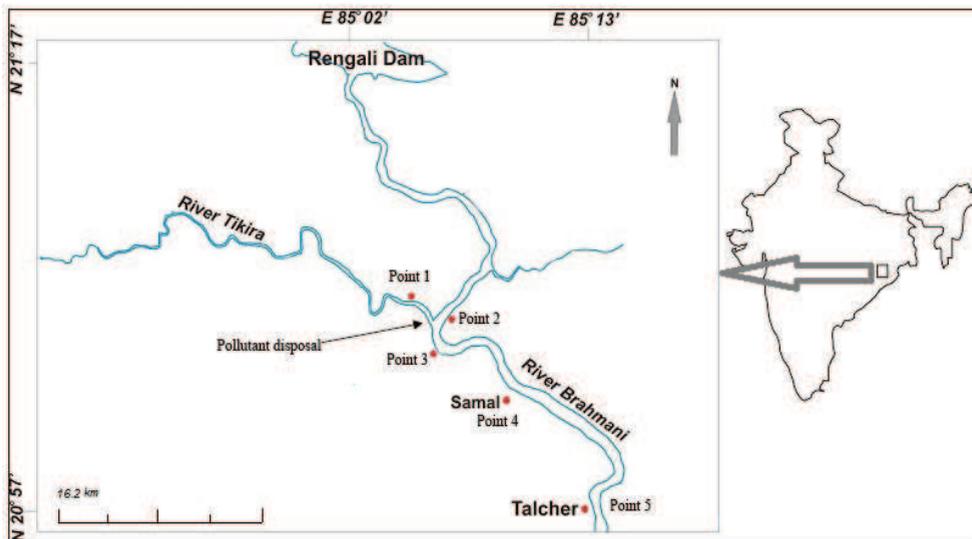
(Adopted from Muthukrishnavellaisamy K, 2007)

Fig. 8. Map showing study river reach and sampling points

Channel geometry, flow characteristics and dispersion co-efficient						
Location	Q (m³/s)	U (m/s)	A (m²)	H (m)	W (m)	D_L (m²/s)
Before Tikira (Point 2)	195.98	0.83	218.12	3.21	67.91	430.74
After Tikira (Point 3)	239.72	0.92	257.99	3.43	75.10	490.05
Talcher	238.62	0.9	257.00	3.42	74.93	488.61
Model parameters having U = 0.91 m/s and D_L = 489.3 m²/s *(these are average values for river reach between Tikira & Talcher)*						
Cell size (Δx), m	P_e		α, min	T_1, min		T_2, min
3200	5.9		15.5	19.4		25.7
Water Quality data						
Location	Measured concentration		Location		Measured concentration	
Point 1 (Q = 13.3 m³/s)	242.3 mg/L		Point 2 (Q = 195.98 m³/s)		25 mg/L	
Point 3	38 mg/ L		Point 4		36 mg/L	
Point 5	32.2 mg/L					

(Source: Muthukrishnavellaisamy K, 2007)

Table 1. Flow and water quality data collected from the river Brahmani

Peclet number, $P_e = \Delta x\, u\, /\, D_L$ which should be greater than or equals to 4 and less than 8 (Ghosh et al., 2004; Muthukrishnavellaisamy K, 2007; Ghosh et al., 2008) as follows:

$$\alpha = \frac{0.04\,\Delta x^2}{D_L} \tag{18}$$

$$T_1 = \frac{0.05\,\Delta x^2}{D_L} \tag{19}$$

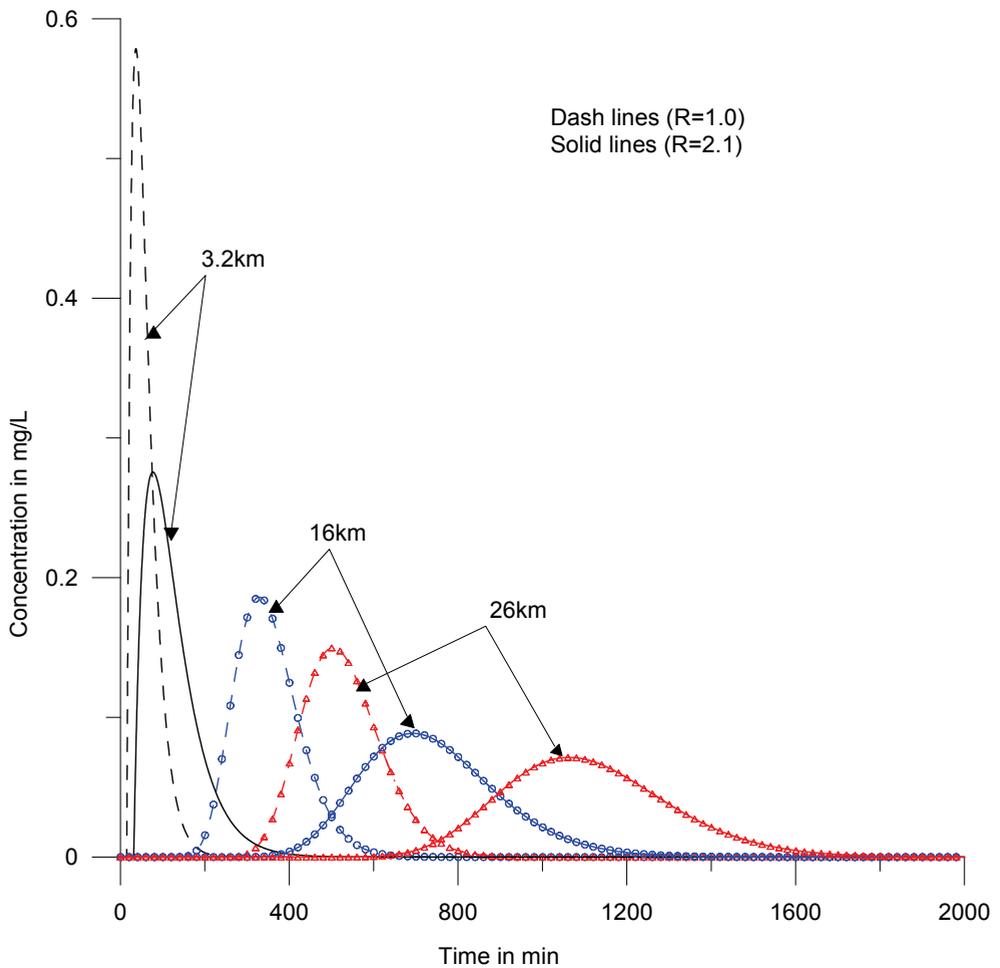$$T_2 = \frac{\Delta x}{u} - \frac{0.09\,\Delta x^2}{D_L} \tag{20}$$

Fig. 9. Pulse responses of the hybrid at the end of 3.2 km, 16 km and 26 km for the data collected from river Brahmani

One can choose any peclet number between 4 and 8 in order to match the response of hybrid model with the ADE model. Having $u = 0.9$ m/s and $D_L = 490$ m²/s, the hybrid unit size (Δx) has been chosen as 3200 m by satisfying the condition of peclet number and the parameters of the hybrid model (α, T_1 and T_2) are approximately estimated as: $\alpha = 15$ min, $T_1 = 19$ min and $T_2 = 25$ min. The reach length of 26 km (from Tikira confluence to Talcher) is covered with 8 hybrid units. By successive convolution, the pollutant concentrations at Talcher (26 km downstream of pollutant source) are predicted for step input. Having the above data collected from river Brahmani, using eqn 11, pulse response at 3.2km (1st hybrid unit), 16km (5th hybrid unit) and 26km (8th hybrid unit) have been simulated with different retardation factors ($R = 1.0$ & 2.1) and presented in fig. 9. The maximum pollutant concentration at various locations downstream of pollutant disposal point can be derived by numerical integration of pulse responses obtained using hybrid model for those downstream locations. The maximum pollutant concentration at Talcher is about 34.5 mg/L, which is very close to the measured value of 32.2 mg/L. It clearly demonstrates the influence of retardation process of pollutant transport. In order for complete verification of model, numerous data are needed towards calculating mass exchange rate constant (R). However, this chapter theoretically compares the model with limited field data.

5. Conclusions

A Hybrid model coupled with hyporheic exchange has been derived by incorporating a time delay factor termed as "retardation factor" with each of the three compartments in the hybrid model to simulate retardation governed pollutant transport in riparian streams or rivers. A linear equilibrium condition between the concentration of pollutants in the hyporheic zone and the mainstream water has been considered. The stagnation or dead or hyporheic zone retards the transport of downstream pollutants. The hybrid model is a four-parameter model representing three time parameters and one constant factor. Theoretical study on non-equilibrium exchange of pollutant has also been done to demonstrate the model.

The unit step response and the unit impulse response functions of the hybrid model have been simulated with synthetic data and limited field data. The characteristics of the concentration-time profiles generated by the hybrid model are comparable to the physical processes of pollutant transport governed by the advection-dispersion-retardation both in equilibrium and non-equilibrium exchanges in a natural stream. This present model can be used to obtain theoretically exact solutions and can be compared with results of ADE model considering with and without retardation of pollutant transport in a stream along with advection and dispersion processes.

Data regarding the influence of the hyporheic zone to pollutant trap in streams are rare due to the absence of simple techniques to get necessary parameters and complexity of the phenomenon. The pollutant exchange between the main channel and the hyporheic zone is very variable and estimation of exchange rate is mostly inaccurate due to channel irregularities and other complexities. In depth analysis and understanding about the hyporheic exchange will over-come the problem in collecting relevant data from natural streams.

It can be concluded that the presented hybrid model for pollutant transport in streams affected by hyporheic exchange is a useful tool in predicting water quality status streams.

Simulation of non-equilibrium exchange of non-conservative pollutant between main channel and stagnation zone is vital. As we have considered conservative pollutant in this chapter, the maximum concentrations of pollutant at different locations were same due to mass conservation, but the residence times were different. Thus, this study also gives a retrospect for the extension of the model considering non-equilibrium condition of decaying pollutant exchange for natural streams.

6. Nomenclature

A_P, A_{M1}, A_{M2} – interface areas of the hyporheic zone and the mainstream flow under plug flow, first and second well mixed cells respectively
$C(x, t)$ – Concentration of pollutant in the main stream
C_P, C_{M1}, C_{M2} – Pollutant concentrations at the end of plug flow, first and second well mixed cells respectively
C_R – Input pollutant concentration of a hybrid unit
$C_s(x, t)$ – Concentration of Pollutant trapped in the hyporheic zone
D – Depth of effective soil layer/hyproheic zone
D_L – Longitudinal dispersion co-efficient
F – Proportionality constant
$K(t)$ – Unit step response of a hybrid unit
$k(t)$ – Unit impulse response of a hybrid unit
M_s – Mass of the pollutant trapped in hyporheic zone
n – Number of cells
Q – Stream discharge
R – Retardation factor
R_D – Mass exchange rate constant
t – Time
T_1 – Residence time of first well mixed cell
T_2 – Residence time of second well mixed cell
u – Stream flow velocity
U ( ) – Unit step function
V_0 , V_1, V_2 – Volumes of mainstream plug flow, first and second well mixed cells
V_0^*, V_1^*, V_2^* - Volumes of hyporheic zones under plug flow, first and second well mixed cells
W_P – Wetted perimeter at the interface of hyporheic zone and the main stream
x – Distance
α – Residence time of plug flow cell
δ_{M1}, δ_{M2} – Ramp kernel co-efficient of first and second well mixed cells respectively
Δt – Small time interval
Δx – Size of control volumes within plug flow cell.
ϕ – Porosity

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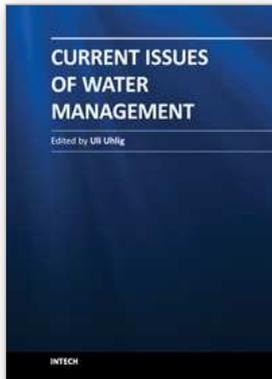
Current Issues of Water Management

Edited by Dr. Uli Uhlig

There is an estimated 1.4 billion km3 of water in the world but only approximately three percent (39 million km3) of it is available as fresh water. Moreover, most of this fresh water is found as ice in the arctic regions, deep groundwater or atmospheric water. Since water is the source of life and essential for all life on the planet, the use of this resource is a highly important issue. "Water management" is the general term used to describe all the activities that manage the optimum use of the world's water resources. However, only a few percent of the fresh water available can be subjected to water management. It is still an enormous amount, but what's unique about water is that unlike other resources, it is irreplaceable. This book provides a general overview of various topics within water management from all over the world. The topics range from politics, current models for water resource management of rivers and reservoirs to issues related to agriculture. Water quality problems, the development of water demand and water pricing are also addressed. The collection of contributions from outstanding scientists and experts provides detailed information about different topics and gives a general overview of the current issues in water management. The book covers a wide range of current issues, reflecting on current problems and demonstrating the complexity of water management.

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