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Analytical solution of the transport equation for linearly decreasing urea concentration in shallow water table condition in an irrigated field

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ABSTRACT

An attempt has been made to develop analytical models for time-dependent nitrification/ denitrification and depth-dependent absorption of urea fertilizer in high water table conditions with fertigation. The Laplace transformation method was used to solve the unsteady-state advection-dispersion equation. The analytical solutions that can be derived by this method assist the understanding of the movement of fertilizer in irrigated fields. The developed models were validated with the experimental results. They were closely predicting the fertilizer movement in one-dimension soil medium. The little deviation of result from observed values may be due to change of dispersion coefficient and velocity with moisture content. Here we have assumed these parameters as constant throughout the time under consideration. The model developed for constant degradation rate is predicting very close to observed values which shows that the soil under study has no depth-dependent degradation. The developed models may be helpful for the planning of drain design, nutrient management and assessment of potential hazards to groundwater in agricultural fields by the knowledge of exact transport parameters and boundary conditions universally.

KEYWORD

Analytical model, Fertilizer movement, flood irrigation, water pollution, Richard's equation

INTRODUCTION

Fertigation or chemigation is the emerging threat of the latest technological advancement in irrigation methods and water management techniques. Fertilizers applied with irrigation water or after receiving low rainfall and heavy shower subsequently are common problems in the present situation. Flow and transport in the upper soil layers represent an important problem for agriculture and subsurface hydrology. Mathematical modeling of processes, in the unsaturated zone, is useful for the agricultural management of cultivated sites, for prediction of the fate of agrochemicals, and assessment of the potential hazard of shallow groundwater contamination. The difficulty of solving the transport equation in the unsaturated zone relies on its strong nonlinearity. Although significant efforts have been made to overcome the mathematical difficulties, most analytical solutions are derived for one-dimensional vertical transport under various simplifying assumptions. Accounting for the spatial heterogeneity of natural soils renders the transport problem even more complicated.

Bresler and Laufer (1974) simulated the movement of nitrate in homogeneous soil profile in the presence of NO_3-N production (nitrification). Saxton *et al.* (1977) modeled nitrate-nitrogen movement and dissipation in fertilized agricultural lands but did not include representation of any other fertilizer from nitrogen. Wagenet *et al.* (1977) extended the mathematical analysis of Misra *et al.* (1974) to describe the transport and transformation of urea, ammonium nitrogen and nitrate nitrogen soil profile as a function of depth and time subject to either steady or pulse feed application of nitrogen, and validated with controlled laboratory experiments. Watts and Hanks (1978), Tillotson and Wagenet (1982) developed a model that simulated most of the major transformations of the nitrate as well as the uptake by the crop, but fell short of fully describing the system in the plant growth and yield response. Benbi *et al.* (1991) developed soil water, nitrogen models. Izadi *et al.* (1996) combined the functional sub-model and analytical solution to the steady-state convection dispersion equations to predict the nitrate concentration in the root zone. Sander and Braddock (2005) presented a range of analytical solutions to the combined transient water and solute transport for horizontal flow. Smedt (2007) reported an analytical solution and analysis of solute transport in rivers affected by diffusive transfer in the hyporheic zone.

Hongbin *et al.* (2009) deduced an analytical solution of two-dimensional solute transport in an aquifer–aquitard system. Srinivasan and Clement (2008) reported analytical solutions for sequentially coupled one-dimensional reactive transport problems. Sadek (2009) compared various available analytical solutions with numerical methods is deduced that the analytical solution may be used as a versatile tool for assessment of contaminant transport. Jozse and Janos (2009) derived an analytical solution of the coupled 2-D turbulent heat and vapor transport equations and the complementary relationship of evaporation . Guerrero and Guerrero (2010) presented a general analytical solution for linear, one-dimensional advection-dispersion equation with distance-dependent coefficients. An integrating factor was employed to obtain a transport equation that has a self-

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adjoint differential operator, and a solution was found using the generalized integral transform technique.

MATERIALS AND METHODS

The mechanisms of solute transport in the irrigated field are significantly influenced by attenuation processes such as adsorption and nitrification/denitrification processes. Most of the available analytical solutions are based on linear equilibrium adsorption and first-order nitrification and possibly zeroth-order production (van Genuchten and Alves, 1982) for several analytical solutions). Here the movement of urea fertilizer was analytically solved under depth-dependent adsorption factor and combination of constant and exponential nitrification/denitrification rate for the constant initial condition. Following assumptions were considered for formulating the boundary value problems:

1. The soil is unconfined, homogeneous and isotropic overlying an impermeable layer which is having water table depth H meter from the soil surface,
2. The water through deep percolation moves vertically downward until it joins the groundwater,
3. Darcy and Fick's laws hold good,
4. The fluid is of constant density and viscosity,

In the present study 1-D Richard's equation in combination with the solute transport equation, which incorporates nitrification and de-nitrification, and depth-dependent soil and water matrix factor were used to characterize the movement of applied fertilizer in irrigated agriculture having shallow water table conditions.

Governing Equation

Transport equation in an unsaturated porous medium is given by:

$$\frac{\partial}{\partial t}\theta C + \rho S) = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z} - qC\right) - \alpha\theta C / \rho\beta 6 \smile \gamma\theta \qquad \ldots(1)$$

where C = C(z, t) is the concentration of chemical in the liquid phase in mg/l , S = S (z, t) is the concentration of chemical in the solid phase in mg/l, D = D(z, t) is the dispersion coefficient in m^2/day, θ = θ (z, t) is the volumetric water content cm^3/cm^3, q = q(z, t) is the flux of water in m/day, ρ = ρ (z) is the soil bulk density in gm/cm^3, α = α (z) is the first-order degradation rate constant in the liquid phase, β = β (z) is the first-order degradation rate constant in the solid phase, ϒ = ϒ (z) is the zero-order production rate constant in the liquid phase. Here α, β and ϒ are zero or greater.

Considering that soil medium remains intact with time, and introducing mass balance equation for one-dimensional unsteady unsaturated flow condition as given by Chow *et al*. (1988), Eqn. (1) reduces to:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^0} - v\frac{\partial C}{\partial z} / E6 \smile \qquad \ldots(2)$$

Where v = ρ / θ and R= $\left(\alpha + \frac{\Lleftarrow\subset}{\theta}\right)$ the factor representing the combined effect of liquid and solid phase degradation rate. Here we assume R(C) = R_o – b (C_o - C) where R_o represents potential degradation rate at the land surface; b is reduction factor due to which degradation decreases linearly as the depth from the land surface it increases up to a specific value; and C_o is initial concentration at the ground surface. For the development of the model, the combination of constant and exponentially decreasing nitrification/de-nitrification rate, which may be given as $\gamma\; t) = \gamma_0 + \iota_/ e^{/ pr}$ where γ_0 and γ_1 are constant nitrification/de-nitrification rates, r is decay constant and t represents time, was taken into consideration.

The initial and boundary conditions in mathematical terms, for the solute flow problem in the unsaturated zone under the above situation, may be written as:

$$\left.\begin{array}{lll} C\,(z, o) = C_z\,(z, o) & \text{at } t = o & \text{for } o < z < H \\ C\,(o, t) = C_1 & \text{at } t > o & \text{for } z = o \\ C\,(H, t) = C_2 & \text{at } t > o & \text{for } z = F \end{array}\right\} \qquad \ldots(3)$$

where, $C_1 = g_1 e^{-ht}$, $C_2 = g\, e^{ht}$, g_1 and g are the concentrations at ground surface and H meter below the soil surface before application of fertigation. C_z (z, 0) is the distribution of initial concentration in the porous medium. Devising a transform given by Eqn. (4) converted the Eqn. (2) and Eqn.(3) into standard heat flow equation and given by Eqn (5) and Eqn(6), respectively.

$$C(z,t) = V(z,t)\exp\left(\frac{v\,z}{2D} - \left(\frac{v^2}{4D} + b\right)t\right) + \frac{\gamma_1 e^{-rt}}{b-r} + \frac{\gamma_0 + bC_0 / R_0}{L'} \qquad \ldots(4)$$

$$\frac{\partial^2 V}{\partial z^2} = \frac{/}{D}\,\frac{\partial V}{\supset \dot{C}} \qquad \ldots(5)$$

$$\left.\begin{array}{l} V(z,0) = C_z - A - B\,)e^{-az} = f(z) \\ V(0,t) = \left(C_1 - A - B\,e^{-rt}\right)e^{dt} = f_1(t) \\ V(H,t) = E\left(C_2 - A - B\,e^{-rt}\right)e^{dt} = f_2(r) \end{array}\right\} \qquad \ldots(6)$$

where, $A = \frac{\gamma_0 + bC_0 / R_0}{L'}$ $d = \frac{v^2}{2D} - L'$ $a\ ?\ \frac{v}{2\,5}$ $E = e^{/\,\breve{A}I}$

and $B = \frac{\iota_/}{b / \,'n}$

The general solution of transformed Eqn (5) under initial and boundary condition Eqn(6) is given by Carslaw and Jaeger (1959) and Ozisik (1980) as below:

$$V(z,t) = \frac{2}{H}\sum_{m=/}^{\infty} A_2 \sin\ \beta_m z\left[\ p - A - B\,)\frac{\beta_m}{a^2 + \delta_m^2}\left[1 - (-1)^m E\right]\right]$$

$$-\frac{2}{H}q\sum_{m=1}^{\infty} A_2 \sin\ \beta_m z\ \frac{a\beta_m}{\left(a^2 + \delta_m^2\right)^2}\left[(-1)^m E\,(1 - a) + \_C\ /\ /\right]$$

$$+\frac{2}{H}\ q\sum_{m=1}^{\infty} A_2 \sin\ \beta_m z\ \frac{H\beta_m}{a^2 + \beta_m^2}\ /\ 1)^m\ C$$

$$+\left(1 - \frac{z}{H}\right)C_1 - A - B\,e^{-rt}\big)e^{dt} + \frac{z}{H}\left(C_0 - A - B\,e^{-rt}\right)e^{dt}e^{/\,\_F}$$

$$-\frac{2}{H}\sum_{m=/}^{\infty}\frac{\sin\ \beta_m z}{\delta_m}\left[\,g_1 - A - B\,)A_2\,\right]$$

$$-\frac{2}{H}\sum_{m=/}^{\infty} A_2\frac{\sin\ \beta_m z}{\delta_m}\left[\frac{A_6}{S}\ e^{-st} - 1\big) - \frac{A_4}{K}\left(e^{-Kt} - 1\right) - \frac{B_1}{N}\left(e^{-Nt} - 1\right)\right]\!\lrcorner A\,0$$

$$+\frac{2}{H}\sum_{m=/}^{\infty} -1)^m A_2 \frac{\sin \beta_m z}{\delta_m}[(g-A-B)E\ ]$$

$$+\frac{2}{H}\sum_{m=/}^{\infty} -1)^m A_2 E \frac{\sin \beta_m z}{\delta_m}$$

$$\left[\frac{A_3}{l} e^{-lt}-1)-\frac{B_1}{N}\left(e^{-Nt}-1\right)-\frac{A_4}{K}\left(e^{-Kt}-/\right)\right] \qquad \ldots(7)$$

where,

$A_1=(\gamma_0+R_0)$ $\quad A_2=e^{-D\beta_m^2 t}$ $\quad A_3=(h+d)g$

$A_4=dA$ $\quad A_5=C_0-A-B$ $\quad A_6=g_1(d-h)$

$A_7=g_1(d_1-k)$ $\quad A_8=A_1 d_1$ $\quad A_9=dC_1-dA$

$B_1=B(d-r)$ $\quad B_2=\dfrac{\gamma_1}{r}$ $\quad B_3=B_2(d_1-r)$

$E=e^{-aH}$ $\quad d_1=\dfrac{v^2}{4D}$ $\quad F_1=(C_0-B_2)$

$F_2=p-B_2$ $\quad G=p-A-B$ $\quad K=D\beta_m^2 t+d$

$l=D\beta_m^2 t+d+h$ $\quad M=D\beta_m^2+d_1+k$ $\quad N=D\beta_m^2 t+d-r$

$S=D\beta_m^2 t+d-h$ $\quad K_1=D\beta_m^2+d_1$ $\quad N_1=D\beta_m^2+d_1-r$

$S_1=D\beta_m^2+d_1-k$

where, β_m is the root of sin β_m H = 0 and τ is a dummy variable. Solution of transport equation was obtained for linearly decreasing initial concentration (*zqpCz–=*) of nitrogen in soil profile with the help of equation (7) and transformed initial and boundary conditions. If $C_Z = P - Q_Z$, i.e. concentration decreases with increase in depth or a function of space, then final solution of Eqn. (7) takes the following form:

$$C(z,t)=\frac{2}{H}e^{az-dt}\sum_{m=1}^{\infty} A_2 \sin \beta_m z\left[(p-A-B)\frac{\beta_m}{a^2+\beta_m^2}[1-(-1)^m E]\right]$$

$$-\frac{2}{H}q\ e^{az-dt}\sum_{m=1}^{\infty} A_2 \sin \beta_m z\ \frac{a\beta_m}{(a^2+\beta_m^2)^2}[(-1)^m E(1-a)+aE-1]$$

$$+\frac{2}{H}\ e^{az-dt}q\sum_{m=1}^{\infty} A_2 \sin \beta_m z\ \frac{H\beta_m}{a^2+\beta_m^2}(-1)^m E$$

$$+\left(1-\frac{z}{H}\right)(C_1-A-Be^{-rt})e^{az}+\frac{z}{H}(C_2-A-Be^{-rt})e^{a(z-H)}$$

$$-\frac{2}{H}e^{az-dt}\sum_{m=1}^{\infty}\frac{\sin \beta_m z}{\beta_m}[(g_1-A-B)A_2]$$

$$-\frac{2}{H}e^{az-dt}\sum_{m=1}^{\infty} A_2\frac{\sin \beta_m z}{\beta_m}\left[\frac{A_6}{s}(e^{-st}-1)-\frac{A_4}{K}(e^{-Kt}-1)-\frac{B_1}{N}(e^{-Nt}-1)\right]A2$$

$$+\frac{2}{H}e^{az-dt}\sum_{m=1}^{\infty}(-1)^m A_2\frac{\sin \beta_m z}{\beta_m}[(g-A-B)E\ ]+A+Be^{-rt}$$

$$+\frac{2}{H}e^{az-dt}\sum_{m=1}^{\infty}(-1)^m A_2 E\frac{\sin \beta_m z}{\beta_m}\ \frac{A_3}{l}(e^{-lt}-1)-\frac{B_1}{N}$$

$$(e^{-Nt}-1)-\frac{A_4}{K}(e^{-Kt}-1)$$

When degradation is constant with depth i.e. b=0 Eqn (8) become imperative so for this situation another transformation equation (Eqn.9) was devised to transform the original problem into standard heat flow equation and given as

$$C(z,t)=V(z,t)\exp\left(\frac{vz}{2D}-\left(\frac{v^2}{4D}\right)t\right)+\frac{\gamma_1 e^{-rt}}{r}+(\gamma_0+R_0)t \qquad \ldots(9)$$

This transformation Eqn. (9) transform the problem into a simple heat flow equation under linearly decreasing initial concentration and gave the final solution of the problem as:

$$C(z,t)=\frac{2}{H}e^{az-d_1t}\sum_{m=1}^{\infty} A_2 \sin \beta_m z(p-B_2)\frac{\beta_m}{a^2+\beta_m^2}[1-(-1)^m E]$$

$$+\frac{2q}{H}e^{az-d_1t}\sum_{m=1}^{\infty} A_2 \sin \beta_m z\begin{bmatrix}\dfrac{\beta_m H}{a^2+\beta_m^2}((-1)^m E)- \\ \dfrac{a\beta_m}{(a^2+\beta_m^2)^2}[(-1)^m E(1-a)+aE-1]\end{bmatrix}$$

$$+\left(1-\frac{z}{H}\right)(C_1-A_1-B_2e^{-rt})e^{az}+E.\frac{z}{H}(C_2-A_1-B_2e^{-rt})e^{az}$$

$$-\frac{2}{H}e^{az-d_1t}\sum_{m=1}^{\infty}\frac{\sin \beta_m z}{\beta_m}(g_1-B_2)A_2\ +B_2+A_1 t$$

$$-\frac{2}{H}e^{az-d_1t}\sum_{m=1}^{\infty}\frac{\sin \beta_m z}{\beta_m}A_2\begin{bmatrix}\dfrac{A_7(e^{S_1t}-1)}{S_1}-\dfrac{B_3(e^{N_1t}-1)}{N_1}-\dfrac{A_1(e^{K_1t}-1)}{K_1} \\ -\dfrac{A_8}{K_1{}^2}+\dfrac{A_8e^{K_1t}}{K_1{}^2}-\dfrac{A_8te^{K_1t}}{K_1}\end{bmatrix}$$

$$+\frac{2}{H}e^{az-d_1t}\sum_{m=1}^{\infty}(-1)^m\frac{\sin \beta_m z}{\beta}(g-B_2)\ E\ A_2$$

$$+\frac{2}{H}e^{az-d_1t}\sum_{m=1}^{\infty}(-1)^m\frac{\sin \beta_m z}{\beta_m}A_2E$$

$$\overset{m}{\ }\begin{bmatrix}\dfrac{A_9(e^{-Mt}-1)}{M}-\dfrac{B_3(e^{-N_1}-1)}{N_1}-\dfrac{A_1(e^{K_1t}-1)}{K_1} \\ -\dfrac{A_8}{K_1{}^2}+\dfrac{A_8e^{K_1t}}{K_1{}^2}-\dfrac{A_8te^{K_1t}}{K_1}\end{bmatrix} \qquad \ldots(10)$$

Equation (8) and equation (10) give the complete solution of transport equation (2) under constant and depth dependent degradation rate for the combination of constant and exponentially denitrification rates. In further analysis, they would be treated as Model 1 and Model 2, respectively.

Experimental plot: The size of the experimental plot was 5 m x 5 m, surrounded by 1 meter buffer zone earlier used by Behera (2003), and Garg *et al.* (2005) and lined by a galvanized iron sheet as discussed by Jaynes *et al.* (1992). The line of tensiometers and soil-water samplers were put 1.5 away from the side boundary, double ring infiltrometer was kept at the center of the plot while access tubes were installed on the centerline of the plot. Depth of both tensiometers and samplers were kept 15, 30, 50, 75, 100 and 150 cm below the ground surface. First and sixth were installed 50 cm away from the boundary and the distance between two was kept 80 cm. access tubes were installed 125 cm from the boundary. Observation wells were installed at two corners diagonally, keeping in mind the general flow direction of water movement. All soil water samplers were connected by a lateral line through HDPP (high-density polyvinyl pipe) and connected to vacuum pump which creates suction and pressure in a sampler for the collection of leachate samples.

Collection of field data: Nitrogen solution of 448 ppm concentration, representing the nitrogen dose of 334 N kg/ ha, was applied in the experimental plot instantaneously to simulate the fertigation. Leachate samples were collected with the help of a soil-water sampler and vacuum pump. Collected samples were brought to the laboratory and analyzed for total nitrogen content with the help of the *Kjeldahl* unit.

RESULTS AND DISCUSSION

Verification of the analytical solution with experimental

Physical, chemical, textural and transport parameters, required to validate the developed models, were obtained by the standard. Computer programs for model-1 and model-2 were developed in C^{++} language with defining all input parameters in program except space and time. Just by giving the value of space and time one can get the concentration of fertilizer at that space and time. The performance of developed models was compared with experimental results and shown in Fig.-1 to Fig.13. (https://jsure.org.in/fig-1-to-fig-52/) The first six figures are showing the performance of developed models at 0.15 m, 0.30 m, 0.50 m, 0.75 m, 1.00 m and 1.50 m, respectively. At 0.15 m first, four days, both model-1 and model-2 were over predicting a little more than observed value, but from the third day onwards, both predicted very close to the observed values, which may be clearly seen in Fig.1. Similar performance of models was also observed for other depths except for 1.5 m and is depictured in Fig. 2 to Fig. 5 that may be due to preferential flow (funneling, fingering and channeling) of water through the soil or highly disturbed upper soil layer during the installation of soil-water sampler or combination of these two. Similar performance of models was also depictured in Fig. 7 to Fig. 15 at different days and further validated their performance. The deviation of predicted values from observed is very less except for the first two days (Table 1).

Table - 1 : Observed and predicted concentration (ppm) by equation 8 and equation 10

Time (days)	Model 1	Model 2	Observed	% deviation Model 1	% deviation Model 2
1	395.22	393.93	375	5.39	5.05
2	464.94	463.98	451	3.09	2.88
3	478.27	477.39	473	1.11	0.93
4	481.04	480.09	478	0.64	0.44
5	481.75	480.67	481	0.16	-0.07
7	482.32	480.83	482	0.07	-0.24
10	483.07	480.72	483	0.01	-0.47

Limiting conditions

Equations give analytical solutions (8) and (10) under different conditions can be used to obtain the following analytical solutions as special cases: (1) Analytical solutions when the nitrification rate is constant by substituting 01=gin the above equations. Graphical comparison of developed models with observed value for this condition is shown in Fig- 13 to Fig- 26. (https://jsure.org.in/fig-1-to-fig-52/) (2) Analytical solutions when the nitrification rate is exponentially decreasing by substituting 00=g in the above equations.

Graphical comparison of developed models with observed value for this condition is shown in Fig- 27 to Fig- 39. (https://jsure.org.in/fig-1-to-fig-52/) (3) Analytical solutions when there is no nitrification by substituting 010=gg*and* in the above equations. Graphical comparison of developed models with observed value for this condition is shown in Fig- 40 to Fig- 52. (https://jsure.org.in/fig-1-to-fig-52/) (4) Analytical solutions for non-absorbing solutes by substituting 00=*bandR* in the above equations. Variations in concentrations under limiting conditions were negligible for model 2 as compared to model 1 in similar situations. Model-2 performed better than Model-1 at each day. Hence it may be concluded that under local soil conditions there is no degradation with depth for nitrogen concentration in shallow groundwater table condition.

CONCLUSION

Developed models would be successfully used for the prediction of fertilizer movement in irrigated fields where the water table is high with the accurate knowledge of local transport parameters. Deviation in observed and predicted concentrations was highest on the first day and decreases continuously as time passes; this may be due to the highly disturbed top layer caused due to the installation of instruments and the G.I. sheet. Hence, the preferential flow of solute must be minimized before taking the actual observation to avoid such an outcome.

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