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ISSN : 1907-5545
Terakreditasi SK Kepala LIPI
Nomor : 99/AKRED-LIPI/P2MBI/5/2007

JURNAL IRIGASI

Terbit 2 kali setahun

Vol. 4, No. 1, Juni 2009

EDITORIAL

MATHEMATICAL MODELING ON WATER LEVEL AND SOIL WATER CONCENTRATION ESTIMATION IN NON-WATER PONDING PADDY FIELD

(PEMODELAN MATEMATIKA UNTUK ESTIMASI LEVEL AIR DAN KONSENTRASI AIR TANAH PADA SAWAH YANG TAK TERGENANG AIR)

Oleh :

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ABSTRAK

System of Rice Intensificataion yang dikenal dengan singkatan SRI telah diperkenalkan di beberapa wilayah di Indonesia. Sistem ini yang dipadukan dengan pemupukan organik telah memberikan hasil yang menggembirakan dalam memperbaiki produktivitas lahan dan air, dan keuntungan yang lebih baik bagi para petani. Salah satu perlakuan penting dalam SRI, yaitu penggenangan air tidak lagi menjadi bagian penting untuk menjaga tinggi muka air di sepanjang pertumbuhan padi. Namun, air kini diberikan secara terputus-putus untuk menjaga agar tanah selalu dalam kondisi mendekati jenuh dan memberi kesempatan agar terjadi kondisi aerobik pada waktu-waktu tertentu. Perlakuan seperti ini akan memberikan tingkah laku yang berbeda pada pergerakan air dan transportasi larutan pada jenis tanah tertentu. Penelitian ini bertujuan untuk mengetahui profil dan perubahan tinggi muka air dan konsentrasi larutan dalam tanah dalam kondisi terkendali atau ideal dengan memperhatikan penyerapan air dan larutan oleh akar tanaman. Disini, dipertimbangkan keberadaan lapisan semi kedap yang biasa ditemui di lapangan. Model matematika dikembangkan berdasarkan pada persamaan Darcy dan Richards untuk pergerakan air, dan persamaan konveksi-dispersif untuk transportansi larutan dalam tanah. Dengan menggunakan sifat fisik dan kimia pada tanah tertentu, ditemukan bahwa penyerapan akar menunjukkan faktor signifikan dalam membentuk profil tinggi muka air dan konsentrasi larutan. Sementara, keberadaan lapisana semi-kedap cukup efektif dalam memperlambat kehilangan air dan konsentrasi karena perkolasi. Hasil ini memberikan informasi yang penting khususnya dalam menerapkan pemberian air secara terputus-putus yang efektif agar tinggi muka air dan konsentrasi larutan di zona perakaran berada dalam kondisi yang terkendali, khususnya bagi pengembangan SRI.

Kata Kunci : **SRI, tinggi muka air, konsentrasi larutan, pemodelan matematika**

I. BACKGROUND

Eventhough System of Rice Intensification (SRI) was recognized in the earlier century in Japan, it was resurrected in Madagascar by Fr. Henri de Laulanie, S.J., a Jesuit priest from France, in the early 1980s (Sato and Uphoff, 2008). He established an NGO called Association Tefy Saina (ATS), to work with farmers, agricultural professionals and other NGOs to improve rice production and livelihood. Before he

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died in June, 1995, he published one article on SRI in the Journal Tropicultura in 1993. Later on SRI has become hot topics and are being practiced else where in paddy cultivating countries (Sato and Uphoff, 2008). Since then, intensive scientific meetings and discussion forums have been conducted, and networks of SRI have been established in Japan (J-SRI) in 2007 and in Indonesia (Ina-SRI) in 2008. Even though SRI has been practiced with gaining promising yields, fundamental researches on SRI have been lagged behind. To date, some attempts to study or to control water level in conventional paddy fields can be found elsewhere (Setiawan, *et. al.*, 2001; Setiawan, *et. al.*, 2004; Iskandar, *et. al.*, 1999; Saptomo, *et. al.*, 2002; Setiawan, *et. al.*, 2001b). But, none of them integrate the water flow with the solute transport with which both of them would have interrelated influences.

The objective of this paper is to develop an integrated model consists of water flow and solute transport in paddy field soils under partially submerged conditions in the System of Rice Intensification.

II. THEORETICAL APPROACHES

2.1. Water Flow Equations

Figure 1 shows a hypothetical representation of SRI model where there is one row or more of paddy plants between two neighboring on-farm canals.

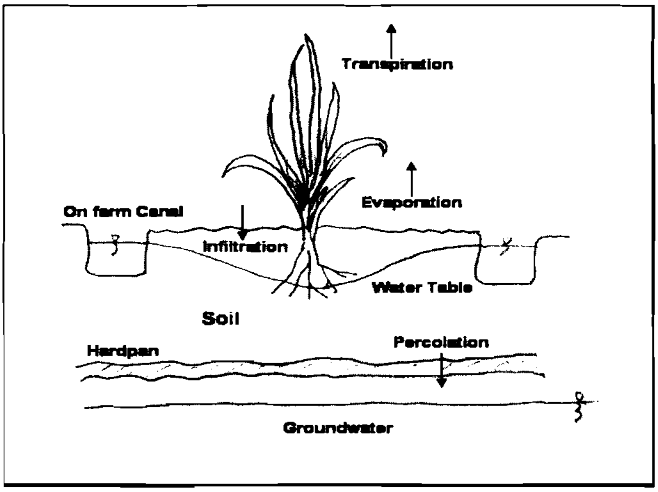


Figure 1. A hypothetical representation of SRI Model for the modeling of water flow

Water flow in the soil under isothermal saturated soil (Bear and Verruijt, 1987, Pages: 276~277), in one dimension:

$$S\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+Q(x,t) \text{ .... (1)}$$

Where, *S* is storativity, *T* is transmissivity (cm_2/d), *h* is water pressure head (cm), *Q* sinks and sources (cm/d), *x* is distance (cm), and *t* is time (days). Transmissivity is treated as a function of saturated hydraulic conductivity (Ks, cm/d) and hence is considered as water pressure head in form of (Bear and Verruijt, 1987, Pages: 43~44):

$$T = K_s \cdot h \quad \text{.................................(2)}$$

Sink/Source (*Q*) is a summation of infiltration (*I*), transpiration (*T*), percolation (*P*) and evaporation (*E*) rates, which can be formulate such as:

$$Q = I - (T + P + E) \quad \text{.....................(3)}$$

Infiltration rate is considered exist only when the rainfall fall through the soil surface into the deeper layers of the saturated soil, such as:

$$I = H_{sw} * K_s \quad \text{...............................(4)}$$

Where, H_{sw} is a digital value (0 or 1) as a function of time of the rainfall occurrence. Transpiration rate is calculated using the following formula (Hillel, 1980. Page: 562):

$$T = \frac{\Delta h_{sr}}{R_{sr}} = \frac{H_{st} - h}{R_{sr}} \quad \text{....................(5)}$$

Where, Δh_{sr} is water pressure difference between those in the soil, *h* and in the stem of the plant, H_{st}. In many cases, H_{st} is assumed constant, approximately 5000 cm (5 bar), when the plant shows a normal growth. And, R_{sr} is hydraulic resistance (d) between the root and the surrounding soil, which is approximated using the following Gardner formula (Hillel, 1980. Pages: 578~587):

$$R_{sr} = \frac{1}{B \cdot K_s \cdot L} \quad \text{..........................(6)}$$

Where, *B* is an empirical constant representing a specific root-activity factor and *L* is the total length of active roots per unit volume of the soil (cm^3/cm^3). In many cases, *L* increases as the plant grows. For example, *L* is approximately 0.2, 0.5 and 1 cm^3/cm^3, respectively for difference stages of plant growth.
Percolation rate is calculated by considering there is a hard pan, which is a semi-previous layer (Bear and Verruijt, 1987. Pages: 72~73):

$$P = K_{st} \cdot (h - h_{gw}) \quad \text{.......................(7)}$$

Where, K_{st} are composite saturated hydraulic conductivity (cm/d) and h_{gw} is groundwater level (cm) below the semi previous layer.

$$\frac{1}{K_{st}} = \frac{h}{K_s} + \frac{D_{sp}}{K_{sp}} \quad \text{........................(8)}$$

Where, K_{sp} are saturated hydraulic conductivity (cm/d) and D_{sp} is the thickness of the semi-previous layer (cm). Evaporation rate is calculated with considering there is a water table using the following formula (Hillel, 1980. Pages: 514):

$$E = \left[1 + \frac{1.886}{n^2 + 1}\right]^{-h} \quad \text{......................(9)}$$

Where, *n* is an empirical constant dependence upon the soil texture. For sandy soil n is about 3 (Gardner, 1958 in Hillel, 1980. Pages: 513~514):

2.2. Solute Transport Equation

Figure2 shows a hypothetical representation of SRI Model for modeling solute transport. Solute balance comprises of fertilization, rainwater, leaching, and root extraction. For a while, emission for a while is neglected since it highly influenced by temperature which is not taken into account in this paper.

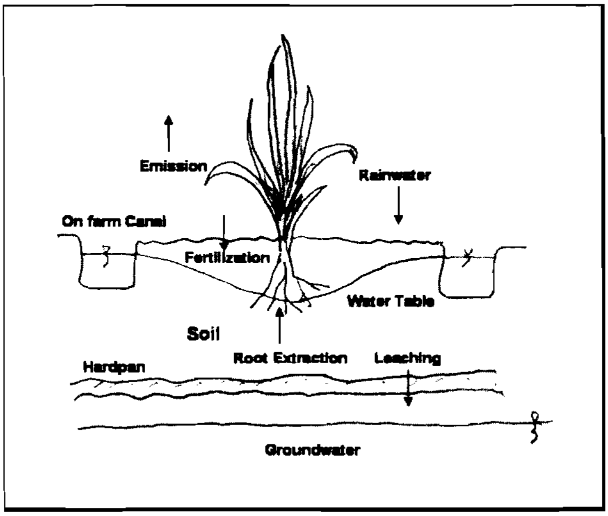


Figure 2. A hypothetical representation of SRI Model for the modeling of solute transport

Solute transport in an isothermal saturated soil (Hillel, 1980, pages: 252~253), in one dimension can be written:

$$\frac{\partial c}{\partial t} = -v\frac{\partial c}{\partial x} + \frac{D_{sh}}{\theta_s}\frac{\partial^2 c}{\partial x^2} + C(x,t) \quad (10)$$

Where, c is concentration of a specific solution (mg/l), v is pore velocity (cm/d), D_{sh} is hydrodynamic dispersion (cm^2/d), θ_s is saturated water content (cm^3/cm^3), and C is source/sink terms (mg/l/d). D_{sh} is obtained from measurement but for practical purpose can be calculated using:

$$D_{sh} = a \cdot v + D_o \cdot \theta_s \cdot \xi \text{ .... } (11)$$

Where, a is an empirical factor, D_o is diffusion in water, and ξ is tortuosity factor. The average velocity is calculated as follow:

$$v = \frac{q}{\theta_s} \text{ .... } (12)$$

Where, q is water flux, which is defined by Darcy's law, which gives a link to the water flow equation (Eq.1).

Sink/Source term reflects solute extraction by plant, application of fertilizer and including incoming solute from rainwater and possible losses to the environment. These can be stated in the following formula:

$$C = C_{fr} + C_{rw} - C_{rt} - C_{ls} \text{ .... } (13)$$

Solute extraction by plant may follow Fruendlich's nonlinear equilibrium isotherm:

$$C_{rt} = B \cdot c^{m} \quad \text{..............................} (14)$$

Where, *B* and *m* are empirical constants. If *m*=1, the equation becomes linear equilibrium isotherm where *B* or symbolized as K_d is then called distribution or partitioning coefficient.

Solute losses to environment can be attributed to the existence of percolation rate, which can be calculated using:

$$C_{ls} = v_{sp} \cdot \frac{c - c_{gw}}{D_{sp}} \quad \text{......................} (15)$$

Where, v_{sp} now is water velocity through semi-previous layer and c_{gw} is solute concentration in the groundwater.

III. MATERIALS AND METHODS

3.1. Solution technique for the Water Flow Equations

Equation 1 can be expanded such a way with considering Eq.2, becomes:

$$S\frac{\partial h}{\partial t} = K_s \cdot \left(\frac{\partial h}{\partial x}\right)^2 + K_s \cdot h \cdot \frac{\partial^2 h}{\partial x^2} + q(x,t) \quad \text{.......} (16)$$

The goal is to find optimal solutions for h_i, which minimize the cumulative differences (ε_i), or numerical error, between the right- and left-sides:

$$\varepsilon_i \approx S\frac{\partial h}{\partial t} - K_s \cdot \left(\frac{\partial h}{\partial x}\right)^2 - K_s \cdot h \cdot \frac{\partial^2 h}{\partial x^2} - q(x,t) \quad \text{....} (17)$$

This error is acceptable if it lies somewhere between 0 and a tolerable value (*TOL*):

$$0 < \sum_{i=1}^{n} \left|\varepsilon_i\right| < TOL \quad \text{........................} (18)$$

Since, Eq.17 is a non-linear equation then an iterative method is necessarily to be applied. Herewith, Newton method is used which involved generation of Jacobian matrix.

The partial derivatives of Eq.17 can be converted into a system of algebraic equation by means of finite difference method, such as:

$$\frac{\partial h}{\partial t} \approx \frac{h_i^{t+1} - h_i^{t}}{\Delta t} \quad \text{............................} (19)$$

$$\frac{\partial h}{\partial x} \approx \frac{h_{i+1}^{t+1} - h_{i-1}^{t+1}}{2 \cdot \Delta x} \quad \text{.....................} (20)$$

$$\frac{\partial^2 h}{\partial x^2} \approx \frac{h_{i+1}^{t+1} - 2 \cdot h_i^{t+1} + h_{i-1}^{t+1}}{\Delta x^2} \quad \text{.....} (21)$$

Where, *i* and *n* as index and total number of discretization, respectively, and h_i is evaluated at time *t+1* after it is given initial condition at time *t*.

The Jacobian matrix of Eq.17 takes a form of tridiagonal matrix in which its components are approximated numerically and evaluated at time *t+1*, such as:

$$\alpha_i = \frac{\partial \varepsilon_i}{\partial h_{i-1}} = \frac{\varepsilon_i(h_{i-1}+\Delta h_{i-1})-\varepsilon_i(h_{i-1})}{\Delta h_{i-1}} \text{ .... (22)}$$

$$\beta_i = \frac{\partial \varepsilon_i}{\partial h_i} = \frac{\varepsilon_i(h_i+\Delta h_i)-\varepsilon_i(h_i)}{\Delta h_i} \text{ .... (23)}$$

$$\gamma_i = \frac{\partial \varepsilon_i}{\partial h_{i+1}} = \frac{\varepsilon_i(h_{i+1}+\Delta h_{i+1})-\varepsilon_i(h_{i+1})}{\Delta h_{i+1}} \text{ .... (24)}$$

Where, $\Delta h_i = \delta \cdot h_i$; $\delta > 0$............ (25)

The Jacobian matrix then can be arranged in the form of algebraic equations:

$$\alpha_i \cdot \delta h_{i-1} + \beta_i \cdot \delta h_i + \gamma_i \cdot \delta h_{i+1} = -\varepsilon_i \text{ ... (26)}$$

Where, δh is the solution which can be found using Thomas algorithm, then h is updated successively:

$$h_i^{k} = h_i^{k-1} + \delta h_i^{k} \text{ .... (27)}$$

Where, k is number of iteration. The iteration will stop after the condition of Eq.18 has been reached.

Later on, water flux at each ascertained time is calculated using Darcy equation:

$$q_i = K_S \cdot \frac{h_i - h_{i-1}}{\Delta x} \text{ .... (28)}$$

These velocities will be used as known variables at ascertained times in the modeling of solute transport.

Boundary conditions are in the form of water fluxes, such as:

$$\left.\frac{\partial h}{\partial x}\right|_{x=0} = q_0(t) \text{ .... (29)}$$

$$\left.\frac{\partial h}{\partial x}\right|_{x=n} = q_n(t) \text{ .... (30)}$$

3.2. Solution technique for the Solute Transport Equation

To find solution for h, Eq.10 is written in the form:

$$\varepsilon_i \approx \frac{\partial c}{\partial t} + v_i \frac{\partial c}{\partial x} - \frac{D_{sh}}{\theta_s}\frac{\partial^2 c}{\partial x^2} + \alpha(x,t) \text{...... (31)}$$

The goal is to minimize cumulative differences (ε_i), or numerical errors, such as:

$$0 < \sum_{i=1}^{n} |\varepsilon_i| < TOL \text{ .... (32)}$$

Where, TOL is acceptable error tolerance. The partial differential equations of Eq.31 are transformed into finite difference equations, such as:

$$\frac{\partial c}{\partial t} \approx \frac{c_i^{t+1} - c_i^{t}}{\Delta t} \quad \text{..........................(33)}$$

$$\frac{\partial c}{\partial x} \approx \frac{c_{i+1}^{t+1} - c_{i-1}^{t+1}}{2 \cdot \Delta x} \quad \text{................(34)}$$

$$\frac{\partial^2 c}{\partial x^2} \approx \frac{c_{i+1}^{t+1} - 2 \cdot c_i^{t+1} + c_{i-1}^{t+1}}{\Delta x^2} \quad \text{....(35)}$$

Where, *i* and *n* as index and number of discretization, respectively, and *c* appeared in all equations is evaluated at time, *t+1*.

The components of Jacobian matrix of Eq.31 are calculated using finite difference method, such as:

$$\alpha_i \approx \frac{\partial \varepsilon_i}{\partial c_{i-1}} = \frac{\varepsilon_i(c_{i-1} + \Delta c_{i-1}) - \varepsilon_i(c_{i-1})}{\Delta c_{i-1}} \quad (36)$$

$$\beta_i \approx \frac{\partial \varepsilon_i}{\partial c_i} = \frac{\varepsilon_i(c_i + \Delta c_i) - \varepsilon_i(c_i)}{\Delta c_i} \quad \text{... (37)}$$

$$\gamma_i \approx \frac{\partial \varepsilon_i}{\partial c_{i+1}} = \frac{\varepsilon_i(c_{i+1} + \Delta c_{i+1}) - \varepsilon_i(c_{i+1})}{\Delta c_{i+1}} \quad \text{... (38)}$$

Where, $\Delta c_i = \delta \cdot c_i$; $\delta > 0$ .... (39)

The Jacobean matrix can be written in form of algebraic equations, such as:

$$\alpha_i \cdot \delta c_{i-1} + \beta_i \cdot \delta c_i + \gamma_i \cdot \delta c_{i+1} = -\varepsilon_i \quad \text{... (40)}$$

Thomas algorithm is used to solve Eq.40 to obtain δc, and *c* is upgraded with the following equation:

$$c_i^{k+1} = c_i^{k} + \delta c_i^{k} \quad \text{.......................(41)}$$

Where, *k* is number of iteration.

Boundary conditions are in the form:

$$\left.\frac{\partial c}{\partial x}\right|_{x=0} = 0 \quad \text{.................................(42)}$$

$$\left.\frac{\partial c}{\partial x}\right|_{x=n} = 0 \quad \text{.................................(43)}$$

3.3. Soil Properties and Numerical Constants

Soil properties required here are saturated hydraulic conductivity (K_S), effective storativity (*S*) and Dispersivity (A_L). As shown in Figure 3 and Figure 4, these values can be given based on the corresponding soil type, and in this study are 0.005 cm/d, 0.5 and 0.1 cm, respectively. Initial condition for water level as well as for solute concentration in the soil can be given whether homogeneously or according to actual values found in the real fields. In this study, the initial water level was given 10 cm below the soil surface and the initial solute was zero fraction of free of the applied solute.

Figure 3 and Figure 4 show also numerical constants for special and temporal discretization, such as number of nodes (*N*), length between two adjacent nodes (*dx*), time step (*dt*), etc. There is an initial time step but this time step will increase according to how fast the error tolerance is attained, as such the iteration (*k*) is lower to any given value. But then the time step is kept constants when it reaches 1 day. The error tolerance is given 0.00001 and less than it for both water flow and solute transport.

3.4. Calculation Procedures

The calculation procedures are separated into 2 stages, as follow:

1) Calculation of water flow equation
    a. Calculate water level (*h*) according to Eq.26 and upgrade *h* until Eq.18 is conformed.
    b. Increase new time with adding the time step (*dt*) to the previous time.
    c. Calculate and record water flow velocity (Eq.12), and infiltration (Eq.4), transpiration (Eq.5), percolation (Eq.7) and evaporation (Eq.9) rates.
    d. Repeat the calculation from step (1.a) above until the new time equals a determined end time.
2) Calculation of solute concentration
    a. Calculate solute concentration (*c*) according to Eq.40 and upgrade *c* until Eq.32 is conformed.
    b. Calculate root extraction (Eq.14) and loss by percolation (Eq.15).
    c. Repeat the calculation from step (2.a) above until the new time equals a determined end time.

IV. RESULTS AND DISCUSSION

4.1. Computer Program

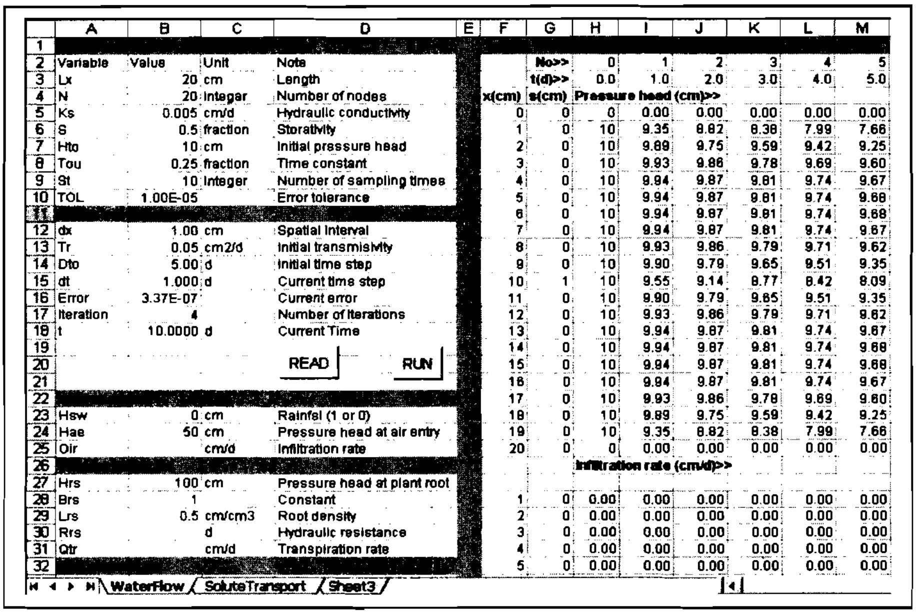
Computer programs are written in Visual Basic Editor within MS Excel. Figure 3 and 4 show partial appearances of the spreadsheets used for inputting data and outputting results of water flow and solute transport equations, respectively. Previously attempts to build computer program in these environments was simulations on unsaturated water flow in various boundary conditions (Setiawan, *et.al.*, 2007).

As shown in Fig. 3, columns A, B, C and D are used for data input, which is then read by a command button READ. After ward, columns E, F, G and H are then generated to visualize nodes, distances, sink/sources, and initial pressure head. Such as an example shown above, sink is given 1 when the respective node is occupied by a plant, and for the otherwise sink is 0. Later on by pressing the command button RUN, the computation begins and the results will be displayed in cells I3 to the right at any given times. Below the pressure head, results for infiltration, transpiration, percolation, evaporation and pore velocity are successively displayed. Results of pore velocity will then be read as inputs for the computation of solute transport equation.

Iterative process completed when Error (B16) is less than TOL (B10). Time interval can decrease or increase when iteration exceeds a maximum or is under a minimum limits. Number of times when results to be displayed can be entered in B9, while the real time can be inserted ascendingly in cells I3 to the right.

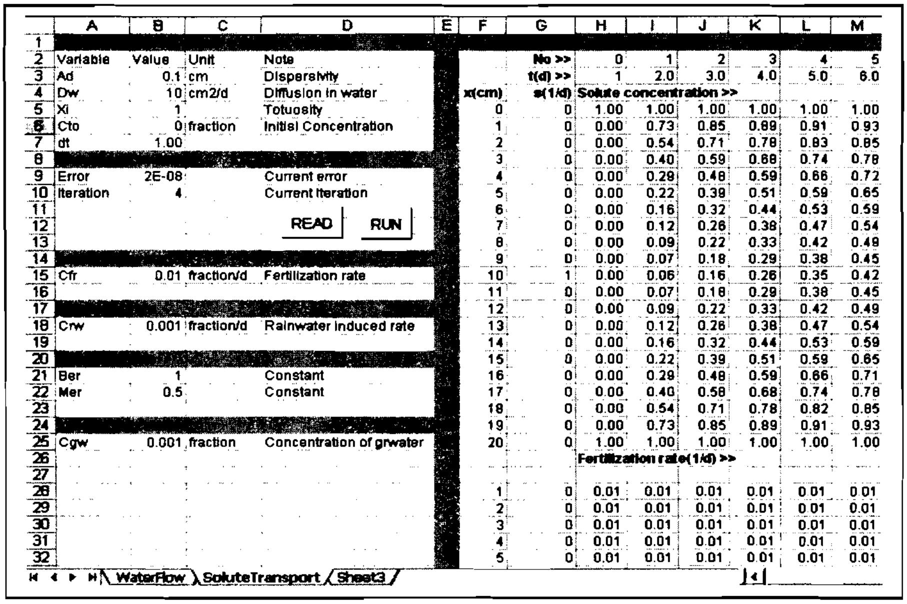
As shown in Fig.4, by pressing button READ, some related data from the previous spreadsheet WaterFlow are read, and additional data in Spreadsheet SoluteTransport is inputted. And by pressing button RUN computation begins, and results data is displayed at any similar given times. Here, the time interval is maintained at the same value throughout the computational process. Iterative process completed when Error (B16) is less than TOL (B10).

Initially, the water level is on the soil surface, and as the time passes by, water levels at the boundaries go to 10 cm below the soil surface. Relative solute concentration is also at high values (1) initially, and the boundaries are set to 0. Fertilization is only applied at the beginning of simulation. There is no rainfall throughout the simulation period.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	Variable	Value	Unit	Note			No>>	0	1	2	3	4	5
3	Lx	20	cm	Length			t(d)>>	0.0	1.0	2.0	3.0	4.0	5.0
4	N	20	integar	Number of nodes		x(cm)	s(cm)	Pressure head (cm)>>					
5	Ks	0.005	cm/d	Hydraulic conductivity		0	0	0	0.00	0.00	0.00	0.00	0.00
6	S	0.5	fraction	Storativity		1	0	10	9.35	8.82	8.38	7.99	7.66
7	Hto	10	cm	Initial pressure head		2	0	10	9.89	9.75	9.59	9.42	9.25
8	Tou	0.25	fraction	Time constant		3	0	10	9.93	9.86	9.78	9.69	9.60
9	St	10	Integer	Number of sampling times		4	0	10	9.94	9.87	9.81	9.74	9.67
10	TOL	1.00E-05		Error tolerance		5	0	10	9.94	9.87	9.81	9.74	9.68
11						6	0	10	9.94	9.87	9.81	9.74	9.68
12	dx	1.00	cm	Spatial interval		7	0	10	9.94	9.87	9.81	9.74	9.67
13	Tr	0.05	cm2/d	initial transmisivity		8	0	10	9.93	9.86	9.79	9.71	9.62
14	Dto	5.00	d	initial time step		9	0	10	9.90	9.79	9.65	9.51	9.35
15	dt	1.000	d	Current time step		10	1	10	9.55	9.14	8.77	8.42	8.09
16	Error	3.37E-07		Current error		11	0	10	9.90	9.79	9.65	9.51	9.35
17	Iteration	4		Number of Iterations		12	0	10	9.93	9.86	9.79	9.71	9.62
18	t	10.0000	d	Current Time		13	0	10	9.94	9.87	9.81	9.74	9.67
19						14	0	10	9.94	9.87	9.81	9.74	9.68
20						15	0	10	9.94	9.87	9.81	9.74	9.68
21						16	0	10	9.94	9.87	9.81	9.74	9.67
22						17	0	10	9.93	9.86	9.78	9.69	9.60
23	Hsw	0	cm	Rainfel (1 or 0)		18	0	10	9.89	9.75	9.59	9.42	9.25
24	Hae	50	cm	Pressure head at air entry		19	0	10	9.35	8.82	8.38	7.99	7.66
25	Oir		cm/d	Infiltration rate		20	0	0	0.00	0.00	0.00	0.00	0.00
26								Infiltration rate (cm/d)>>					
27	Hrs	100	cm	Pressure head at plant root									
28	Brs	1		Constant		1	0	0.00	0.00	0.00	0.00	0.00	0.00
29	Lrs	0.5	cm/cm3	Root density		2	0	0.00	0.00	0.00	0.00	0.00	0.00
30	Rrs		d	Hydraulic resistance		3	0	0.00	0.00	0.00	0.00	0.00	0.00
31	Qtr		cm/d	Transpiration rate		4	0	0.00	0.00	0.00	0.00	0.00	0.00
32						5	0	0.00	0.00	0.00	0.00	0.00	0.00

Figure 3. Partial appearances of spreadsheet for inputting data and outputting results of water flow computation



	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	Variable	Value	Unit	Note			No >>	0	1	2	3	4	5
3	Ad	0.1	cm	Dispersivity			t(d) >>	1	2.0	3.0	4.0	5.0	6.0
4	Dw	10	cm2/d	Diffusion in water		x(cm)	s(1/d)	Solute concentration >>					
5	Xi	1		Totuosity		0	0	1.00	1.00	1.00	1.00	1.00	1.00
6	Cto	0	fraction	Initial Concentration		1	0	0.00	0.73	0.85	0.89	0.91	0.93
7	dt	1.00				2	0	0.00	0.54	0.71	0.78	0.83	0.85
8						3	0	0.00	0.40	0.59	0.68	0.74	0.78
9	Error	2E-08		Current error		4	0	0.00	0.29	0.48	0.59	0.66	0.72
10	Iteration	4		Current Iteration		5	0	0.00	0.22	0.39	0.51	0.59	0.65
11						6	0	0.00	0.16	0.32	0.44	0.53	0.59
12						7	0	0.00	0.12	0.26	0.38	0.47	0.54
13						8	0	0.00	0.09	0.22	0.33	0.42	0.49
14						9	0	0.00	0.07	0.18	0.29	0.38	0.45
15	Cfr	0.01	fraction/d	Fertilization rate		10	1	0.00	0.06	0.16	0.26	0.35	0.42
16						11	0	0.00	0.07	0.18	0.29	0.38	0.45
17						12	0	0.00	0.09	0.22	0.33	0.42	0.49
18	Crw	0.001	fraction/d	Rainwater induced rate		13	0	0.00	0.12	0.26	0.38	0.47	0.54
19						14	0	0.00	0.16	0.32	0.44	0.53	0.59
20						15	0	0.00	0.22	0.39	0.51	0.59	0.65
21	Ber	1		Constant		16	0	0.00	0.29	0.48	0.59	0.66	0.71
22	Mer	0.5		Constant		17	0	0.00	0.40	0.58	0.68	0.74	0.78
23						18	0	0.00	0.54	0.71	0.78	0.82	0.85
24						19	0	0.00	0.73	0.85	0.89	0.91	0.93
25	Cgw	0.001	fraction	Concentration of grwater		20	0	1.00	1.00	1.00	1.00	1.00	1.00
26								Fertilization rate(1/d) >>					
27													
28						1	0	0.01	0.01	0.01	0.01	0.01	0.01
29						2	0	0.01	0.01	0.01	0.01	0.01	0.01
30						3	0	0.01	0.01	0.01	0.01	0.01	0.01
31						4	0	0.01	0.01	0.01	0.01	0.01	0.01
32						5	0	0.01	0.01	0.01	0.01	0.01	0.01

Figure 4. Partial appearances of spreadsheet for inputting data and outputting results of solute transport computation

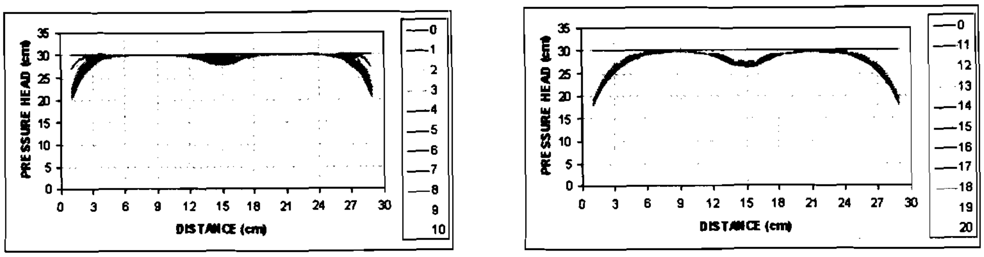
4.2. Pressure Head Profiles

4.2. Pressure Head Profiles

Figure 5 shows profiles of water pressure head in the soil when there is a paddy plant in between two neighboring on-farm canals. At this simulation, the distance between the two canals is 30 cm, and the location of the paddy plant is at 15 cm. In the initial time, water head is at 30 cm above a reference level, and the water head at the boundary conditions, 0 cm and 30 cm are maintained constant at 15 cm and there is an insignificant rainfall through out the simulation.

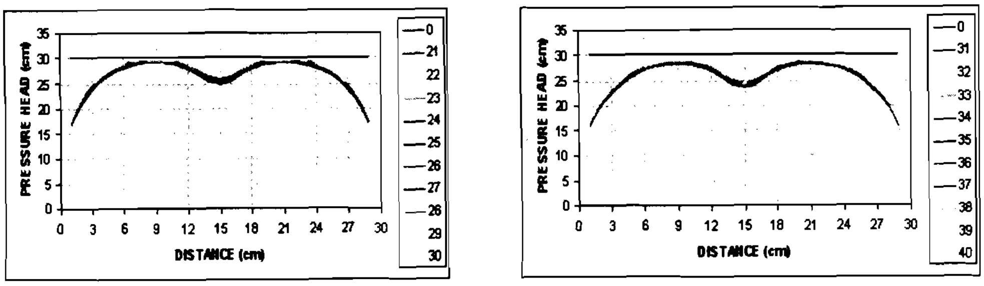
Decrease of water head is mainly due to evaporation from the soil surface and evapotranspiration of the plant and deep percolation which are all depend upon the water level. As shown in Fig.5 (a), after 10 days there is no significant change of water level in the soil but slowly the water level decrease furthermore with time. After 40 days, Fig.5 (d) water level just below the plant maintains at 25 cm. Its position will be lower as time passes and in the infinite time it will reach below 15 cm.

Water which is available for the plant is that the portion of water which is retained in the soil pore above the water level. It will depend on the water level its self. According to water retention curve (suction head vs. water content), the available water content is also dependent upon texture and structure of the soil and the most important thing is the net of water fluxes which is mostly vary with climate fluctuation and plant growth. Once a preferable water content or suction head has been determined it can be controlled by setting the water level at boundary conditions. These boundary conditions may vary with time as they give response to climate fluctuation and plant growth. These boundary values can be manipulated artificially by applying drainage and irrigation in the on farm canals. It is then possible to simulate water level controller which is incorporated to the water flow equation.



(a) After 10 days

(b) After 20 days



(c) After 30 days

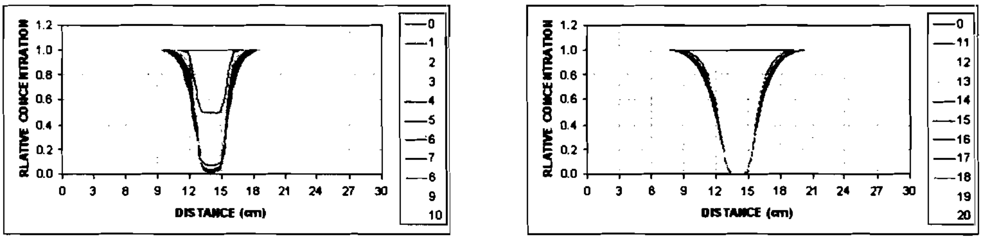
(d) After 40 days

Figure 5. Profiles of simulated pressure head at successive times

4.3. Solute Concentration Profiles

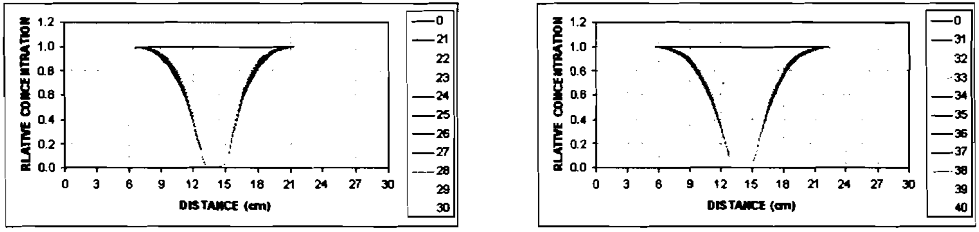
Figure 6 shows solute concentration profiles in the soil at several elapsed times. Hence, type of solute is not specifically given and the concentration is given as fraction. Initially, the concentration is applied at unity. As shown in Fig.2, the dispersivity is 0.1 cm and the diffusion coefficient is 10 cm^2/d. Previously, water flow velocity was calculated at each corresponding time shown in Fig.4 using Eq. 4.1. 1, and then stored in form of spreadsheet. Herewith, the time step is constant at 1 day, and data of water flow velocity is inputted subsequently. As shown in Fig.6 (a), solute concentration in the middle of the soil profile decreases fast with passing times, and reaches about nil, the lowest reasonably fixed value, after 10 days. Later on, decrease of solute concentration spreads to lateral distances. But because, at the boundary conditions, the concentrations are fixed at the unity values, the decreasing spread of solute is restraint somewhere about 2-3 cm to the inner part from the boundary points even after passing 40 days.

This setting of boundary conditions may not go along with the real phenomenon which is more likely following natural boundary condition, or Neumann's boundary condition. Course, applying Neumann's boundary condition is not difficult one. However, in this moment it is clear that this simulation has gained reasonable results which to some extent show the capability to incorporate water flow equation and solute transport. In SRI practices, this simulation technique is of interest when a precise application of fertilizer in precise time and quantity becomes an important issue along with water productivity. This simulation is also possible to find an exact location of a ransom fertilizer, such as point source in the soil whether just below the plant's roots or between two neighboring plants. In this matter, efficient and effective fertilizations can be guaranteed.



(a) After 10 days

(b) After 20 days



(c) After 30 days

(d) After 40 days

Figure 6. Profiles of solute concentration at successive times

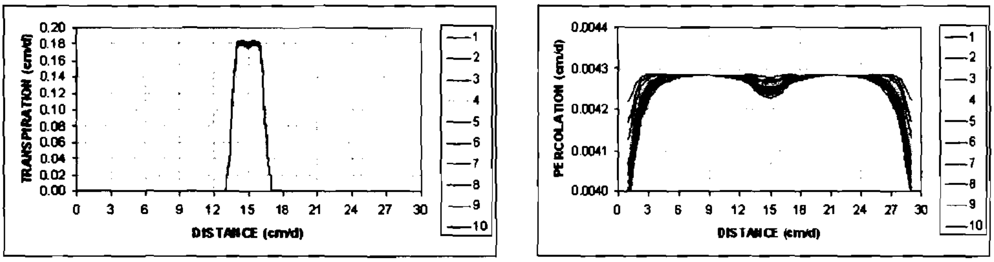
4.4. Transpiration, Percolation, Root Extraction and Leaching

Figure 7 shows transpiration, percolation, root extraction and leaching at successive times over 10 days. Here again, transpiration Fig.7 (a) is higher closer to the plant but its effect to the lateral decrease of water head is not significant in which attains less than 1 cm.

Percolation, Fig.7 (b) is higher at higher water level and decreases proportionally as water level gets lower. Percolation may cease when groundwater level rise eventually and its position are closer to the water level. In this situation, water clogged may occur. Thus, to lower the water level may needs artificial drainage such as mole drain or draining pipe submerged below the groundwater table. This is what have been applied in modernized paddy fields, i.e., in Japan. This simulation technique is applicable to find precise locations and intervals of draining pipes, i.e., when it is given preferably reasonable percolation rate.

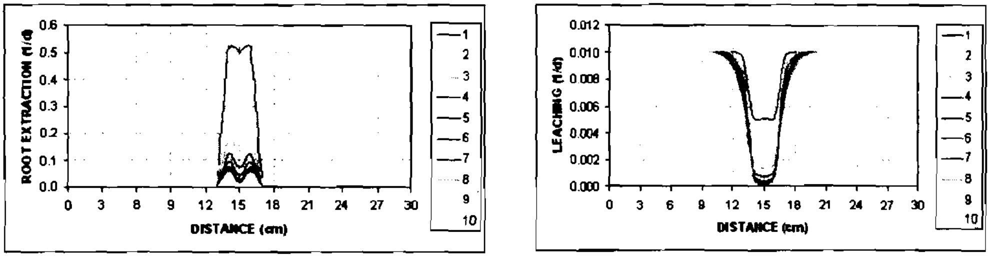
Root extraction, Fig.7 (c) decreases fast over 10 days as solute becomes unavailable but its effects are laterally limited within 1 cm distance from the location of the plant. It is suggestible to introduce a subsequent fertilizer, say that when root extraction goes beyond a half or more from the initial value since this situation may severe plant growth. However, as plant's roots expand, their capability to extract fertilizer from farther location will increase.

Solute leaching to groundwater, Fig.7 (d) decreases as solute concentration in the soil decreases. Percolation rate, the convective flow contributes more on this process compared to solute concentration (diffusion) difference between that in the soil and the groundwater. However, it may be on the contrary when the soil clogged with water up to the groundwater.



(a) Transpiration

(b) Percolation



(c) Root extraction

(d) Leaching

Figure 7. Transpiration, percolation, root extraction and leaching at successive times

V. CONCLUSIONS AND RECOMMENDATIONS

Mathematical modeling and simulation have been initially developed to estimate water level and solute concentration in a paddy field soil under partially submerged conditions. The computational techniques have shown outstanding stabilities and fast convergences. Using rather hypothetical data and parameters, the models have shown reasonable results. The models are widely open to revise and/or include more sink/source terms.

Heat transfer equation needs to be integrated since most chemical and biological activities in soil are highly influenced by soil temperature. Appropriate control system should be developed, in example to maintain preferable depth of water table that will optimize plant growths and yields.

Further development of these integrated models need involvement of scientists in related fields, in particular Soil Physics and Hydrology, Soil Chemistry, Soil Biology, Agronomics, Paddy Field Engineering, etc.

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