MODELING OF SOLUTE TRANSPORT IN AGRICULTURAL FIELDS USING SWIM

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ABSTRACT

Modern agricultural activities are based on the extensive use of fertilizers and pesticides to obtain high crop yield. Some of the chemicals applied to farm land, however, move down with the deep percolating water from the root zone and can contaminate underlying ground water. The problem becomes more complicated when dealing with different kinds of soil with varying properties. In the present study, solute transport in three agricultural plots (Jowar, Gram and Safflower located at Belvatgi in Malaprabha subbasin in Dharwad district, Karnataka) has been modelled using a software package, SWIM (Soil Water Infiltration and Movement). Known quantities of fertilizer were applied and field/laboratory investigations were carried out for monitoring the chemical constituent (Nitrogen/Phosphorous/Potassium) at varying depths upto 120 cm. Field observed and simulated (through SWIM) solute concentration (N, P and K) profiles after application of fertilizer were compared. The model can be used to predict the cumulative solute in the soil profile for different scenarios of fertilizer applications.

1.0 INTRODUCTION

Pollution of water resources from agricultural activities is a very complex, social, and environmental problem that poses a challenge to our social and economic institutions, government, agribusiness, and the public at large. The increasing use of plant nutrients in agriculture, mainly through inorganic fertilizers, contributes nutrients to water sources because plants do not absorb all the nutrients applied on the land (Singh et al., 1999). The impact of agricultural activities on groundwater quality is closely related with the quality of water from precipitation, and irrigation water.

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In order to reach a phreatic aquifer, water from precipitation, from irrigation, or from an influent river, infiltrates through the ground surface and percolates downward through the unsaturated zone. The same is true for pollutants carried with the water. These pollutants may be already present in the water reaching the ground surface, or they may be added to the water by processes of leaching, dissolution, and desorption along its path, from the ground water to an underlying aquifer. Solid waste in landfills, septic tanks, fertilizers, pesticides and herbicides, applied over extended areas and dissolved in the water applied to the ground water, may serve as examples of sources of pollutants that travel through the unsaturated zone (Ratnoji, 2001).

Soil-Water systems in the unsaturated zone are highly complex. Firstly, it is seldom in stable equilibrium and is in constant flux. The degree of saturation of soil-water (θ) varies both in time and space. This in turn affects flow parameters namely the suction head h (θ) and the hydraulic conductivity $K(\theta)$ which are not unique functions of θ, but exhibit hysterises. In addition, there is the effect of airflow through the soil and the compressibility of air, which may have some effect on unsaturated flow, and in some cases, the soil may undergo chemical changes.

Water quality problems of all kinds stem from the lack of awareness of these processes. Fertilizers are normally applied to agricultural fields to increase the crop yields. However, a part of the chemical constituents present in the fertilizer may percolate down to reach the ground water table thereby polluting the fresh water aquifers. It is therefore important to limit the application of fertilizers and monitor their movement in the unsaturated zone.

The downward movement of a chemical in the field is generally measured by applying known amount of the chemical at the surface and then measuring the increase in the amount of the chemical found at different depths in the unsaturated zone at suitable intervals. Because of the variability from one site to another, measurements at many locations are needed to obtain a good estimate of the downward movement in an area such as an agriculture field.

In the present study, a numerical model, SWIM (Verburg et al., 1996) based upon Richard’s equation, has been applied to simulate the movement of solute in the unsaturated zone. SWIM is an acronym that stands for Soil-Water-Infiltration and Movement. It is based on a numerical solution of the Richard’s equation and the advection-dispersion equation. It can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. Soil water and solute transport properties, initial conditions, and time dependent boundary conditions (e.g. precipitation, evaporative demand, and solute input) need to be supplied to run the model.

2.0 STUDY AREA

The agricultural plots selected for the present study are located in Nargund and Navalgund taluks in Malaprabha subbasin in Dharwad district, Karnataka. The geographical area of these taluks is about 743 sq.km., surrounded by Malaprabha river in the north, Tupari nalla in the south, and Bennihalla on the East. Length of the Malaprabha river in this reach measures about 30 kms. Western boundary is considered as outcrop boundary. The zone lies between $15^0$30' and 16^0 N latitudes and 75^0 30' and 75^0 45' E longitudes. Average surface gradient is 0.80 m/km and in general West to East. Figure 1 presents the location map. Three agricultural plots (Jowar, Green Gram, and Safflower) were selected in Belvatgi for the present study.

Geologically, the area comprises of schistose rock formations (Dharwar Super Group) which includes granites, gneisses and crystalline rocks. The lithological sequence of the study area shows that top 3m is composed of purely black soil, and below that upto 30 m weathered granite and medium hard granites with fractures. There is no major fault or dykes controlling the ground water flow. Deep black to medium black soils constitute the important group of soils in the study area. These soils are derived mainly from the parent materials like gneiss, schists and traps. The texture of the soil is usually clayey throughout the profile. At places, on surface, clay loam to silty clay texture is also common. Soils are highly retentive and fertile and are moderately well drained to imperfectly drained with very low permeability.

Rainfall is the primary source of recharge to groundwater storage. Rainfall occurs due to south-west monsoon from June to October. Irrigation water requirement has shown increasing trend against a decreasing trend of water availability over the last 10 to 15 years. On introduction of irrigation in command area, the fertiliser consumption has also been increased.

Hydrogeological studies conducted by various state and Central departments reported that groundwater occurs in all formations of the area. However, movement of groundwater in these rocks is controlled by degree of weathering and presence of joints (Majumdar et al., 1997). Overall groundwater quality of the region is poor. Almost all the chemical constituents either have crossed or on the verge of crossing their permissible limits in most of the locations. As per the data provided by Department of Mines and Geology, TDS value is as high as 9000 mg/l at some places. Chloride, Sulphate, Bicarbonate and Sodium contents in groundwater are alarming in almost all the places (Majumdar et al., 1997).

3.0 METHODOLOGY

The present study involves modelling of soil moisture movement and solute transport in agricultural fields using the SWIM model. The following steps were undertaken for the study.

- **Identification of agricultural plots** in Belvatgi – Jowar, Green Gram, and Safflower.

- **Field investigations –** measurement of saturated hydraulic conductivity using Guelph Permeameter and soil sampling before and after application of fertilizer (N-P-K).

- **Laboratory investigations –** Determination of saturated moisture content, soil moisture retention characteristics using the Pressure Plate Apparatus, and total available nitrogen, phosphorous, potassium concentrations in soil before and after application of fertilizer (N-P-K) and irrigation.

- **Modelling** of soil moisture movement and solute transport using the SWIM model. Field observed and simulated (through SWIM) solute concentration (N, P and K) profiles after application of fertilizer and irrigation were compared.

4.0 THE SWIM

SWIM is an acronym that stands for Soil Water Infiltration and Movement. It is a software package developed within the CSIRO Division of Soils for simulating infiltration, evapotranspiration, and redistribution. The first version (SWIMv1) was published in 1990 (Ross, 1990). Version 2 of the model (identified as SWIMv2.0), which combines water movement with transient solute transport and which accommodates a variety of soil property descriptions and more flexible boundary conditions, was completed in 1992. The latest version, SWIMv2.1, has been described here.

SWIMv2 is based on a numerical solution of the Richards' equation and the advection-dispersion equation. It can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. The physical system and the associated flows addressed by the model are shown schematically in Figure 2. Soil water and solute transport properties, initial conditions, and time dependent boundary conditions (e.g., precipitation, evaporative demand, solute input) need to be supplied by the user in order to run the model.

The model deals with a one-dimensional soil profile. For a vertical soil profile, this means that it may be vertically inhomogeneous, but must be horizontally uniform. This assumption has two consequences of importance in many common simulations. There is only one hydraulic conductivity function for each soil layer, so that any macropore, or bypass, flow can only be accounted for in a limited way. Secondly, the calculated solute concentrations apply to the whole soil layer, which means that there is no concentration gradient from the bulk soil to near the root surface. The presence of such a concentration gradient may in reality affect the soil osmotic potential and hence water and solute uptake. The overall purpose of the model is to address issues relating to the soil water and solute balance. As such, it is a research tool that can be integrated in laboratory and field studies concerned with soil water and solute transport.

5.0 ANALYSIS AND RESULTS

5.1 Soil Moisture Characteristics

To model the retention and movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure, water content and hydraulic conductivity. It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model

The measurements of $\theta(h)$ from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model. Once the retention function is estimated, the hydraulic conductivity relation, $K(h)$, can be evaluated if the saturated hydraulic conductivity, K_s, is known. In the present study, parameters of van Genuchten model were derived for soil moisture retention and hydraulic conductivity functions. For the van Genuchten model (1980), the water retention function is given by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = [1 + (\alpha_v |h|)^n]^{-m} \quad \text{for } h < 0$$
$$= 1 \quad \text{for } h \geq 0 \quad \ldots(1)$$

and the hydraulic conductivity function is described by

$$K = K_s S_e^{1/2} [1 - (1 - S_e^{1/m})^m]^2 \quad \ldots(2)$$

where, θ_r and θ_s are residual and saturated moisture contents respectively; α_v and n are van Genuchten model parameters, m = 1 – 1/n.

Saturated hydraulic conductivity was measured in field using Guelph Permeameter. Soil samplings were done in the three agricultural plots before and after application of fertilizer (N-P-K). Soil moisture retention characteristics were determined in the laboratory using the Pressure Plate Apparatus. The experimental soil moisture retention data were fitted to the van Genuchten model (1980). The parameters of soil moisture retention function and hydraulic conductivity function were obtained through non-linear regression analysis. Table 1 presents the van Genuchten parameters α and n (equations 1 and 2) for the three agricultural plots.

Table 1 : van Genuchten Parameters for the Agricultural Plots

S. No.	Plot	Saturated Moisture Content (θ_s)	Residual Moisture Content (θ_r)	Van Genuchten Parameters	
				α	n
1.	Jowar	0.372	0.098	0.00119	1.327
2.	Gram	0.398	0.097	0.00083	1.385
3.	Safflower	0.345	0.092	0.00037	1.492

5.2 Model Conceptualization

Modelling of soil moisture movement and solute transport was done using the SWIM model. Solute is included in the simulation through application of fertilizer (N-P-K) at the surface. The model was simulated for 30 days comprising two irrigations of 6 cm each on 3rd and 20th day and one application of fertilizer (solute). This solute will enter the soil profile with the irrigation. One vegetation type is present in each of the three plots (Jowar, Green Gram, Safflower) selected for the study. Exponential root growth with depth and linear interpolation with time was considered. The following parameters were considered for the three vegetations.

Jowar

Root radius (rad)	=	0.08 cm
Root conductance (groot)	=	$1.2 * 10^{-7}$
Minimum xylem potential (psimin)	=	-15,000 cm
Root depth constant (xc)	=	30 cm
Maximum root length density (rldmax)	=	4 cm/cm^3

Green Gram

Root radius (rad)	=	0.12 cm
Root conductance (groot)	=	$1.0 * 10^{-7}$
Minimum xylem potential (psimin)	=	-15,000 cm
Root depth constant (xc)	=	30 cm
Maximum root length density (rldmax)	=	3 cm/cm^3

Safflower

Root radius (rad)	=	0.10 cm
Root conductance (groot)	=	$1.4 * 10^{-7}$
Minimum xylem potential (psimin)	=	-15,000 cm
Root depth constant (xc)	=	30 cm
Maximum root length density (rldmax)	=	5 cm/cm^3

The profile is 200 cm deep with surface at 0 cm and bottom boundary condition applying at 200 cm. There is no solute exclusion from plant water uptake, i.e. all solute dissolved in the uptake water is also taken up by the plant. Vapour conductivity is not taken into account, nor is the effect of osmotic potential. There is one hydraulic property set for each plot and one solute property set that applies to all 21 depth nodes of the 200 cm deep profile. Hysteresis is not taken into account. Solute gets adsorbed with linear isotherm.

Initially, there is no water ponded on the surface and (hence) solute concentration of “ponded” water is zero. Runoff is governed by a simple power law function and a surface conductance function. A matric potential gradient of 0, i.e. “unit gradient”, has been applied as bottom boundary condition throughout the simulation. No bypass flow was included. There is no solute input with rain or irrigation.

5.3 Modelling of Solute Transport

The solute transport in the unsaturated zone was modelled by using SWIM. The fertilizer (N-P-K) was applied at the surface once during the 30 days of simulation period. The amount of fertilizer applied included 106 mg Nitrogen/kg of soil, 106 mg Phosphorous/kg of soil, and 53 mg Potassium/kg of soil for all the three plots.

Total available nitrogen, phosphorous, and potassium concentrations for soil samples collected from the three plots (before and after application of fertilizer) were determined in the laboratory by alkaline potassium permanganate method, Olsen's method, and Flame-photometry respectively. The model simulations provide solute concentration profiles and cumulative solute at different times.

Field observed and simulated (through SWIM) solute concentration (N, P and K) profiles after application of fertilizer and irrigation are given in Tables 2 to 10 for the three agricultural plots. It can be seen that observed and simulated concentration profiles match reasonably well for almost all the cases, thereby validating the model parameters.

Different scenarios of fertilizer applications were also tested to find the impact of quantity of fertilizer applied on the cumulative solute in the soil profile. The tested quantities involved 2, 3, 5 and 10 times the original. It was observed that with increase in the amount of fertilizer applied, the cumulative solute (N, P, K) increases proportionately, thereby enhancing the risk for pollution of ground water in due course of time. Care should therefore be taken to limit the amount of fertilizer application in the irrigated fields only to the extent required by the crops.

Table 2 : Observed and Simulated Nitrogen Concentration Profiles in Jowar Plot

S. No.	Sample Depth (cm)	Initial observed Nitrogen		Observed Nitrogen after 24 days		Simulated Nitrogen after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	134.82	0.06741	168.33	0.084165	0.0861
2.	20-40	74.90	0.03745	76.11	0.038055	0.0391
3.	40-60	44.94	0.02247	48.88	0.024440	0.0232
4.	60-80	89.88	0.04494	98.15	0.049075	0.0453
5.	80-100	104.86	0.05243	109.81	0.054905	0.0534
6.	100-120	70.90	0.03545	74.94	0.037470	0.0360

Table 3 : **Observed and Simulated Nitrogen Concentration Profiles in Gram Plot**

S. No.	Sample Depth (cm)	Initial observed Nitrogen		Observed Nitrogen after 24 days		Simulated Nitrogen after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	194.74	0.09737	208.17	0.104085	0.1150
2.	20-40	194.74	0.09737	196.35	0.098175	0.0985
3.	40-60	104.86	0.05243	107.77	0.053885	0.0543
4.	60-80	134.82	0.06741	146.22	0.073110	0.0682
5.	80-100	164.78	0.08239	177.66	0.088830	0.0838
6.	100-120	104.86	0.05243	108.80	0.054400	0.0533

Table 4 : **Observed and Simulated Nitrogen Concentration Profiles in Safflower Plot**

S. No.	Sample Depth (cm)	Initial observed Nitrogen		Observed Nitrogen after 24 days		Simulated Nitrogen after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	155.98	0.07799	179.76	0.08988	0.09630
2.	20-40	88.80	0.04440	89.88	0.04494	0.04660
3.	40-60	113.40	0.05670	119.84	0.05992	0.05710
4.	60-80	137.64	0.06882	149.80	0.07490	0.06950
5.	80-100	98.70	0.04935	104.86	0.05243	0.05050

Table 5 : **Observed and Simulated Potassium Concentration Profiles in Jowar Plot**

S. No.	Sample Depth (cm)	Initial observed Potassium		Observed Potassium after 24 days		Simulated Potassium After 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	625	0.3125	1002.00	0.5010	0.4819
2.	20-40	486	0.2430	744.60	0.3723	0.3733
3.	40-60	428	0.2140	653.40	0.3267	0.3273
4.	60-80	237	0.1185	363.80	0.1819	0.1827
5.	80-100	340	0.1700	521.80	0.2609	0.2603
6.	100-120	381	0.1905	581.80	0.2909	0.2915

Table 6 : Observed and Simulated Potassium Concentration Profiles in Gram Plot

S. No.	Sample Depth (cm)	Initial observed Potassium		Observed Potassium after 24 days		Simulated Potassium After 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	525	0.2625	798.00	0.3990	0.4054
2.	20-40	312	0.1560	490.60	0.2453	0.2423
3.	40-60	293	0.1465	448.00	0.2240	0.2239
4.	60-80	262	0.1310	420.00	0.2100	0.2005
5.	80-100	293	0.1465	450.00	0.2250	0.2244
6.	100-120	237	0.1185	362.00	0.1810	0.1814

Table 7 : Observed and Simulated Potassium Concentration Profiles in Safflower Plot

S. No.	Sample Depth (cm)	Initial observed Potassium		Observed Potassium after 24 days		Simulated Potassium After 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	200	0.1000	299.20	0.1496	0.1587
2.	20-40	260	0.1300	390.00	0.1950	0.1972
3.	40-60	160	0.0800	250.60	0.1253	0.1240
4.	60-80	320	0.1600	483.40	0.2417	0.2423
5.	80-100	440	0.2200	682.00	0.3410	0.3352

Table 8 : Observed and Simulated Phosphorous Concentration Profiles in Jowar Plot

S. No.	Sample Depth (cm)	Initial observed Phosphorous		Observed Phosphorous after 24 days		Simulated Phosphorous after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	48	0.0240	79.80	0.0399	0.0425
2.	20-40	34	0.0170	35.80	0.0179	0.0175
3.	40-60	37	0.0185	37.20	0.0186	0.0187
4.	60-80	54	0.0270	55.80	0.0279	0.0273
5.	80-100	111	0.0555	122.00	0.0610	0.0564
6.	100-120	68	0.0340	70.00	0.0350	0.0346

Table 9 : **Observed and Simulated Phosphorous Concentration Profiles in Gram Plot**

S. No.	Sample Depth (cm)	Initial observed Phosphorous		Observed Phosphorous after 24 days		Simulated Phosphorous after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	20	0.0100	61.80	0.0309	0.0269
2.	20-40	45	0.0225	45.00	0.0225	0.0223
3.	40-60	40	0.0200	40.00	0.0200	0.0203
4.	60-80	15	0.0075	16.20	0.0081	0.0078
5.	80-100	12	0.0060	11.80	0.0059	0.0061
6.	100-120	36	0.0180	37.80	0.0189	0.0183

Table 10 : **Observed and Simulated Phosphorous Concentration Profiles in Safflower Plot**

S. No.	Sample Depth (cm)	Initial observed Phosphorous		Observed Phosphorous after 24 days		Simulated Phosphorous after 24 days
		Kg/ha	mg/cm^3	Kg/ha	mg/cm^3	mg/cm^3
1.	0-20	68	0.0340	120.00	0.0600	0.0518
2.	20-40	128	0.0640	131.80	0.0659	0.0635
3.	40-60	44	0.0220	48.40	0.0242	0.0238
4.	60-80	50	0.0250	51.00	0.0255	0.0253
5.	80-100	94	0.0470	96.20	0.0481	0.0473

6.0 CONCLUSION

Modelling is important for the study of agriculture system since it helps in gaining a better understanding of the present and past of the system and better forecasting of future behaviour of the system; in evaluation of policies and strategies without implementing them on the real world; and in selection of better policies and strategies. Application of SWIM model is one of the simplest techniques, which is well suited for unsaturated zone.

In the present study, soil moisture movement and solute transport in three agricultural plots (Jowar, Gram and Safflower located at Belvatgi in Malaprabha subbasin in Dharwad district, Karnataka) has been modelled using SWIM. Field observed and simulated (through SWIM) solute concentration (N, P and K) profiles after application of fertilizer were compared and found to match reasonably well. The model can therefore be used to predict the cumulative solute in the soil profile for different scenarios of fertilizer applications.

The scope of the present study can be extended by monitoring the solute concentration profiles during the entire crop growth period in response to various irrigation and fertilizer applications and determining the leaching requirements.

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