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Anomaly between the Theoretical and Actual Groundwater Flow Velocity in the Unsaturated Zone

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Various studies have shown that groundwater tends to flow faster than predicted by the conventional advection-dispersion-diffusion model. This tendency is pronounced in the unsaturated zone compared to the saturated zone. To determine this tendency quantitatively, an experiment was conducted on intact and repacked soil columns. The columns were subjected to simulated irrigation. The resulting soil moisture breakthrough curves (BTCs) were analyzed and compared with the theoretical BTCs to assess the degree of anomaly between the theoretical and actual groundwater flow velocity. The results show that, due to the preferential (bypass) flow, the actual velocity of groundwater flow is about two times faster than the theoretical one. The dye experiment, conducted to obtain visual evidence of the preferential flow, matched the conclusions of the chemical experiment.

1. Introduction

The accurate prediction of effective groundwater velocity in the unsaturated zone facilitates the environmental planners and policy makers to come up with better plans and to devise better policies towards prevention of groundwater contamination. The unsaturated zone is the boundary between the earth surface and the groundwater table. The understanding of the mechanism of groundwater transport in this zone is important to find the relationship between groundwater pumping, industrial waste disposal, leaking underground petroleum tanks etc. and the contamination of the groundwater. For a sustainable growth of Matsuyama city, the only sensible solution to the ever growing water demand is to tap the city's groundwater systematically. It is, therefore, critical to prevent the city's groundwater from being contaminated. Any policies for the groundwater protection, however, cannot be successful without proper understanding of the mechanics of groundwater transportation in the unsaturated zone.

Most of the traditional methods of estimating the rate of water and solute transport in the unsaturated zone regard the effect of the preferential flow as negligible. For example, the Green and Ampt (1911) model assumes groundwater velocity in unsaturated conditions as a function of potential difference, hydraulic conductivity and water content only and proposed the following relation.

$$v_s = K_s \left\{ \frac{\left(\dfrac{h_0 - h_L}{L} + 1 \right)}{\theta_s} \right\} \quad (1)$$

where,
v_s = velocity of wetting front,
θ_s = volumetric water content
$h_0 - h_L$ = potential difference, K_s = hydraulic conductivity, L = distance between two points

Similarly, Biggar and Nielson (1967) described a relationship between concentration gradient and concentration as a function of time, for a reactive solute. As per their model,

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$$R\left(\frac{\partial C}{\partial t}\right)=D\left(\frac{\partial^2 C}{\partial x^2}\right)-v\left(\frac{\partial C}{\partial x}\right) \qquad (2)$$

where, R = retardation factor of a solute = $1 + \frac{\rho K_D}{\theta}$

$\partial C/\partial t$ = rate of change of solute concentration with time
$\partial C/\partial x$ = change of solute concentration with distance
D = hydrodynamic dispersion coefficient, v = average pore water velocity = q/θ
ρ = average bulk density of porous medium
K_D = linear partition coefficient, θ = volumetric water content
q = flux rate = Q/A, Q = discharge rate, A = cross-sectional area of flow

Both these models, represented by equations (1) and (2), completely ignore the effect of preferential flow in predicting the groundwater velocity in the unsaturated zone.

However, recent studies show that the effect of preferential flow may not only be non-negligible but can be the determining factor in some cases of groundwater contamination by different solutes. The preferential flow phenomenon increases the contamination potential of a water-borne chemical, because the flow becomes more concentrated and, therefore, faster and less susceptible to degradation and adsorption.

A study of the effects of preferential flow in groundwater movement in the unsaturated zone and its effect in the adsorption of organic chemicals was conducted. Four soil columns, two intact and two repacked, were used in this study. Two organic tracers, one slightly retarded and one non-reactive, were used to obtain breakthrough curves. A color dye experiment was performed to obtain visual evidence of the preferential flow.

2. Methodology

Two soil columns, each approximately 15.24- cm in diameter and 100-cm in length, were hand-carved from a field. The intact columns were wrapped with fiberglass cloth, which provided support to the outer surface of the intact columns and prevented the wall effect in the experiment. Soil from the pits, which were the source of the intact columns, was used to prepare two homogeneous repacked columns of approximately same dimensions and density as the intact columns

2.1 Soil Characterization

The different properties of the soil were determined in the laboratory following the standard procedure. The results of soil property determination follow.

2.1.1 Moisture Content and Porosity

The table 1 is the summary of saturated volumetric moisture content (θ_s) and porosity at different depths. Ideally, the saturated volumetric water content and the porosity value should match. However, since the intact columns were not homogenous, these values do not match.

Table 1: θ_s and Porosity

Depth (cm)	θ_s	Porosity
34	0.434	0.419
65	0.451	0.388
96	0.399	0.321

2.1.2 Water Content and Bulk Density

The air-dried water content (W_{ad}) of the soil was determined to calculate the mass of air-dried soil required to pack the repacked columns to the same bulk density (ρ) as the intact columns. The table 2 is the summary of W_{ad} and ρ of the soil.

Table 2: ρ, W_{ad}, and ρ_{ad} of soil

Depth (cm)	ρ (g/cm^3)	W_{ad}	ρ_{ad} (g/cm^3)
10	1.57	0.025	1.609
34	1.54	0.026	1.580
65	1.62	0.026	1.672
96	1.80	0.028	1.850

2.1.3 Soil Moisture Characteristic (SMC) Curve

The SMC curve was determined by using the Klute's method (1986). A hanging column of deaired water, connected to a graduated burette, was used to saturate the sample and to determine the sample's matric potential and water retention. The figure 1 shows the plot of equilibrium points of matric potential (suction) and water content of the soil samples.

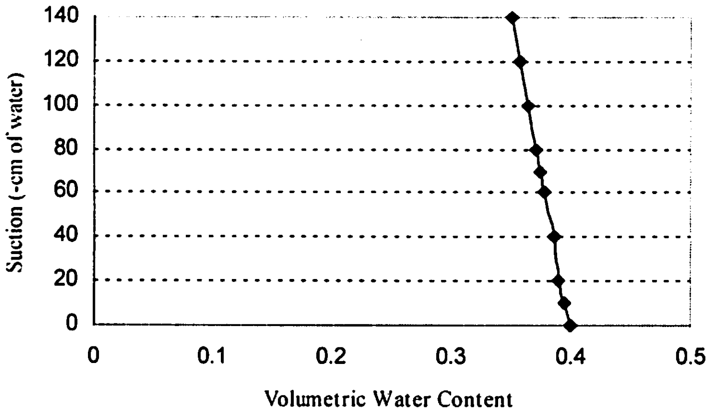


Figure 1: Soil Moisture Characteristics Curve

2.2 Laboratory Setup

The stainless steel porous plates were set at the bottom of both intact columns. The cut pieces of PVC pipes were fitted at the top of the column to support a drip emitter. The base assembly was set up to collect effluent water. All four columns were erected on angle iron frames, with effluent collector at the bottom of each column.

Five equally spaced tensiometers were inserted on each of the four columns. The tensiometers were connected to the Scanivalve pressure transducer system by urethane tubing, to measure the soil water tension. The water supply system consisted of multi-channel syringe water pump and drip emitters.

The effluent collection system on each column consisted of steel cylindrical vacuum chamber, a Moore Model Series 44 pneumatic null-balance pressure regulator and an ISSCO Retriever II fraction collector. The vacuum chamber enhanced the flow of water and solute through the soil columns while maintaining a unit gradient.

The data acquisition system consisted of a 24-port scanning fluid switch wafer Scanivalve, a Druck PDCR 22 differential, strain gauge pressure transducer, an AD-500 data acquisition board and a computer. As the scanning valve rotated through each fluid switch wafer port, the pressure transducer measured the pressure in each tensiometer. The multi-volt outputs from the transducer were stored on the computer for analysis.

2.3 Experiment Design

The soil columns were subjected to unsaturated conditions using constant flow rate of 123.05 mL/day (0.015 pore volume per day). The outflow rate was determined by outflow in 42 21-

mL vials and dividing the total amount of outflow by the duration of effluent collection. The soil suction, which indicated dryness of the columns, was monitored every 30-minutes by tensiometers. Once a unit gradient was achieved, as indicated by constant suction at all elevations of each column and by inflow rate equaling outflow rate, a slug input of tracer solution was made at the top of all four columns simultaneously, at the same steady-state flux rate. The tracer solution consisted of 500 mg/L bromacil (5-bromo-3-sec-butyl-6-methyluracil) and 250 mg/L meta-trifluoromethylbenzoic acid (m-TFMBA). The m-TFMBA served as tracer of soil moisture movement; m-TFMBA has been found to be a non-reactive stable anionic tracer in unsaturated zone tracer tests.

After a slug input of solutes the water supply system was turned on again. The effluent was collected and the soil water tension was monitored for 110 days. The effluent samples were analyzed for the solutes using High Performance Liquid Chromatography (HPLC).

To obtain visual evidence of preferential pathways of groundwater movement, a color dye experiment was performed on all four columns at the end of this study. The Erioglaucine dye was introduced on the soil surface for 12 days at the steady-state flux rate. The soil was then removed from each column in 5-cm depth increments. Each new exposed surface was photographed and the approximate areas of the unstained portion were calculated.

2.4 Computer Model and BTC Analysis

CXTFIT (Parker and van Genuchten, 1984), a non-linear least squares curve-fitting program for simulating one-dimensional advective-dispersive flow, was used to estimate different transport parameters and to fit BTCs of bromacil and m-MTFMBA. A comparison between simulated and observed BTCs was made to find the difference between the theoretical and actual groundwater velocity in unsaturated zone.

3. Results and Discussion

3.1 Unit Gradient in Columns

The experiment was conducted under unit gradient condition in all four columns, as indicated by constant suction in all five tensiometers of each column at various elevations (figure 2).

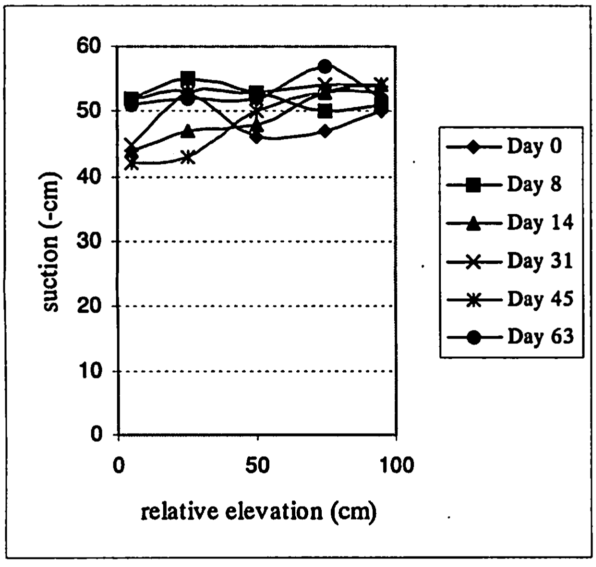
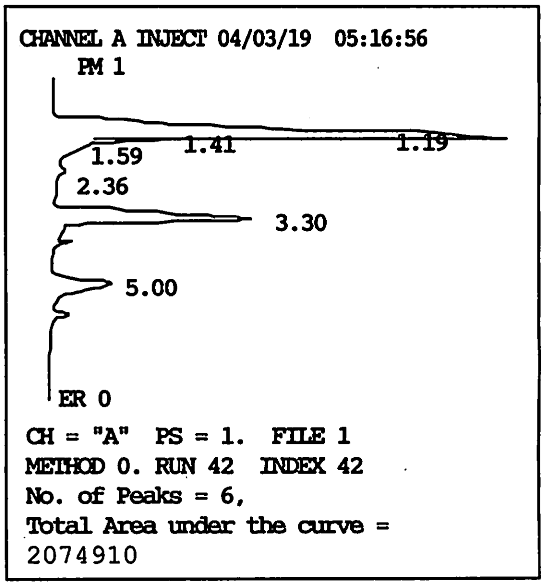


Figure 2: Unit Gradient Condition



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CHANNEL A INJECT 04/03/19   05:16:56
   PM 1
ER 0
CH = "A"   PS = 1.   FILE 1
METHOD 0. RUN 42   INDEX 42
No. of Peaks = 6,
Total Area under the curve =
2074910
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Figure 3: Example Chromatogram

3.2 Observed BTCs

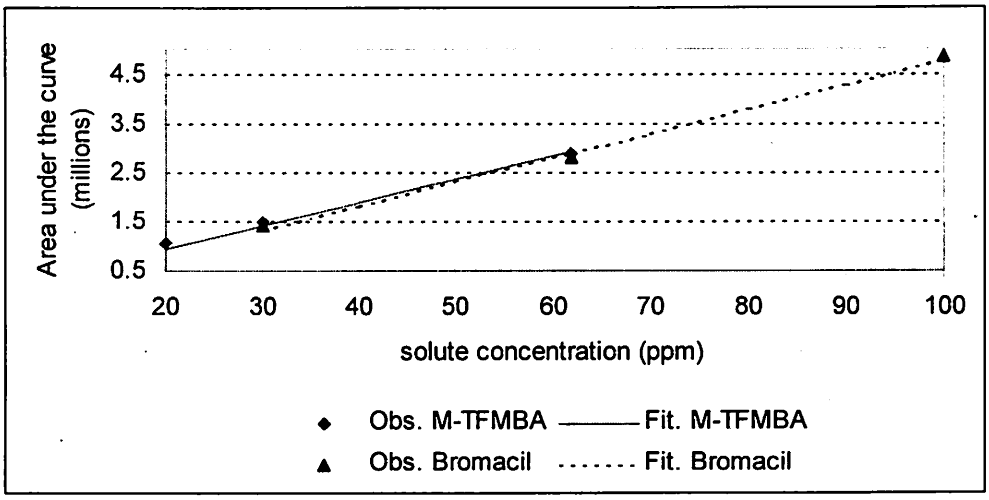

Figure 4: Relation between area under the curve and solute concentration

Using HPLC, the column effluent was analyzed to obtain observed BTCs of bromacil and m-TFMBA. The area under the peak (AUP) of the chromatogram, an example of which is shown in figure 3, was calibrated using standard solutions of different concentrations. The relation between area and concentration was found to be approximately linear (figure 4).

3.3 Mass Balance

The observed mass balances of m-TFMBA and bromacil were calculated from the observed BTCs of the tracers, using trapezoidal integration. The following relation provided mass recovered in each duration:

$$M = \frac{QC\Delta t}{1000}$$

where, M = mass recovered in time Δt; Q = steady-state flow rate
C = solute concentration; Δt = time

The fitted mass balance was checked from the fitted pulse value, a parameter in CXTFIT that indicates the time duration of tracer application. The mass recovery of a species depends on several factors, such as its bio-chemical degradation rate, duration of the experiment, and experimental conditions. The mass recovery of m-TFMBA and bromacil, shown in Table 3, was approximately 97% in both the intact and repacked columns.

Table3: Mass Recovery (%) of tracers in soil columns based on observed and fitted BTCs

	Intact Columns				Repacked Columns			
	Column 1		Column 2		Column 3		Column 4	
Tracer	Observed	Fitted	Observed	Fitted	Observed	Fitted	Observed	Fitted
m-TFMBA	97	98	92	92	96	95	98	96
Bromacil	97	98	89	88	96	94	98	96

3.4 Analytical Model

Based on the shape of the observed BTCs of m-TFMBA in the intact columns, the appropriate solute transport model for this study wad deemed to be the two-region concept of CXTFIT. In the two-region concept, all solute transport occurs in the mobile (dynamic) region and solute moves from the immobile (stagnant) region to the mobile region through diffusion only. This diffusion of solutes from the immobile region causes tailing of both reactive and non-reactive tracers' BTCs. The governing equations for the two-region concept are:

$$[\theta_{im}+(1-f)\rho K_D]\left(\frac{\partial C_{im}}{\partial t}\right)=\lambda\,(C_m-C_{im})$$

$$(\theta_m+f\rho K_D)\left(\frac{\partial C_m}{\partial t}\right)+[\theta_{im}+(1-f)\rho K_D]\left(\frac{\partial C_{im}}{\partial t}\right)=\theta_m D_m\left(\frac{\partial^2 C_m}{\partial x^2}\right)-v_m\theta_m\left(\frac{\partial C_m}{\partial x}\right)$$

where, C_m = resident solute concentration in mobile region

C_{im} = resident solute concentration in immobile region

θ_m = mobile volumetric water content,

θ_{im} = immobile volumetric water content

D_m = dispersion coefficient for the mobile region

f = fraction of the sorption sites that equilibrates with the mobile liquid phase

λ = first-order rate constant governing solute exchange rate between mobile and immobile regions

The parameters pertinent to this study are the average pore water velocity (v), hydrodynamic dispersion coefficient (D), retardation coefficient (R), pulse (t_0), and the two dimensionless parameters, β and ω. For the mass balance to be met, the fitted t_0 value should closely correspond to the known amount of time of solute flux.

3.5 Observed and Fitted BTC Parameters

The observed and the fitted BTCs for each tracer in each column were plotted; an example of such a plot is given in figure 5. The fitted BTCs were derived by using the fitted parameters as the fixed values in CXTFIT and simulating the BTCs for these values. Various derived and fitted parameters for all four columns are given in table 4.

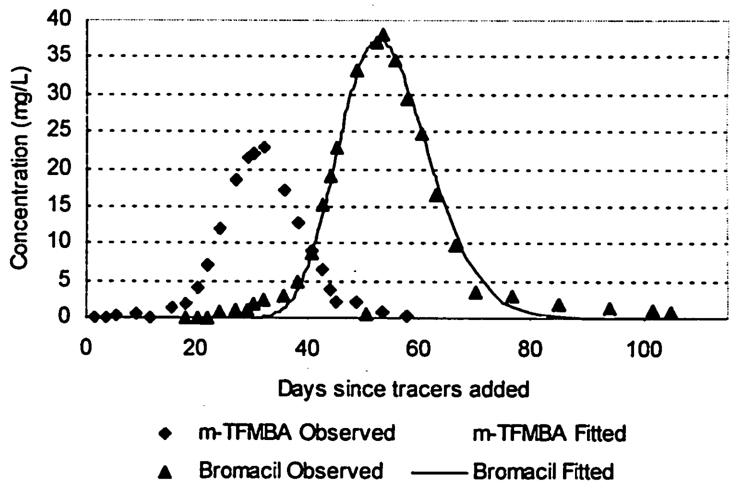

Figure 5: Observed and Fitted BTCs of Column number 3

If the wetting front of the groundwater or solute is stable and the whole soil matrix takes part in the soil moisture movement, then the fitted v should equal the derived v. But if the groundwater or solute bypass a portion of the soil matrix, then the fitted v (actual velocity) will be higher than the derived v (theoretical velocity).

As shown in table 4, a large difference existed between the derived and fitted value in all four columns. The v_{fitted} values were 2.06, 2.30, 1.80, and 1.93 times higher than the $v_{derived}$ values in columns 1, 2, 3, and 4, respectively (row 3, Table 4). The $v_{derived}$ values were obtained using the relation $v = q/\theta$. The $\theta_{gravimetric}$ was determined by weighing the column after the experiment.θ was calculated using the relation $\theta = (\rho / \rho L)\ \theta_{gravimetric}$. Figure 6 is a graphical representation of the differences between theoretical and actual groundwater flow velocity in the unsaturated zone.

The liquid density was taken to be 1.0 g/cm^3. The q was the constant flux rate of the leaching solution and was equal to 0.67 cm/day. The average v_{fitted} values of intact and repacked columns were 3.619 cm/day and 3.108 cm/day, respectively.

Table 4: The Derived and Fitted Parameters

	Intact Columns		Repacked Columns	
Parameters	Column 1	Column 2	Column 3	Column 4
$v_{derived}$ (cm/day)	1.751	1.576	1.758	1.576
v_{fitted} (cm/day)	3.615	3.623	3.163	3.054
$v_{fitted} / v_{derived}$	2.06	2.30	1.80	1.93
$\theta_{gravimetric}$ (θ_g)	0.234	0.260	0.233	0.260
θ_{fitted} (θ_f)	0.185	0.185	0.212	0.219
θ_f/θ_g	0.803	0.711	0.908	0.845
PV bypassed	0.197	0.289	0.092	0.155
D_{fitted} (cm^2/day)	10.53	14.01	3.21	3.41
α_{fitted} (cm)	2.913	3.878	1.015	1.117
R_{fitted}	1.602	1.341	1.701	1.606
β_{fitted}	0.809	0.689	0.912	0.849
ω_{fitted}	6.639	1.166	5.345	6.637

The reason for this higher v_{fitted} values compared to $v_{derived}$ values could be the wall effect, anion exclusion or preferential flow. Therefore, a dye experiment, using Erioglaucine dye, also known as FD&C Blue No. 1, was conducted to get the visual evidence for the reason of this higher groundwater flow velocity.

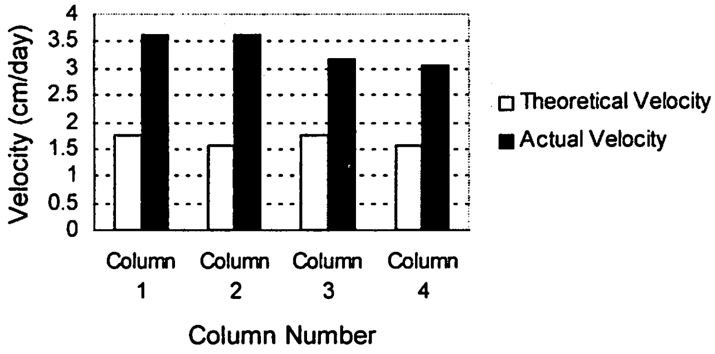

Figure 6: Theoretical and Actual groundwater velocity

3.6 Dye Experiment

The table 5 gives the summary of percentage of unstained area with depth of the dye experiment. The relative amount of unstained area to stained area at various depths from the soil surface was interpreted as an indication of degree of bypassing. The results of this experiment indicated that at a depth of 25 cm from the surface the stained area was only about 90% and 40% in the cross sectional area in intact columns 1 and 2, respectively. The amount of stained area decreased significantly at 35-cm depth, indicating a progression in bypassing with depth. A similar trend was observed, although to a lesser degree, in both of the repacked columns. A very similar phenomenon has been observed by numerous investigators, including Seyfried and Rao (1987), Booltink and Bouma (1991), and Ghodrati and Jury (1990).

Table 5: Approximate % of unstained area at various depths

Depth (cm)	Column No.			
	1	2	3	4
15	0	0	0	0
20	5	6	0	0
25	10	60	11	6
30	24	64	15	33
35	65	74	58	43

The pattern of unstained areas confirmed that most of the groundwater flow occurred via preferential pathways, and not due to anion exclusion or wall effect. They dye experiment results were consistent with the tracer experiment results.

3.7 Summary of the results

Both the observed BTCs and the dye experiment showed a bypassing of the soil matrix in the water and solute transport in both the intact and the homogeneously repacked columns. The bypassing was much higher in the intact columns than in the repacked columns. The results of this study support the findings of several previous studies concerning the presence of preferential flow in soil under unsaturated conditions. The presence of bypass flow can significantly increase the groundwater flow velocity than would be predicted by the conventional advection-dispersion model.

The results of this study also indicated that the transport parameters obtained from the repacked columns underestimate the average groundwater flow velocity in the field soil. Therefore, better site characterization can be accomplished by tracer studies in the field soil rather than in repacked soil columns.

4. Conclusions

The following conclusions are based on the results of this study:

a. The presence of preferential flow in natural soil conditions must always be considered in predicting the transport of groundwater in the unsaturated zone.
b. In the unsaturated zone, the actual groundwater velocity can be up to two times faster than theoretical velocity predicted by conventional model based only on advection and dispersion.
c. The groundwater velocity is different in repacked and intact columns. The parameters obtained from repacked columns should be used with caution to estimate actual groundwater velocity.
d. A dye experiment is an effective technique to obtain visual evidence of the pathways of groundwater flow in the unsaturated zone.

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