# Modelling of Soil Moisture Movement in a Watershed using SWIM

C P Kumar, *Member*

B K Purandara, *Non-member*

*The present study aims at modelling of soil moisture movement in Barchi watershed (Karnataka) using SWIM (Soil Water Infiltration and Movement). Field and laboratory investigations were carried out to determine the saturated hydraulic conductivity at eight locations using Guelph Permeameter and soil moisture retention characteristics using the Pressure Plate Apparatus. The van Genuchten parameters of soil moisture retention function and hydraulic conductivity function were obtained through non-linear regression analysis. Daily rainfall and evaporation data of Barchi for the period 1996-1997 to 1999-2000 were used for the simulations. Water balance components like runoff, evapotranspiration and drainage (groundwater recharge from rainfall) were determined through SWIM. The drainage was found to vary between 38% and 47% of rainfall (1241 mm to 1887 mm) while the runoff coefficient varied between 12% and 32% for the study period.*

***Keywords :*** Modelling; Soil Moisture; Infiltration; Runoff; Ground water recharge

## NOTATION

$c$ : solute concentration in solution, μmol or μg solutes/ cm$^3$ water

$D$ : combined dispersion and diffusion coefficient, cm$^2$/h

$K$ : hydraulic conductivity, cm$^2$ water/cm soil/h

$q$ : water flux density, cm/h

$s$ : adsorbed concentration, μmol/g soil or μg/g soil

$S$ : source (or sink, if negative) strength, cm$^3$ water/cm$^3$ soil/h

$t$ : time, h

$x$ : depth, cm

$z$ : gravitational potential, cm

$\theta$ : volumetric water content, cm$^3$/cm$^3$

$\Psi$ : matric potential, cm

$\psi_0$, $\psi_1$ : shifting and scaling parameters, respectively

$\rho$ : soil bulk density, g/cm$^3$

$\phi$ : source/sink term, μ mol/cm$^3$/h or μg/cm$^3$/h

## INTRODUCTION

In many arid and semi-arid regions, surface water resources are limited and ground water is the major source for agricultural, industrial and domestic water supplies. Because of lowering of water tables and the consequently increased energy costs for pumping, it is recognized that ground water extraction should balance ground water recharge in areas with scarce fresh water supplies. This objective can be achieved either by restricting ground water use to the water volume which becomes available through the process of natural recharge or by recharging the aquifer artificially with surface water. Both options require knowledge of the ground water recharge process through the unsaturated zone from the land surface to the regional water table.

The theory for transient isothermal flow of water into non-swelling unsaturated soil is well understood and has been developed to a large extent in terms of solutions of the non-linear Richards equation. The governing partial differential flow equation can be interpreted numerically by a finite difference, a finite element or a boundary element technique. Then a discretization scheme is applied for a system of nodal points that is superimposed on the soil depth-time region under consideration. Implementing the appropriate initial and boundary conditions then leads to a set of (linear) algebraic equations that can be solved by different methods. The operation by means of such a mathematical model is termed simulation, while the model is called simulation model.

The objective of the present study is to simulate the movement of soil moisture in Barchi watershed (sub-basin of Kali river in North Kanara district of Karnataka) using the SWIM model. The SWIM (Soil Water Infiltration and Movement) is a software package developed by Division of Soils, CSIRO, Australia[1] for simulating infiltration, evapotranspiration, and redistribution. It has been selected for the present study in view of its simpli-city, ease of use, graphical display of intermittent results, and use of input parameters (soil moisture characteristics) which can be directly measured in the field/ laboratory.

---

**C P Kumar is with National Institute of Hydrology, Roorkee 247 667, Uttaranchal and B K Purandara is with Hard Rock Regional Centre, National Institute of Hydrology, Belgaum, Karnataka 590 001.**

This paper (redrafted) was received on August 14, 2002. Written discussion on this paper will be received until February 29, 2004.

## MATERIALS AND METHODS

The Barchi watershed upstream of Barchi is located in the leeward side of western ghat and is a sub-basin of Kali river. It lies in Haliyala taluk of Karwar (North Kanara) district in Karnataka. The location and drainage system of Barchi watershed is shown in Figure 1.

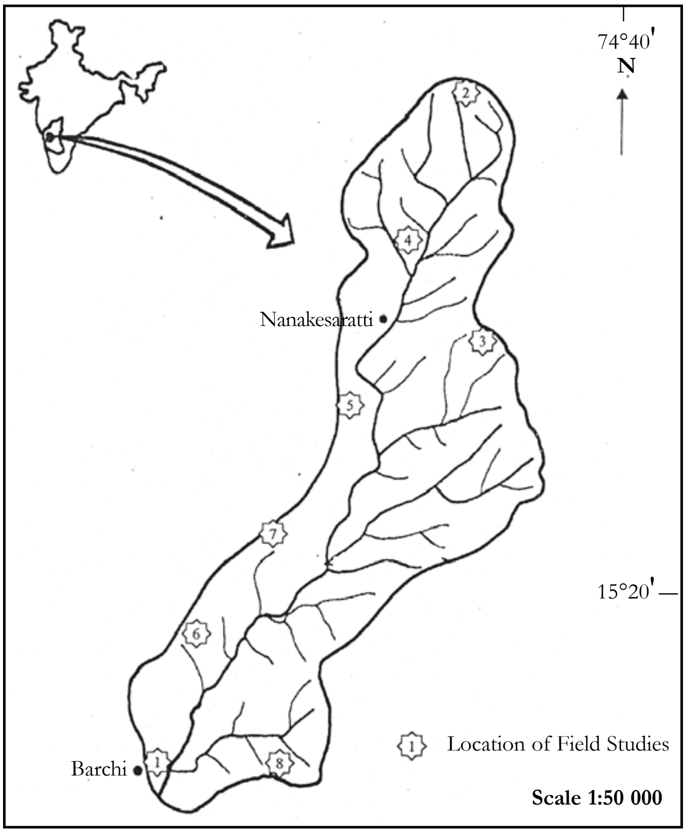


**Figure 1 Drainage system of Barchi watershed**

The Barchinala stream originates from Thavargatti in Belgaum district at an altitude of about 734 m, 20 km north of Dandeli and flows through North Kanara district of Karnataka state. The catchment is relatively short in wiidth and river flows in a southerly direction and joins the main Barchi river near the gauging site. The geographical area covered by Barchi watershed is 21.126 km$^2$. The watershed lies between 74°36' and 74°39' East longitudes and 15°18' and 15°24' North latitudes.

High land region consists of dissection of high hills and ridges forming part of the foot hills of western ghats. It consists of steep hills and valleys intercepted with thick forest. The slopes of the ghats are covered with dense deciduous forest. Forest cover occupies around 76% of the study area. The watershed is mainly covered with bamboo, teak and mixed plantations. The brownish and fine-grained soils are the principal types of soils found in the area. The following land uses were observed in the watershed:

1. Bamboo plantation = 4%
2. Teak plantation = 40%
3. Mixed forest = 32%
4. Agricultural land = 24%

The stream gauging site is located at an elevation of 480 m, where the nala crosses Dandeli-Thavargatti road, about 5 km from Dandeli. The stream is a fourth order stream and joins main Barchi river downstream of the gauging site. A full fledged meteorological station, maintained by Water Resources Development Organisation (WRDO), Karnataka, is located near the gauging site.

The Barchi raingauge station is located at 15°18' N and 74°37' E. Average annual rainfall for the watershed is 1500 mm, majority of which occurs during the south-west monsoon period. Depth to water table varies between 4 m to 12 m during pre- and post-monsoon periods. The yield of borewells in the study area is found to vary between 120 gallons per hour to 1170 gallons per hour.

The present study involves modelling of soil moisture movement in Barchi watershed using the SWIM model. The following steps were undertaken for the study.

### Field Investigations

Field investigations consisted of measurement of saturated hydraulic conductivity at eight locations using Guelph Permeameter and soil sampling.

### Laboratory Investigations

Laboratory investigations included determination of saturated moisture content, and soil moisture retention characteristics using the Pressure Plate Apparatus.

### Modelling

Modelling of soil moisture movement using the SWIM model. Daily rainfall and evaporation data of Barchi for the period 1996-1997 to 1999-2000 were used for the study. Water balance components like runoff, evapotranspiration and drainage (recharge to groundwater from rainfall) were determined through 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[2]). Version 2 of the model (identified as SWIMv2), 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.

SWIMv2 is based on a numerical solution of the Richards' equation (1) and the advection-dispersion equation (2), as given below. The model deals with a one-dimensional soil profile.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x} K \left[\frac{d\psi}{dp}\,\frac{\partial p}{\partial x} + \frac{dz}{dx}\right] + S \qquad (1)$$

with

$$-\frac{\psi-\psi_0}{\psi_1} = \sinh p \qquad \psi<\psi_0$$

$$-\frac{\psi-\psi_0}{\psi_1} = p \qquad \psi\geq\psi_0$$

Solute movement is based on the following solute transport equation

$$\frac{\partial(\theta c)}{\partial t} + \frac{\partial(\rho s)}{\partial t} = \frac{\partial}{\partial x}\left[\theta D \frac{\partial c}{\partial x}\right] - \frac{\partial(qc)}{\partial x} + \phi \qquad (2)$$

The SWIM 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 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.

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 ($h$), water content ($\theta$) and hydraulic conductivity ($K$). 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[3] model, the water retention function is given by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = [1 + (\alpha\,|\,h\,|)^n]^{-m} \quad \text{for } h < 0$$
$$= 1 \quad \text{for } h \geq 0 \qquad (3)$$

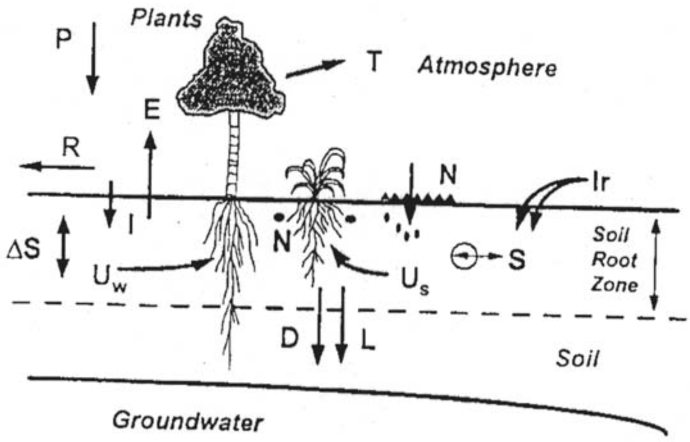
and the hydraulic conductivity function is described by

$$K = K_s S_e^{1/2} [1 - (1 - S_e^{1/m})^m]^2 \qquad (4)$$

where, $S_e$ is effective saturation; $\theta_r$ is residual water content; $\theta_s$ is saturated water content; $\alpha$ and $n$ are van Genuchten model parameters; and $m = 1 - 1/n$.

Modelling of soil moisture movement in Barchi watershed has been done using SWIM. The model was simulated for 1461 days (May 1, 1996 to April 30, 2000). One vegetation type (teak, covered in most parts of the watershed) was considered for the study. Exponential root growth with depth and linear interpolation with time was assumed. The following vegetation parameters were adopted for the simulations:

| | |
|---|---|
| Root radius, (rad), cm | = 0.5 |
| Root conductance, (groot) | $= 4.0 \times 10^{-7}$ |
| Minimum xylem potential, (psimin), cm | = –15 000 |
| Root depth constant, (xc), cm | = 150 |
| Maximum root length density (rldmax), cm/cm$^3$ | = 4 |



Components of the soil water and solute balances addressed by SWIMv2.1; P= precipitation, R= runoff, I= infiltration, $U_w$= water uptake, $U_s$= solute uptake, T= transpiration, E= evaporation, D= drainage, L= solute leaching, Ir= irrigation/ fertigation, N= nutrients/ fertiliser, ΔS= storage, S= solute source/ sink.

**Figure 2 Components of the soil water and solute balances addressed by SWIMv 2.1**

## RESULTS AND DISCUSSION

### Soil Moisture Characteristics

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[3] model. Residual moisture content ($\theta_r$) was assumed to be equivalent to moisture retained corresponding to 15 bar pressure. The parameters of soil moisture retention function and hydraulic conductivity function were obtained through non-linear regression analysis. Tables 1 and 2 present the van Genuchten parameters $\alpha$ and $n$ (equations (3) and (4)) for upper and lower soil layers in Barchi watershed. Average values of these parameters were also determined through non-linear regression analysis and used in modelling of soil moisture movement through SWIM.

**Table 1 van Genuchten parameters for upper soil layer**

| Station | $K_s$, cm/h | $\theta_r$ | $\theta_s$ | van Genuchten Parameters | | Proportion of Variance Explained, % |
|---|---|---|---|---|---|---|
| | | | | $\alpha$ | $n$ | |
| 1 | 0.580 | 0.080 | 0.370 | 0.0073 | 1.4340 | 80.78 |
| 2 | 0.570 | 0.140 | 0.370 | 0.0023 | 1.5090 | 74.08 |
| 3 | 0.600 | 0.090 | 0.380 | 0.0021 | 1.4650 | 79.07 |
| 4 | 0.180 | 0.300 | 0.530 | 0.0067 | 1.5230 | 92.00 |
| 5 | 0.200 | 0.280 | 0.530 | 0.0129 | 1.3730 | 80.66 |
| 6 | 0.180 | 0.280 | 0.530 | 0.0235 | 1.3000 | 64.09 |
| 7 | 0.240 | 0.250 | 0.520 | 0.0020 | 1.5800 | 84.07 |
| 8 | 0.160 | 0.300 | 0.540 | 0.0019 | 1.5520 | 91.51 |
| Average | 0.339 | 0.215 | 0.471 | 0.0047 | 1.4385 | 24.43 |

**Table 2 van Genuchten parameters for lower soil layer**

| Station | $K_s$, cm/h | $\theta_r$ | $\theta_s$ | van Genuchten parameters | | Proportion of Variance Explained, % |
|---|---|---|---|---|---|---|
| | | | | $\alpha$ | $n$ | |
| 1 | 1.660 | 0.110 | 0.380 | 0.0148 | 1.5630 | 97.04 |
| 2 | 0.600 | 0.090 | 0.320 | 0.0045 | 1.7600 | 99.52 |
| 3 | 0.007 | 0.060 | 0.430 | 0.0154 | 1.3580 | 87.12 |
| 4 | 0.580 | 0.140 | 0.410 | 0.0134 | 1.3100 | 81.71 |
| 5 | 0.580 | 0.160 | 0.430 | 0.0070 | 1.4440 | 91.68 |
| 6 | 0.180 | 0.280 | 0.530 | 0.0235 | 1.3000 | 64.09 |
| 7 | 0.590 | 0.130 | 0.310 | 0.0120 | 1.5960 | 95.35 |
| 8 | 0.600 | 0.200 | 0.450 | 0.0123 | 1.6880 | 91.97 |
| Average | 0.648 | 0.121 | 0.394 | 0.0095 | 1.4212 | 58.31 |

Based upon the available information, two distinct soil layers were identified (0-45 cm and 45 cm-150 cm). Saturated hydraulic conductivity was measured at eight locations in the study area by using Guelph Permeameter (locations are shown in Figure 1). The average saturated hydraulic conductivity values for the upper layer (0- 45 cm) and lower layer (45 cm -150 cm) were found to be 0.339 cm/h and 0.648 cm/h, respectively.

## Model Conceptualization

The profile is 150 cm deep with surface at 0 cm and bottom boundary condition applying at 150 cm Vapour conductivity is not taken into account, nor is the effect of osmotic potential. There are two hydraulic property sets (for upper and lower soil layers) that are applied to 31 depth nodes of the 150 cm deep profile. Hysteresis is not taken into account.

Initially, there is no water ponded on the surface. Runoff is governed by a simple power law function and a surface conductance function. No bypass flow was included. A matric potential gradient of 0, *i e*, 'unit gradient', has been applied as bottom boundary condition throughout the simulation. Cumulative rainfall and evaporation records (daily) for the period 1996-1997 to 1999-2000 were given in the input file for determination of water balance components (runoff, evapotranspiration and drainage).

**Table 3 Water balance components for the Barchi watershed**

| Year | Rainfall, mm | Infiltration, mm | Drainage, mm | ET, mm | Runoff, mm | Runoff Coefficient, % | Recharge Coefficient, % |
|---|---|---|---|---|---|---|---|
| 1996-1997 | 1345.85 | 1083.37 | 514.46 | 519.52 | 262.48 | 19.50 | 38.22 |
| 1997-1998 | 1765.25 | 1195.05 | 698.63 | 500.43 | 570.20 | 32.30 | 39.58 |
| 1998-1999 | 1241.30 | 1087.46 | 579.55 | 507.92 | 153.84 | 12.39 | 46.69 |
| 1999-2000 | 1886.80 | 1278.18 | 784.90 | 493.28 | 608.62 | 32.26 | 41.60 |
| Total | 6239.20 | 4644.06 | 2577.54 | 2021.15 | 1595.14 | 24.11 | 41.52 |

## Simulation of Water Balance Components

The model parameters (soil moisture characteristics) were actually measured in the field and laboratory. Therefore, the model does not require any calibration as such. The model was validated by comparing the observed and simulated runoff. However, the observed runoff values were suspected to be erroneous in view of inaccurate positioning of zero of gauge.

Self-recording raingauge data (hourly rainfall values) were not available for the watershed. Therefore, daily rainfall values were used. However, with the available input data and parameters, the model was found to underestimate the runoff values. It happened because daily rainfall data generated low rainfall intensities (distributed over 24 h) with most of the rainfall infiltrating into the ground and contributing less runoff. Therefore, daily rainfall values were equally distributed to 4 h for the periods exceeding 20 mm rainfall in a day. This made a better agreement between the observed and simulated runoff and therefore validated the model. The distribution of daily rainfall into 4 h was decided on the basis of trial simulations by testing varying divisions with part of actual data. The resulting water balance components for the simulation period have been presented in Table 3.

The yearly rainfall varied between 1241 mm to 1887 mm during the period under study (Table 3). The drainage (recharge from rainfall) varies from 38% to 47% with the average value being 42%. The runoff coefficient was found to vary between 12% (low rainfall year) to 32% (high rainfall year) with the average value being 24%. Runoff coefficient was lower in low rainfall years (1996-1997 and 1998-1999). It can be attributed to low rainfall intensities enabling more infiltration and less runoff. Antecedent moisture conditions also play an important role in the runoff generation process. Simulation of variable infiltration suggests that it has relatively little effect on evapotranspiration, but considerable effect on point drainage.

## CONCLUSION

Application of SWIM model is one of the simplest techniques, which is well suited for unsaturated zone.

Water balance components like runoff, evapotranspiration and drainage were determined through SWIM for the period 1996-1997 to 1999-2000. The groundwater recharge was found to vary between 38% to 47% of rainfall while the runoff coefficient varied between 12% (low rainfall year) to 32% (high rainfall year) for the study period. Variable infiltration was observed to have relatively little effect on evapotranspiration, but considerable effect on drainage.

The SWIM model demonstrated the possibility of predicting water balance components of the unsaturated zone, but only with careful selection of input parameters. It would appear that when actual observed data is not available, it would be difficult to rely upon numerical models alone.

## REFERENCES

1. K Verburg, Peter J Ross and Keith L Bristow. 'SWIMv2.1 User Manual'. *CSIRO Division of Soils,* Australia, Divisional Report No130, 1996.

2. P J Ross. 'SWIM– A Simulation Model for Soil Water Infiltration and Movement'. 'Reference Manual to SWIMv1', *CSIRO Division of Soils,* Australia, 1990.

3. M Th van Genuchten. 'A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils'. *Soil Sci Soc Am J,* vol 44, 1980, pp 892-898.

## ACKNOWLEDGEMENT

The Institution gratefully acknowledges the valuable services rendered by the following experts in bringing out (April 2003 to March 2004) of the Agricultural Engineering *Journal.*

**Chandra, Dr P**, *FIE; Manager (Engineering), Indian Agricultural Research Institute,* New Delhi 110 012.

**Dash, Shri N K**, *MIE; Engineering Cell, Directorate of Horticulture,* Nayapalli, Bhubaneswar 751 015

**Gowde, Dr C**, *Agricultural Engineer, University of Agricultural Sciences,* G K V K, Bangalore 560 065

**Krishna, Ms C V**, 20B Sham Vihar, Jagamara, Jagamara, Khandagiri, Bhubaneswar 751 030

**Manian, Dr R**, *Professor and Head, Department of Farm Machinery, College of Agricultural Engineering, Tamil Nadu Agricultural University,* Coimbatore 641 003.

**Michel, Dr A M**, FIE; 1/64 Vattekunnam, Methanam Road, P O: Edapppally North, Cohin 682 024, Kerala

**Modi, Dr B S**, *Principal Scientist, Indian Agricultural Research Institute,* Regional Station, Karnal 132 001

**Misra, Shri I M**, *Scientist, Division of Agricultural Engineering, IARI,* New Delhi 110 012

**Misra, Shri K**, *Director of Soil Conservation Damodar Valley Corporation, Soil Conservation Department,* Hazaribagh 826 301

**Nehru, Shri C**, *Scientist, Section of Horti Engineering, Indian Institute of Horticultural Research*, Bangalore 560 089.

**Paul, Shri J C**, Qr No IV 33, DUAT Colony, Bhubaneswar 751 003.

**Pradhan, Shri S N**, *Managing Director,* Plot No 9, Surye Nagar Bhubaneswar 751 003

**Sharma Dr S D**, *Head Department of Soil and Water Conservation Engineering, College of Agricultural Engineering and Technology* Bhubaneswar 751 003

**Shri Omkar**, *AMIE; National Institute of Hydrology, I and FC Complex,* Satwari, Jammu Cantt 180 003

**Singh, Dr B**, *SWM Service (P) Ltd*, B- 94, Pallav Puram, Phase-1, Meerut 250 110

**Singh, Shri P M**, *Narendra Deva University of Agriculture and Technology,*Narendra Nagar, Kamarganj, Faridabad 224 229.

**Singh, Dr R**; 72- G Bhai Ranadhir Singh Nagar, Ludhiana 141004

**Srivastava, Dr A P**, *Senior Scientist*, *Division of Agricultural Engineering, Indian Agricultural Research Institute*, New Delhi.

**Srivastava, Dr R C**, *Water Technology Centre for Eastern Region,* Chandrasekharpur, Bhubaneswar 751 016