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MODELLING OF FLOW IN AN UNSATURATED ZONE OF A TANK CLUSTERED CATCHMENT

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ABSTRACT

The soil surface plays an important role as a boundary between the atmosphere and the unsaturated zone; it separates hydrologic processes (e.g., rainfall and irrigation, into runoff and infiltration). Existing mathematical models that simulate water movement in unsaturated zone do not take into account the water uptake by plant crop roots resulting in an error in the prediction of water flux. Moreover the application of these models is often limited due to the lack of easily accessible and representative soil hydraulic properties, like moisture retention characteristic and unsaturated hydraulic conductivity. In this study, focus on estimating the water retention and hydraulic conductivity of unsaturated zone through soil textural analysis, carrying out simulation flow in unsaturated zone using MIKE SHE model, comparing the soil hydraulic properties of the unsaturated zone of tank clustered catchment. Sindapalli Uppodai a sub basin, of Vaippar river basin in Tamilnadu was selected for this study. Soil samples were collected at different location at different depths (0-30, 30-60 and 60-90 cm).MIKE SHE is a deterministic, fully-distributed and physically-based hydrological model is developed for simulating water movement in unsaturated zones by integrating the one-dimensional transient unsaturated water flow equation (Richard's equation) with a root water extraction term (sink), and also incorporates pedo-transfer functions (PTF) for estimating soil hydraulic properties. The measured or estimated hydraulic properties with formulations such as Darcy's law and Richards' equation were used for finding the movement of water in the unsaturated zone. The flow rate of water is often used in irrigation scheduling and in estimation of aquifer recharge rate i.e., how fast water moves down to the water table.

Keywords: ***Unsaturated zone; Pedo Transfer Function; MIKE SHE; Soil hydraulic parameters***

INTRODUCTION

The soil surface plays an important role as a boundary between the atmosphere and the unsaturated zone; it separates hydrologic processes (e.g., rainfall and irrigation, into runoff and infiltration). Unsaturated flow processes are in general complicated and difficult to describe quantitatively since they often entail changes in the state and content of soil water during flow. The formulation and solution of unsaturated flow problem very often require the use of indirect methods of analysis, based on approximations or numerical techniques.The mathematical model consists of explicit sequential set of equations and numerical and logical steps, which converts numerical inputs into numerical outputs. The flow of water in the unsaturated zone has been described as a complex phenomenon involving transfers of water, air, vapour and solutes through dynamic flow path. Such complex and often site specific nature of the hydrologic processes taking place in the soil-plant-atmosphere continuum requires the use of indirect methods of analysis based on approximation.

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The essential parameters in studying the unsaturated flow are hydraulic conductivity and soil-water retention curves. The unsaturated zone is an intrinsic part of the hydrologic cycle, essentially controlling interrelationships between precipitation, infiltration, surface runoff, evapotranspiration and groundwater recharge. The unsaturated zone regulates the transfer of water from the land surface to the groundwater and vice versa, while providing protection, screening, filtering, transfer and attenuation of potential groundwater contaminants that are delivered via the land surface. Yet, unlike the groundwater below and surface water resources above, the dynamics of the unsaturated zone have not been subjected to regular monitoring at regional scales. For that reason, and because the unsaturated zone itself is not considered a resource reservoir, the unsaturated zone is generally not an explicit part of regulatory or planning guidelines that control or protect its waters. When considering the unsaturated zone and its linkages to the groundwater and surface water, it is helpful to remind ourselves of the vast differences between its horizontal and vertical extent of the unsaturated zone, is a key consideration in building a framework for regional-scale unsaturated zone hydrology.

STUDY AREA and DATA AVAILABILITY

The surface water storage bodies termed as tanks are commonly adopted in the Tamilnadu state located in the south eastern part of India. Sindapalli Uppodai sub basin, situated in Tamilnadu, consists of many tanks forming cascade type and some are isolated. The maximum amount of rainfall is collected and stored in these 15 tanks and utilized for the irrigation and drinking water demands through directly as well as by recharging ground water aquifers. In the sub basin, tank irrigation is followed in the vicinity of tanks and well irrigation is practiced in other areas.

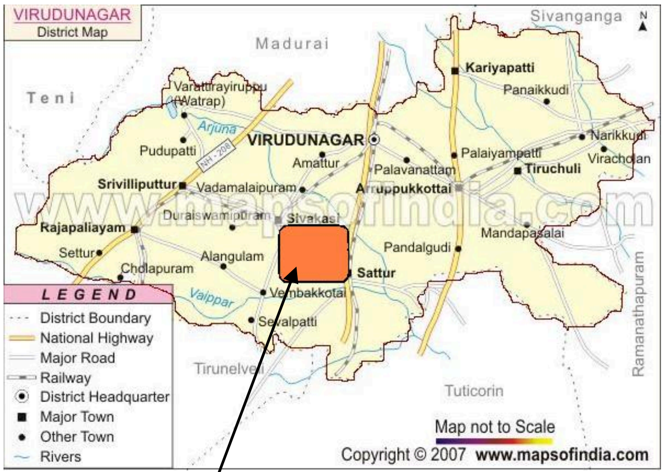
Sindapalli Uppodai sub basin of Vaippar river basin, receives drainage from its own catchment. It originates from the plain terrain near by Duraiswamypuram village of Sivakasi taluk, runs for a distance of 26 km and it joins in Arjunanadhi at the downstream of Allampatti Village. The location of the basin is at latitude of 9° 25’00”N to 9° 30’00” N and longitude 77° 45’00”E to 77° 55’00”E situated in taluks of Sivakasi and Sattur in Virudhunagar District of Tamilnadu.

Normally subtropical climate prevails over district without any sharp variation. The temperature rise slowly to maximum in summer months up to may and after which it drops slowly. The mean maximum temperature is 33.95 ºC to the mean minimum temperature is 23.78ºC. The seventy years average annual rainfall is 799.8 mm from three distinct seasons that is South West monsoon, North East monsoon and transitional period. There are seven rain gauge stations spread over the district and maintained by different organisation. In this, Sindapalli Uppodai is influenced by 3 rain gauge stations namely Vembakottai, Sathur and Sivakasi. The average annual rainfall values are 828.1, 665.3and 694.8 in mm respectively. Paddy is the main crop in both Kharif and Rabi seasons, whereas vegetables are grown in few patches in summer season. On an average, three irrigations are provided in each cropping season. Data on various aspects of the watershed viz. topography, geology, soils, crops, groundwater and meteorology are obtained from PWD, Virudhunagar.

Fig. 2 presents the topographic map of the area. As evident, the area is slightly undulating with elevation difference of about 78 m between the highest point on the ridge and the outlet. It is also seen that the elevation is decreasing upper watershed to downward watershed from both sides of the boundary, along the length of the watershed. This directs the runoff water upper watershed to downward watershed first and then to the outlet.

Fig. 3 shows the land use patterns of the area. The central part of the area is cultivated land where the elevations are comparatively less. There are a few patches of fallow land. The major proportion of the watershed is under forest.

Tamilnadu District Map



Virudhunagar District Map

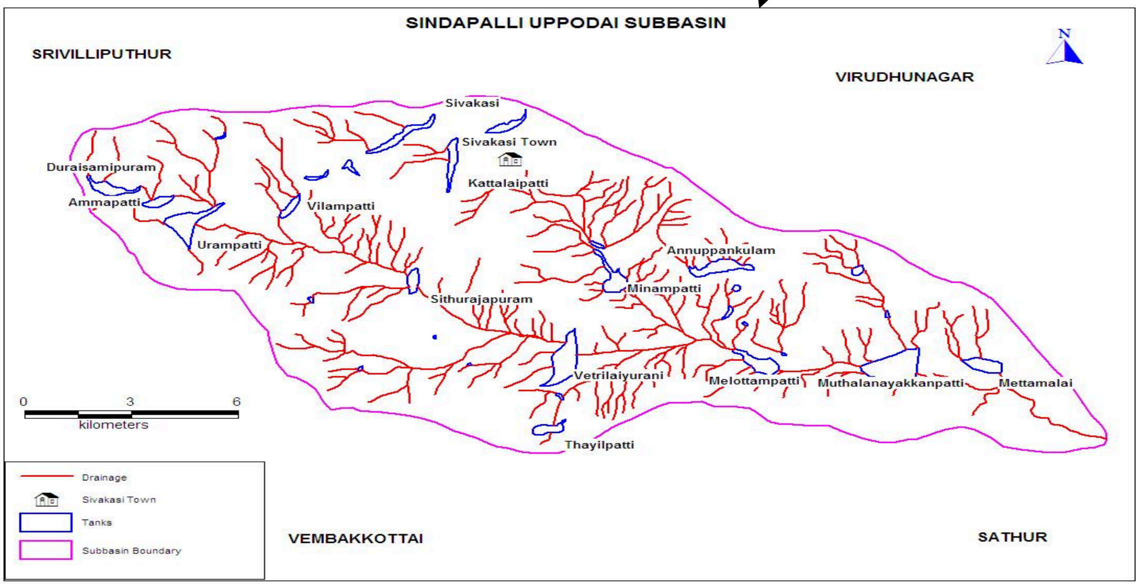


Fig .1 Sindapalli Uppodai Sub basins

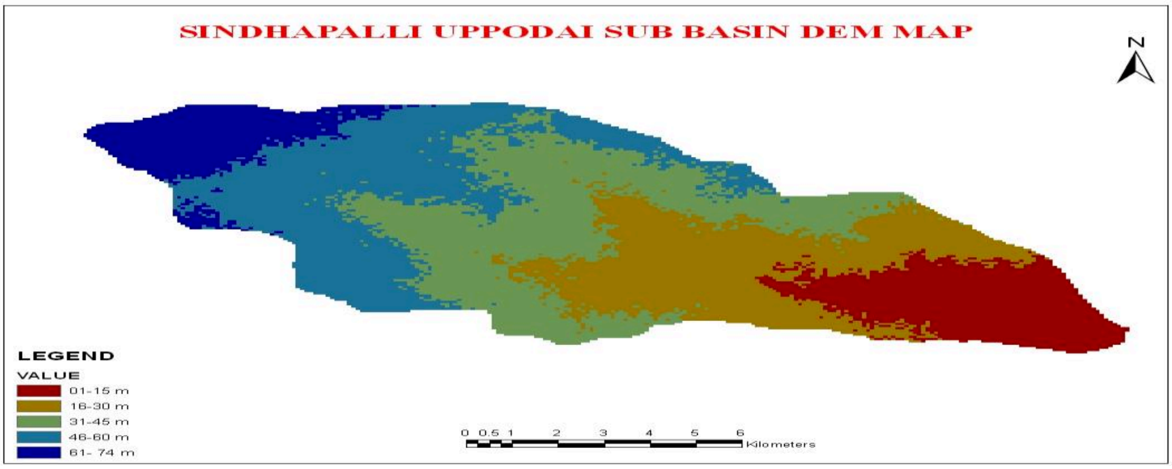


Fig.2.Sindhapalli Uppodai Sub Basin Elevation Map

Fig. 4 shows the soil type distribution map of the watershed. There are three types of soil present in the area, ranging from slow to rapid draining. However, medium draining soils cover most of the cultivated area. Table 1 presents the experimentally determined pertinent physical characteristics of the soils in the area.

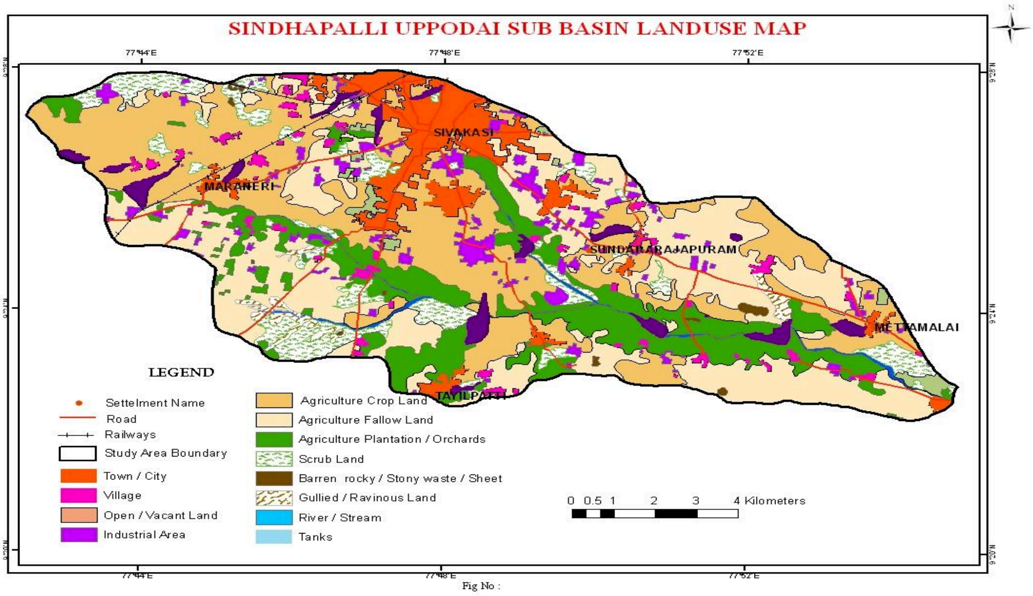


Fig.3. Sindhapalli Uppodai Sub Basin Land Use / Land Cover Map

Fig. 5 shows the stream network having a 4th order main stream. The main stream discharges into a storage tank constructed at the outlet. The water stored in the storage tank is pumped and used for the supplemental irrigation through a network of field channels. To model the inflow into the storage tank, a point neat the outlet is selected for storing the stream flow data during the simulation.

PRECIPITATION

The MIKE SHE model required rainfall for climatic input data. Rainfall records were collected from two rain gauges within and adjacent the watershed. Rainfall data were used as an input in each grid on a daily basis for model set-up. It was spatially distributed according to a Thiessen polygon technique. The watershed was divided into Thiessen polygons enclosing a specific rain gauge in the middle of the polygon. Rainfall data of each grid was obtained from the point rainfall of rain gauge within the polygon.

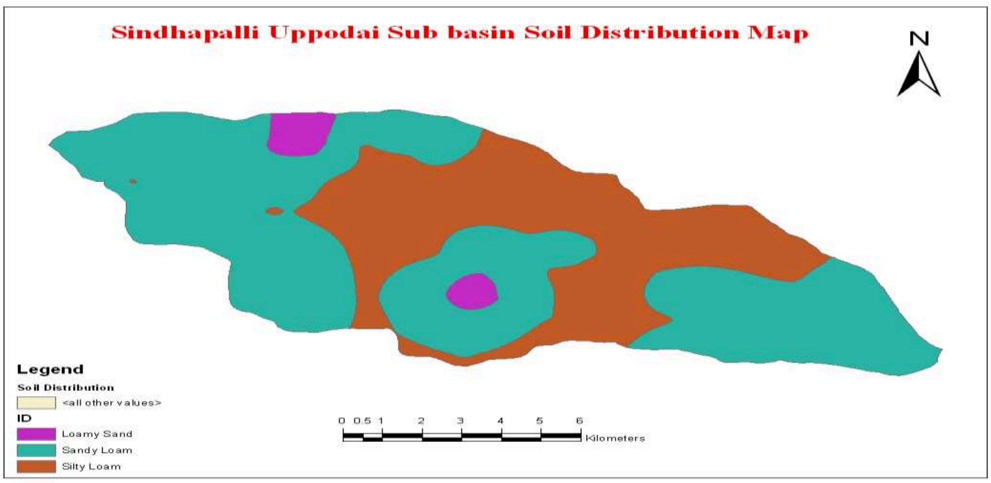


Fig.4.Sindhapalli Uppodai Sub Basin Soil Distribution Map

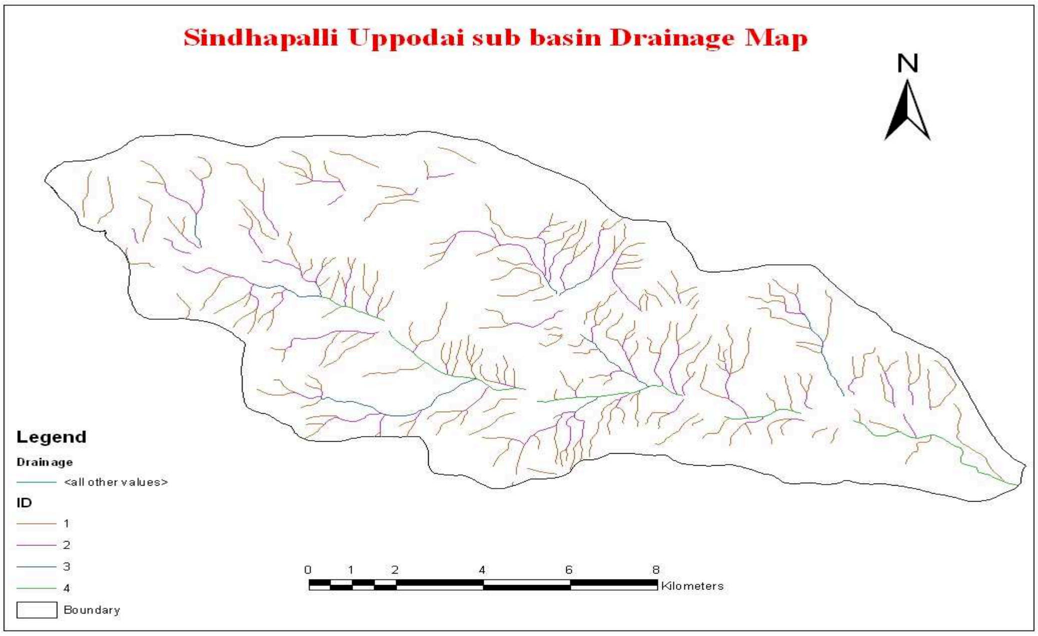


Fig.5.Sindhapalli Uppodai Sub Basin Drainage Map

Soil Texture Analysis

Soil samples, were collected at different locations (by referring with soil map and land use map) at different depth (0-30, 30-60 and 60-90 cm). For soil testing, wet methods were used for determining the relative amounts of the soil separates (sand, silt, and clay particles). Soil/water slurry was placed in a graduated cylinder. At different time intervals, the density of water was measured to determine how much soil was remaining in suspension. Since sand particles will fall out of suspension first, followed later by silt particles, the relative amounts of sand, silt, and clay were determined and the textural class were calculated.The percent sand is the depth of the sand divided by the depth of the total soil. The percent silt is the depth of the silt divided by the depth of the total soil. The percent clay is 100 minus the percent sand plus silt. The intersection of the three sizes on the triangle gives the texture class. For instance, if you have a soil with 20% clay, 60% silt, and 20% sand it falls in the "silt loam" class.

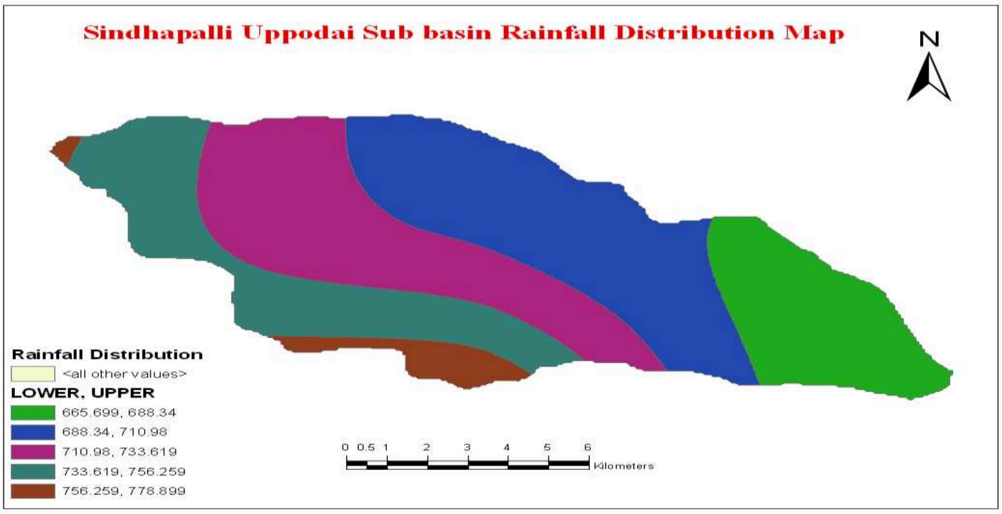


Fig.6.Sindhapalli Uppodai Sub Basin Rainfall Distribution Map

Soil Hydraulic Parameter According to Pedo Transfer Function

The governing equation for water movement in unsaturated soil, was derived by the combination of Darcy's law and the principle of mass conservation (Richards, 1931). The pressure head form of the equation for the one-dimensional vertical flow is

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{dz} + 1\right)\right] - S(h) \qquad (1.1)$$

where C (h) is the differential water capacity (∂θ/∂h) (1/L), h is the volumetric water content (L^3/ L^3), h is the soil water pressure head (matrix) (L), t is the time (T), z is the vertical coordinate (L), K is the isotropic hydraulic conductivity (L /T), and S is the sink term which represents the root water extraction (L^3 /L^3 T).

Retention function is the most widely used because it is continuous over the entire range of pressure head which leads to stable numerical solutions for Eq. (1.1). Van Genuchten also derived the K (h) relationship using the capillary-based unsaturated hydraulic conductivity prediction model developed by Mualem (1976). The soil hydraulic functions are

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \qquad (1.2)$$

$$K(h) = K_s S_e^{\frac{1}{2}}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \qquad (1.3)$$

$$S_e = \frac{\theta - \theta_s}{\theta_s - \theta_r}$$

Where θ_s and θ_r are the saturated and the residual water content, respectively (L^3/ L^3), α is approximately the inverse of bubbling pressure head (L^{-1}), n is the pore size distribution index (–), m is 1-1/n (–), K_s is the saturated hydraulic conductivity (L /T), and l is a parameter (–) usually chosen to be 0.5.

The solution in equation (1.1) requires the definition of the appropriate constitutive relationships of retention curve θ (h) in equation (1.2) and the hydraulic conductivity K (h) in equation (1.3). In this study, model for soil water retention and hydraulic conductivity, was used.

The parameters of retention function were evaluated using Pedo Transfer Functions. The Pedo Transfer Functions proposed by Vereecken et al. (1989) were based on a four-parameter retention function of the above Van Genuchten model and the regression equations proposed were,

$$\theta_s = 0.838 - 0.283(\rho_d) + 0.0013(Cl)$$

$$\theta_r = 0.015 + 0.005(Cl) + 0.014(c)$$

$$\ln(\alpha) = -2.486 + 0.025(Sa) - 0.351(C) - 2.617(\rho_d) - 0.023(Cl)$$

$$\ln(n) = 0.053 - 0.009(Sa) - 0.013(Cl) + 0.00015(Sa)^2$$

$$\ln(K_s) = 20.62 - 0.96\ln(Cl) - 0.66\ln(Sa) - 0.46\ln(C) - 8.43(\rho_d)$$

Where ρ_b is the bulk density (g /cm^3), C the carbon content (%), Cl the clay content (%), and *Sa* the sand content (%), Si is the silt content (%). He assumed that parameter m was equal to 1, unlike the original Van Genuchten model with m=1–1/n.

Table1 Soil Hydraulic Parameters Through Pedo Transfer Function

Sample Name	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Water Content (-)	Hydraulic Conductivity (cm/day)
Muthalampatti	0-30 cm	56.96	37.54	5.5	0.365208	44.84093
	30-60 cm	53.96	39.54	6.5	0.372682	36.69992
	60-90 cm	53.71	40.29	6	0.376314	38.55008
Vilampatti	0-30 cm	32.73	34.27	33	0.40898	4.938007
	30-60 cm	29.96	53.84	16.2	0.407447	16.95616
	60-90 cm	31.47	53.53	15	0.405533	19.17178
Sithrajapuram	0-30 cm	57.35	22.45	20.2	0.351055	13.83326
	30-60 cm	49.93	29.07	21	0.367274	9.983114
	60-90 cm	50.45	28.35	21.2	0.366311	10.06878
Duriswamypuram	0-30 cm	48.62	35.98	15.4	0.383424	12.987
	30-60 cm	44.17	36.83	19	0.38936	8.115808
	60-90 cm	47.97	30.83	21.2	0.371457	8.993283
Sengulam	0-30 cm	50.66	33.54	15.8	0.364326	14.25902
	30-60 cm	49.48	35.52	15	0.367584	14.04728
	60-90 cm	50.46	34.54	15	0.365169	14.86834

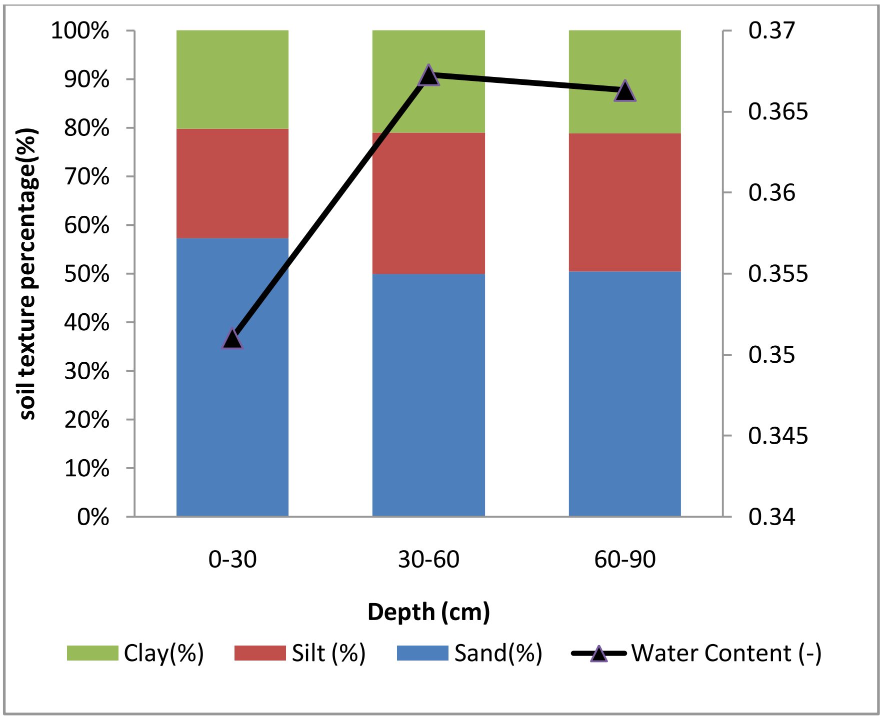


Fig.7.Water Content Data Measured at Various Depths in the Soil Profile in Sithrajapuram

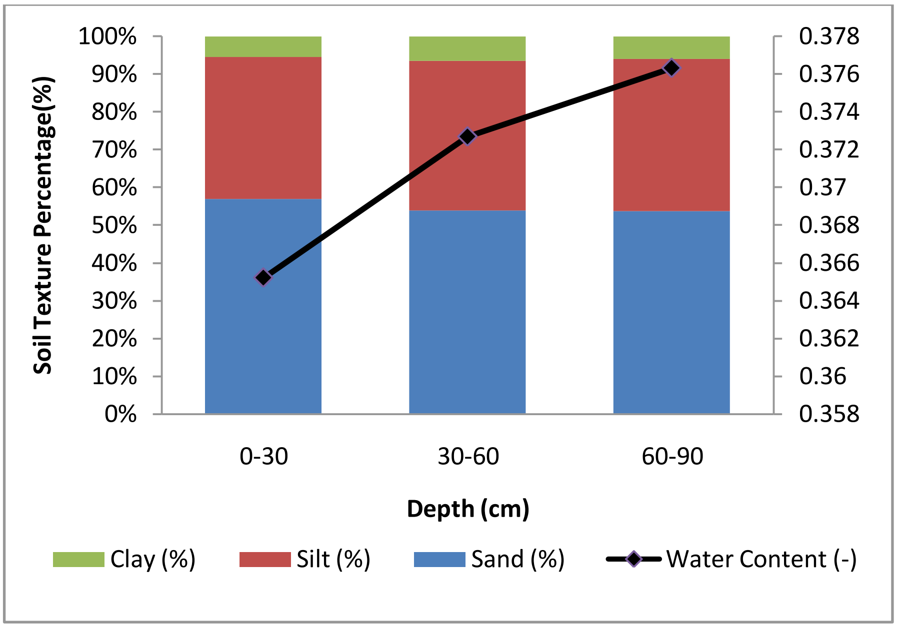


Fig.8.Water Content Data Measured at Various Depths in the Soil Profile in Muthalampatti

Description of MIKE SHE

MIKE SHE is a deterministic, fully-distributed and physically-based hydrological and water quality modelling system. It is capable of simulating hydrology and water quality processes occurring in watersheds and their underlying aquifers. The MIKE SHE modelling system was designed with a modular structure. The water movement (WM) module in MIKE SHE is the basic module of the entire modelling system. It represents the finite differences and solutions of the partial differential equations that describe processes of overland, channel, saturated, and unsaturated flows. The watershed is represented by two analogous horizontal-grid square networks for surface and groundwater flow components. These are linked by vertical columns of nodes at each grid representing the unsaturated zone. The hydrologic simulation consists of subcomponents describing the processes of evapotranspiration, overland and channel flow, unsaturated flow, saturated flow, and channel/surface aquifer exchanges (Fig. 3.3).

MIKE SHE is a first generation of spatially distributed and physically based hydrologic model. MIKE SHE simulates the terrestrial water cycle including evapotranspiration (ET), overland flow, unsaturated soil water, and ground-water movements. Evapotranspiration is modelled as a function of PET, Leaf Area Index (LAI), and soil moisture content using the Kristiansen and Jensen (1975) method. The unsaturated soil water infiltration and redistribution processes are modelled using Richard's equation or a simple wetland soil water balance equation.

Model Parameters

MIKE SHE requires empirical vegetation parameters C_{int}, A_r, C_1, C_2 and C_3 to simulate the interception, root distribution and actual evapotranspiration. Note that these parameters are kept constant for each simulation, even though the optimization of these parameters may improve the simulation of output variables. However, the objective of this study is not to optimize these parameters; rather, parameter values from published values are chosen, as summarized using literature sources.

Parameter Calibration

For identifying certain unsaturated hydraulic properties, the observed soil moisture along with trial-and-error procedure was used. According to the soil water characteristic curve equation (1.2), soil moisture changes mainly affected by n, because n is the index of ah with a value ranging from 0.02 to 0.2, which is sensitive to moisture change. The parameters were determined by MIKE SHE model and field data in the duration from 1/1/2009 to 30/1/2009 because there are no crops and evaporation after winter irrigation and water flows down only.

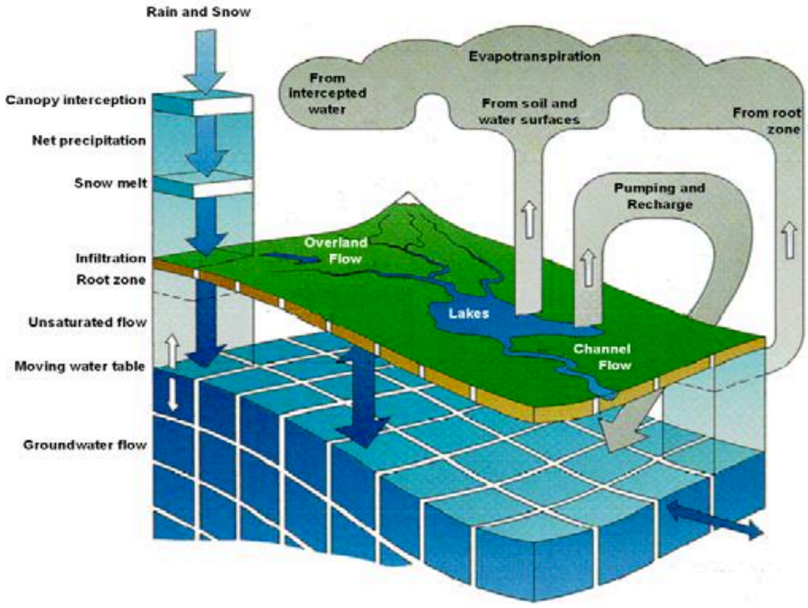


Fig .9. Schematic representation of MIKE SHE model

The model with the parameters derived from soil characteristic curve run, and the calculated moisture curve was compared with the field data curve (such as fig.4), if the error between calculated moisture and field data was larger than the standard value expected, n was changed and the model ran again. The process was repeated until the error was lower than the upper limit expected, and finally the best parameter obtained at last. The parameters in the derived from the model were as follows,

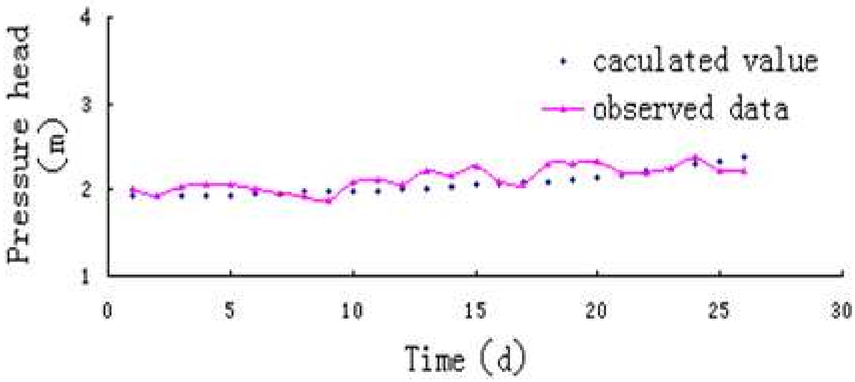


Fig.10. Compare with observed and calculated pressure head value

WATER BALANCE of the WATERSHED

The actual evapotranspiration is 195 mm against the total precipitation of 82 mm which includes actual rainfall and total irrigation simulated as rainfall. Also, the deficit in the unsaturated zone varies from -468 to -654 mm (a change of -186 mm). This shows that the soil water stored in the root zone mostly meets the crop water demand. The result here is in tune with the existing conditions in the field where the crops are grown with bare minimum irrigation.

ERROR ANALYSIS

Pressure head and practical observed data is described in Fig.4. Fig.4 is practical observed pressure on soil profile and model simulation comparing. From Fig-4, there were some error between simulated soil moisture and practical observed data.

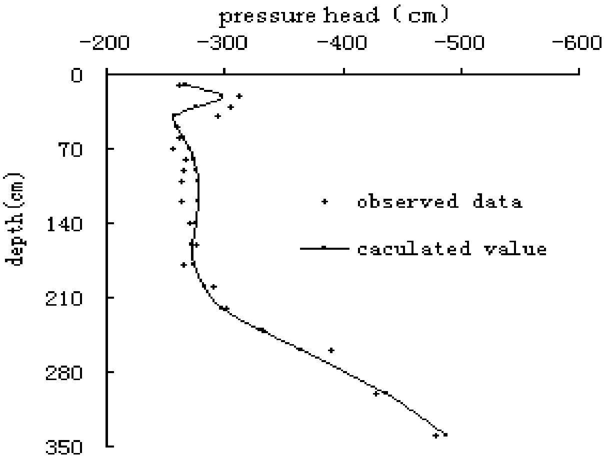


Fig.11. Compare with observed and calculated pressure head value in depth

RESULTS

A comparative graph between calculated and observed data was obtained using which the irrigation scheduling can be done. According to the pressure head measured (by soil hydraulic parameters), the corresponding depth of irrigation water can be supplied to the field. Finally by using MIKE SHE model, it easy to assess crop water requirement and identify suitable the irrigation scheduling to the field, with consuming less time and labour saving and can be used for the long period.

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