Experimental Study and Numerical Modeling of Surface/Subsurface Flow at field scale

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Abstract—**Infiltration which occurred in the process of runoff on farmland surface causes the increasing of soil moisture in unsaturated zone. It's necessary to comprehend the dynamic process during farmland runoff process, analyze the coupling mechanism of water movement and solute transport among surface/subsurface zone. In this paper, a physically-based, spatially-distributed model was built for simulation of surface/subsurface flow and the interactions between two domains. The system is represented by the three-dimensional saturated – unsaturated flow equation for the subsurface, coupled with the diffusion wave equation for overland flow, Ground surface unevenness at the grid scale is incorporated via the concept of detention storage. The system of equations is discretized using a fully implicit procedure, with the Newton-Raphson method to handle non-linearity of the equations. In order to assess this modeling approach, the simulations compared with the experiment results. It shows that the model can simulate the process of farmland runoff production and soil water movement accurately. Finally, Statistics and mass balance analysis was also performed to examine the model accuracy and response to changes of specific input data.**

Index Terms—**agricultural overland flow; soil water; coupling; integration of equation**

I. INTRODUCTION

Management of surface and groundwater quality has emerged as an environmental problem, particularly in agricultural watersheds, where conjunctive use of water for agriculture and human needs, represents a major problem. Modeling is the most cost effective means of determining the impact of management alternatives on water resources.

There are already some models to combine the surface hydrological and groundwater flow, such as SWAP, MIKE SHE, and SWAT model. The upper boundary of SWAP model is plant canopy and the bottom boundary is groundwater system. Soil water flow is solved using Richard's equation with differential format. The arithmetic is improved compared with provided by Van Dam J C et al[1]. Characteristics of handling transpiration are to calculate the soil evaporation and crop transpiration separately. MIKE SHE is a further developed model on the basis of SHE model provided by Danish Hydraulic Institute in the early 90s of last century, it is widely used in resource and environmental issues related to surface water, groundwater, and their dynamic interactions [2-5].

Singh et al created a mathematical model on simulation of slope runoff combining surface and underground water flow[6]. For surface runoff, de Saint-Venant equation and simple explicit numerical method without swing (ENO) was used, and for subsurface water flow, two-dimensional Richard's equation and fully implicit finite difference numerical method was used .It can be used to study two-dimensional effects produced by non-uniform features of underground and to deal with complex underground conditions. Sophocleous et al also combined SWAT with MODFLOW and developed SWATMOD model, taking infiltration flow in root layer calculated by SWAT as groundwater recharge of MODFLOW[7].

Gandolfi et al built coupled model based on two-dimensional shallow water equation and one-dimensional Richards equation, using joint calculus, explicit finite difference and MacCormack interpolation table, the model can be used to simulate dry soil initial surface conditions and the case with changing initial water content, and spatial variation characteristics such as slope, roughness, soil hydraulic properties and so on[8]. Panday et al established hydrological evaluation which can be used in different scale[9]. It coupled three-dimensional saturated - unsaturated groundwater flow and diffusion wave equation of surface flow, in taking a series of models of rivers, channels and hydraulic structures account. Bixio et al evaluated field capacity under certain conditions with

FLOW3D and analyzed the connection with surface flow that was simulated using DEM SURF ROUTE model based on DEM mode[10-12].

In China, some researches were also made. XIE Xin min et al proposed a unified model of surface water and groundwater with transformation among atmospheric water, surface water, soil water and ground water[13]. Wu Qiang et al analyzed interaction of the river – aquifer with simultaneous solution of a surface rivers one-dimensional unsteady gradually varied flow and groundwater imitate three-dimensional unsteady flow equations[14]. Jiang R et al evaluated transportation processes and loss fluxes of nitrogen and phosphorous through storm runoff in a typical small watershed in the hilly area of purple soil[15]. Yang JL et al analyzed Dynamic changes of nitrogen and phosphorus losses in ephemeral runoff processes by typical storm events in Sichuan Basin, Southwest China[16].

In this paper, the model was built basing on the physical mechanism of farmland surface runoff and the theory of water movement in unsaturated soil. Under certain condition of rainfall, the farmland surface runoff-water movement in unsaturated soil water flow coupling model is related to soil physical parameters, irrigation and drainage and crop growth stage. In the context of ensuring the water balance among rainfall, farmland surface water, soil water and ground water changing, the model can describe the surface runoff production process of farmland irrigation.

II. EXPERIMENT AND METHODS

A. Study Area

The study area is located in Lishui, Jiangsu Province, an agricultural region of Baima fork River watershed (31°34′N, 119°10′E). The area has a transitivity monsoon climate from North subtropical to Central subtropical with a mean annual temperature of 15.4℃, an annual rainfall of 1087.4mm, about 52.6% of which falls from June to September. The soil in study farmland is waterlogged paddy soil (physical and chemical properties of soil is shown in Table I). The crop management of seeding, irrigation and fertilization in the study area are followed the planting custom of local farmer. The drainage system of whole area made good performance. Finally, farm rainfall runoff flows to the main road of drainage system－Baima fork River mainly by drainage ditch and pond system.

TABLE I .
PHYSICAL AND CHEMICAL PROPERTIES OF SOIL PROFILE IN DRY LAND AREA

Soil layer	Soil depth (cm)	PH	Particle size distribution (%)			Soil bulk density (g/cm3)
			Sand	Silt	Clay	
Arable layer	0-15	5.5	8.6	67.4	24.1	1.29
plow pan	16-30	6.9	14.8	66.3	18.9	1.64

B. Experimental Design and Discharge Observation

Three treatments were designed based on the different arrangement of field drainage ditch (Figure 1). The treatment a has one drainage ditch 1and two drainage ditch 2, the treatment b has one drainage ditch 1 and three drainage ditch 2, and the treatment c has one drainage ditch 1 and four drainage ditch 2. Each treatment plot are 224m2 in area,68m long, 3m wide, and has an average slopes of 1/500 along the long edges(topography changed from higher to lower in the east) and 1/2000 along the shorter edges (topography changed from higher to lower in the north). The sectional dimensions of drainage ditch 1 in each treatment are 30cm×25cm(width×height), and 30cm×25cm(width×height) of drainage ditch 2. Zhongzhi No.16 variety of sesame were raised in the treatment plots evenly with density of $180,000/hm^2$.

The soil berms with the height 30-40cm between experiment fields was bed up and plastic film along the berms was buried with the depth about 70cm to reduce the influence by lateral leakage.

Set drainage outlet in each plot. Leave only one drain outlet when it rains (A1, A2 and A3 in Figure 1). Connect the drainage outlet to the cylindrical water meter by PVC pipe to convenient for real-time observation and collect water samples.
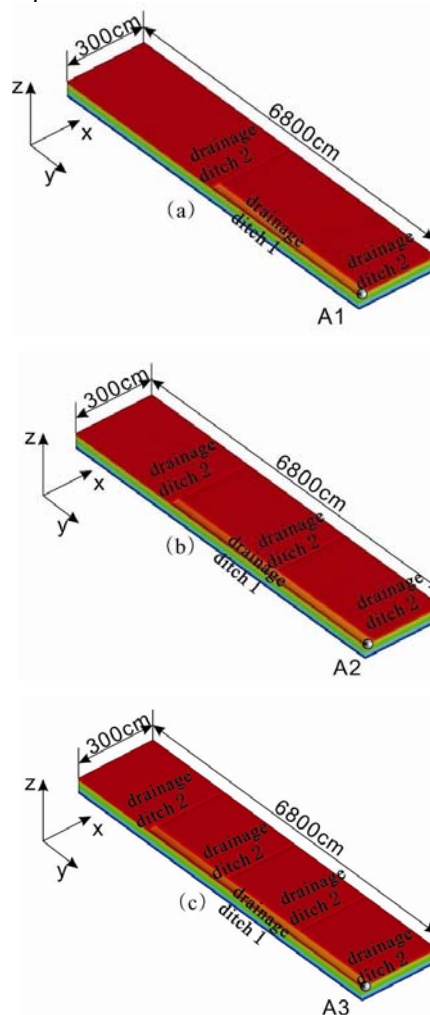
Figure 1. Schematic diagram of experiment area

Observe the whole process of rainfall by using self-registering siphon-type rain gauge (type SJ1). Keep rainfall records every 10 min. With the help of stopwatch and cylindrical water meter, real-time monitor of the surface runoff process of each treatment was conducted by using volumetric methods. Observation started from rainfall beginning and continued through the whole process of surface runoff. In the meantime, emphasis of observation is the variation of surface runoff as the change of rainfall rate with the frequency of 1-10min per time.

III. MODEL DESCRIPTION

A. Introduction

Mathematical modeling of overland flow involves the solution of the governing equations for both the surface flow and the groundwater flow by the interior physical mechanism. We should give comprehensive consideration to the landform, hydrometeorology, soil vegetation, etc. Also the interaction among hydrogeological condition, ground water and surface water should be considered. The surface flow equation is solved on a 2-D finite-element mesh stacked upon a subsurface grid when solving for both domains (i.e. the x- and y-locations of nodes are the same for each layer of nodes), as shown in Figure 2. For superposition, the grid generated for the subsurface domain is mirrored areally for the surface flow nodes, with surface flow node elevations corresponding to the top elevation of the topmost active layer of the subsurface grid.
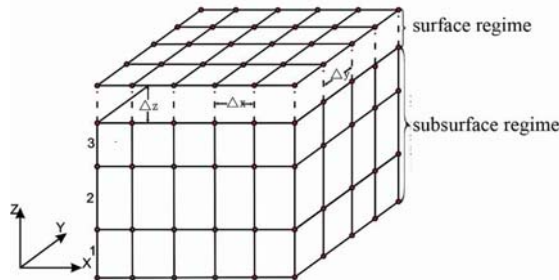

Figure. 2. Spatial discretization of the surface flow system and its connection to the subsurface[17-18].

B. Mathematical Model of Soil Water Movement

The equation of three-dimensional saturated-unsaturated soil water movement (Richard's equation) satisfies flow continuity in three-dimensions in both the saturated and unsaturated zones of the subsurface, it can be expressed as

$$\frac{\partial}{\partial x_i}\left[K_{ij}K_{rw}\frac{\partial h_G}{\partial x_j}\right]\pm Q = \frac{\partial}{\partial t}(\theta_s S_w) \tag{1}$$

where x, y, and z are Cartesian coordinates $[L]$; K_{ij} is the principal components of hydraulic conductivity along the x, y, and z axes, respectively $[LT^{-1}]$; K_{rw} is the relative permeability which is a function of water saturation as provided by the relative permeability curve[-

]; h_G is the hydraulic head of the subsurface flow system $[L]$; Q is a volumetric flux per unit volume of the subsurface domain and represents sources and/or sinks of water, or the flux per unit volume of subsurface from the 2-D overland flow domain $[L^{-1}]$; θ_S is saturation moisture content $[L^3 L^{-3}]$; S_w is the degree of water saturation and is determined by the moisture retention curve as a function of the pressure head, ψ ($\psi = h_g - z$ where z =nodal elevation in a vertically upward coordinate system).

A functional form of the moisture retention curve is given by van Genuchten as

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr}} = \begin{cases} \dfrac{1}{[1+(\alpha\psi)^\beta]^\gamma} & for\ \psi < 0 \\ 1 & for\ \psi \geq 0 \end{cases} \tag{2}$$

Functional forms of the relative permeability curve are provided by van Genuchten as

$$K_r = S_e^{1/2}\left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{3}$$

Where, S_e is the effective water saturation; S_{wr} is the residual water saturation; α and β are fitting parameters; $\gamma = 1 - 1/\beta$.

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr}} \tag{4}$$

$$m = 1 - 1/\beta \quad , \qquad n > 1 \tag{5}$$

The van Genuchten functions for the moisture retention and relative permeability characteristics may be obtained by curve-fitting to laboratory measurements, by correlation to soil type, or by consulting in soils databases.

C. Surface Flow Model

The surface runoff in the study area is influenced by tiny terrain. The movement of the runoff belongs to the type of slowly varying unstable flow. In consideration of the fact that:

1. The distribution of hydrodynamic pressure and hydrostatic pressure are almost the same.

2. The streamline curvature of runoff is small, basically parallel.

3. The frictional resistance between water and boundary and frictional resistance between water and water is the main dissipation power.

4. The scale of level movement is larger than vertical movement. And the vertical velocity and vertical acceleration of flow can be ignored.

Based on the assumptions, taking the two-dimensional Saint-Venant equations with momentum term ignored (two-dimensional shallow water equations) to describe surface runoff movement.

$$\frac{\partial h_s}{\partial t} - \frac{\partial}{\partial x}(d_s k_{sx}\frac{\partial h_s}{\partial x}) - \frac{\partial}{\partial y}(d_s k_{sy}\frac{\partial h_s}{\partial y}) + d_s Q_{GS} + Q_S = 0 \tag{6}$$

Where h_s is surface altitude [L] ($h_s = d_s + z_s$); z_s is ground altitude [L]; d_s is water depth[L]; Q_s is source-sink item[LT-1]; k_{sx} and k_{sy} are land surface conduction coefficient in x direction and in y direction[LT-1]; k_{sx} and k_{sy} can be accounted respectively by the two formula as follows:

$$k_{sx} = \frac{d_s^{2/3}}{n_x} \frac{1}{[\partial h_s / \partial s]^{1/2}} \quad k_{sy} = \frac{d_s^{2/3}}{n_y} \frac{1}{[\partial h_s / \partial s]^{1/2}} \quad (7)$$

Where n_x and n_y are Manning roughness coefficient in x direction and in y direction [L-1/3T]; k_n is the land surface normal vector conduction coefficient of boundary [LT-1]; Q_S is water flux of boundary [LT-1].

D. Discretized Flow Equations and Flow Interaction between Two Domains[17-18]

Using the control volume finite element method, with fully implicit time weighting, the following discretized porous medium flow equation is obtained[17-18]:

$$\left[(\theta_s S_w)_i^{L+1} - (\theta_s S_w)_i^{L}\right] \frac{v_i}{\Delta t} \qquad (8)$$
$$= \sum_{j \in \eta_i} (\lambda)_{(ij+1/2)}^{L+1} \gamma_{ij}(h_{Gj}^{L+1} - h_{Gi}^{L+1}) - (\sum \Gamma_{ex}^{L+1}) \pm Q_i^{L+1}$$

where: $$h_{Gi} = \psi_{Gi} + z_i$$

and: $$\gamma_{ij} = \int_v \nabla N_i \cdot K \cdot \nabla N_j dv$$

For interpolation function N define for the 3-D porous medium elements and where the 3-D volume associated with a given node is given by:

$$v_i = \int_v N_i dv$$

For upstream weighting, the $\lambda_{ij+1/2}$ values are given by:

$$\lambda_{ij+1/2} = k_{rj} \ \text{if} \ \gamma_{ij}(h_j - h_i) > 0$$
$$\lambda_{ij+1/2} = k_{ri} \ \text{if} \ \gamma_{ij}(h_j - h_i) < 0$$

The discretized 2-D surface flow equation is:

$$\left[(h_s)_i^{L+1} - (h_s)_i^{L}\right] \frac{a_i}{\Delta t} = \qquad (9)$$
$$\sum_{j \in \eta_{oi}} (\lambda_s)_{(ij+1/2)}^{L+1} \gamma_{sij}(h_{sj}^{L+1} - h_{si}^{L+1}) + d_s \Gamma_s^{L+1} a_i \pm q_{si}$$

where η_{oi} is the set of surface nodes connected to the surface node i through the 2-D surface elements and where:

$$h_{oi} = d_{oi} + z_{oi}$$

and: $$\gamma_{oij} = \int_a \nabla N_i \cdot K_o \cdot \nabla N_j da$$

with interpolation function N define for the 2-D surface element.

The 2-D area associated with a given surface node is given by:

$$a_i = \int_v N_i da$$

For upstream weighting, the $(\lambda_o)_{ij+1/2}$ values are given by:

$$(\lambda_o)_{ij+1/2} = k_{roj} \ \text{if} \ \gamma_{oij}(h_{oj} - h_{oi}) > 0$$
$$(\lambda_o)_{ij+1/2} = k_{roi} \ \text{if} \ \gamma_{oij}(h_{oj} - h_{oi}) < 0$$

From soil water flow movement discrete equation (shown in formula (8)), we can see that node I has double character of the two zones if node I is shared by soil and surface. Presume $h_i = h_a$, for the soil water flow movement discrete equation of node I, $\sum \Gamma_{ex}^{L+1}$ contains water exchange item of the two zones. But for the discrete equation of surface,

$d_0 \Gamma_0^{L+1} a_i$ is the exchange item of the two zones, formula (9) can be shown as follows:

$$d_o \Gamma_o^{L+1} a_i = \left[(h_o)_i^{L+1} - (h_o)_i^{L}\right] \frac{a_i}{\Delta t} - \qquad (10)$$
$$\sum_{j \in \eta_{oi}} (\lambda_o)_{(ij+1/2)}^{L+1} \gamma_{oij}(h_{oj}^{L+1} - h_{oi}^{L+1}) \pm q_{oi}$$

Substituting (8) into (10) leads to the integrated equation of two domains:

$$\left[(\theta_s S_w)_i^{L+1} - (\theta_s S_w)_i^{L}\right] \frac{v_i}{\Delta t} =$$
$$\sum_{j \in \eta_i} (\lambda)_{(ij+1/2)}^{L+1} \gamma_{ij}(h_{Gj}^{L+1} - h_{Gi}^{L+1}) \pm Q_i^{L+1} \qquad (11)$$
$$-(\left[(h_s)_i^{L+1} - (h_s)_i^{L}\right] \frac{a_i}{\Delta t} -$$
$$\sum_{j \in \eta_{oi}} (\lambda_s)_{(ij+1/2)}^{L+1} \gamma_{sij}(h_{sj}^{L+1} - h_{si}^{L+1}) \pm q_{si})$$

Fully implicit coupling of the surface and subsurface flow regimes provides an integral view of the movement of water, as opposed to the traditional division of surface and subsurface regimes. Flux across the land surface is, therefore, a natural internal process allowing water to move between the surface and subsurface flow systems as governed by local flow hydrodynamics, instead of using physically artificial boundary conditions at the interface.

IV. BOUNDARY CONDITIONS AND PARAMETERS ESTIMATION

A. Initial and Boundary Conditions

The upper boundary of the three treatments that mentioned before adopt atmospheric boundary. The rainfall process is as shown in Figure 3. Set the lowest of the land surface—— point A1,A2 and A3 as the critical depth drainage boundary. The critical depth (CD) condition forces the depth at the boundary to be equal to

the critical depth, as would occur at free-fall boundaries.

The discharge (Q_0) per unit width at the critical depth boundary is given by

$$Q_o = \sqrt{gd_o^3}$$

Initial soil water content was taken from the measured value before the experiment on July 11, 2010 by linear interpolation.

B. Hydrodynamic Parameters

Soil water characteristic parameters(Table II) can be obtained by the analogy between the actual soil water characteristic curve and the database of soil water characteristic curves provided by Hydrus-2D.

The hydrodynamic parameters of field surface and drainage ditch were calibrated by the comparison between runoff production process of treatment c and the simulation results (Figure 4), In the stage of model calibrating, the runoff volume relatively error counted is less than 20% which satisfied the demands of modeling. The relative error is 0.47%, which is small and acceptable. Simulation parameters adopted in the simulation are listed in Table III.

TABLE II.

SOIL WATER CHARACTERISTIC PARAMETERS

parameters	loam
saturation moisture content θ_s	0.45
residual water saturation θ_r	0.067
saturated hydraulic conductivity K/m·min-1	0.25
β	1.41
α /m-1	0.02

TABLE III.

HYDRAULIC PARAMETER OF LAND SURFACE AND RILL DRAINAGE

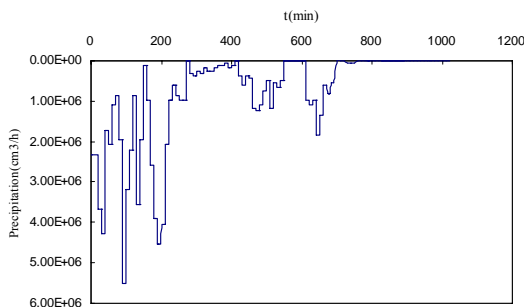|	Manning coefficient n /s · m-1/3	water storage height of rill drainage /cm
field surface	0.167	2.5
drainage ditch 1	0.00835	1
drainage ditch 2	0.00835	1

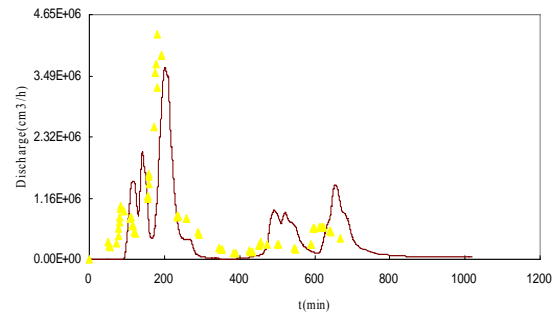Figure 3. A pictorial diagram of precipitation procession

Figure 4. The comparison of experimental data (dot) and simulated curve (line) of treatment c

V. RESULTS AND DISCUSSION

A. Simulation Results

Figure 5 expresses the comparison of experimental data (dot) and simulated curve (line) of the discharge. It is indicated that simulated results from the proposed numerical model have good agreements to the measured data. The water moisture that was simulated of the soil profile is saturated as the same as experiment observation.

B. Statistics and Mass Balance Analysis

In order to estimate the accuracy of the model simulation result, statistics analysis has been conducted. Statistics analysis of the model performance includes the determination of the root mean square error (RMSE) and the relative RMSE (RRMSE) for the selected pairs of data (simulation values and measured values).

$$RMSE = \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n} \tag{12}$$

$$RRMSE = RMSE / O_{ave} \times 100 \tag{13}$$

where P_i, O_i are simulation results and observation value respectively, n is the number of simulation results and observation value, O_{ave} is average of observation value.

According to the statistical analysis between observed and calculated values of discharge shows that there is a statistically significant relationship between them. The small RRMSE indicates the small deviations between measured and simulated values. A good agreement between observed and simulated values of discharge is obtained.

Mass balance calculation is done after solving for fluid flow. It was performed by first computing the total mass change in the domain for a given time step. The mass entering or leaving the domain through the boundaries or through internal sources and sinks is then computed and is compared to the total mass change, providing the mass balance check for the simulation.

The water balance information for the region consists of the actual volume of water, V, in that region, and the

rate, O, of inflow or outflow to or from the region. V and O are given by

$$V = \sum_e kA_e \frac{\theta_i + \theta_j + \theta_k}{3}$$

$$O = \frac{V_{new} - V_{old}}{\Delta t} \qquad (14)$$

respectively, where θ_i, θ_j and θ_k are water contents evaluated at the corner nodes of element e, and where V_{new} and V_{old} are volumes of water in the region computed at the current and previous time levels, respectively. The summation in (14) is taken over all elements within the region.

The accuracy of the numerical solution is evaluated in terms of the relative error, $\varepsilon_r^w [\%]$, in the water mass balance as follows:

$$\varepsilon_r^w = \frac{\left| \varepsilon_a^w \right|}{\max[\sum_e |V_t^e - V_0^e|], L_t \int_0^t T_a dt + \int_0^t \sum_{n_\Gamma} |Q_n| dt]} \% \qquad (15)$$

Where V_t^e and V_0^e are the volumes of water in element e at times t and zero, respectively.

Table IV show water balance analysis of the simulation, it can be seen that the relative error is less than 5% of the whole water mass. That mean result simulated by this model is reasonable.

TABLE IV

WATER BALANCE ANALYSIS OF THE SIMULATION

Item	a	b	c
Relative error (%)	2.64	1.33	1.56

C. Parameter Sensibility Analysis

In order to examine the model response to changes of specific input data, a sensitivity analysis of the model was performed. The model includes 5 main parameters, that is θ_r, θ_s, α, n, K. In this paper, the parameter that was used in the simulation was plus 10% (Table V) and then analysis the parameter sensibility. Base on the simulation, the sensitivity analysis was performed to assess the effect produced by a given variation of the input data on the model output, Take an emphases calculate on the influence of discharge.

Among these parameters, the soil water characteristic parameters have the major influence on the simulation results. The model shows the highest sensitivity to Manning coefficient n. Therefore, a proper assessment of surface characteristic parameters is very important for the rational use of the model because these parameters rarely can be measured directly and mostly adopted by experience. The model is less influenced by the residual water saturation parameters.. Regarding the model

sensitivity, greater attention should be pay to the soil water characteristic parameters except residual water saturation.
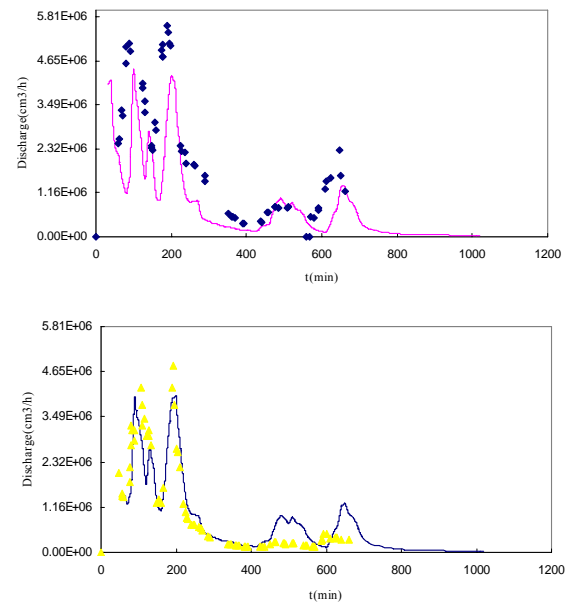

Figure 5. The comparison of experimental data (dot) and simulated curve (line) of treatment a and treatment b

TABLE V

SENSIBILITY ANALYSIS OF MAIN PARAMETER OF THE MODEL

parameter value and computation results	number	1	2	3	4	5
subsurface	saturation moisture content t θ_s	0.495	0.45	0.45	0.45	0.45
	residual water saturation θ_r	0.067	0.0737	0.067	0.067	0.067
	saturated hydraulic conductivity K/m·min-1	0.25	0.25	0.275	0.25	0.25
	α /m-1	0.02	0.02	0.02	0.022	0.02
surface	Manning coefficient n /s·m-1/3	0.167	0.167	0.167	0.167	0.1837
the discharge change (adopt absolute value)		2.26%	0.95%	1.78%	1.49%	4.08%

D. Discussion

In the past, the popular models of farmland runoff yield are not always suitable for the present situation conditions of agricultural cultivation in China. Runoff yield models based mainly on empirical model and statistical model. For the farmland runoff which has wide area of distribution and great different of types, parameter calibration and regional differences had limited application of model. It should be said that in the field which has small area, flat field surface and bund controlled, whose runoff process is relatively simple. In order to make it easy to practical application, we had to

study on the physical model of farmland runoff under the condition of irrigation and drainage, and describe the surface runoff production process of farmland irrigation accurately. Combined groundwater dynamics with soil water dynamics and solute transports in porous media theory, considering the mass balance mass conversion of solute between soil system and surface runoff system, to build the analysis model of theory is the key problem which needs to further improve at present. It can not only interpret the mechanism of material transformation between soil system and surface runoff in the theory, but also can solve the malady by using empirical model and statistical model during study on the dispersion irrigation and drainage field when the statistical parameters is difficult to measure.

VI. CONCLUSION

In this study, a conjunctive surface-subsurface numerical model is developed for the simulation of overland flow. The model includes a fully three dimensional solution for saturated–unsaturated flow in the subsurface coupled with two dimensional solutions for surface-water flow; the proposed conjunctive model is verified using experimental data. The ability of the proposed model to handle complex subsurface conditions is demonstrated through the numerical simulation studies. Contrasting with the experiment result, it shows that the model can simulate the process of farmland runoff production and soil water movement accurately. Comparison between measured and calculated values as well as mass balance analysis indicated that the model is reliable and can be used to predict water movement in surface/subsurface. Simple model sensitivity analysis can guide the choice of input data values. The analysis shows that the model is more sensitive to the soil water characteristic parameters but less to the hydraulic parameter of land surface.

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