Simulation of Drainage Systems in unsteady state condition, using system dynamics

Nozari, H. , Liaghat, A. and Kholghi, M.
University of Tehran
Department of Irrigation and Reclamation Engineering
Tel:0098-261-2241119
Email: hanozari@yahoo.com, aliaghat@ut.ac.ir and kholghi@ut.ac.ir

Abstract:
The system dynamics technique is one of the object oriented approaches that studies and manages complex feedback systems. Its merits include the friendly and easily development and improvement of model. It's also used as a decision tool for engineering problems.
In this paper, the system dynamics technique was used to simulate the performance of a drainage system in unsteady state condition. The model is capable to predict many hydrological parameters such as water table fluctuation, drainage discharge, upward flux, evapotranspiration, deep percolation, infiltration, runoff, soil moister content and unsaturated hydraulic conductivity on the basis of variation of soil moister content. All above parameters were investigated theoretically and their trends were found to be legible. The model was validated using observed experimental field data collected from amirkabir unit in sugar beet development plan located at khozestan, Iran. The observed data were water table level and drainage discharge. The standard error index was calculated to determine the agreement between the observed and simulated values of water table and drainage discharge. The results indicated that Standard Error (S.E.) for water table and drainage discharge were 10.2 and 0.13 centimeter per day respectively.
Key words: System dynamics, Unsteady state, Drainage system, hydrological parameters

1. Introduction

Draining water from the soil profile is an important hydrologic component in most agricultural soils. Natural drainage processes include groundwater flow to streams or other surface outlets; vertical seepage to underlying aquifers; or lateral flow (interflow) which may reappear at the surface at some other points in a landscape. Artificial or improved drainage may be provided by installing drainage ditches or drain tubes (Alaa El-Sadek et al, 2001). Artificial drainage has been known to be an important water management practice for farming of the most productive soils of the Midwest (X.wang et al, 2005). These systems are usually installed in irrigated arid and semi arid lands to control water logging and salinity. The successful performance of a drainage system depends on optimal design of drain depth and drain space. Because it is important for irrigation management, pesticide management and subsurface contaminant restoration analysis. The need to have guidelines for drainage design and water management for different soils and climates has driven both the experimental field research and computer modeling. Computer-based simulation models can predict subsurface drain flows, water table fluctuations, and crop yields in a greater variety of conditions than what is feasible through monitoring, which allows timely decisions to be made about complex problems when field data are both difficult and expensive to obtain (Haan and Skaggs, 2003).

System dynamics is a methodology developed by J.W. Forrester to analyses dynamic behavior of complex systems containing biological, economic, social, technological and political elements, aided by computer (Forrester, 1968). This technique has been successfully applied to many types of dynamic systems since its creation (Richardson, 1999) though must focus remains on business and corporate policy (scroll, 1995). In this study the attempt was to apply this technique to simulate soil water movement in saturate and unsaturae condition and drainage system. The system dynamics tool, Vensim is used as it provides a fully integrated simulation system to conceptualize, document, simulate and analyze models of dynamic systems.

The objective of this work was to develop a model to predict drain discharge behavior and water table fluctuations for different drainage density (the depth of the drain and the drain spacing), soils and climate. Results of the drain discharge and water table predictions can be use to drainage design and water management for long time.

2. Model Development

2.1. Conceptual model

The water balance model is formulated for unsaturated condition. This condition can be conceptualized as four boxes in which the water content fluctuates over time. The model traces the portion of the irrigation water evapotranspired and the portion infiltrated through each layer and finally recharges the groundwater. The dynamics of water table and groundwater intrusion to the root zone are also represented. The soil water storage in the first layer was calculated as:

$$S_j = S_{j-1} + I_j + R_j + UP_j - ET_{a\ j} - P_j - SR_j$$

Where S_j and S_{j-1} are the soil water storage at the end of day *j* and $j-1$ respectively; I_j is the amount of irrigation on day *j;* R_j is the amount of rainfall on day *j;* UP_j is the amount of upward flux from the underlying water table on day *j* depending on the depth of water table; $ET_{a\ j}$ is the amount of evapotranspiration on day *j;* P_j is the amount of percolation on day *j;* and SR_j is the amount of runoff on day *j*. the unit of all parameters is the same and is expressed as millimeter per day.

The soil water storage in the other layers was calculated as:

$$S_{j,i} = S_{j-1,i} + P_{j,i-1} + UP_{j,i} - UP_{j,i-1} - ET_{a\ j,i} - P_{j,i} \qquad i > 1$$

Where i is the layer number. Also it was assumed that the water do not move to sub layer, until the upper layer reach to its field capacity. Therefore the amount of water that each layer needs to get its field capacity is determined as follow:

$$I_i = (\Theta_{FC} - \Theta_i)\Delta Z$$

Where θ_i and θ_{FC} are water content and field capacity in layer i respectively and ΔZ is the thickness of layer *i*.

In saturate condition, Hooghoudt's equation (1940) was used to calculate the drainage outflow. The drain tube and its sub layer, each can be conceptualized as one box.

$$q = \frac{8kD_e h}{L^2} + \frac{4kh^2}{L^2}$$

Where q is drainage discharge (L/T); $K1$ and $K2$ are hydraulic conductivity above and below the drains (L/T), respectively; h is water table height at the midpoint and above the drains (L); L is drain spacing (L) and *De* is equivalent depth of the aquifer below the drain base.

2.2. System dynamics

Despite the efforts of several alternative approaches to manage intangible factors, none has been sufficient to fully incorporate relationships between variables, delays and feedback, all of which characterize the behavior of intangible resources. So, Managers continue taking decisions only based (or support) on their experience, knowledge that constitute their mental models (Adriana Ortiz et al., 2006). Therefore, there is a need to explore new tools to represent the complex relationships found in systems. One promising option is system dynamics (SD) which is a feedback-based, object-oriented approach. Although SD is not a novel approach, it offers a new way of modeling for future dynamics of complex systems. According to Simonovic and Fahmy (1999), system dynamics is based on a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior. The most important feature of system dynamics is that it helps to elucidate the endogenous structure of the system under consideration, and demonstrate how different elements of a system actually relate to each other. This facilitates experimentation as relations within the system are changed to reflect different decisions (Elmahdi et al., 2005).

Agricultural systems and their environmental effects, like many other environmental problems, constitute complex systems, which study requires systemic approaches capable of explicitly managing the temporal dimension, sustainability conditions, uncertainty and externalities (Bergh 1996). Therefore the system dynamic is good approach to model this system.

2.2.1. The causal loop diagram

Causal loop diagram is an important tool for representing the feedback structure of systems. A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. A feedback loop is a succession of causes and effects such that a change in a given variable travels around the loop and comes back to affect the same variable. If an initial increase in a variable in a feedback loop eventually results in an increasing effect on the same variable, then, the feedback loop is identified as a 'reinforcing or positive' feedback loop. If an initial increase in a variable eventually results in a decreasing effect on the same variable, then the feedback loop is identified as a negative, counteracting or balancing' loop (Saysel and Barlas, 2001).

The causal loop diagram in this study has shown in figure 1. The first negative feedback loop represents the evapotranspiration effect: the larger the evapotranspiration, the less the soil water content and soil moisture stress "ket", which in turn decreases evapotranspiration. The second feedback loop represents the interaction between evapotranspiration and upward flux: the larger the evapotranspiration, the larger the upward flux, then the larger the soil water content and ket, which in turn increases evapotranspiration. The third feedback loop represents the interaction between soil water storage and percolation: the larger the storage, the larger the hydraulic conductivity, then the larger the percolation, which in turn decreases soil water storage.

The fourth feedback loop represents interaction between water table and soil water storage: an increase in the percolation increases water table and upward flux and soil water content. In the fifth feedback loop as water table rises by deep percolation, the depth of water above the drain increases which increases the drain discharge, and in turn decreases the water table.

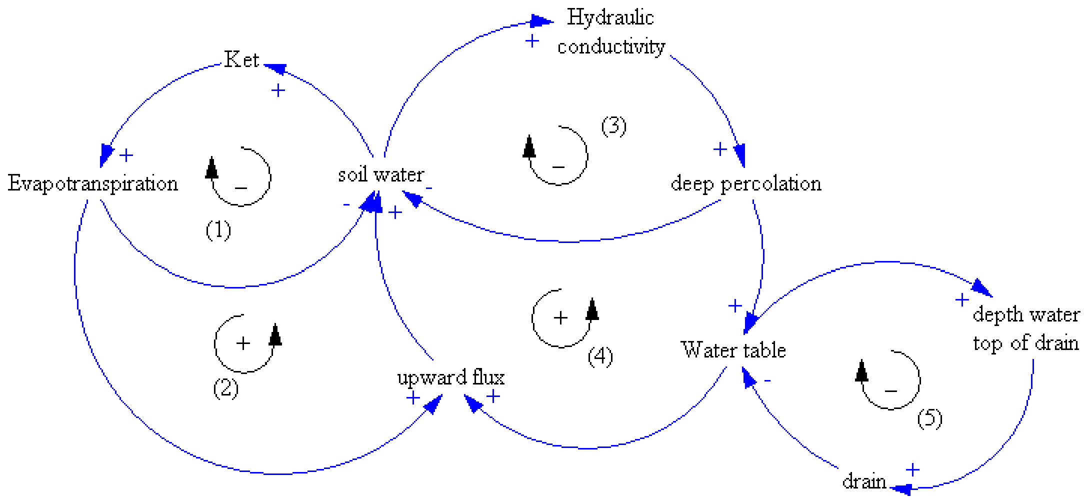

Fig. 1. Causal loop diagram

2.2.2. The stock and flow structure

Stocks accumulate the net flow which is the inflows minus outflows. Stocks are the states of the system upon which decisions and actions are based, are the source of inertia and memory in systems, create delays, and generate disequilibrium dynamics by decoupling rates of flow. The rate of change of a stock is the total inflow minus the total outflow. Thus a stock and flow map corresponds exactly to a system of integral or differential equations (Sterman, 2000). The stock and flow structure are shown in figure 2. The soil water storage in each layer, the water table and ground water are modeled as stock variables which represent the accumulation of water in them. The rate of change in soil water storage is represented in the modeled by five flow-rate variables, two of them are representing the increase through irrigation and upward flux from the ground water, and the other representing the decrease through evapotranspiration, percolation and upward flux that exit from the sub layer to upper layers. The rate of change in water table is modeled by six flow variables, two of them representing the increase through percolation and seepage from surround, and the other representing the decrease through upward flux, drain, deep percolation to ground water and seepage to surround. The rate of change in ground water is modeled by two flow variables, one representing the increase through deep percolation and the other representing the decrease through drainage.

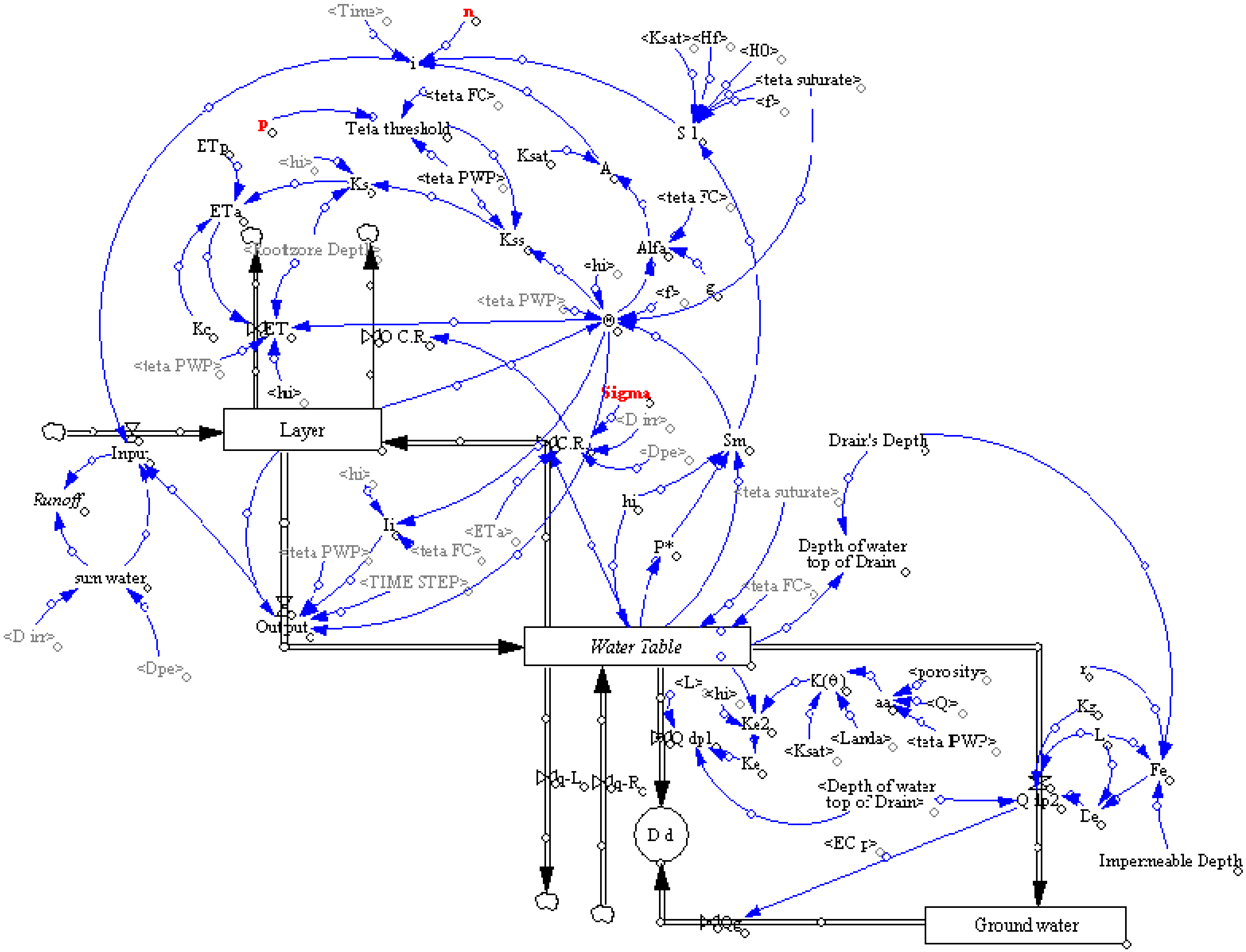

Fig. 2. Stock and flow structure

3. Validation and analysis of the model

To validate the model, the simulated data were compared with the observed data. For this purpose the study area, ARC2-5 with 25 ha, was selected in Amirkabir unit in sugar beet development plan located at khozestan, Iran in the year of 2006. This site has a flat topography with a shallow water table. The drain space is 40 meters and the drain depth is 1.8 m at the shallowest end to 2.2 at the drainage sump. To evaluate water table fluctuation, 21 pizometers were installed on three rows (seven piezometers on each row) with distance of 100, 250 and 375 m far from collector. Irrigation water was applied in 2005 for five months. Parameters such as daily water table and drainage outflow were recorded.

3.1. Water table

The water table is an important parameter for evaluating the performance of drainage systems. The comparison between simulated and measured average water table levels has been shown in figure 3. This picture illustrates a good agreement between the observed and simulated data which indicates that the model provides a realistic representation of the water table. The measured rapid rises in water table levels correspond to irrigation or rainfall events.

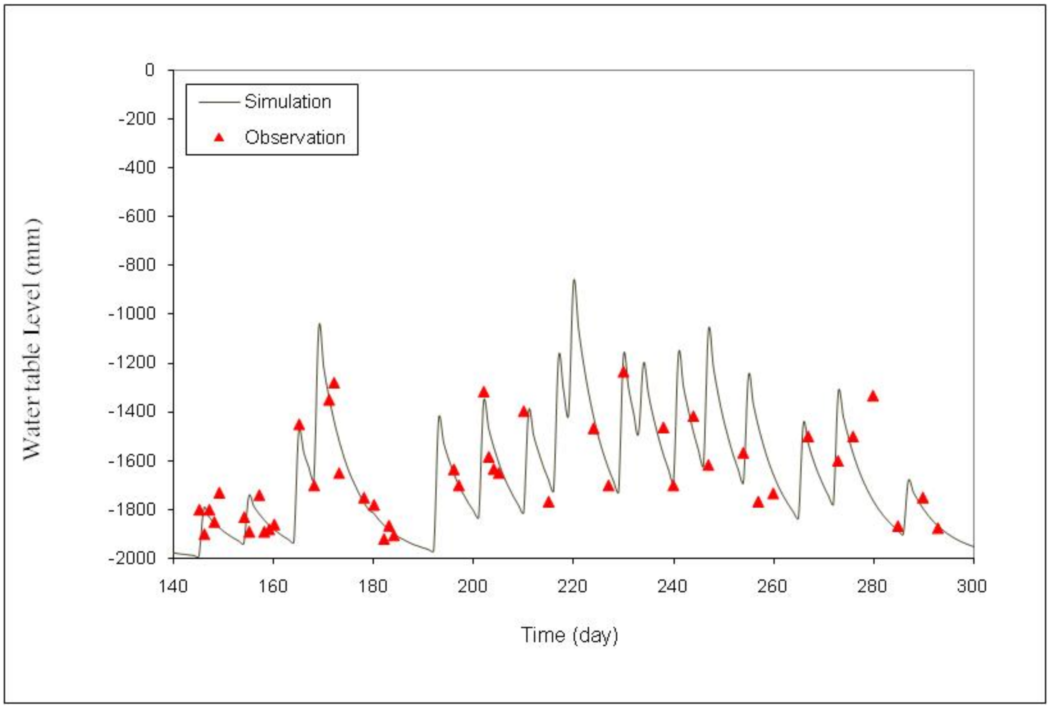

Fig. 3. The comparison between simulated and measured average water table levels

3.2. Drain discharge

Drainage discharges and water table levels were measured simultaneously. Figure 4 shows the comparison between the observed and simulated drain out flows. This figure illustrates a good agreement between the observed and simulated values. Figure 3 and 4 indicate when water table rises, drain discharge increase. According figure 4 drainage discharge was found to be in a range of 0.104-22.47 millimeter per day and its average value was 6.25

millimeter per day during recording period. It should be Noticed that the drainage coefficient is proposed to be 6 millimeter per day for that area which agreed well with the average drainage discharge.

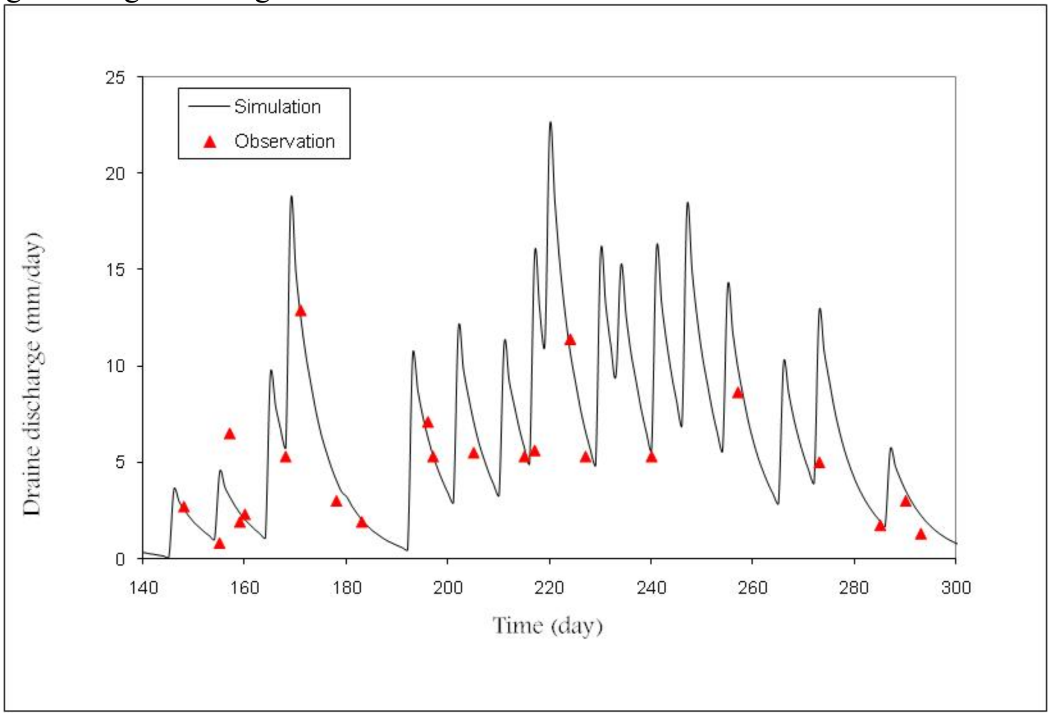

Fig. 4. The comparison between simulated and measured drain discharge

3.3. Statistical analysis

Statistical criteria are used for the quantitative judgment. In this study the standard error criteria was used to evaluate the performance of the model.

$$S.E. = \sqrt{\frac{\sum (O_i - S_i)^2}{n}}$$

Where O_i is observation data and S_i is simulation data.

The statistical analysis between estimated and observed data, as shown in table 1, revealed that the model is able to predict water table levels and drainage discharges properly.

Table 1. standard error and determination coefficient for water table and drainage discharge

Parameters	S.E.	R^2
Water table (cm)	10.2	0.72
Drainage flux	0.13	0.8

figure 5 shows The upward flux in the soil which its average is 0.34 millimeter per day during summer time (Julian days of 150 to 240) and 0.09 millimeter per day during fall and winter(Julian days of 240 to end of period). The reason for this difference is the seasonal effect which in summer evapotranspiration rate is high and irrigation interval is short, but in fall and winter evapotranspiration rate is small and irrigation interval is long. The upward flux was ranged from 0.02 to 1.12 millimeter per day. In this model it was assumed that evapotranspiration is zero during irrigation and rainfall events and thus upward flux is assumed to be zero.

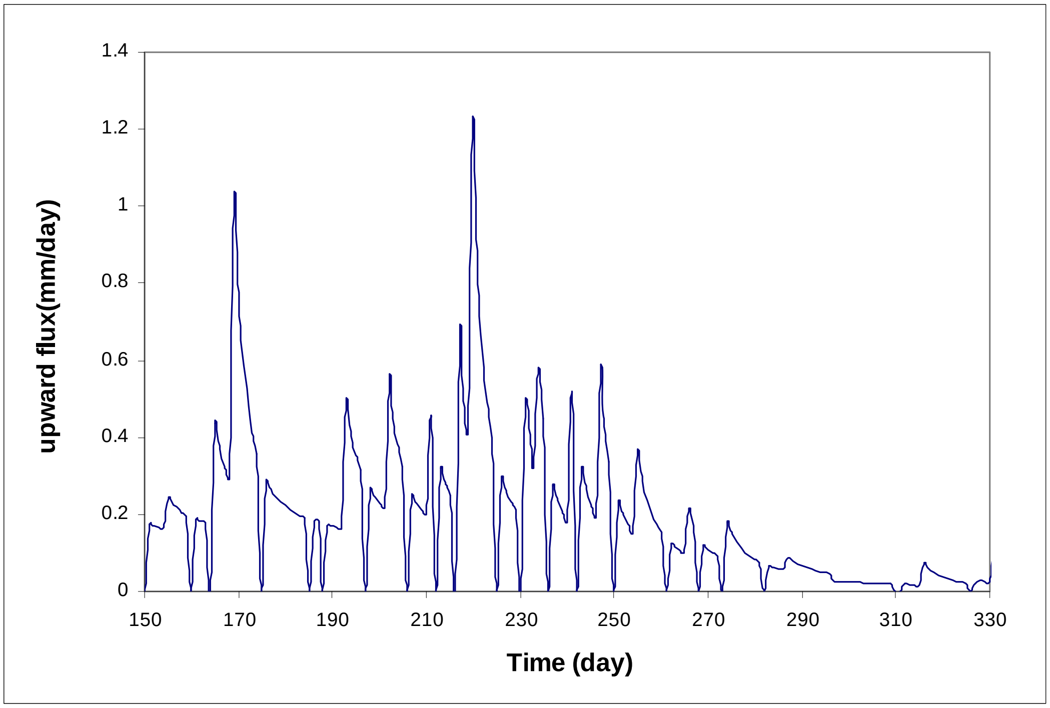

Fig.5. the upward flux from ground water level

4. Conclusion

The present model was used to simulate the water table head at the midpoint of drain space and the daily drainage flux in the soil. The estimated and observed data were compared in terms of water table level and drainage discharge. The statistical analysis implies the good fitness between observed data and simulation results. The comparative study reveals that the model performs well and is reliable and accurate for predicting water table, drainage flux, upward flux, evapotranspiration, deep percolation, infiltration, runoff, soil moister content and unsaturated hydraulic conductivity on the basis of variation of soil moister content.

Therefore this model can help us to have guidelines for drainage design and water management for different drainage density (the depth of the drain and the drain spacing), soils and climate.

The model can potentially be used by the policy makers in long term strategic management of large scale irrigation development project.

5. References

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