Araştırma Makalesi/*Research Article*

AKDENİZ ÜNİVERSİTESİ
ZİRAAT FAKÜLTESİ DERGİSİ
(2010) 23(2): 151-156

www.ziraatdergi.akdeniz.edu.tr

Evaluating drainage design parameters by numerical experimentation

Drenaj tasarım parametrelerinin sayısal denemelerle değerlendirilmesi

Dursun BÜYÜKTAŞ[1], Ruhi BAŞTUĞ[1], Köksal AYDİNŞAKİR[2]

[1] Akdeniz University Faculty of Agriculture Department of Farm Structures and Irrigation, 07070 Antalya, Turkey
[2] West Mediterranean Agricultural Research Institute, Antalya, Turkey

Sorumlu yazar (*Corresponding author*): Dursun BÜYÜKTAŞ, e-posta *(e-mail)*: dbuyuktas@akdeniz.edu.tr

ARTICLE INFO

Received 28 May 2010
Received in revised form 12 November 2010
Accepted 23 November 2010

***Keywords*:**

Drainage
Numerical model
Simulations

ABSTRACT

Drainage is necessary for agricultural production in many humid regions of the world, where it is used to improve crop yields and trafficability by removing excess water from the surface and root zone. In arid regions, drainage is often needed to prevent waterlogging and to control salinity in irrigated fields. Water table depths, crops grown in the area, and drain flow rates are critical in the proper design of drainage systems. Numerical models developed by solving the governing water flow equations provide the most exact prediction of these values. Both finite elements and finite difference methods have been used effectively in drainage research. In this study, the effects of soil texture and drainage design parameters such as drain spacing, drain depth, and depth to impervious layer on drain flow rate and water table depth are studied by numerical experimentation using SWMS_3D that simulates water flow, heat transfer and solute movement in variably saturated porous media. The model developed by U.S. Salinity Laboratory can deal with a wide range of boundary conditions including ditches and drain tubes as well as boundaries controlled by atmospheric conditions. The results showed that light-textured soils are draining faster than that of the heavy-textured soils. As drain spacing and drain depth increased, drain flow rate also increased. The water table height in the middle of the drains was found to be lower when the depth of the impermeable layer below the drain increased. The numerical results are consistent with the results of the drainage studies. It is concluded that numerical models can be used to foresee the possible effects of drainage design criteria before installing tile drains in the field.

MAKALE BİLGİSİ

Alınış tarihi 28 Mayıs 2010
Düzeltilme tarihi 12 Kasım 2010
Kabul tarihi 23 Kasım 2010

***Anahtar Kelimeler*:**

Drenaj
Sayısal model
Simülasyon

ÖZ

Dünyanın birçok nemli bölgesinde tarımsal üretim için drenaj kaçınılmazdır. Bu tür alanlarda drenajla beraber, yüzey ve kök bölgesindeki fazla su uzaklaştırılarak bitkisel üretim artırılmaktadır. Kurak alanlarda ise drenaj, sulanan topraklarda yüzeyde aşırı su birikmesini önlemek ve tuzluluğu kontrol etmek için gereklidir. Uygun bir drenaj sistemi tasarımı için su tablası derinliği, yetiştirilen bitki ve dren akış miktarı kritik öneme sahiptir. Temel su akış denklemlerinin çözümüyle geliştirilen sayısal modeller, söz konusu değerlerin belirlenmesinde en doğru tahmini sağlamaktadır. Sonlu elemanlar ve sonlu farklar yöntemlerinin her ikisi de drenaj araştırmalarında etkin bir şekilde kullanılmaktadır. Bu çalışmada, toprak bünyesinin yanında dren aralığı, dren derinliği ve geçirimsiz tabaka derinliği gibi drenaj tasarım parametrelerinin drenaj debisi ve su tablası derinliği üzerine etkileri, değişik düzeyde doygun gözenekli ortamlarda su akışını, ısı transferini ve çözünen madde hareketini sayısal olarak çözen SWMS_3D modeli kullanılarak sayısal denemelerle incelenmiştir. ABD Tuzluluk Laboratuvarı tarafından geliştirilen SWMS_3D modeli, hem atmosferik koşullar tarafından kontrol edilen sınır koşullarını hem de drenaj kanalı ve drenaj boruları da dahil olmak üzere çok değişik sınır koşullarını kapsamaktadır. Sonuçlar, hafif bünyeli topraklardaki drenajın ağır bünyeli topraklara göre daha hızlı olduğunu göstermiştir. Dren aralığı ve dren derinliği arttıkça drenaj debisinin de arttığı belirlenmiştir. Dren altındaki geçirimsiz tabakanın derinliği arttığı zaman, drenlerin ortasındaki su tablası yüksekliğinin azaldığı bulunmuştur. Sayısal sonuçlar, drenaj çalışmalarının sonuçları ile uyumlu çıkmıştır. Çalışma sonunda, toprak altı drenaj sistemlerinin araziye kurulmadan önce, drenaj tasarım kriterlerinin drenaj sistemi üzerine olası etkilerini önceden kestirebilmek için sayısal yöntemlerin kullanılabilir olduğu sonucuna varılmıştır.

1. Introduction

Agricultural drainage may be defined as the removal and disposal of excess water from agricultural lands. It is necessary for agricultural production in many humid regions of the world, where it is used to improve crop yields and trafficability by removing excess water from the surface and root zone. In arid regions irrigated, drainage is often needed to prevent waterlogging and soil salinity (SCS 1973).

Agricultural drainage systems involve the movement of water through both unsaturated and saturated soil. Water flow processes in this system can be simply described by combining appropriate flux equations with expressions of material balance to form the partial differential equations. The problem statement is completed by specifying the boundary and initial conditions and the required equations of the state and auxiliary equations that relate variable coefficients to properties of soil, the fluids, and the dependent variables (McWhorter and Marinelli 1999). However, governing equation for soil water flow, known as Richards Equation, is highly non linear because both the hydraulic conductivity and soil water pressure head depend on the soil water content. Exact analytical solutions of this equation are only possible for simplified flow cases under a number of restrictive assumptions. On the other hand, numerical solution of the flow equation offers a powerful tool in approximating the real nature of the unsaturated/saturated zone for a wide variety of soil systems and external conditions (Feddes et al. 1988).

The partial differential equation can be solved numerically by a method used in other areas of engineering. These methods are finite difference, integrated finite difference, finite elements, and boundary elements methods. Of these methods, the finite difference and the finite elements have received most of the attention for application in modeling flows through agricultural soils. The application of these numerical techniques to the governing differential equation yields a set of algebraic equations, which can be solved either directly or iteratively with imposed boundary and initial conditions. The advantage of numerical solution approach, compared to the analytical solution approach, is the flexibility in handling arbitrary boundary and initial conditions, arbitrary spatial parameter distributions, and nonlinearities in the governing equations (Nieber and Feddes 1999).

A number of numerical models have been developed for simulating the movement of water and solute transport in variably saturated porous media. They range from approximate methods for conducting a water balance in the soil profile to complex numerical solutions of differential equations (e.g. Srivastava and Yeh 1992; Simunek et al. 1995; Somma et al. 1995; Buyuktas and Wallender 2002). Many of the models developed have been field tested and are routinely applied to describe the hydrology of shallow water table soils, including the effect of drainage and related water management practices on yields.

In the past, the focus of the drainage project has been to improve land productivity and increase crop yield. However, there is now additional pressure to ensure system sustainability, from technological, economic, and environmental standpoint. Considering that the drainage projects include large areas, have environmental impacts, and large amount of money is invested, it is essential that the drainage schemes be properly designed, installed, and operated. More attention must be paid to the planning and design process if investments are to be protected and benefits to all stakeholders maximized. Although it is important to recognize that some fieldwork is essential, computer simulation models may be used in designing drainage systems (Madramootoo 1999). The use of computer simulation models will give the opportunity to forecast how the drainage system will be working before installing in the field.

In this study, the effects of soil texture and drainage design parameters such as drain spacing, drain depth, and depth to impervious layer on drain flow rate and water table depth are studied by numerical experimentation using SWMS_3D that simulates water flow, heat transfer and solute movement in variably saturated porous media. The aim of the study is to show that numerical models can be used in drainage studies. More realistic results can be obtained if the model is calibrated using site-specific parameters.

2. Material and Method

Numerical domain used in the simulation is given in Figure 1. In the figure S, D, d, and L stand for drain spacing, depth to impervious layer, drain depth and drain length, respectively. Drain length (L) is fixed at 20 m. Initially, the domain was assumed saturated. This situation occurs after heavy rains or irrigations.

The simulations were performed using the model, SWMS_3D, developed by Simunek et al. (1995). The water movement and solute transport are modeled by numerical solution of Richards' equation and convection-diffusion equation, respectively, using Galerkin finite element method, subject to appropriate initial and boundary conditions. The model can deal with a wide range of boundary conditions, including ditches and drain tubes, as well as boundaries controlled by atmospheric conditions. SWMS_3D can handle flow domains delineated by irregular boundaries. The flow region may be composed of non-uniform soils having an arbitrary degree of local anisotropy. The details of the model can be found elsewhere (Simunek et al. 1995).

Different soil textures (loam, silty loam and silt) were simulated by changing van Genuchten parameters (θ_s, θ_r, α, n, m, Ks) (Table 1), taken from Carsel and Parrish (1988). The van Genuchten parameters are basically fitting parameters for representing the soil-water retention curve. The n value is generally restricted to values larger than one, so that the slope of the soil water retention curve (dθ/dh) is zero as the water content approaches the saturated water content. Whereas the parameter α is related to the inverse of the air-entry value and the strict definition of this parameter is unclear (Kosugi et al. 2002).

Table 1. The van Genuchten parameters used in the simulations (Carsel and Parrish 1988).

Parameters	Loam	Silty loam	Silt
θ_s	0.430	0.450	0.460
θ_r	0.078	0.067	0.034
α, cm^{-1}	0.036	0.020	0.016
n	1.560	1.410	1.370
m=1-1/n	0.360	0.290	0.270
Ks, cm day^{-1}	24.96	10.80	6.000

Different drain spacing (S) (60 m, 100 m and 150 m), drain depth (d) (1.8 m, 2.2 m and 2.7 m) and depth to impervious layer (D) (2 m, 5 m, 10 m and 20 m) were used in the simulations.

At the soil surface a specified flux (zero) boundary condition while a no-flow boundary was used at the bottom and

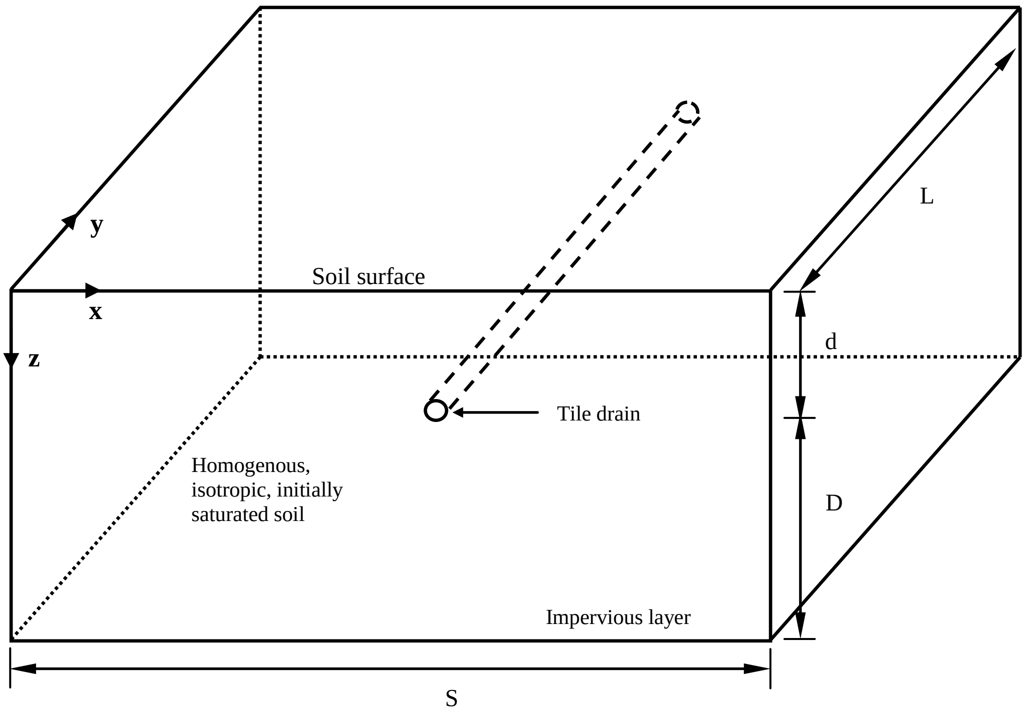

Figure 1. Numerical domain used in the simulations.

all other sides. The tile drain in the domain were treated as a boundary node surrounded by four regular square elements with adjusted hydraulic conductivities using the electric analog approach of Vimoke et al. (1963) and Fipps et al. (1986). The numerical domain was divided into quadrilateral elements. As pointed out by Istok (1989), element shape influences the size of the time step required to obtain a stable solution and the accuracy of the resulting solution. Finer discretizations were used near the soil surface and around the subsurface tile drain to accommodate abrupt changes in local fluxes and hence pressure gradients. The simulations were performed over 60 days. The results are presented in terms of drain flow rate or water table depth.

3. Results and Discussion

The effect of soil texture on drain flow rate is given in Figure 2. The highest drain flow rate belongs to loamy soil, followed by silty loam and silt. In other words, heavy-textured soils are draining slowly. Generally, coarse-textured soils drain more readily than fine-textured ones.

The hydraulic conductivity plays an important role in drainage. The highest drain flow rate was obtained from the loamy soil which has the highest hydraulic conductivity (Table 1). The results of the model are consistent with intuition. Information about drainable porosity can also be drawn from Figure 2.

Drainable porosity is defined as the ratio of volume of drainage water to the volume of soil drained (Bahceci 2008). For silty loam soil, volume of drainage water, (i.e. area under the curve representing silty loam soil in Figure 2) is computed as 71.75 m^3. Corresponding soil volume drained (i.e. volume of soil above water table for impermeable depth of 20 m at the day 60 in Figure 7e) is computed as 1364 m^3. The drainable porosity can be computed as 0.053 m^3 m^{-3} using these values. In a field study conducted in Konya Plain (Turkey), Bahceci (2008) determined the drainable porosity as 0.072 m^3 m^{-3} for silty loam soil. One should keep in mind that the value found in this study is an uncalibrated value. More realistic results could be obtained if the model is calibrated for site specific conditions.

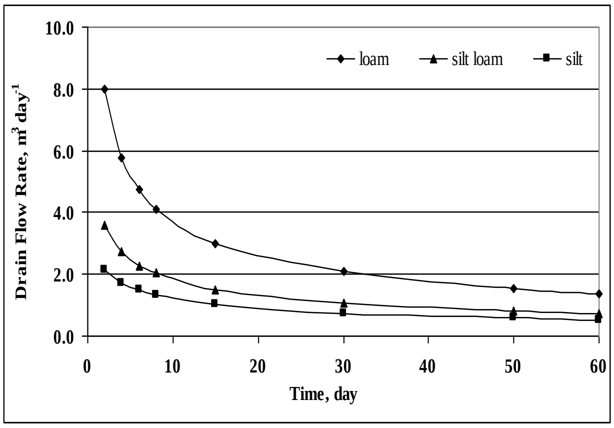

Figure 2. Drain flow rates for different soil textures (S=60 m, d=1.8 m, D=20 m).

The effect of drain spacing on drain flow rate is presented in Figure 3. Initially, drain flows for different drain spacing are almost equal to each other because the hydraulic head above the drain level is the same. Higher drain flow rate is obtained from wider drain spacing because larger volume of soil has to be drained out and the hydraulic head is changing as a result of differences in matric and gravitational potential in the profile. However, increase in drain spacing is not proportional to the drain flow. Hillel (1998) points out that the discharge per drain might become constant when the drains were spaced far apart. Then, the total drainage discharged from a field becomes proportional to the number of drains installed.

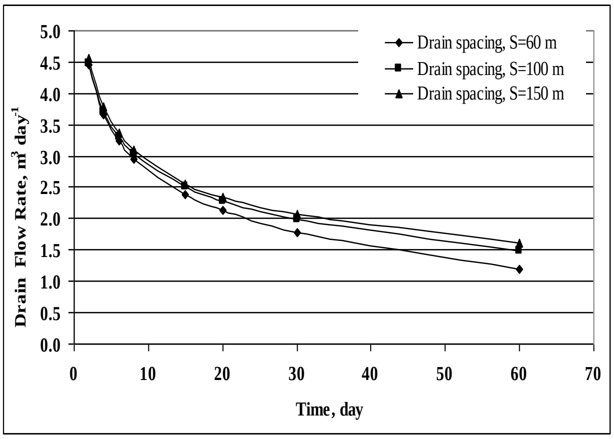

Figure 3. Drain flow rates for different drain spacing (Soil texture=silt loam, d=1.8 m, D=20 m).

The effect of drain depth on drain flow rate is shown in Figure 4. Increase in drain depth causes also increase in drain flow rates. Contrary to the case of drain spacing, the hydraulic head is different for each drain depth, resulting variations in drain flow rate. The depth of the tile drains is often controlled by the depth of outlet and depth of permeable layer (USDI 1978). Crop requirements should also be taken into the consideration. USDI (1978) reports that if drain depth increases drain spacing also increase, resulting less length of drain per area and less total costs. Trenchers' speed is also affecting drain depth. Drains installed with high speed trenchers at a depth of 7 feet will cost the least. If conventional trenchers are used, the least cost would be obtained when drain dept is about 9 feet (USDI 1978).

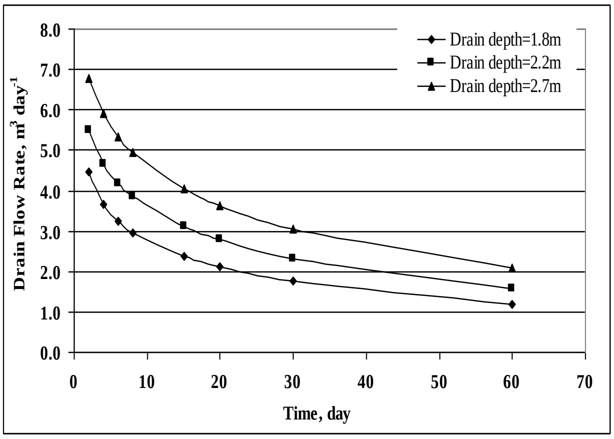

Figure 4. Drain flow rates for different drain depth (Soil texture=silt loam, S=60 m, D=20 m).

By reducing drain depth and spacing, less ground water is collected from deep in the soil profile, and in cases where the water quality declines with increased depth in the soil profile, less poor-quality water will be extracted (Grismer 1993). The reduction in drain depth will also lead to smaller volume of water being discharged from the drains and more water being used by the crop. Including crop water use in the design, although not considered in this study, will increase the lateral spacing for a specific drain depth. Such a mechanism may be possible if the shallow ground water quality is suitable for crop use (Ayars et al. 1997).

The effect of impervious layer depth on drain flow rate is given in Figure 5. Initially, the drain flow rates are not equal because the hydraulic head is changing depending on the depth of impervious layer.

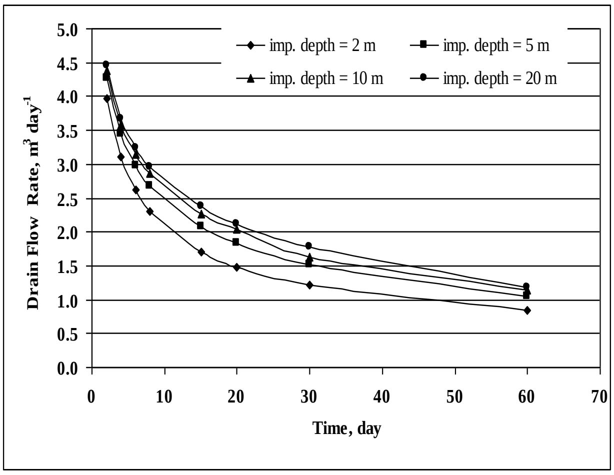

Figure 5. Drain flow rates for different impervious depth (Soil texture=silt loam, S=60 m, d=1.8 m).

Drain flow rates are increasing as the depth of impervious layer below the drain increased. However, increase in the drain flow is not proportional to the increase in the depth of impervious barrier. The depth of impervious layer does not affect drain flow rate if it is more than 10 m deep.

Evolution of water table height above drain level for the impermeable depth of 2 m is given in Figure 6. The shape of the water table looks like an ellipse. This shape of water table is encountered in the field. Water table height in the middle of the drains is decreasing about 60 cm at the end of the simulation period of 60 days for a silty loam soil.

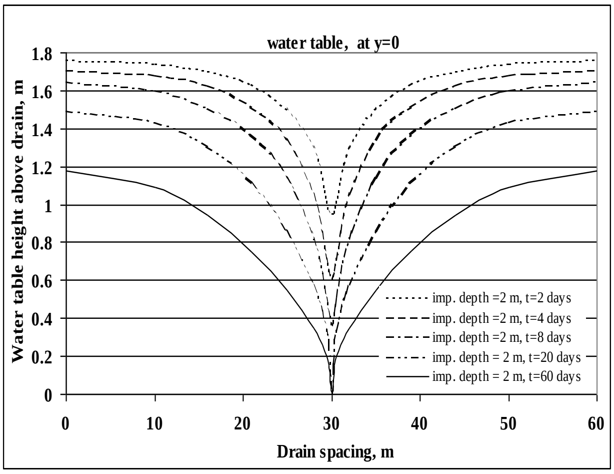

Figure 6. Evolution of water table depth for the impervious depth of 2 m. (Soil texture=silt loam, S=60 m, d=1.8 m).

Evolution of water table height above drain level for different depth of impervious layers is shown in Figure 7a, b, c, d and e. The drop in water table height at the end of simulation period is slightly higher than 60 cm for impervious depth of 2 m, whereas it is about 1 m for impervious depth of 20 m (Figure 7e).

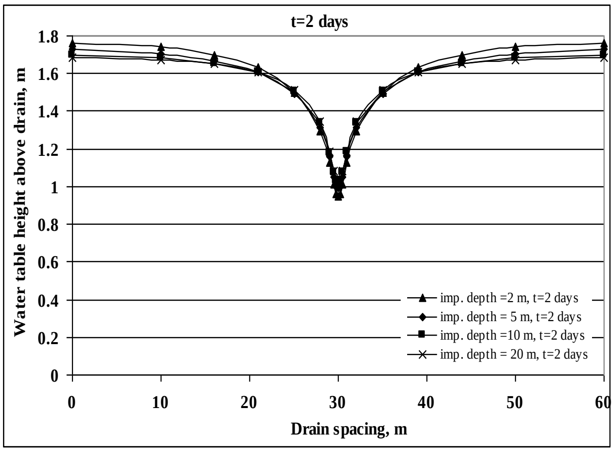

Figure 7a. Evolution of water table depth for different depth of impervious layers (Soil=silty loam, S=60 m, d=1.8 m).

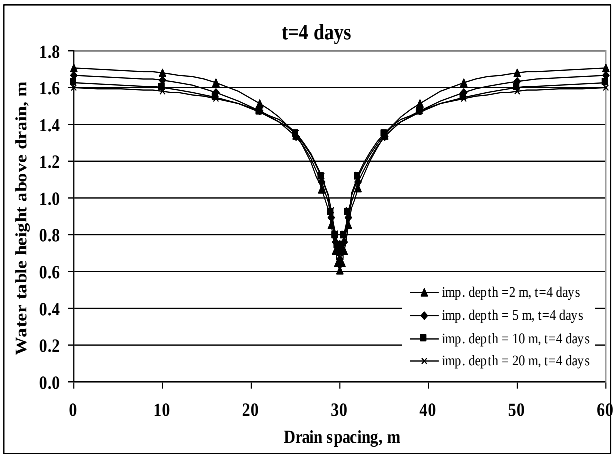

Figure 7b. Evolution of water table depth for different depth of impervious layers (Soil=silty loam, S=60 m, d=1.8 m).

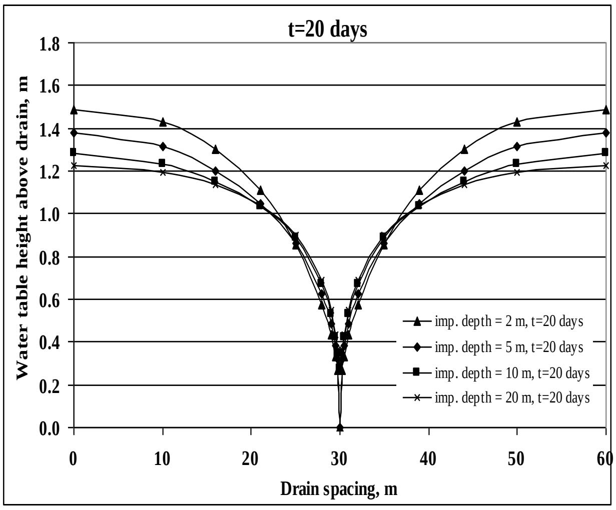

Figure 7c. Evolution of water table depth for different depth of impervious layers (Soil=silty loam, S=60 m, d=1.8 m).

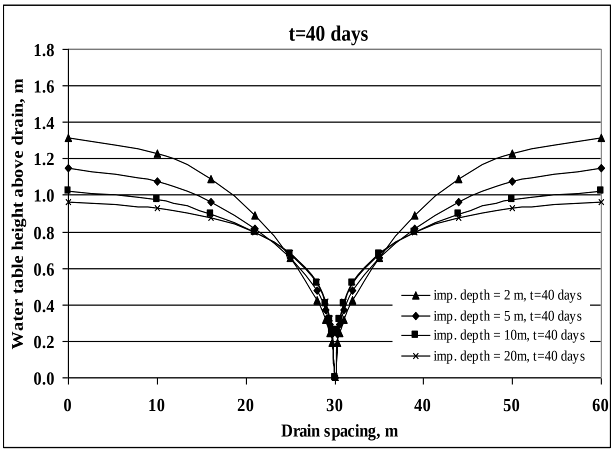

Figure 7d. Evolution of water table depth for different depth of impervious layers (Soil=silty loam, S=60 m, d=1.8 m).

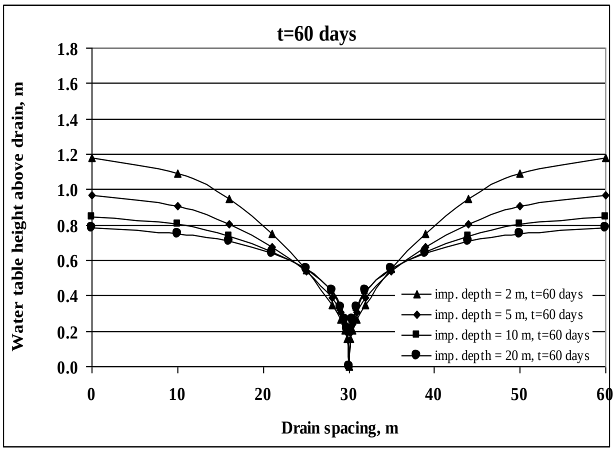

Figure 7e. Evolution of water table depth for different depth of impervious layers (Soil=silty loam, S=60 m, d=1.8 m).

Water table heights are also in accord with drain flow rates given in Figure 5. Lower water table depths correspond to higher drain flow rates because the volume of water stored in soil is decreasing.

As the depth of impervious layer increased from 10 m to 20 m, the drop in water table height is about 6 cm. In other words, as the bottom boundary condition is far apart from the drain, its effect on water table depth is not pronounced well.

4. Conclusion

Results for a simple domain given above demonstrate that the numerical simulation models can be used to analyze performance of alternative drainage systems and to optimize the drainage design. Such analyses are often not possible in practice because of time constraints, absence of meteorological and other input data.

This study can also be extended to include the effect of drainage on crop yield and water quality.

References

Ayars JE, Grismer ME, Guitjens JC (1997) Water quality as design criterion in drainage water management systems. ASCE Journal of Irrigation and Drainage Engineering 123:154-158.

Bahceci İ (2008) Determininig the drainable pore space through field tests in Konya plain, Turkey. Irrigation and Drainage 57: 71-82.

Buyuktas D, Wallender WW (2002) Enhanced subsurface irrigation hydrology model. ASCE Journal of Irrigation and Drainage Engineering 128: 168-174.

Carsel RF, Parrish RS (1988) Developing joint probability distributions of soil water retention characteristics. Water Resource Research 24: 755-769.

Feddes RA, Kabat P, Van Bakel PJT, Bronswijk JJB, Halbertsma J (1988) Modelling soil water dynamics in the unsaturated zone-state of the art. Journal of Hydrology 100: 69-111.

Fipps G, Skaggs RW, Nieber JL (1986) Drain as a boundary condition in finite elements. Water Resource Research 22: 1613-1621.

Grismer ME (1993) Subsurface drainage system design and drain water quality. ASCE Journal of Irrigation and Drainage Engineering 119: 537-543.

Hillel D (1998) Environmental Soil Physics. Academic Press, London.

Istok J (1989) Groundwater Modeling by the Finite Element Method. AGU American Geophysical Union, Washington.

Kosugi K, Hopmans JW, Dane JH (2002) Parametric Models. In: Dane JH (Ed), Methods of Soil Analysis Part 4-Physical Methods. Topp GCSSSA Book Series No 5, pp.739-757.

Madramootoo CA (1999) Planning and Design of Drainage Systems. In: Skaggs RW, van Schilfgaarde J (Eds), Agricultural Drainage. Madison, Wisconsin.

McWorther DB, Marinelli F (1999) Theory of Soil Water Flow. In: Skaggs RW, van Schilfgaarde J (Eds), Agricultural Drainage. Madison, Wisconsin.

Nieber JL, Feddes RA (1999) Solutions for Combined Saturated and Unsaturated Flow. In: In: Skaggs RW, van Schilfgaarde J (Eds), Agricultural Drainage. Madison, Wisconsin.

SCS (1973) Drainage of Agricultural Land. Soil Conservation Service, Water Information Center Inc., New York.

Simunek J, Huang K, van Genuchten MTh (1995) The SWMS_3D code for simulating water flow and solute transport in three-dimensional variably saturated media. USSL/ARS, Report No 139.

Somma F, Hopmans JW, Clausnitzer V (1995) Transient three-dimensional modelling of soil water and solute transport with root growth, root water and nutrient uptake. Plant and Soil 202: 281-293.

Srivastava R, Yeh TCJ (1992) A three-dimensional numerical model for flow and transport of chemically reactive solute through porous media under variable saturated conditions. Advances in Water Research 15: 275-287.

USDI (1978) Drainage Manual. USDI Bureau of Reclamation. United States Department of Interior, Washington.

Vimoke BS, Tyra TD, Thiel TJ, Taylor GS (1963) Improvements in construction and use of resistance networks for studying drainage problems. Soil Science Society American Journal 26: 203-207.